# Comparative Life Cycle Assessment of CSPI's 1,800 mm Corrugated Steel Pipes With North American Reinforced Concrete Pipes

Presented to

corrugated steel pipe institute

Final report

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## Report presented to

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## EXECUTIVE SUMMARY

### CONTEXT AND OBJECTIVES OF THE STUDY

The main purpose of this study is to compare the **cradle-to-grave** environmental profile of Corrugated Steel Pipe Institute (CSPI)'s 1,800 mm diameter corrugated steel pipes with a generic North American reinforced concrete pipe. The functional unit used for the comparison the storm water drainage pipes is defined as "**Provide a 11.8 m long, 1,800 mm diameter storm water drainage pipe for the North American market in 2016 for 75 years.**" Products compared in this study are presented in the table below with their main characteristics.

| Characteristics | North American reinforced concrete pipe (RCP) | Corrugated steel pipe (CSP) |
|---|---|---|
| Linear density (kg/m) | 2,690 | 85 |
| Manufacturing locations | Canada and United States | Canada |
| Sources of main inputs | Canada and United States | Canada and United States |

### METHODOLOGY

The LCA presented in this report includes the following cradle-to-grave stages: (1) raw material supply (2) transport to the manufacturer, (3) manufacturing, (4) construction, (5) use, (6) end-of-life and (7) benefits and loads from recycling as the system expansion approach was used to define the system boundaries. Data were collected from CSPI's members and are representative of the year 2016. The North American RCP was modeled based on the industry average EPD for North American underground products.

The environmental impact assessment covered six (6) indicators calculated with the TRACI 2.1 environmental impact assessment method: global warming, ozone depletion, smog, acidification, eutrophication and fossil fuel. These categories are often used in EPDs in the construction industry.

As conclusions presented in this report will be disclosed publicly, results are subject to a peer review process. Therefore, this project follows ISO 14040 and 14044 standards for reports with comparative assertions intended to be disclosed to the public.

### KEY FINDINGS AND CONCLUSIONS

Most potential impacts of the corrugated steel pipes are associated with the **production of hot-dip galvanized (HDG) coils, the transport of pipes to the construction site and machinery work for installation**. **The credit for primary steel substitution** after end-of-life recycling, which acknowledges the value of steel scrap, enables the corrugated steel pipes to significantly **reduce its impacts.**

Overall, when compared to a reinforced concrete pipe manufactured in North America, **CSPI's 1,800 mm diameter corrugated steel pipe has lower potential impacts on all studied indicators**.

The **main advantage of CSPI's CSP over the RCP is the lower mass of the product**. The RCP requires considerable amounts of raw materials, especially steel and cement, which production accounts for most of the RCP's potential impacts. Also, due to the heavier weight of the RCP product, the transport stage has higher impacts. Besides, the CSP potential impacts on environment are partly reduced by the **credit attributed to its recyclability**.

For CSPI's CSP to keep its competitive position on the environmental aspects, it is recommended:

- **Promote the use of coatings improving durability.** Results highly depend on the difference of durability between the two products. As long as CSPI can maintain the durability of its pipe, CSPI’s 1,800 mm diameter steel pipes will remain competitive.
- **Increase CSPI’s members participation in data collection.** Practices vary from one plant to another depending on the suppliers, loss and energy use. By improving the sample representativeness, CSPI can have a better understanding of its members’ plants performance and work to improve it.
- **Work with HDG suppliers to improve HDG environmental performance.** Since HDG coil production is responsible for most of the CSP potential impacts, this will help CSPI keep their competitive position on the long term.

## TABLE OF CONTENTS

## LIST OF TABLES

## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AR5 | Fifth Assessment Report of the Intergovernmental Panel on Climate Change |
| bd ft | Board foot (unit of volume 1 foot x 1 foot x 1 inch) |
| CA | Canada (for *ecoinvent* datasets which are representative of activities valid for Canada) |
| CA-QC | Canada-Quebec (for *ecoinvent* datasets which are representative of activities valid for Quebec, Canada) |
| CH | Switzerland (for *ecoinvent* datasets which are representative of activities valid for Switzerland) |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| CSPI | Corrugated Steel Pipe Institute |
| CSP | Corrugated Steel Pipe |
| eq. | Equivalent |
| GHG | Greenhouse gas |
| GLO | Global (for *ecoinvent* datasets which represent activities that are considered an average valid for all countries in the world) |
| GWP | Global warming potential |
| HDG | Hot-dip galvanized |
| IPCC | Intergovernmental Panel on Climate Change |
| ISO | International Standard Organization |
| kg | kilogram |
| km | Kilometre |
| kWh | Kilowatt-hour |
| LCA | Life cycle assessment |
| LCI | Life cycle inventory |
| LCIA | Life cycle impact assessment |
| MJ | Megajoule |
| $m^3$ | Cubic metre |
| $NO_x$ | Nitrogen oxides |
| RCP | Reinforced Concrete Pipe |
| RER | European (for *ecoinvent* datasets which are representative of activities valid for Europe) |
| RoW | Rest of the world (for *ecoinvent* datasets which represent activities that are considered an average for all countries in the world with uncertainty adjusted in comparison with Global (GLO) datasets) |
| $SO_2$ | Sulphur dioxide |

| | |
|---|---|
| tkm | Tonne-kilometre (unit of measurement equivalent to one metric tonne of material transported over a distance of one kilometre) |
| U | Unit process dataset (for *ecoinvent* datasets containing the linked, allocated input and output flows) |
| US EPA | United States Environmental Protection Agency |
| yr | Year |

## GLOSSARY

| | |
|---|---|
| Comparative assertion | As per ISO 14044:2006(en): "environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function" (ISO, 2006b). |
| Cradle-to-grave LCA | Life cycle assessment covering all activities from the extraction and production of raw materials (cradle) up to the end of life management of the studied product (grave). |
| Environmental issue | As per ISO/Guide 64:2008(en): "any concern for environmental aspects and impacts" (ISO, 2008). |
| ISO 14040 and 14044 standards | International standards for life cycle assessments. ISO 14040 defines the principles and framework for LCA and ISO 14044 describes requirements and guidelines to perform an LCA.<br>• ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework:<br>• ISO 14044:2006 - Environmental management -- Life cycle assessment -- Requirements and guidelines |
| Primary data | As per ISO 14067:2013: "quantified value of a unit process or an activity obtained from a direct measurement or a calculation based on direct measurements at its original source" (ISO, 2013). |
| Secondary data | As per ISO 14067:2013: "data obtained from sources other than a direct measurement or a calculation based on direct measurements at the original source" (ISO, 2013). |

# 1. INTRODUCTION AND CONTEXT

### WHAT THIS STUDY IS ABOUT

The Corrugated Steel Pipe Institute (CSPI) is the Canadian association representative of corrugated steel pipes (CSP) manufacturers. CSPI has conducted in 2018 a reviewed life cycle assessment (LCA) for the production of one metric tonne of corrugated steel pipe. This cradle-to-gate plus options[1] LCA was intended to support an industry average environmental product declaration (EPD) which was published in 2018, conforming to ISO 14025 and the SCS PCR "North American Product Category Rule for designated steel construction products".

CSPI now wishes to establish the complete environmental profile of one of its corrugated steel pipes, a 1,800 mm diameter CSP. This completes the previous cradle-to-gate analysis by taking into account other life cycle stages of the product. CSPI thus commissioned Groupe AGÉCO, a firm that specializes in LCA and corporate responsibility, **to conduct a comprehensive cradle-to-grave LCA** of its 1,800 mm diameter CSP.

A **comparative analysis** between CSPI's CSP and an equivalent generic North American reinforced concrete pipe – representing the average concrete pipe manufactured in North America – was also included in this study.

### USING THE MOST RIGOROUS AND RECOGNIZED TOOL FOR ENVIRONMENTAL ASSESSMENTS: LCA

This LCA was conducted in line with the ISO 14040:2006, 14044:2006 and 14044:2006/Amd1:2017 standards (ISO, 2006a, 2006b, 2017). When appropriate, the ISO 21930:2017 and EN 15804:2012 + A2:2019 standards were consulted. The study is now submitted to a peer-review process to conform to the requirement for public disclosure of comparative assertion. The first draft of this report was sent to the review panel in July 2020.

LCA is a science-based, internationally recognized tool for evaluating the relative potential environmental and human health impacts of products and services throughout their life cycle. The method can be used to identify opportunities to improve the environmental performance of products, inform decision-making, and support marketing, communication, and educational efforts.

This report presents the results and analysis of the environmental performance of CSPI's 1,800 mm diameter corrugated steel pipes according to conditions representative of the year 2016, as well as its comparison with a generic North American reinforced concrete pipe.

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[1] Terminology used in CSPI's LCA report (Arcelor Mittal, 2018) to refer to an EPD covering the information modules A1 to A3, along with Module D.

# 2. GOAL OF THE STUDY

## 2.1 OBJECTIVES

The main purpose of this study is to compare the **cradle-to-grave** environmental profile of CSPI's corrugated steel pipes with a generic North American reinforced concrete pipe. The specific goals for this study are to:

- **Determine the cradle-to-grave potential environmental impacts of corrugated steel pipes** manufactured by the CSPI's members in Canada in 2016.
- **Compare** the cradle-to-grave potential environmental impacts of CSP **with a functionally equivalent reinforced concrete pipe** representing the average RCP manufactured in North America.
- **Ensure the study meets all the requirements of ISO 14040:2006, 14044:2006 and 14044:2006/Amd1:2017** standards for conducting an LCA.

This study used an attributional product LCA approach.

## 2.2 INTENDED APPLICATIONS, AUDIENCE AND COMPARATIVE ASSERTIONS

The report is intended to provide results in a clear and useful manner to inform CSPI on the environmental performance of its corrugated steel pipe as well as on its comparison with a reinforced concrete pipe manufactured in North America.

Results and conclusions presented in this report are subject to a peer review process, as they will be disclosed publicly. According to ISO standards, the peer review of an LCA is mandatory if its results are intended for public disclosure (see section 3.5). Therefore, this project follows ISO 14040 and 14044 standards for reports with comparative assertions intended to be disclosed to the public.

# 3. Scope of the Study

## 3.1 General Description of the Studied Systems

Products under study are round storm drainage pipes characterized by an internal diameter of 1,800 mm.

### CSPI’s 1,800 mm Corrugated Steel Pipe (CSP)

Corrugated steel pipes are manufactured in Canadian mills from hot-dip galvanized (HDG) coils produced in North America. Between 2014 and 2019, 85 to 95% of HDG coil used by CSPI members were produced in Canada and the rest was imported from the USA (based on CSPI internal confidential data on HDG coil use). The manufacturing process consists in roll forming HDG steel coils at the required profile and conduit dimension. This is done by a continuous operation of incremental bending when the steel strip passes through each consecutive set of rolls.

*Image: CSPI, 2020*

The 1,800 mm diameter corrugated steel pipes are designed as storm water drainage systems. It is typically made of a steel substrate (95.9% of the mass) with a zinc coating (4.1% of the mass). The length from 1 metric ton is 11.8 m.

CSPI’s pipes are intended to be sold on the North American market.

### North American Generic Reinforced Concrete Pipe (RCP)

*Image: CPCI et al. (2019)*

The North American RCP is meant to be representative of the average product manufactured in North America. “Precast concrete (UN CPC 3755) is a construction product produced by casting concrete in a reusable mold or "form" which is then cured in a controlled environment, transported to the construction site and lifted into place. In contrast, standard concrete is placed into site-specific forms and cured on site. Precast concrete is primarily composed of portland cement, aggregates and steel reinforcement materials, but may also include a number of materials depending on its application (e.g., insulation materials in the case of an insulated panel or other types of finishes and reinforcement materials).” (CPCI & al, 2019).

According to the industry-wide EPD for North American underground concrete products (CPCI & al, 2019), underground precast products are conventionally reinforced. The North American RCP was modelled with information supporting this industry-wide EPD covering North American underground precast products, including pipe products.

Publicly available catalogues from RCP manufacturers were consulted to determine typical dimensions of a generic 1,800 mm diameter RCP. Based on data from these catalogues, it was determined that the typical length of these pipes is 2.44 m. The lightest RCP found was used as a baseline scenario.

**Table 3-1: Main characteristics of the studied products**

| Characteristics | | North American reinforced concrete pipe | Corrugated steel pipe (CSPI) |
|---|---|---|---|
| **Linear density** (kg/m) | | **2,690** | **85** |
| | *Source* | *Lafarge (2018)* | *CSPI* |
| **Manufacturing locations** | | **Canada and United States** | **Canada** |
| | *Source* | *Athena Sustainable Materials Institute (2015)* | *CSPI* |
| **Sources of main inputs** | | **Canada and United States** | **Canada and United States** |
| | *Source* | *Athena Sustainable Materials Institute (2015)* | *CSPI* |
| **Minimal height of cover (mm)** | | *600* | *450* |
| | *Source* | *OPS (2018b)* | *OPS (2018a)* |

## 3.2 FUNCTION, FUNCTIONAL UNIT AND REFERENCE FLOWS

Life cycle assessment relies on a 'functional unit' as a reference for evaluating the components within a single system and/or among multiple systems on a common basis. It is therefore critical that this parameter is clearly defined and measurable.

CSPI's CSP is a round pipe mainly used for **underground storm water drainage**. The North American reinforced concrete pipe (RCP) serves the same purpose. This study focuses on water drainage pipes characterized by an **internal diameter of 1,800 mm.** This study is valid to a maximum water drainage flow rate that corresponds to a CSP Manning's roughness coefficient of 0.02.

The RCP and the CSP under study are installed underground with a **minimal height of cover of 600 and 450 mm** respectively, in compliance with the Ontario Provincial Standards Drawings (OPS (2018a, 2018b)). Requirements from other Canadian provinces are equivalent to what stated in the OPSD. As the baseline scenario for the CSP has a corrugation profile of 125 x 25 mm and a wall thickness of 1.6 mm, **the maximum depth of installation for the baseline scenario is 11 m**, which corresponds to the maximum depth at which the baseline CSP can be installed (FDOT, 2006). For projects requiring a deeper installation, the CSP wall must be thicker. The influence of the CSP wall thickness is studied in a sensitivity analysis in which the link between the required depth of installation is linked to the CSP wall thickness. The maximum depth of cover for the RCP depends on the class of pipe and is up to 15.5 m for class V pipes (FDOT, 2006).

The baseline scenario is a project for which pipes have been designed to meet a 75-year durability requirement, and for which materials have been installed in a suitable environment. A 75 years design service life is required by provincial ministries on some projects such as storm water drainage for freeways (Ontario Ministry of Transportation 2014). Based on the NCSPA guidelines (NCSPA, 2016), the site pH has to be higher than 4 and its resistivity 750 ohm-cm to install the CSP. In such conditions, the CSP can be designed to meet the durability requirement. Even when pipes are designed for 75 years, there is still high uncertainty on how many years the pipes will actually last. Durability assessment of steel pipes found in literature ranges from 30 to 100 years and of concrete pipes from 50 to 120 years (National Academies of Sciences, Engineering, and Medicine, (2015)). **In the baseline scenario, it is assumed that both pipes are replaced after the 75-years period**, i.e. that they both have a 75-year reference service life. As shown in the sensitivity analysis in Section 6.6.1, this hypothesis does not affect the conclusions of this study.

The functional unit used for the inventory and impact assessment of the storm water drainage pipes is defined as follows:

**Provide a 11.8 m long, 1,800 mm diameter underground storm water drainage pipe for the North American market in 2016 for 75 years.**

In terms of mass, the functional unit represents:

- 1 metric tonne of CSP; and
- 31,744 metric tonnes of RCP.

Reference flows describe the types and quantities of material required to fulfill the functional unit. In this study, the inventory of these flows is therefore scaled to consider the production of a 11.8 m long, 1,800 mm diameter pipe. Intermediate flows (i.e. material and energy resources used for the operation of each activity related to the life cycle of each product) are described in section 5.

## 3.3 System boundaries and system description

The system boundaries identify the life cycle stages, processes, and flows considered in the LCA and should include all activities relevant to attaining the study objectives and fulfill the functional unit defined in section 3.2 . The following sections (3.3.1 and 3.3.2) present a description of the life cycle stages included in the system boundaries as well as temporal and geographical boundaries of this study.

Within each of these stages, the LCA considers all identifiable "upstream" inputs to provide as comprehensive a view as is practical of the product system. For example, when considering the environmental impact of transportation, not only are the emissions of the truck considered, but also included are the impact of processes and inputs needed to produce the fuel. The production chain of all inputs is thus traced back to the original extraction of raw materials.

All system components and production processes have been included using either readily available information or a reasonable estimate except for the processes excluded according to the cut-off criteria described in section 3.4.

### 3.3.1 Life cycle stages

The life cycle stages considered are: (1) raw material supply (2) transport to the manufacturer, (3) manufacturing, (4) construction, (5) use, (6) end-of-life and (7) benefits and loads from recycling. These stages are illustrated in Figure 3-1 and Figure 3-2. These stages can also be referred to according to the EN 15804 and ISO 21930 information modules listed in Table 3.2. Throughout the report, these modules will be disclosed for reference next to the life cycle stage.

**Table 3.2: Stages included or not considered in the system boundaries**

| Production stage | | | Construction stage | | Use stage | | | | | | | End-of-life stage | | | | Benefits and loads from recycling |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
| Raw material supply | Transport | Manufacturing | Transport | Construction - Installation | Use | Maintenance | Repair | Replacement | Refurbishment | Operational energy | Operational water use | Deconstruction, | Transport | Waste processing | Disposal | Potential net benefits from recycling beyond the system boundary |
| Included | | | Included | | Inclu-ded | Excluded | | | | | | Included | | | | Included |

(1) **Raw material supply (A1)** includes all upstream activities related to the production of raw materials that are used to produce studied pipes and joint systems. These activities start with raw material extraction or secondary material acquisition and end at the gate of the raw material supplier. It includes, but is not limited to, the recovery or extraction and processing of feedstock materials, furnace and related process operations at the steel mills and cement production. It also includes purchased chemicals and plastic used for the pipe manufacturing.

(2) **Transport to manufacturer (A2)** includes the transportation by truck, freight train, transoceanic ship or barge of the raw materials to the manufacturing facility.

(3) **Manufacturing (A3)** refers to activities occurring at the manufacturing facility including processing of input materials, packaging production, waste management and treatment (solid waste). Electricity, natural gas and other fuels as well as water use at the facility are thus considered in this stage. Used oil is recovered and solid wastes are either sent to landfills, incinerated or recycled. Waste transportation to the treatment sites is done by truck. Emissions related to waste management are accounted for in this stage.

(4) **Construction (A4 and A5)** refers to the transport of CSP and RCP by truck to the construction site as well as machinery use (e.g. excavator, compaction equipment, etc.) and material required for pipe installation.

(5) **Use stage (B1)** refers to the oxidation of the zinc coating of the CSP and to the carbonation of the RCP. Maintenance activities consist of cleaning the invert of the pipes from accumulated debris. Repair activities consist of relining, patching, and paving inverts. Due to the high variability of the maintenance and repair activities – which depend on the environment (such as water flow, slope, pH) in which the pipes are installed – it was not reasonable to model an average use profile. Therefore, the maintenance and repair activities are excluded from this in the baseline scenario. A sensitivity analysis was performed to assess the influence of excluding these activities on results with several repair scenario. As the reference service life of each product is equal to the study period, there is no replacement included in the baseline scenario. Given that the systems under study are passive systems, the energy and water operational demand during the use stage is not relevant. Therefore, B6 and B7 are excluded of the scope.

(6) **End-of-life stage (C1-C4)** covers stages from the deconstruction and demolition of the pipes to the end-of-life treatment. For the RCP, it includes handling of pipes and crushing mechanical work. For the CSP,

it includes handling of pipes. It also includes for both products the collection of pipes by truck and the post-consumer treatment, i.e. landfilling and recycling.

(7) **Net benefits or loads from recycling stage (D)** covers benefits and burdens beyond the primary function of the systems assessed. In the allocation approach applied in this study – the system expansion approach – the potential impacts (i.e. burdens) due to the recycling of pipes at their end of life are attributed to the systems under study. A credit equivalent to the primary material substituted by the recycling processes (i.e. benefit) is also accounted in this stage.

The ‘Utilities, infrastructure and natural resources’ sub-system shown in Figure 3-1 and Figure 3-2 pertains to resource procurement (water, energy, chemicals and materials) including extraction, treatment and transformation of natural resources and transport to use sites (e.g. polymer, fuels, etc.). The ‘Emissions’ sub-system pertains to emissions into air, water and soil over the considered life cycle stages.

**Figure 3-1: Life cycle stages of the corrugated steel pipe**

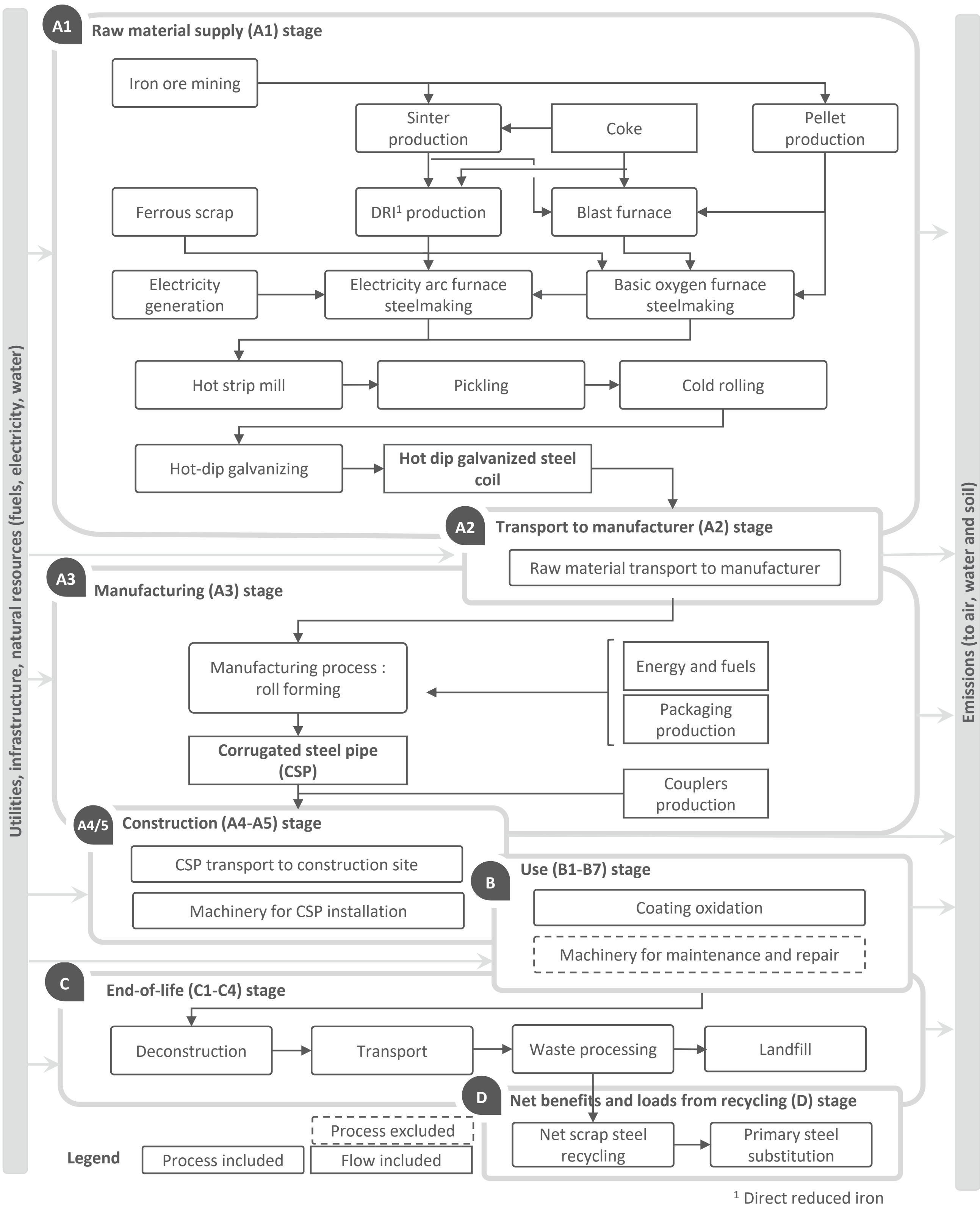
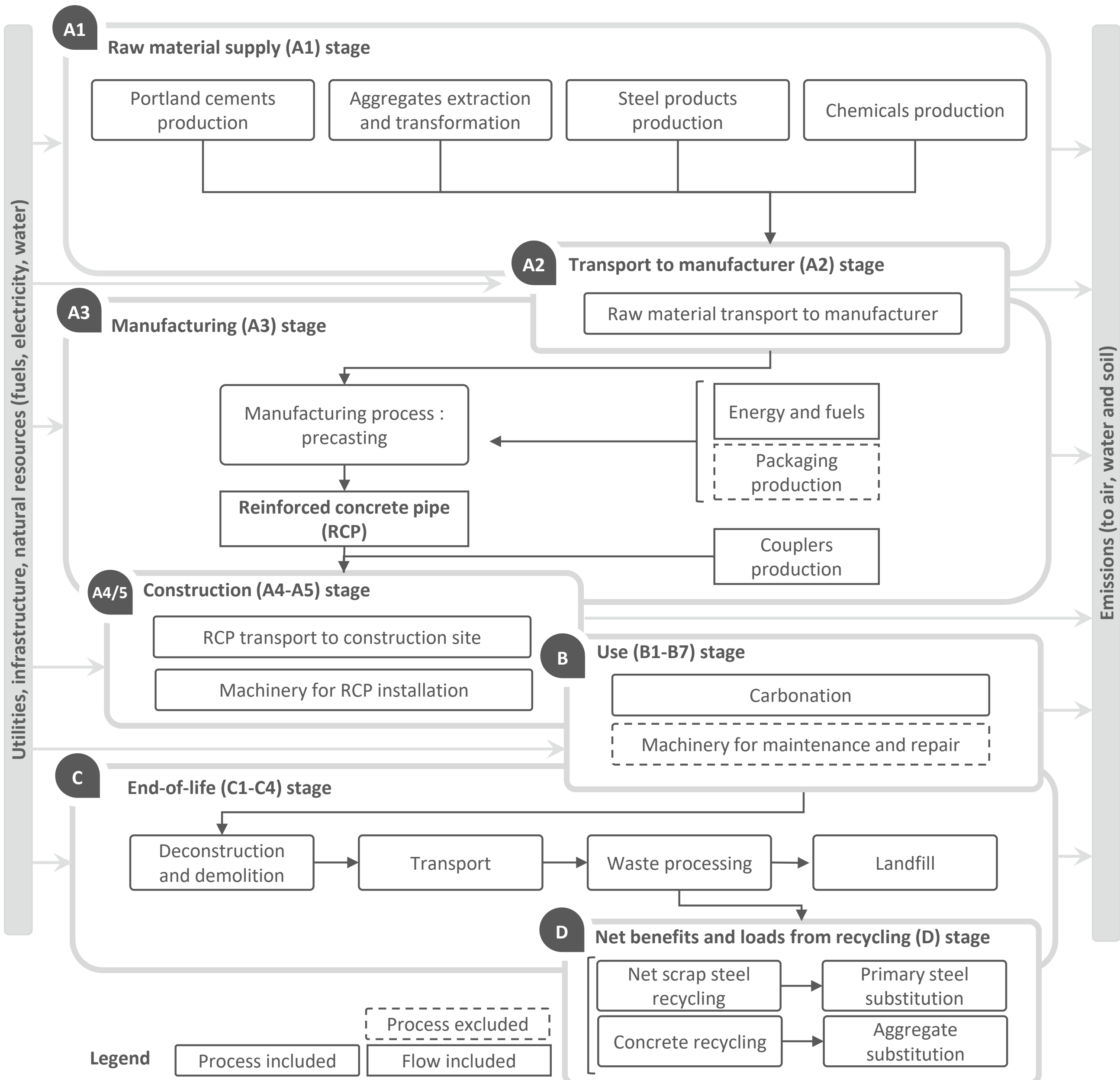


**Figure 3-2: Life cycle stages of the reinforced concrete pipe**




## 3.3.2 TEMPORAL AND GEOGRAPHIC BOUNDARIES

Data and assumptions are intended to be representative of the production of CSPI's CSP and a generic North American RCP during the operational year of 2016. Primary data was collected for operations occurring in 2016 (12 consecutive months) and assumptions were based on operations performed in 2016 (see section 5). Data used for modelling the generic North American RCP was taken from an LCA performed by the Athena Sustainable Materials Institute (2015) and assessing activities occurring in 2014 (12 consecutive months). This data covers underground precast products manufactured in Canada and the United States and using the technology available in these countries. This LCA was used to establish an industry-wide EPD for North American precast products.

It is important to note that some processes may generate emissions over a longer period than the studied timeframe which is the reference service life of products. This applies to landfilling, which causes emissions (chromium VI, phosphate) over a period whose length (several decades to over a century/millennium) depends on the design and operation parameters of the burial cells and how the emissions are modelling in the environment.

Primary data and assumptions for both CSP and RCP are representative of current equipment and processes associated with CSP and RCP manufacturing in North America. For the RCP, datasets were modified to adapt the European data to the North American context and to ensure robust comparisons. Default electricity grid mixes used in *ecoinvent* datasets were adapted with country-specific grid mixes for the activities contributing the most to the environmental profile.

## 3.4 CUT-OFF CRITERIA

Processes or elementary flows may be excluded if their contributions to the total system's mass or energy flow or environmental impact are less than 1%. All product components and production processes were included when the necessary information is readily available or a reasonable estimate could be made. It should be noted that the capital equipment and infrastructure available in the *ecoinvent* database are included in the background data (e.g. data indirectly involved in the model) for this study in order to be as comprehensive as possible.

Based on Groupe AGÉCO's past experience and previous studies[2] or the relatively low contribution of the life cycle substages to which they pertain, the following processes are excluded from the study due to their expected contribution lower than the cut-off criteria and the lack of readily available data:

- Packaging for the inputs delivered to the manufacturing facilities (e.g. plastic films, pallets, plastic straps, steel wire, etc.) for RCP supply
- Packaging of the finished RCP
- Benefits and loads from recycling used oil for CSP manufacturing and waste from RCP manufacturing
- Employee commuting and administrative activities
- Office heating
- Infrastructure of the manufacturing facilities
- Lubricating oil for joint
- Material for bedding

It is estimated that the combined effects of the excluded processes represent less than 5% of the total potential environmental impacts.

## 3.5 CRITICAL REVIEW

As CSPI wishes to publicly disclose the results of this study, which includes a comparative scenario, a peer review process is mandatory under the ISO 14040 series standards. This critical review is necessary "to decrease the likelihood of misunderstanding or negative effects on external interested parties" (ISO, 2006a). The role of the critical review, as defined in ISO 14044, is to ensure that:

[2] More than 250 LCA studies conducted over the past 10 years.

- the methods used to carry out the LCA are consistent with ISO 14040:2006, ISO 14044:2006 and ISO 14044:2006/Amd1:2017 standards;
- the methods used to carry out the LCA are scientifically and technically valid;
- the data used are appropriate and reasonable in relation to the goal of the study;
- the interpretation reflects the limitations identified and the goal of the study;
- the study report is transparent and consistent.

The critical review is carried out by a panel of external independent reviewers (as stated in ISO 14044, section 6.3). The selected panel members and their experience in relation to this study are presented in Table 3-3.

**Table 3-3: Composition of the peer review panel**

| Member | Role | Affiliation/ Organization | Relevant experience |
|---|---|---|---|
| **Tom Gloria** | Chair | Industrial Ecology Consultants | Dr. Gloria is the Managing Director of Industrial Ecology Consultants and is an internationally recognized life cycle practitioner. He is a Life Cycle Assessment Certified Professional and a member of the Board of Directors of the American Center for Life Cycle Assessment (ACLCA). He has contributed to the development of product category rules (PCR) in the construction sector and has revised numerous environmental product declaration (EPD) from construction products including steel and concrete products. |
| **Brandie Sebastian** | Reviewer, steel expert | John Beath Environmental | Brandie Sebastian is the Sustainability Practice Co-Leader at John Beath Environmental. She also serves as the Vice Chair/Secretary of the ACLCA. She has conducted and reviewed LCA in various sectors including steel products. She is also experienced in the development of ISO and ASTM standards, but also of PCR and EPD. In particular, she co-led the development of the initial North American Steel Product PCR and is currently serving on the critical review panel for the update to this PCR. She is knowledgeable of green building rating systems such as LEED. |
| **Jeremy Gregory** | Reviewer, concrete expert | Massachusetts Institute of Technology – Concrete Sustainability Hub | Jeremy Gregory is the Executive Director of the Concrete Sustainability Hub and a Research Scientist at MIT in Civil and Environmental Engineering. His research topics include product environmental footprinting and characterization of sustainable material systems. He has applied these methods to a range of products and industries – including the building and infrastructure sectors – and published scientific articles on LCA in the building and infrastructure sectors. |

The panel was solicited to review the final draft report of the detailed LCA study. The first draft report was submitted to the panel on July 1st, 2020, and the final report was approved on October 19th, 2020. See Appendix D for the external critical review statement.

Note that a critical review in no way implies that the panel members endorse the results of the LCA study, nor that they endorse the products assessed.

# 4. APPROACH

## 4.1 ALLOCATION METHODOLOGY

A common methodological decision point in LCA occurs when the system being studied is directly connected to a past or future system or produces co-products. When systems are linked in this manner, the boundaries of the system of interest must be widened to include the adjoining system, or the impacts of the linking items must be distributed—or allocated—across the systems. ISO 14044 prioritizes the methodologies related to applying allocation. It is best to avoid allocation through system subdivision or expansion. If that is not possible, then one should perform allocation using an underlying physical relationship. If using a physical relationship is not possible or does not make sense, then one can use another relationship.

The CSP was modelled in part with data from the Worldsteel Association. This data used the system expansion approach for the allocation of co-products during the HDG steel coil production.

The RCP was modelled using data from Athena Sustainable Materials Institute (2015). According to the documentation supporting this data, RCP precast facilities did not only manufacture underground precast products but also structural, architectural and insulated precast products. The allocation of RCP manufacturing operations was then done on a mass basis (i.e. mass of the products manufactured). The RCP was modelled with data from the Worldsteel Association for the rebar production. This data used the system expansion approach for the allocation of co-products during the rebar production.

### 4.1.1 RECYCLED MATERIAL

The system expansion approach was used as the end-of-life allocation method for the two systems.

**CSP system:** As inherent properties of steel are not affected by the recycling process for steel, the closed-loop allocation procedure from ISO 14067 was applied to steel products. In the resource production stage, there is no burden associated with the use of scrap. However, the recycling of scrap at the steel mills are included in the scope of the system. At the end-of-life stage, deconstruction and transport to the recycling facility are considered as well as the recycling of net scrap (i.e. steel scrap recycled minus steel scrap entering the system) to steel. A substitution credit for the net scrap recycling is given to the steel life cycle for avoiding primary steel production.

**RCP system:** The open-loop allocation procedure from ISO 14067 was applied to concrete production and end-of-life treatment. In the resource production stage, raw material enters the system as 100% virgin material. At the end-of-life stage, deconstruction and transport to the recycling facility are considered as well as the recycling of concrete to aggregates. A substitution credit is given to the concrete life cycle for avoiding primary aggregates production. The open-loop allocation procedure enables consistency with the system expansion methodology used by Worldsteel for slag, a co-product of steel production. The same allocation procedure was applied to rebar as to the CSP.

### 4.1.2 ECOINVENT PROCESSES WITH ALLOCATION

Many of the processes in the *ecoinvent* database also provide multiple functions, and allocation is required to provide inventory data per function (or per process). It should be noted that the allocation methods used in *ecoinvent* for background processes (i.e. processes representing the complete supply chain of a good or service used in the CSP and RCP life cycles) may be inconsistent with the approach used to model the foreground system (i.e. to model the manufacturing of products). While mass allocation was used for foreground processes from RCP, continuation of this methodology into the background datasets would add complexity without substantially improving the quality of the study. Therefore, the study accepts the allocation method used by *ecoinvent* for processes included in the model. Note that the *ecoinvent* 3.4 database with the recycled content allocation method was used in this study.

## 4.2 DATA QUALITY REQUIREMENTS AND ASSESSMENT METHOD

Data sources are assessed on the basis of time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, source description and uncertainty of the information, as prescribed in ISO 14044. The pedigree matrix (Weidema et al., 2013) for rating inventory data is a useful tool that was used in this study as a guide for the qualitative evaluation of data quality, and to conduct a quantitative uncertainty analysis. The matrix used in this study is presented in Table 4-1.

The importance of given data on the total system results is examined using sensitivity testing and contribution analysis. Explanations of their influence on the confidence of the results are reported in section 6.6.

Although every effort was made to use the best available information and to consider key influential factors such as geography, temporal relevance, scientific credibility, and internal study consistency, life cycle assessment is a complex task that relies on numerous data sources and assumptions. While the results presented in this study are intended to be reliable, they should be used only within the context of the boundaries and limitations discussed in this report (see section 3.3). In cases where important information was unknown, uncertain or highly variable, sensitivity analyses were performed to evaluate the potential importance of the data gap (see section 6.6).

**Table 4-1: Pedigree matrix used for data quality assessment developed by Weidema et al. (2013)**

| Score | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **Reliability** | Verified data based on measurements | Verified data partly based on assumptions or non-verified data based on measurements | Non-verified data partly based on qualified estimates | Qualified estimate (e.g. by industrial expert) | Non-qualified estimate |
| **Completeness** | Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations | Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations | Representative data from only some sites (<50%) relevant for the market considered or >50% of the sites but from shorter periods | Representative data from only one site relevant for the market considered or some sites but from shorter periods | Representativeness unknown or data from a smaller number of sites and from shorter periods |
| **Temporal correlation** | Less than 3 years of difference to the time period of the dataset | Less than 6 years difference to the time period of the dataset | Less than 10 years difference to the time period of the dataset | Less than 15 years difference to the time period of the dataset | Age of data unknown or more than 15 years of difference to the time period of the dataset |
| **Geographical correlation** | Data from area under study | Average data from larger area in which the area under study is included | Data from area with similar production conditions | Data from area with slightly similar production conditions | Data from unknown area or distinctly different (North America instead of Middle East, OECD-Europe instead of Russia) |
| **Further technological correlation** | Data from enterprises, processes and materials under study | Data from processes and materials under study (i.e. identical technology) but from different enterprises | Data from processes and materials under study but from different technologies | Data on related processes or materials | Data on related processes on laboratory scale or from different technologies |

## 4.3 DATASET QUALITY ASSESSMENT

Datasets used to model the systems were also assessed with the pedigree matrix (Weidema et al., 2013) for their quality. Results presented in section 6.7 are based on the following criteria:

**High quality:** The dataset selected to model the flow has an average score of 2 or under.

**Acceptable quality:** The dataset selected to model the flow has an average score between 2 and 4.

**Low quality:** The dataset selected to model the flow has an average score of 4 or over.

The results from this assessment are presented in section 6.7 with a discussion regarding their influence on the confidence of the life cycle impact assessment.

## 4.4 IMPACT ASSESSMENT METHOD AND INDICATORS

Impact assessment classifies and combines the flows of materials, energy, and emissions into and out of each product system by the type of impact their use or release has on the environment. In this study, the chosen life cycle impact assessment (LCIA) method for all indicators is TRACI v2.1. (U.S. EPA, 2012), a method widely used in North America. The TRACI impact assessment methodology assesses ten impact categories. Six of them were studied in the report. These are the categories presented in EPDs and certification systems such as LEED. The global warming indicator from TRACI was updated with GWP characterisation factors from the Intergovernmental Panel on Climate Change (IPCC)'s fifth assessment report (AR5). This updated impact assessment methodology is the most commonly used and internationally accepted methodology for LCA studies of products for the North American market. The six (6) indicators covered in this study are presented below.

**Global warming:** The **global warming potential** refers to the impact of a temperature increase on the global climate patterns (e.g. severe flooding and drought events, accelerated melting of glaciers) due to the release of greenhouse gases (GHG) (e.g. carbon dioxide and methane from fossil fuel combustion). GHG emissions contribute to the increase in the absorption of radiation from the sun at the earth's surface. These emissions are expressed in units of kg of carbon dioxide equivalents **(kg $CO_2$ equivalent)**. The GWP from the IPCC's AR5 were calculated on a basis of a cumulative radiative forcing over 100-year time horizon (Myhre et al. 2013). They do not include climate carbon feedback. This is coherent with recognized GHG accounting frameworks such as the GHG Protocol.

**Ozone depletion:** The **ozone depletion potential** indicator measures the potential of stratospheric ozone level reduction due to the release of some molecules such as refrigerants used in cooling systems (e.g. chlorofluorocarbons). When they react with ozone ($O_3$), the ozone concentration in the stratosphere diminishes and is no longer sufficient to absorb ultraviolet (UV) radiation which can cause high risks to human health (e.g. skin cancers and cataracts) and the terrestrial environment. The concentration of molecules that are responsible of ozone depletion is expressed in kilograms of trichlorofluoromethane equivalents **(kg CFC-11 equivalent).**

**Acidification:** The **acidification potential** refers to the change in acidity (i.e. reduction in pH) in soil and water due to human activity. The increase in $CO_2$ emissions and other air pollutants (e.g. $NO_x$ and $SO_2$) generated by the transportation and manufacturing sectors are the main causes of this impact category. The acidification of land and water has multiple consequences: degradation of aquatic and terrestrial ecosystems, endangering numerous species and food security. The concentration of the gases responsible for the acidification is expressed in sulphur dioxide equivalents **(kg $SO_2$ equivalent).**

**Eutrophication:** The **eutrophication potential** measures the enrichment of an aquatic or terrestrial ecosystem due to the release of nutrients (e.g. nitrates, phosphates) resulting from natural or human activity (e.g. the discharge of wastewater into watercourses). In an aquatic environment, this activity results in the growth of algae which consume dissolved oxygen present in water when they degrade and thus affect species sensitive to the concentration of dissolved oxygen. Also, the increase in nutrients in soils makes it difficult for the terrestrial environment to manage the excess of biomass produced. The concentration of nutrients causing this impact is expressed in nitrogen equivalents **(kg N equivalent)**.

**Smog:** The **formation of tropospheric ozone** indicator covers the emissions of pollutants such as nitrogen oxides and volatile organic compounds (VOCs) into the atmosphere. They are mainly generated by motor vehicles, power headquarters and industrial facilities. When reacting with the sunlight, these pollutants create smog which can affect human health and cause various respiratory problems. The concentration of pollutants causing smog are expressed in kg of ozone equivalents (**kg $O_3$ equivalent**).

**Fossil fuel:** The depletion of **fossil fuels** refers to the use of energy from non-renewable resources (e.g., natural gas, coal, petroleum). The extraction of hard coal, oil and natural gas for heating, transportation and electricity production can cause the depletion of fossil fuels. The fossil fuel indicator quantifies damages to fossil fuels resources and is expressed as surplus energy for the future mining of resource (**MJ surplus**).

A sensitivity analysis on the impact assessment method was performed using the CML (baseline) method.

## 4.5 Calculation tool

SimaPro 9.0 software, developed by PRé Consultants (www.pre.nl), was used to assist the LCA modelling, link the reference flows with the LCI database, and compute the complete LCI of the systems. The final LCI results were calculated combining foreground data (intermediate products and elementary flows) with generic datasets providing cradle-to-gate background elementary flows to create a complete inventory of all the storm water pipes under study.

## 4.6 Comparison between systems

This study was intended to deliver a complete ISO compliant LCA report (PDF) to enable future public communications on CSPI's products environmental performance, which are not part of this study. The results of this study will be used by CSPI to communicate publicly. This communication will rely on the interpretation of the results on the environmental performance of CSP in comparison to RCP detailed in section 6.3. As required by ISO 14044, the equivalence of the two systems being compared was evaluated before interpreting the results. Based on the performance characteristics and the main function of the two systems, it was assumed that a 11.8 m long and 1,800-mm diameter underground storm water drainage corrugated steel pipe is functionally equivalent to an underground storm water drainage reinforced concrete pipe having the same dimensions. The same functional unit, methodological considerations (i.e. performance, system boundary, data quality, allocation procedures, decision rules on evaluating inputs, and outputs and impact assessment) were thus used for the comparison. The main limitation regarding the comparative analysis is that the results are only applicable to CSP and RCP products with a profile of 1,800 mm diameter and 11.8 m length, an RSL of 75 years and that are manufactured in North America. Other limitations related to methodological considerations were the same for both systems.

# 5. LIFE CYCLE INVENTORY

## 5.1 DATA SOURCES

Life cycle inventory (LCI) data collection mainly concerns the materials used, the energy consumed, the waste generated, and the emissions released by each process included in the system boundaries. Data sources for the RCP model were selected to represent North American industry average production in 2014. Data sources for the CSP were selected to represent Canadian industry average production in 2016.

For CSP, primary data have been collected in three manufacturing plants members of the CSPI in Canada regarding HDG steel coil supply, energy consumption, lubricant use, packaging, and waste. Data collection is based on operations during the 2016 year.

The RCP was modelled based on the LCA report for North American underground precast concrete products (Athena Sustainable Materials Institute, 2015). This LCA is the most recent LCA available for North American concrete pipes representative of the industry. It was intended to support the EPD for North American precast products. This LCA is representative of underground precast products manufactured by the Canadian Precast/Prestressed Concrete Institute, the National Precast Concrete Association and the Precast/Prestressed Concrete Institute members in 2014. Life cycle inventory data were collected in Canadian and American facilities of precast products. Data collected covers less than 10% of all members. Underground precast products, which is one of the four categories of precast products studied in this LCA, include pipe production. As mentioned in the Athena report (Athena Sustainable Materials Institute, 2015), underground pipes are conventionally reinforced.

Most life cycle inventory data were taken from the *ecoinvent* database 3.4 (*ecoinvent*, 2017). The *ecoinvent* datasets that were the most representative of the products and contexts being examined were selected. The data's geographical representativeness is one aspect taken into account as part of the data quality assessment.

As a North American LCI was available for HDG coil production from the Worldsteel Association, it was selected to model the CSP. The inventory for HDG production in North America from the Steel Recycling Institute (2017) was used. LCI is representative of HDG coil production via electric arc furnace and blast-furnace by several steel mills in North America. The data for this LCI was collected during 12 consecutive months between 2006 and 2010 in North America steel mills. The LCI is based on data covering more than 30% of production of HDG coil production in North America. In order to allow better consistency in the comparison, Worldsteel LCI were also used to model steel products in RCP with inventories as compiled by SimaPro in the Industry Data 2.0 database. Worldsteel LCIs used have not been updated since 2011 but they are the most up-to-date industry average available (an update will be released in 2020 but was not available at the time of this study). This approach is likely conservative since GHG emissions intensity of the iron and steel sector have slightly decreased in the USA (US EPA, 2020a), and seems to be stable in Canada (ECCC, 2020).

The global average dataset for rebar production from the Worldsteel Association was used to model North American rebar for the RCP. This choice was made to enhance modeling comparability as datasets to model steel in both products come from the same source. However, the dataset which is publicly available and was used for this study is of low geographical and technical representativity as it represents global production. The recycled content of North American rebar is much higher than the global rate as most of the production is done via EAF in North America.

A few modifications to the *ecoinvent* dataset modelling portland and portland limestone cement were made by AGÉCO regarding the composition of cement, electricity mixes and $CO_2$ emissions from clinker production to better represent Canadian and American cement production. These modifications are described in Table 5-1.

**Table 5-1: Main modifications made to *ecoinvent* processes**

| Activity | Modifications to *ecoinvent* inventory | Data source |
|---|---|---|
| **Clinker production** | $CO_2$ emissions | Canada: ECCC, 2020<br>USA: US EPA, 2020 |
| **Portland cement production** | Composition | Canada: Cement Association of Canada, 2016<br>USA: PCA, 2016 |
| **Portland limestone cement production** | Composition | Canada and USA: Cement Association of Canada, 2016 |

Note: modifications made to ecoinvent are detailed in Table A.4.

- In their annual national inventory reports, ECCC and US EPA disclose the GHG emissions for the clinker industry in Canada and in the USA respectively. GHG emissions covering both calcination of limestone and stationary fuel combustion for the year 2018 were used to better reflect regional practices for clinker production.
- The compositions of portland cement and portland limestone cement manufactured in Canada were taken from the Canadian industry average EPD for general use and portland limestone cements (Cement Association of Canada - CAC, 2016). Data supporting this EPD was collected in 2014 and covered more than 60% of the Canadian production. The composition is representative of production from CAC member facilities in Canada (74% in Ontario and Western provinces; 26% in Quebec and Eastern provinces). Portland limestone cement composition for American manufacturing plants was assumed to be the same as the Canadian composition. Portland cement composition from American manufacturing plants is based on the American industry average EPD for portland cements (PCA, 2016). Data supporting this EPD was collected in 2014 from plants representing more than 70% of the American production.

Table 5-2 lists the sources of primary and secondary data used for the modelling of CSP and RCP. Appendix B presents the *ecoinvent* datasets used to model each reference flow.

**Table 5-2: Sources of primary and secondary data for both products**

| Life cycle stage | CSP | | RCP | |
|---|---|---|---|---|
| | Description of parameter and data source | Unit as provided by the data source | Description of parameter and data source | Unit as provided by the data source |
| **Raw material production (A1)** | | | | |
| **Characteristics of the storm pipes** | - Mass per metre: CSPI primary data | kg / piece of 11.8 m | - Mass per metre: Lafarge (2018) | kg / piece of 2.44 m |
| **Raw material** | - Mass of HDG coil: CSPI primary data | kg / tonne of finished product | - Mass of cement, aggregates, steel, plastic and chemicals used: Athena Sustainable Materials Institute (2015) | kg / tonne of finished product by material |
| **Packaging** | - Mass of steel strap: CSPI primary data | kg / tonne of finished product | *See note below the table* | |
| **Transport to manufacturer (A2)** | | | | |
| **Transport of purchased material for pipe production** | - Transportation mode and average supply distance between suppliers and Canadian manufacturers: CSPI primary data | km and tonne of transported good / tonne of finished product | - Transportation mode and aggregated average distance between suppliers and North American manufacturers for all inputs: Athena Sustainable Materials Institute (2015) | tkm / tonne of finished product (aggregated over all materials) |
| **Manufacturing plant (A3)** | | | | |
| **Pipe manufacturing** | - Energy (electricity, natural gas, propane and diesel) and water use: CSPI primary data | kg of combustible consumed or MJ / tonne of finished product | - Energy (electricity, natural gas, propane and diesel) and water use: Athena Sustainable Materials Institute (2015) | L of combustible consumed or MJ / tonne of finished product |
| **Transport of waste generated on-site** | - Average distance between CSPI's facilities and waste management sites: assumption made by AGÉCO | km | - Average distance between manufacturers and waste management sites: assumption made by AGÉCO | km |
| **Treatment of waste generated on-site** | - Quantities of waste generated by type: CSPI primary data<br>- End-of-life treatment for each type of waste: CSPI primary data | kg / tonne of finished product by waste type and treatment | - Quantities of waste generated by type: Athena Sustainable Materials Institute (2015)<br>- End-of-life treatment for each type of waste: Athena Sustainable Materials Institute (2015) | kg / tonne of finished product by waste type and treatment |
| **Packaging** | - Mass of skids: CSPI primary data | kg / tonne of finished product | *See note below the table* | |
| **Couplers manufacturing** | - Mass of steel connecting band, angles rubber gasket and bolts: CSPI primary data | kg / piece of 11.8 m | - Mass of rubber gasket: assumption made by Groupe AGÉCO | kg / piece of 2.44 m |
| **Transport to construction site (A4)** | | | | |

| Life cycle stage | CSP | | RCP | |
|---|---|---|---|---|
| | Description of parameter and data source | Unit as provided by the data source | Description of parameter and data source | Unit as provided by the data source |
| **Transport of finished pipes and joints to construction site** | - Average truckload (weight of pipes per truck): CSPI primary data<br>- Transportation distance: assumption made by AGÉCO | number of pieces per truck<br>km | - Average truckload (weight of pipes per truck): Con Cast Pipe (2020)<br>- Transportation distance: assumption made by AGÉCO | number of pieces per truck<br>km |
| **Installation (A5)** | | | | |
| **Machinery for excavation, handling and back filling** | - Fuel consumption by machinery: Chilana et al. (2016) in gallons over a given project | | | |
| **Transport and treatment of packaging** | - Average distance between construction site and waste management sites: assumption made by AGÉCO<br>- Quantities of waste generated by type: CSPI primary data<br>- End-of-life treatment for each type of waste: CSPI primary data | km<br>kg per type of waste and end-of-life treatment | *See note below the table* | |
| **Use (B1)** | | | | |
| **Coating or rebar oxidation** | - Percentage of coating oxidized through the whole service life of the product: assumption made by AGÉCO | | - Carbonation depth to determine whether oxidation is possible: H.Stripple et al. (2018) | |
| **Carbonation** | - Not applicable | | - $CO_2$ emissions: H.Stripple et al. (2018) | |
| **End of life (C1-C4)** | | | | |
| **Machinery for deconstruction and demolition** | - Volume excavated, time for handling pipes, volume backfilled: assumption made by AGÉCO in m$^3$ of excavated and backfilled soil and L of diesel per FU<br>- Crushing for reinforced concrete pipe: assumption made by AGÉCO in m$^3$ per FU | | | |
| **Transport of used pipes and couplers** | - Distance to treatment sites: assumption made by AGÉCO in km | | | |
| **Treatment of used pipes and couplers** | - Average recycling, landfilling in Canada and in the USA: Steel Recycling Institute (n.d.) | % | - Average recycling, landfilling in Canada and in the USA: US EPA (2020b) | % |
| **Net benefits from recycling (D)** | | | | |

| Life cycle stage | CSP | | RCP | |
|---|---|---|---|---|
| | Description of parameter and data source | Unit as provided by the data source | Description of parameter and data source | Unit as provided by the data source |
| **Recycling of steel and concrete pipes** | - Average recycling, landfilling in Canada and in the USA: Steel Recycling Institute (n.d.) | % | - Average recycling, landfilling in Canada and in the USA: US EPA (2020b)<br>- Crushed concrete is assumed to be used as aggregates for filling without no further crushing: assumption made by AGÉCO | % |

Note: grey cells represent data excluded due to the cut-off criteria as described in Section 3.4.

## 5.2 DATA AND KEY ASSUMPTIONS

Key assumptions made for each life cycle stage included in the LCA models of CSP and RCP are detailed in this section as well as the reference flows (i.e. inputs and outputs per functional unit). Table 5-3 to Table 5-7 separately do not allow a fair comparison between the two products as manufacturing activities are of different nature and the raw material supply stage (A1) already accounts for part of the transformation activities such as cement production and HDG manufacturing.

#### RAW MATERIAL SUPPLY

Table 5-3 and Table 5-5 present the data used for modelling the resource production stage for both products.

- **Characteristics of the CSP**: the mass of a 1,800 mm diameter CSP, its composition and the location of raw material suppliers was based on primary data collection from CSPI. CSP is made from HDG coils made in North America. The co-product allocation methodology for HDG coil production is system expansion, as described in Table 5-4. HDG coils are the raw material for the production of CSP. HDG coil production include all upstream activities leading to the supply of a HDG coil, including the transportation of inputs such as steel scrap, iron ore, and coke, to the HDG manufacturing plants as well as energy use for the manufacturing of coils as described in Figure 3-1.
- **Mass of the RCP:** publicly available catalogues from North American RCP manufacturers were consulted to determine the average mass of the 1,800 mm diameter RCP. The RCP with the lowest mass was taken as a baseline scenario (Lafarge, 2018). This RCP is a B wall reinforced concrete pipe with a linear weight of 2,690 kg/m and a length of 2.44 m which is a standard length in the industry according to the data found in this research.
- **Composition of the RCP:** the composition of the 1,800 mm diameter RCP was based on the average composition of underground precast products in North America.
- **Location of clinker manufacturing plants for the RCP**: RCP manufacturing location was based on the market size distribution of precast concrete manufacturing between the USA (85%) and Canada (15%) (IBISWorld, n.d.a and n.d.b). It was assumed that clinker supply comes from the same country.
- **Packaging of raw materials**: packaging of raw materials for the RCP was excluded. Packaging raw material for the CSP consists of steel strap holding HDG coils together and was included in the model as the data was easily available.

**Table 5-3: Main input to the resource production stage for corrugated steel pipes per functional unit**

| Material | Quantity | Unit | Notes |
|---|---|---|---|
| Hot-dip galvanized coil | 1,017 | kg | Production of coils in North America (occurring at the suppliers' plants).<br>The model accounts for all upstream activities leading to HDG coil (raw material supply, transportation to the HDG supplier and manufacturing). It also includes loss from rolling pipes. |
| Steel strap | 1.6 | kg | |

**Table 5-4: Allocation methodology followed for co-product during HDG coil manufacturing**

| | Main co-products | Allocation method |
|---|---|---|
| Coke oven | CO gas | System expansion |
| | Coke, benzene, tar, toluene, xylene, sulphur | |
| Blast furnace gas | Hot metal, slag | |
| Basic oxygen furnace (OF) | Basic oxygen furnace gas, crude steel, slag | |
| Electric Arc Furnace (EAF) | Electric arc furnace crude steel, slag | |

**Table 5-5: Main inputs to the resource production stage for reinforced concrete pipes per functional unit**

| Material | Quantity | Unit | Notes |
|---|---|---|---|
| Portland cement | 4,291 | kg | |
| Portland limestone cement | 98 | kg | |
| Pre-blended cement | 1 | kg | |
| Fine aggregate - natural sand | 10,834 | kg | |
| Fine aggregate - manufactured | 1,549 | kg | |
| Coarse aggregate - natural gravel | 2,818 | kg | |
| Coarse aggregate - crushed | 9,291 | kg | |
| Natural lightweight aggregate | 10 | kg | |
| Supplementary cementing materials - Fly ash | 565 | kg | Considered as raw material due to system expansion allocation[3] |
| Slag cement | 432 | kg | |
| Chemical Admixture (CA) - Air entraining | 13 | L | |
| CA - Water reducer/plasticizer | 3 | L | |
| Chemical Admixture - Accelerator | 3 | L | |
| CA - High Range Water Reducer (HRWR)/Super Plasticizer and/or Viscosity Modifying Admixture (VMA) | 20 | L | |
| CA - Corrosion inhibiting | 15 | L | |
| Form release agent | 5 | L | |
| Rebar | 454 | kg | |
| Welded Wire Reinforcement (WWR) | 365 | kg | |
| Steel anchors | 16 | kg | |
| Steel stressing strand | 25 | kg | |
| Polypropylene fibers | 88 | kg | |
| Steel fibers | 2 | kg | |
| Glass Fibre Reinforced Polymer (GFRP) reinforcing bars | 3E-03 | kg | |
| Expanded polystyrene | 5 | bd ft | |
| Brick | 1 | kg | |
| Pigments | 95E-03 | kg | |
| Net consumables | 2 | L | |
| Total batch water use | 1,819 | L | |

### TRANSPORT TO MANUFACTURER

Table 5-6 lists the main assumptions for the transport to the manufacturer stage for both products.

- **Distance and transportation mode for the transportation of inputs to the CSP manufacturing facility:** the 288 km distance represented a weighted average distance between one HDG supplier and its clients which are also CSPI members. This plant covers more than 50% of CSPI's member supply for HDG coil.
- **Distances and transportation modes for the transportation of inputs to the RCP manufacturing facility:** data were based on the North American EPD for underground precast products (Athena Sustainable Materials Institute, 2015). They did not manage to cover all inputs supply, however, heaviest inputs, including cement, aggregates and steel, were covered by the data collection. Results are available as an average aggregated data in tonne.km per metric tonne of underground precast concrete products per mode of transport. This inventory limitation does not enable to fully understand

[3] The cut-off allocation procedure used by the concrete industry is tested in a sensitivity analysis.

what contributes to the transport stage between the weight of constituents and the distance on which constituents are transported.

**Table 5-6: Assumptions for A2 – transport to the manufacturing plant stage per functional unit**

| | CSP | RCP | Unit | Note |
|---|---|---|---|---|
| **Transport of materials to CSP and RCP manufacturers** | | | | |
| Truck | 294 | 3,485 | tkm/FU | **CSP:** Transportation of raw materials to HDG manufacturers is accounted for in the raw material supply stage (as a subset of this stage). **RCP:** Transportation of raw materials listed in Table 5-5 are accounted for in this stage. |
| Freight train | | 1,140 | | |
| Transoceanic ship | | 857 | | |
| Barge | | 384 | | |

Note: grey cells represent zero values.

#### MANUFACTURING STAGE

Table 5-7 lists the inputs and outputs to the manufacturing stage for both products.

- **Allocation of the manufacturing inputs and outputs**: the majority of the precast facility operations were dedicated to the production of one or more of the four precast product groups. The quantities of energy and water use as well as the quantity of waste generated at the RCP manufacturing were allocated on a mass basis approach. This means that they were equally allocated to a given mass unit of precast product regardless of the type of product manufactured. No allocation was required for the manufacturing of the CSP.
- **Losses:** the quantities of energy and water use allocated to one metric tonne of finished pipe took into account losses occurring during the manufacturing processes.
- **Electricity mix for the CSP:** Canadian manufacturing facilities are connected to the Canadian electric grid.
- **Electricity mixes for the RCP:** the electricity grid mixes were modelled based on the financial share of the precast manufacturing in North America. The data on the production volume are taken from IBISWorld (n.d.a and n.d.b). The electricity was therefore provided by the American (87%) and Canadian grids (13%).
- **Waste from manufacturing activities transportation:** all waste is treated in a radius of 50 km and is transported in a municipal collection truck.
- **Recycling benefits and loads:** the recycling and credits regarding the avoidance of virgin material production due to the recycling of steel waste during CSP manufacturing was accounted in the benefits and loads from recycling stage (D). The recycling of used oil from CSP manufacturing and waste from RCP manufacturing were excluded.
- **Packaging:** no packaging manufacturing was considered for the RCP products since the packaging is reused (spacers, pallets and bunks). Once these elements are worn, their disposal is accounted for in the waste section of the manufacturing stage (non-hazardous waste). For the CSP, skids are only used once before being externally recycled. Therefore, the manufacturing of skids is accounted for in the manufacturing stage, based on EN 15804:2012 +A2:2019.
- **Characteristics of joints for both products**: the mass and type of material used to joint CSP was based on primary data. Gasket weight for RCP is assumed to be the same as the one used for CSP for each joint. As the RCP has a shorter length than CSP, more joints are required per metre of pipe.

**Table 5-7: Main inputs and outputs to the manufacturing stage per functional unit**

| | RCP | CSP | Unit | Note |
|---|---|---|---|---|
| **Manufacturing location** | | | | |
| Canada | 13% | 100% | % production | |
| USA | 87% | | | |
| **Energy consumption** | | | | |
| Electricity | 624 | 104 | kWh | Solar and wind electricity generated on site for RCP is assumed to be burden free |
| Natural gas | 115 | 4.6 | $m^3$ | |
| Gasoline | 11 | | L | |
| Diesel | 70 | 3.0 | L | |
| Heavy fuel oil | 3 | | L | |
| Liquefied Propane Gas | 15 | | L | |
| Propane | | 0.1 | kg | |
| **Water consumption** | | | | |
| Public water | 10 | | $m^3$ | 0% of the batch water is recycled |
| **Waste generated** | | | | |
| Used oil | | 0.25 (100% recycling) | kg | |
| Steel scrap (including strap) | | 19 (100% recycling) | kg | |
| Hazardous solid waste | 316 (6% landfill; 94% recycling) | | kg | |
| Other solid waste | 2,039 (70% landfill; 27% recycling; 3% incineration) | | kg | |
| **Packaging** | | | | |
| Skid production | | 5.4 | kg | |
| Polyurethane | | 0.05 | kg | |
| **Couplers** | | | | |
| Connecting band (steel) | | 50 | kg | |
| Gasket (rubber) | 1.93 | 0.4 | kg | |
| Bolt (steel) | | 0.20 | kg | |

Note: grey cells represent zero values.

### TRANSPORT TO THE CONSTRUCTION SITE

- **Average distribution distances:** the average distribution distance for both products and their joints is 250 km.
- **Transportation mode:** both products are transported by truck.
- **Truckload:** the average truckloads for CSP and RCP are is 1,931 kg/truck and 34,955 kg/truck respectively.

- **Loss:** no loss is considered during transportation since it is very rare for both products to be damaged. It is also possible to fix minor deformation of the CSP at the construction site.

#### INSTALLATION

- **Loss:** no loss is considered during the installation since it is very rare for both products to be damaged. It is also possible to fix minor deformation of CSP on site.
- **Machinery:** diesel consumption for excavation, backfilling, handling and other mechanical work during the construction phase was based on Chilana et al. (2016). The average consumption over the project was taken, regardless of the inner diameter of pipes which are of the same order as studied products.
- **Backfilling material:** material from excavation is used for backfilling trenches.
- **Bedding:** material for bedding is excluded.
- **Packaging end-of-life**: most skids used for CSP transport are landfilled.

**Table 5-8: Main data to the installation stage**

| | RCP | CSP | Unit |
|---|---|---|---|
| **Deconstruction and demolition - C1** | | | |
| Diesel consumption in machinery | 46 | 46 | L/FU |
| **Treatment of waste from packaging** | | | |
| Transport distance to end-of-life facility | | 50 | km |
| Skid | | 5.4<br>(90% recycling; 10% landfill) | kg |

Note: grey cells represent zero values

#### USE

- **CSP coating corrosion:** as no data was available for this parameter and since environmental impacts on indicators do not exist for zinc or aluminium emissions to water, coating corrosion was not included in the baseline model.

- **RCP carbonation and corrosion:** assumptions related to the carbonation of the RCP are presented in section 5.3. The carbonation depth was calculated with data from the Tier 2 approach from H.Stripple et al. (2018). With a carbonation rate of 0.85 mm/year$^{0.5}$ for underground infrastructure, the carbonation depth is 7 to 8.5 mm for a reference service life of 75 to 100 years. It is therefore unlikely for the carbonation front to reach the rebar of the RCP and for the rebar to be corroded. Besides, as mentioned for the CSP, rebar corrosion would not affect studied indicators.

- **Reference service life (RSL):** the reference service life of the two products is assumed equal to the study duration, i.e. 75 years,. Therefore, no replacement is required in the baseline scenario. As there is high uncertainty on the durability of both products (National Academies of Sciences, Engineering, and Medicine, (2015)), and since results highly rely on the reference service life of each product, the impact of the reference service life of products is studied in a sensitivity analysis. As shown in section 6.6.1, when pipes are installed in a suitable environment and designed based on the soil characteristics, the uncertainty of the reference service life does not affect conclusions.

#### END-OF-LIFE

Table 5-9 presents the end-of-life treatment rates and machinery work used to model the end-of-life stages of both products. Both the CSP and the RCP are managed at the end of their reference service life, i.e. not left in place. Is it assumed that products are replaced at the end of their reference service life, which means that another pipe is installed at the same place the RCP and CSP were first located. Therefore excavation, backfilling and compaction work serve both for uninstalling studied pipes and for installing new installed pipes which are out of the scope of this study. It is assumed that the materials from both infrastructures (the RCP and the CSP) are sorted directly on site and sent to a treatment facility.

- **Deconstruction and demolition (C1):** machinery work shared with the future installed products, which includes excavation and backfilling is attributed to the future product life cycle. The impact of this allocation is studied in section 6.6.5. Fuel consumption for handling pipes during the deconstruction phase was based on Chilana et al. (2016) for handling pipes during construction. As the RCP is reinforced concrete, crushing was added to this stage.

- **Transport to end-of-life facility:** both products are collected by a conventional truck. RCP is sent to end-of-life treatment facilities (such as storage for concrete aggregates, landfilling and sorting or recycling plants for rebar) while CSP is directly sent to a recycling facility. In both cases, a 50 km distance was considered.
- **Waste processing:** it was assumed that CSP is sent to a recycling facility without any treatment since it is made of one material. RCP is sorted on site and sent to end-of-life treatment facilities.

- **End-of-life treatments:** the average profile of the end-of-life treatments was based on the average waste management statistics over the period 2009-2013 provided by the Steel Recycling Institute (2014) for steel compounds and the U.S. EPA (2017) data for concrete recycling in 2015. Data for the five most recent years available was taken from SRI (2014) to reduce the influence of variations over time. Data used for CSP recycling is representative of general steel scrap recycling rates in North America and is specific to neither the construction sector nor the type of product. This rate can be considered as conservative since at the end-of-life of the product, large quantities of steel are easily available (no sorting is required) in a single location so steel from the CSP is typically recycled. Data used for the recycling of rebar in the RCP is representative of rebar recycling in North America. This rate was applied to the steel content of the RCP (2.6% based on the mass inventory for A1 for the RCP).

**Table 5-9: Main data to the end-of-life stages**

| | RCP | CSP | Unit |
|---|---|---|---|
| **Deconstruction and demolition - C1** | | | |
| Handling | 3.5 | 3.0 | L/FU |
| Crushing | 31,744 | | kg/FU |
| **Transport to end-of-life facility – C2** | | | |
| Transport distance | 50 | 50 | km |
| **End-of-life treatment – C4** | | | |
| **End-of-life for steel compounds** | | | |
| Recycling rate | 70% | 90% | - |
| Landfilling rate | 30% | 10% | - |
| **End-of-life for concrete** | | | |
| Recycling rate | 83% | | - |
| Landfilling rate | 17% | | - |

Note: grey cells represent zero values

### NET BENEFITS OR LOADS FROM RECYCLING

- **End-of-life benefits - CSP:** as mentioned in section 4.1.1, the system expansion was applied to account for the secondary function of CSP's life cycle, i.e. providing scrap to the recycling stream and avoiding the production of primary steel. A credit was thus attributed to the CSP's life cycle. This credit, called the scrap value by Worldsteel, considers the potential impacts of steel scrap recycling and the avoided burden of producing a functionally equivalent primary steel. The net scrap approach, which subtracts the scrap recycled at the end-of-life from the input scrap (equivalent to the recycled content of the steel at the raw material supply stage), was used to be consistent with the allocation procedure at the entrance of the system (closed loop approximation). The recycling rate used is 90% for the scrap generated at the end-of-life of the CSP (Steel Recycling Institute, n.d.), 100% for the scrap generated during the manufacturing stage (CSPI primary data) and the scrap input is 0.44 tonne / tonne of hot-dip galavanized steel based on the north american Worldsteel dataset for HDG. The net scrap is therefore equal to 1,000x(0.92-0.44) + 17x(1-0.44) = 489 kg per functional unit.

- **End-of-life benefits - RCP:** as mentioned in section 4.1.1, the system expansion was applied to account for the secondary function of RCP's life cycle, i.e. providing crushed concrete to the recycling stream and avoiding the production of aggregates. A credit was thus attributed to RCP's life cycle. This credit considers the potential impacts of concrete recycling and the avoided burden of producing functionally equivalent primary aggregates. When a material is recycled into a lower quality material, an allocation factor is required. The market-based allocation methodology suggested in ISO 14067 for the allocation factor is not applicable to the aggregate market as there is no global market price for aggregates. Therefore, an allocation factor of 1 was applied, as it represents the best-case scenario for concrete recycling (this is equivalent to ignoring the degradation of aggregates). RCP recycling also provides steel scrap from rebar. The same allocation procedure was applied to rebar as to the CSP. A recycling rate of 70% (Steel Recycling Institute, n.d.) and a scrap input of 0.37 tonne per tonne of rebar, based on the global Worldsteel dataset for rebar, were used.

## 5.3 DATA AND KEY ASSUMPTIONS FOR THE CARBONATION LCI

Carbonation is the reaction of products containing calcium oxide or calcium hydroxide with atmospheric carbon dioxide. During the lifetime of the RCP, $CO_2$ in the air reacts with the material in the concrete and becomes bound. This results in $CO_2$ uptakes. As the RCP is buried underground, the carbonation taked place on the inner surface of the pipe, where the concrete is in contact with $CO_2$. The methodology followed in this study for $CO_2$ uptake calculation was based on Tier 1 approached suggested by H.Stripple et al. (2018). Uptakes from cement during the RCP reference service life were accounted for as well as concrete end-of-life (demolishing, crushing and storage) and secondary use uptakes by aggregates since the system expansion allocation procedure was chosen for the RCP.

With the Tier 1 approach, the $CO_2$ uptakes by concrete in the RCP in kg $CO_2$ correspond to 20% of $CO_2$ emissions from calcination of clinker during the use stage, and to 3% of $CO_2$ emissions from calcination of clinker during the end-of-life and secondary use stages. Table 5-10 describes parameters used and calculation steps. As $CO_2$ emissions represent less than 1% of the RCP global warming results, the Tier 1 approach was selected. **Results from carbonation calculation are not displayed in the final results due to their low contribution.**

**Table 5-10: Calculation of carbonation emissions for the RCP per FU**

| Cement composition | Mass | Unit | Emissions from calcination | Uptake from carbonation | | Total | Unit |
|---|---|---|---|---|---|---|---|
| | | | | Use | End-of-life and secondary use | | |
| **Portland cement (PC)** | **135** | **kg** | | | | | |
| PC - USA | 117 | kg | | | | | |
| Clinker in PC - USA | 108 | kg | 94 | 19 | 3 | 22 | kg $CO_2$ |
| PC - Canada | 18 | kg | | | | | |
| Clinker in PC - Canada | 17 | kg | 13 | 2.6 | 0.39 | 3 | kg $CO_2$ |
| **Portland limestone cement (PLC)** | **3.1** | **kg** | | | | | |
| PLC - USA | 2.7 | kg | | | | | |
| Clinker in PLC - USA | 2.2 | kg | 1.9 | 0.39 | 0.06 | 0.45 | kg $CO_2$ |
| PLC - Canada | 0.41 | kg | | | | | |
| Clinker in PLC - Canada | 0.34 | kg | 0.27 | 0.05 | 0.01 | 0.06 | kg $CO_2$ |
| **Pre-blended cement (PBC)** | **0.04** | **kg** | | | | | |
| Clinker in PBC | 0.04 | kg | 0.03 | 0.01 | 0 | 0.01 | kg $CO_2$ |
| **Total captured $CO_2$** | | | | **22** | **3.3** | **25** | **kg $CO_2$** |

# 6. LIFE CYCLE IMPACT ASSESSMENT AND INTERPRETATION

This section presents the results of the life cycle impact assessment for the selected indicators. It starts with the **environmental profile** (section 6.1) and a **contribution analysis** (section 6.2) of corrugated steel pipe. Then, the **comparison between the environmental performance** of CSPI's CSP and the RCP is presented (section 6.3). The interpretation is completed with **sensitivity analyses** (section 6.6), **scenario analyses** (section 6.6), **data quality assessment** (section 6.7) and **uncertainty analysis** (section 6.8). Detailed LCI and LCIA results are presented in Appendix B.

## 6.1 ENVIRONMENTAL PROFILE OF CSPI'S CORRUGATED STEEL PIPES

The cradle-to-grave results for CSPI's corrugated steel pipes are presented in Table 6-1. As explained in section 3.3.1, the information modules (A1-A5, C1-C4 and D) are only disclosed next to the life cycle stages for reference purposes.

**Table 6-1: Results per UF (one metric tonne) of corruragted steel pipe**

| Indicators[1] | Units | Production (A1-A3) | Construction (A4-A5) | End-of-life (C1-C4) | Net benefits or loads from recycling (D) | Total |
|---|---|---|---|---|---|---|
| **Global warming** | kg $CO_2$ eq. | 2.4E+03 | 3.1E+02 | 1.6E+01 | -7.6E+02 | **2.0E+03** |
| **Ozone depletion** | kg CFC-11 eq. | 1.7E-05 | 7.4E-05 | 3.9E-06 | 5.3E-06 | **1.0E-04** |
| **Smog** | kg $O_3$ eq. | 1.9E+02 | 7.6E+01 | 4.1E+00 | -2.1E+01 | **2.5E+02** |
| **Acidification** | kg $SO_2$ eq. | 1.1E+01 | 2.6E+00 | 1.4E-01 | -1.5E+00 | **1.2E+01** |
| **Eutrophication** | kg N eq. | 6.6E-01 | 4.6E-01 | 2.1E-02 | -6.1E-02 | **1.1E+00** |
| **Fossil fuel depletion** | MJ surplus | 1.7E+03 | 6.7E+02 | 3.5E+01 | -3.5E+02 | **2.1E+03** |

*Note: Results may not add up due to rounding.*

[1] *All indicators are evaluated using the TRACI 2.1 method.*

## 6.2 CONTRIBUTION ANALYSIS FOR CSPI'S CORRUGATED STEEL PIPE

A contribution analysis is performed to determine the extent to which each process modelled contributes to the total indicator results of the systems under study. Lower quality data may be suitable in the case of a process whose contribution is minimal. Similarly, processes with a major influence on the study results should be characterized by high-quality information. In this study, the contribution analysis is a simple observation of the relative importance of the different processes to the overall potential impact.

The main contributors to each midpoint indicator are presented in Table 6-2 for CSPI's corrugated steel pipe. An activity or process is considered a major contributor when its potential impacts represent at least 10% of the impact for the indicator. Explanations on the causes of these contributions are provided in Table 6-3. **Most potential impacts are associated with the production of HDG coils, the transport of pipes to the construction site and machinery work for installation. The credit for primary steel substitution after end-of-life recycling, which acknowledges the value of steel scrap, enables the corrugated steel pipes to significantly reduce its results for most of the indicators assessed.**

#### CONTRIBUTION ANALYSIS OF POTENTIAL CRADLE-TO-GRAVE LIFE CYCLE IMPACTS OF CSPI'S CORRUGATED STEEL PIPE EXCLUDING BENEFITS AND LOADS FROM RECYCLING

**Figure 6-1: Contribution analysis of potential cradle-to-grave life cycle impacts of CSPI's corrugated steel pipe excluding benefits and loads from recycling**

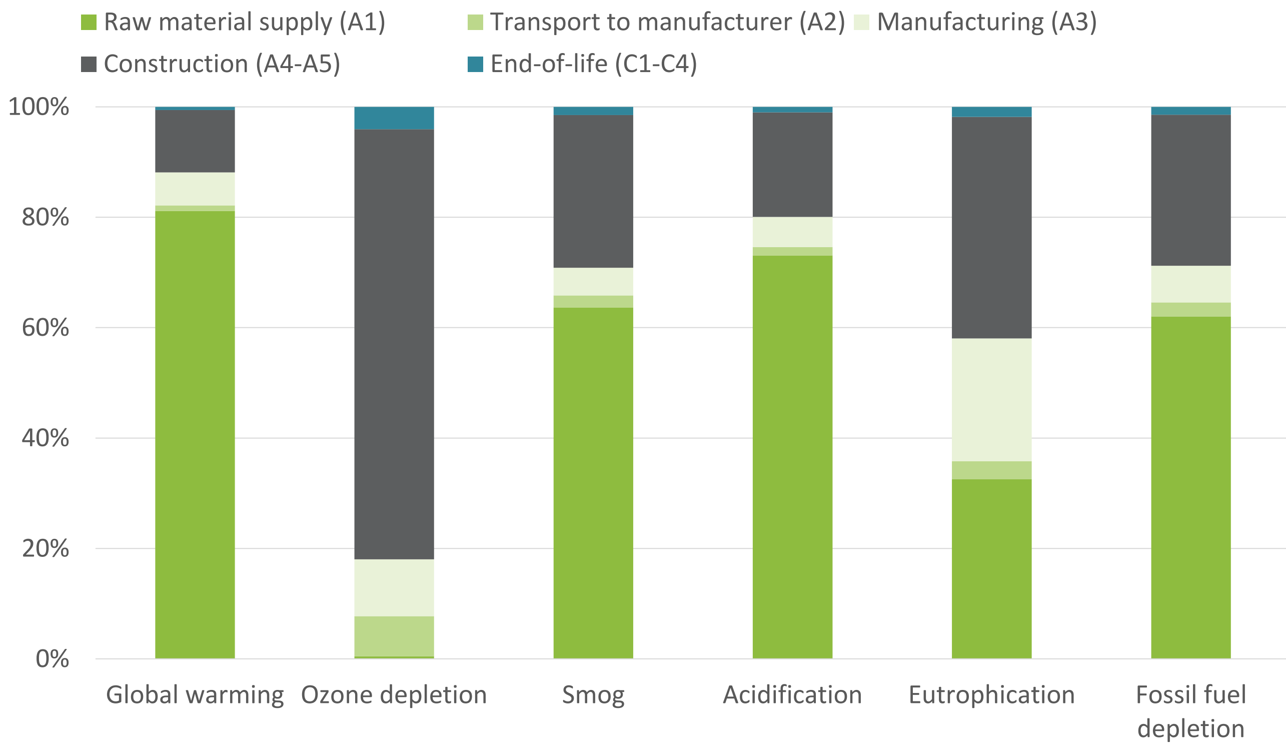



**Table 6-2: Summary of the major contributors to each indicator over the cradle-to-grave life cycle of CSP excluding benefits and loads from recycling**
*(absolute impacts representing at least 10% of the indicator excluding benefits and loads from recycling)*

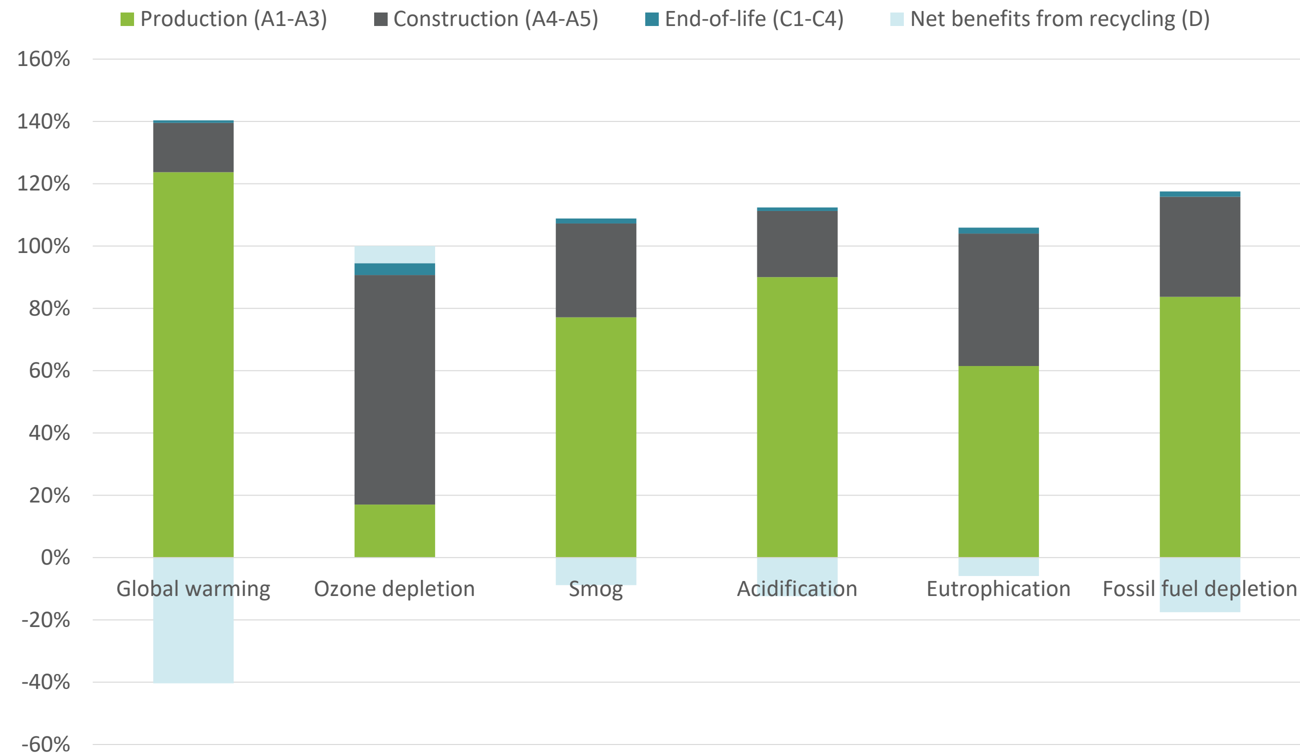
| Indicator | Main contributors (life cycle stage) | Main contributors (activity) | % contribution of activity to life cycle impacts |
|---|---|---|---|
| **Global warming** | Raw material supply | Hot dip galvanized coil production | 81% |
| **Ozone depletion** | Manufacturing | Natural gas consumption | 10% |
| | Installation | Transport to construction site | 39% |
| | | Machinery use | 39% |
| **Smog** | Raw material supply | Hot dip galvanized coil production | 64% |
| | Installation | Transport to construction site | 11% |
| | | Machinery use | 16% |
| **Acidification** | Raw material supply | Hot dip galvanized coil production | 73% |
| | Installation | Machinery use | 11% |
| **Eutrophication** | Raw material supply | Hot dip galvanized coil production | 33% |
| | Manufacturing | Electricity consumption in Canada | 22% |
| | Installation | Transport to construction site | 19% |
| | | Machinery use | 22% |
| **Fossil fuel depletion** | Raw material supply | Hot dip galvanized coil production | 62% |
| | Installation | Transport to construction site | 14% |
| | | Machinery use | 14% |

**Table 6-3: Main contributors to the potential life cycle impacts of CSPI's corrugated steel pipe excluding benefits and loads from recycling**

| Main contributors | % contribution of the activity across all indicators |
|---|---|
| **Hot dip galvanized coil production**<br>Emissions from steel mills are the main causes of potential impacts for six indicators. Emissions of carbon dioxide ($CO_2$), sulphur dioxide ($SO_2$) and nitrogen oxides (NOx) are separately or together responsible for the potential impacts on global warming, smog, acidification, eutrophication. The extraction of natural gas (used at the mills) is the main source of potential impacts on fossil resource scarcity. | **0 to 81%** |
| **Transport to the construction site**<br>Most impacts from the transport stage are related to the **fuel combustion.** NOx emissions from diesel combustion account for the impacts on smog and eutrophication.<br>Halon gases (1301 and 1211) are used in petroleum production facilities which supply fuel for transportation trucks and excavators. These gases are used in fire suppression systems of critical equipment. Because of its ozone depletion potential, industrial states stopped the production of halon in 1994 (Peterson, 2001). However, the countries involved received a ten-year prolongation before the closure of production (*ecoinvent*, 2007). The *ecoinvent* datasets related to crude oil, natural gas and uranium were created in the beginning of the 2000s and these flows have not been modified in the subsequent updates of the *ecoinvent* database. **This result is therefore of low confidence**. | **0 to 39%** |
| **Machinery work for installation**<br>Most impacts from the installation stage are related to the **fuel combustion.** NOx emissions from diesel combustion account for the impacts on smog, acidification and eutrophication.<br>The **diesel consumption** accounts for the installation impact on ozone depletion due to Halon 1301 emissions. As mentioned before, this result is of low confidence. | **0 to 39%** |
| **CSP manufacturing**<br>Part of the **electricity consumed in manufacturing plants** in **Canada** is produced with lignite. The potential impacts of electricity consumption on **eutrophication** come from the treatment of spoil – from lignite mining – in surface landfills. Associated emissions will occur after a long period of time (after 100 years); therefore, uncertainty on the model used is high. If long-term emissions are excluded, manufacturing potential impacts are no longer significant. Therefore, this is considered a conservative estimate of manufacturing potential impacts.<br>The **natural gas and diesel consumption** for the CSP manufacturing accounts for the manufacturing impact on ozone depletion due to Halon emissions. As mentioned before, this result is of low confidence. | **0 to 22%** |

#### CONTRIBUTION ANALYSIS OF POTENTIAL CRADLE-TO-GRAVE LIFE CYCLE IMPACTS OF CSPI'S CORRUGATED STEEL PIPE INCLUDING BENEFITS AND LOADS FROM RECYCLING

**Figure 6-2: Contribution analysis of potential cradle-to-grave life cycle impacts of CSPI's corrugated steel pipe including benefits and loads from recycling**




**Steel recycling reduces the impacts of the CSP** on the global warming, acidification and fossil fuel indicators by enabling the production of steel products made of secondary steel rather than primary steel. The EAF route relies on energy mixes with a higher use of renewable energy resources and is less energy intensive than the BOF route. This credit is particularly high (contribution from -39% to 5% to the indicators) due to the low content of secondary scrap in the North American HDG coil. The credit acknowledges the value of steel scrap: since the inherent properties of steel are not affected by the recycling process, steel is the most recycled material.

## 6.3 COMPARISON BETWEEN THE CSP AND THE RCP

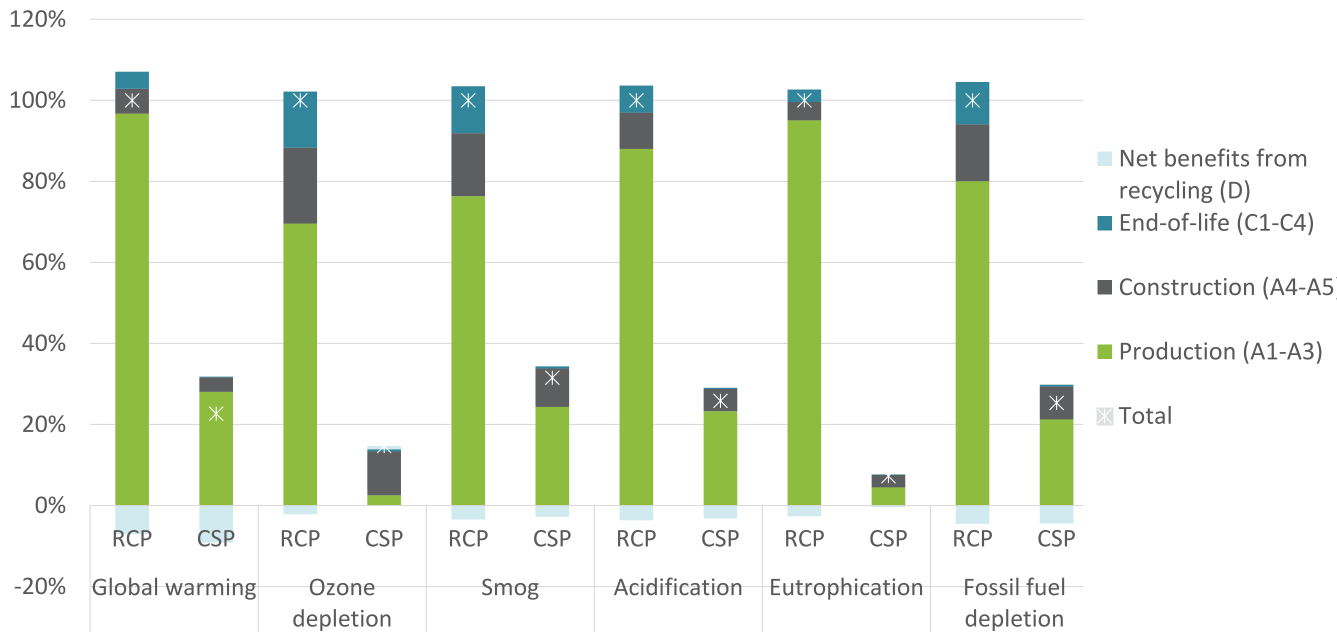
The purpose of this analysis is to compare CSPI's corrugated steel pipe with a generic North American reinforced concrete pipe. In Figure 6-3, the potential impacts of CSPI's CSP are compared to the ones of the RCP for each studied indicator. In this graph, the results of the product with the highest potential impact are set to 100%, meaning that the results for the product with the lowest potential impacts are presented as a percentage of those with the highest potential impacts. For example, for the global warming indicator, the potential impacts of CSP are equivalent to 31% of the potential impacts of the RCP.

**CSPI's CSP has lower potential impacts than the RCP on all studied indiactors** as shown in Figure 6-3. It has lower results for the global warming, ozone depletion, smog, acidification, eutrophication and fossil fuel depletion.

A minimum difference threshold of 10% was used to consider any comparison between the two products as significant. Explanations of the main sources of differences are discussed later in this section along with results in absolute terms for each indicator. The use stage is not displayed as it does not have any impacts on studied indicators.

**Figure 6-3: Potential life cycle impacts of CSPI's corrugated steel pipe relative to the profile of the North American market for reinforced concrete pipe for the global warming, ozone depletion, smog, acidification, eutrophication and fossil fuel depletion**

*(RCP = 100%)*




### GLOBAL WARMING

As shown in Table 6-4, the **RCP has a higher carbon footprint** than CSPI's corrugated steel pipe. The hefty masses of concrete and steel used in the RCP account for most of its impact. The mass of the CSP is one metric tonne per functional unit while the mass of the RCP is above 30 metric tonnes per functional unit, i.e. thirty times higher than the CSP. The majority of GHG emissions come from the clinker and rebar production in the form of $CO_2$. Clinker is the main component of portland cement. The calcination of limestone ($CaCO_3$) during clinker production is responsible for $CO_2$ emissions, both direct ($CaCO_3$ + heat → calcium oxide CaO + $CO_2$) and indirect (combustion of various fuels to produce heat). Finally, as concrete, which constitutes the majority of the RCP, is downcycled to aggregates, the credit for virgin material substitution is not significant compared to the production stage (the credit is around 5% of the product stage impacts).

**Table 6-4: Global warming results for the studied storm drainage pipes per functional unit**

| Life cycle stages | RCP | CSP |
|---|---|---|
| | kg $CO_2$ eq. | |
| Production (A1-A3) | 8400 | 2435 |
| Construction (A4-A5) | 533 | 312 |
| End-of-life (C1-C4) | 368 | 16 |
| Benefits and loads from recycling (D) | -546 | -762 |
| **Total** | **8,755** | **2,001** |
| ***Difference in results compared to the RCP*** | | **- 77%** |

*Note: Numbers may not add up due to rounding.*

### OZONE DEPLETION

As shown in Table 6-5, the **RCP has a higher potential impact on ozone depletion** than CSPI's corrugated steel pipe. The heavy weight of the RCP accounts for its higher impact. The high use of fuel for transport and handling processes (construction stage) as well as the combustion of natural gas at the manufacturing stage are the main contributors to the higher profile for RCP. However, this is a low confidence result since the results include on halon emissions which are unlikely to be representative of actual activities.

**Table 6-5: Ozone depletion results for the studied storm drainage pipes**

| Life cycle stages | RCP | CSP |
|---|---|---|
| | kg CFC-11 eq. | |
| Production (A1-A3) | 4.8E-04 | 1.7E-05 |
| Construction (A4-A5) | 1.3E-04 | 7.4E-05 |
| End-of-life (C1-C4) | 9.6E-05 | 3.9E-06 |
| Benefits and loads from recycling (D) | -1.5E-05 | 5.3E-06 |
| **Total** | **6.9E-04** | **1.0E-04** |
| ***Difference in results compared to the RCP*** | | **- 85%** |

*Note: Numbers may not add up due to rounding.*

### SMOG

As shown in Table 6-6, the **RCP has a higher potential impact on smog** than CSPI's corrugated steel pipe. The heavy weight of the RCP accounts for its higher impact. Rebar production and fuel combustion in transport trucks as well as construction machinery are responsible for NOx emissions during the RCP life cycle.

**Table 6-6: Smog results for the studied storm drainage pipes**

| Life cycle stages | RCP | CSP |
|---|---|---|
| | kg $O_3$ eq. | |
| Production (A1-A3) | 609 | 194 |
| Construction (A4-A5) | 124 | 76 |
| End-of-life (C1-C4) | 93 | 4 |
| Net benefits from recycling (D) | -26 | -21 |
| **Total** | **800** | **253** |
| ***Difference in results compared to the RCP*** | | **- 68%** |

*Note: Numbers may not add up due to rounding.*

### Acidification

As shown in Table 6-7, the **RCP has a higher potential impact on acidification** than CSPI's corrugated steel pipe. Again, the heavy weight of the RCP accounts for its higher impact. Rebar production and fuel combustion in transport trucks as well as construction machinery are responsible for NOx and $SO_2$ emissions during the RCP life cycle.

**Table 6-7: Acidifaction results for studied storm drainage pipes**

| Life cycle stages | RCP | CSP |
|---|---|---|
| | kg $SO_2$ eq. | |
| Production (A1-A3) | 42 | 11 |
| Construction (A4-A5) | 4 | 3 |
| End-of-life (C1-C4) | 3 | 0 |
| Benefits and loads from recycling (D) | -2 | -1 |
| **Total** | **48** | **12** |
| ***Difference in results compared to the RCP*** | | **- 74%** |

*Note: Numbers may not add up due to rounding.*

### Eutrophication

As shown in Table 6-8, the **RCP has a higher potential impact on eutrophication** than CSPI's corrugated steel pipe. The American electricity grid mix partly relies on electricity production from hard coal and lignite combustion. Eutrophication potential impact is caused by water emissions in the treatment of spoil from lignite and hard coal mining in surface landfills. These emissions are long-term emissions (after 100 years); therefore, uncertainty on the model used is high. Even though these are low confidence results as results rely on long-term emissions models, conclusion of the study is not affected by the exclusion of long-term emissions.

**Table 6-8: Eutrophication results for studied storm drainage pipes**

| Life cycle stages | RCP | CSP |
|---|---|---|
| | kg N eq. | |
| Production (A1-A3) | 1.4E+01 | 6.6E-01 |
| Construction (A4-A5) | 6.7E-01 | 4.6E-01 |
| End-of-life (C1-C4) | 4.6E-01 | 2.1E-02 |
| Benefits and loads from recycling (D) | -3.9E-01 | -6.1E-02 |
| **Total** | **1.5E+01** | **1.1E+00** |
| ***Difference in results compared to the RCP*** | | **- 93%** |

*Note: Numbers may not add up due to rounding.*

### FOSSIL FUEL DEPLETION

As shown in Table 6-9, the **RCP has a higher potential impact on fossil fuel depletion** than CSPI's corrugated steel pipe. The heavy weight of the RCP accounts for its higher impact. Extraction of natural gas for rebar production is the main source of potential impacts on fossil resource scarcity during the RCP life cycle. Fossil fuel use for transport of raw materials to the RCP manufacturing plants, in the manufacturing processes and for transport of the to the construction site also accounts for a significant part of RCP potential impact on fossil fuel depletion.

**Table 6-9: Fossil fuel depletion results for studied storm drainage pipes**

| Life cycle stages | RCP | CSP |
|---|---|---|
| | MJ surplus | |
| Production (A1-A3) | 6,566 | 1,741 |
| Construction (A4-A5) | 1,152 | 669 |
| End-of-life (C1-C4) | 860 | 35 |
| Benefits and loads from recycling (D) | -340 | -350 |
| **Total** | **8,237** | **2,096** |
| ***Difference in results compared to the RCP*** | | **- 75%** |

*Note: Numbers may not add up due to rounding.*

### KEY FINDINGS AND CONCLUSIONS

Overall, **CSPI's CSP has lower potential impacts** on global warming, ozone depletion, smog, acidification, eutrophication and fossil fuel, i.e. **on all indicators.**

Most potential impacts of CSPI's CSP are associated with the **production of HDG coils, the transport of pipes to the construction site and machinery work for installation**. The **credit for primary steel substitution** after end-of-life recycling, which acknowledges the value of steel scrap, enables the corrugated steel pipes to significantly reduce its results for most of the indicators assessed.

**The main advantage of CSPI's CSP over the RCP is the lower mass of the product**. The RCP requires considerable amounts of raw materials, especially steel and cement, which production accounts for most of the RCP potential impacts. Also, due to the heavier weight of the RCP product, the transport stage has higher impacts. On the other hand, CSP is made of steel, a highly recycled material, which enables the CSP to have a **credit for its recyclability**. As steel is recycled at its end-of-life, the use of steel for the CSP prevents the use of primary steel for another product by providing steel scrap which is used as raw material by the EAF and BOF routes.

## 6.4 COMPLETENESS ANALYSIS

Efforts were made to ensure that models are as complete as possible. Overall, the systems are considered to fulfill the completeness principle, as the main elementary flows contributing to a relevant degree of the impact categories are included. The elementary flows that were excluded from the system boundaries based on the cut-off criteria (see section 3.4) were estimated to represent less than 1% of the total system's mass, energy flow or environmental impact. The completeness analysis of specific data is provided in the data quality assessment (see sections 6.7 and 6.7.2).

## 6.5 CONSISTENCY ANALYSIS

Consistency analysis is intended to ensure comparativeness of the studied system. Efforts were made to ensure consistency between models despite various data gaps. One means used to overcome this issue is to use equivalent data or models for all systems. Other parts of the systems for which no primary data were available are modelled using secondary data and estimated data and are applied equivalently to all systems. Differences and equivalence in the studied systems are specified in the related sections of the report (see sections 3.1, 5.2).

## 6.6 SENSITIVITY AND SCENARIO ANALYSES

The parameters, methodological choices and assumptions used when modelling the systems present a certain degree of uncertainty and variability. It is important to evaluate whether the choice of parameters, methods, and assumptions significantly influences the study's conclusions and to what extent the findings are dependent upon certain sets of conditions. Following the ISO 14044 standard, a series of sensitivity analyses are used to study the influence of the uncertainty and variability of modelling assumptions and data on the results and conclusions, thereby evaluating their robustness and reliability. Sensitivity analyses help in the interpretation phase to understand the influence of methodological choices, data and assumptions on the outcomes of the study. The following parameters and choices are varied to test the sensitivity of the results and conclusions for impact categories:

- Reference service life of the RCP
- Wall thickness of the CSP
- Repair and rehabilitation activities
- Allocation of deconstruction work
- Life cycle impact assessment (LCIA) method
- Allocation method for recycling (cut-off)

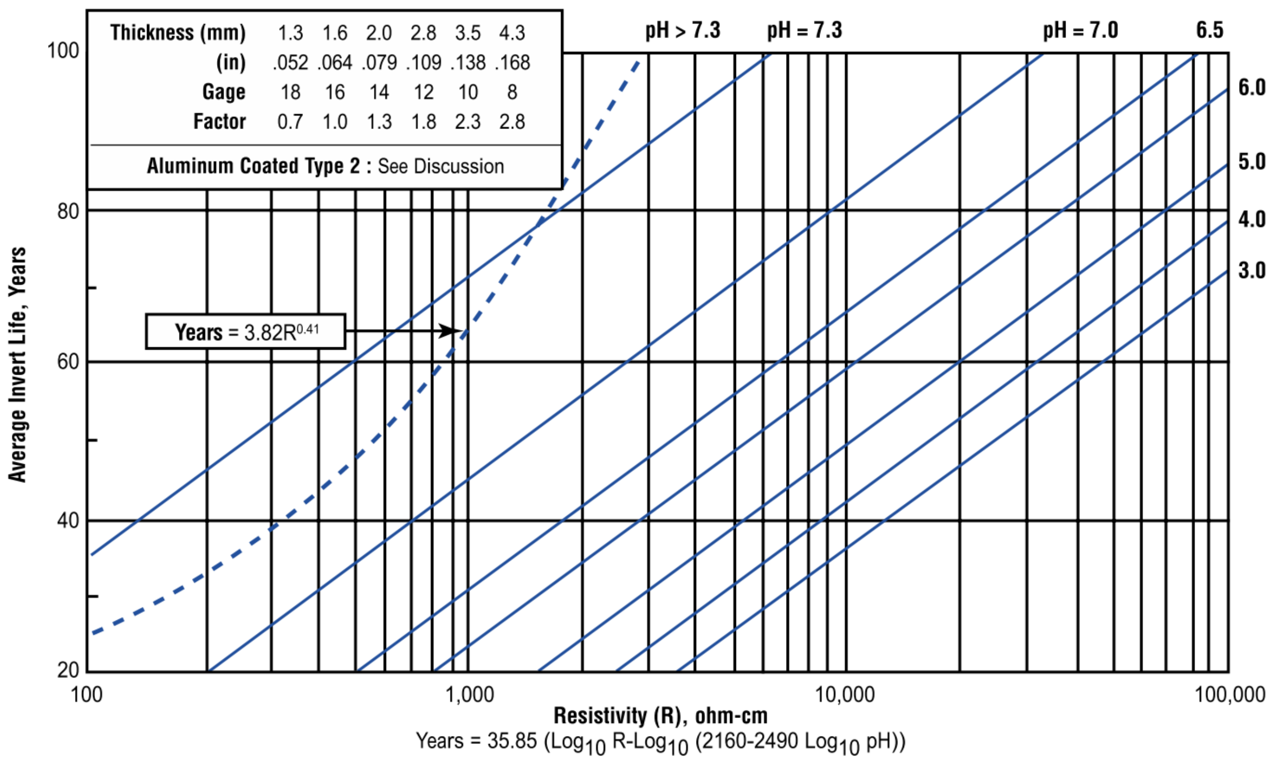
Two **scenario analyses** on the composition and on the end-of-life management were conducted for the RCP.

### 6.6.1 SENSITIVITY ANALYSIS ON THE REFERENCE SERVICE LIFE

Durability assessment of steel and concrete pipes found in literature ranges from 30 to 100 years and from 50 to 120 years, respectively (National Academies of Sciences, Engineering, and Medicine, 2015). These variations can be explained by several factors including the environment in which the pipes were installed, as well as methodological considerations such as the criteria defining the end of life of the pipe (e.g. first perforation or 25% metal loss (National Academies of Sciences, Engineering, and Medicine, 2015)). Due to the high variability of the expected service life found in literature and its high influence on results, the influence of this parameter on results is discussed in this section.

The durability of the CSP is affected by corrosion and abrasion on the invert of the pipe. The pipe environment is characterized by the corrosive conditions on the waterside (water pH and resistivity), the abrasion level (flow velocity, size and amount of abrasive and slope of installation) and water hardness. The American Iron and Steel Institute chart in Figure 6-4 is used to predict galvanized CSP service life depending on corrosive conditions.

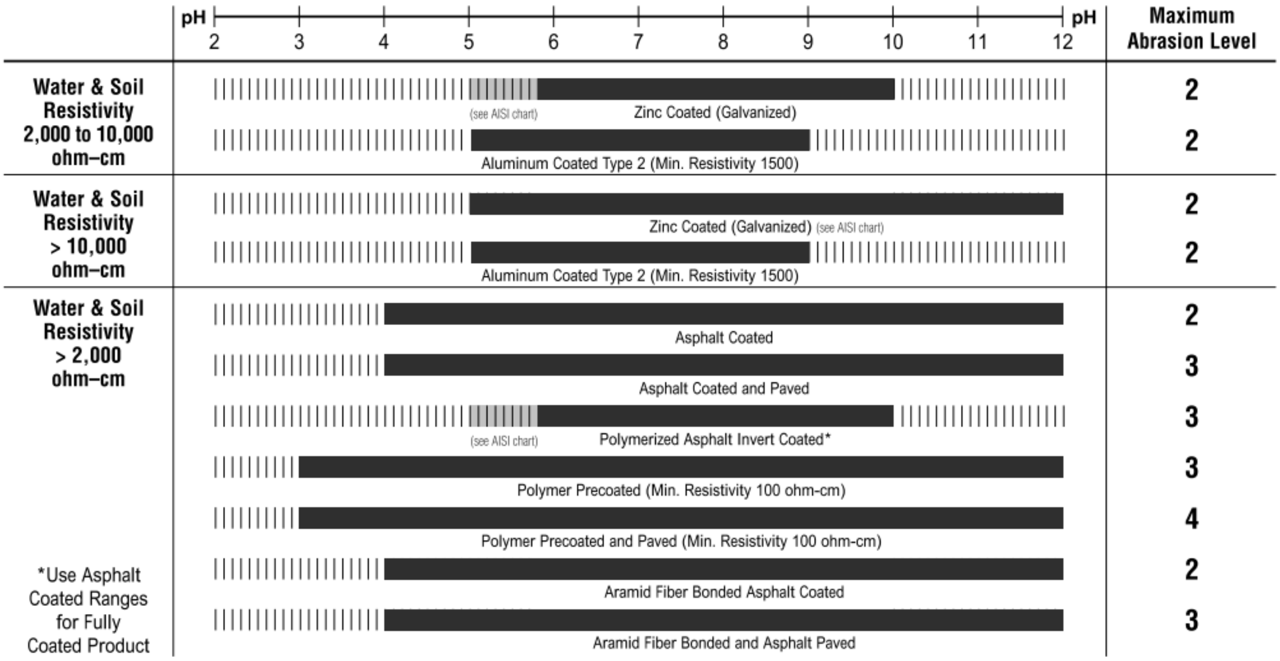
**Figure 6-4: American Iron and Steel Institute chart for estimating average invert life for galvanized CSP**




Source: CORRPRO Companies Inc., 2002

In normal conditions (5.8 ≤ pH ≤ 8, resistivity > 2000 ohm-cm) with low abrasion level, metallic coating (galvanized or aluminized) is sufficient to meet the 75-year durability requirement. In soft water conditions, the aluminized CSP will be used rather than the galvanized CSP. In more corrosive conditions or when abrasion is higher, coatings and pavement have to be added to the CSP to increase its service life. Figure 6-5 shows which coatings and pavement are best suited depending on the site conditions.

**Figure 6-5: Guidelines for CSP coatings and pavement depending on site conditions**




Source: CORRPRO Companies Inc., 2002

The durability of the RCP is affected by corrosion of the rebar and concrete degradation. Potential cracks formed during production and handling of pipes, sulfate content and acidity of the environment (soil- and water-side) are responsible for concrete failure. The RCP design integrates these parameters to meet the requirement for the expected reference service life by adjusting concrete class, strength, content and thickness. Joint failure also contributes to lower service life of the system since the RCP require numerous joints due to the shorter size of the pieces.

The expected service lives have been established with field observations to reflect average durability of pipes under given conditions with a suitable design and coating (National Academies of Sciences, Engineering, and Medicine, 2015). Therefore, the expected service may not reflect the actual service life of a given pipe. In particular, it does not account premature deterioration. However, the service lives documented in the literature review by National Academies of Sciences, Engineering, and Medicine (2015) are representative of average expected service lives for the CSP and RCP installed in suitable conditions.

The baseline scenario assessed in this study is representative of a project for which pipes have been designed to meet a 75-year durability requirement, and for which material have been installed in a suitable environment. Based on the NCSPA guidelines (NCSPA, 2016), the site pH has to be higher than 4 and its resistivity 750 ohm-cm to install the CSP. In such conditions, the CSP can be designed to meet the durability requirement.

Even when pipes are designed for 75 years, there is still a high level of uncertainty on how many years the pipes will actually last. Durability assessment of steel pipes found in literature ranges from 30 to 100 years and of concrete pipes from 50 to 120 years (National Academies of Sciences, Engineering, and Medicine, 2015). In this sensitivity analysis, it is assumed that the CSP has to be replaced after 75 years and that the environment is favorable to the RCP so that it lasts 120 years. The functional unit is "provide a 11.8 m long, 1,800 mm diameter underground storm water drainage pipe for the North American market in 2016 for 120 years."

The CSP is replaced on average 120/75 -1 = 0.6 times over the 120-year on average. The results of this analysis show that the effect of **the longer RSL does not compensate for the heavier mass of the RCP and so it does not affect the conclusions of this study** as shown in Table 6-10. For the results to be reversed, the **RSL of the RCP would have to be at least three times higher than the CSP's**.

**Table 6-10: Life cycle results of the sensitivity analysis on the reference service life (RSL)**

| Indicator | Unit | RCP | CSP | Difference with new RSL[1] (%) | Difference with current RSL[1] (%) |
|---|---|---|---|---|---|
| | | Per FU | | | |
| **Global warming** | kg $CO_2$ eq. | 8.8E+03 | 3.2E+03 | -63% | -77% |
| **Ozone depletion** | kg CFC-11 eq. | 6.9E-04 | 1.6E-04 | -76% | -85% |
| **Smog** | kg $O_3$ eq. | 8.0E+02 | 4.0E+02 | -49% | -68% |
| **Acidification** | kg $SO_2$ eq. | 4.8E+01 | 2.0E+01 | -59% | -74% |
| **Eutrophication** | kg N eq. | 1.5E+01 | 1.7E+00 | -88% | -93% |
| **Fossil fuel depletion** | MJ surplus | 8.2E+03 | 3.4E+03 | -59% | -75% |

[1] *A negative result means that CSPI's pipe has a lower result.*

### 6.6.2 Sensitivity analysis on the wall thickness of the CSP

As mentioned in section 3.2, **the maximum depth of installation for the baseline design of the CSP is 11m** (FDOT, 2006). For projects requiring a deeper installation, the CSP wall must be thicker. For a 1,800 mm diameter CSP, with a corrugation profile of 125 x 25 mm, to be **installed to a depth of 15.5m**, walls should be 2.8 mm thick (FDOT, 2006). In that case, the CSP would have a linear mass of 148 kg/m (CSPI, 1984), which corresponds to a mass of 1,746 kg/FU. As shown in Table 6-11, **results are not affected by the wall thickness required for the considered range of installation depth**. It should be noted that the CSP can be installed up to 30 m deep with a wall thickness of 4.2mm (FDOT, 2006), which corresponds to a linear mass of 221 kg/m. As the RCP can be installed up to 15.5 m, this thickness was not studied.

**Table 6-11: Life cycle results of the sensitivity analysis on the wall thickness of the CSP**

| Indicator | Unit | RCP | CSP | Difference with new FU (%) | Difference with current FU (%) |
|---|---|---|---|---|---|
| | | Per new FU | | | |
| **Global warming** | kg $CO_2$ eq. | 8.8E+03 | 3.5E+03 | -60% | -77% |
| **Ozone depletion** | kg CFC-11 eq. | 6.9E-04 | 1.8E-04 | -74% | -85% |
| **Smog** | kg $O_3$ eq. | 8.0E+02 | 4.4E+02 | -45% | -68% |
| **Acidification** | kg $SO_2$ eq. | 4.8E+01 | 2.2E+01 | -55% | -74% |
| **Eutrophication** | kg N eq. | 1.5E+01 | 1.9E+00 | -87% | -93% |
| **Fossil fuel depletion** | MJ surplus | 8.2E+03 | 3.7E+03 | -56% | -75% |

### 6.6.3 Sensitivity analysis on the repair and maintenance activities

Maintenance activities consist of cleaning the invert of the pipes from accumulated debris every 15 years which potential impacts on the studied indicators is negligible (Byrne et al., 2017). Repair activities consist of relining, patching, and paving invert. Due to the high variability of the maintenance and repair activities – which depend on the environment (such as water flow, slope, pH) in which the pipes are installed – it was not reasonable to model an average use profile. Therefore, the maintenance and repair activities are excluded from the baseline scenario. After a 60-year lifetime, major rehabilitation is likely required (Byrne et al., 2017). In this sensitivity analysis, two scenarios of rehabilitation for the CSP are studied to assess the influence of these activities on results.

CSP rehabilitation often requires providing a new wear surface in the invert and do not require structural repair (CSPI, 1984). Two scenarios of repair are assessed for the CSP: in-place installation of concrete invert and relining the CSP with internal grouting. It is assumed that rehabilitation does not extend the service life of the pipe.

**Table 6-12: Hypothesis for the CSP rehabilitation**

| Parameter | Concrete invert | Data source | Internal grouting | Data source |
|---|---|---|---|---|
| Required material | 40% of the invert is covered with a reinforced concrete layer of 15 cm.<br>Rebar content in reinforced concrete is 110 kg of steel / $m^3$ of concrete | National Academies of Sciences, Engineering, and Medicine, (2015)<br>Assumption by Groupe AGECO | A CSP of a diameter 150 mm to 200 mm smaller is inserted and gap between the two structures is filled with concrete<br>CSP weight is 76 kg/m for an internal diameter of 1,600 mm | CSPI (1984) |
| | - concrete: 8 $m^3$/FU<br>- rebar: 844 kg/FU | | - CSP: 900 kg/FU when 100% of the CSP is grouted<br>- concrete: 25 $m^3$/FU when 100% of the CSP is grouted | |
| Diesel for CSP handling | None | | 3 L/FU | Chilana et al. (2016) |
| Material end-of-life | - concrete: 83% recycled, 17% landfilled<br>- rebar: 70% recycled, 30% landfilled | Assumption by Groupe AGECO | - CSP: 90% recycled, 10% landfilled<br>- concrete: 83% recycled, 17% landfilled | Assumption by Groupe AGECO |

**Several scenarios for internal grouting are presented in Figure 6-6,**
Figure 6-7 and Table 6-13: internal grouting of 10%, 50% and 100%[4] of the CSP. Including repair activities do **not change the conclusion of this study,** except if the CSP is 100% grouted but is still replaced after 75 years, which is unlikely.

[4] This arbitrary range is used to represent extreme scenarios.

**Figure 6-6: Overall results for sensitivity analysis on the repair activities of the CSP**

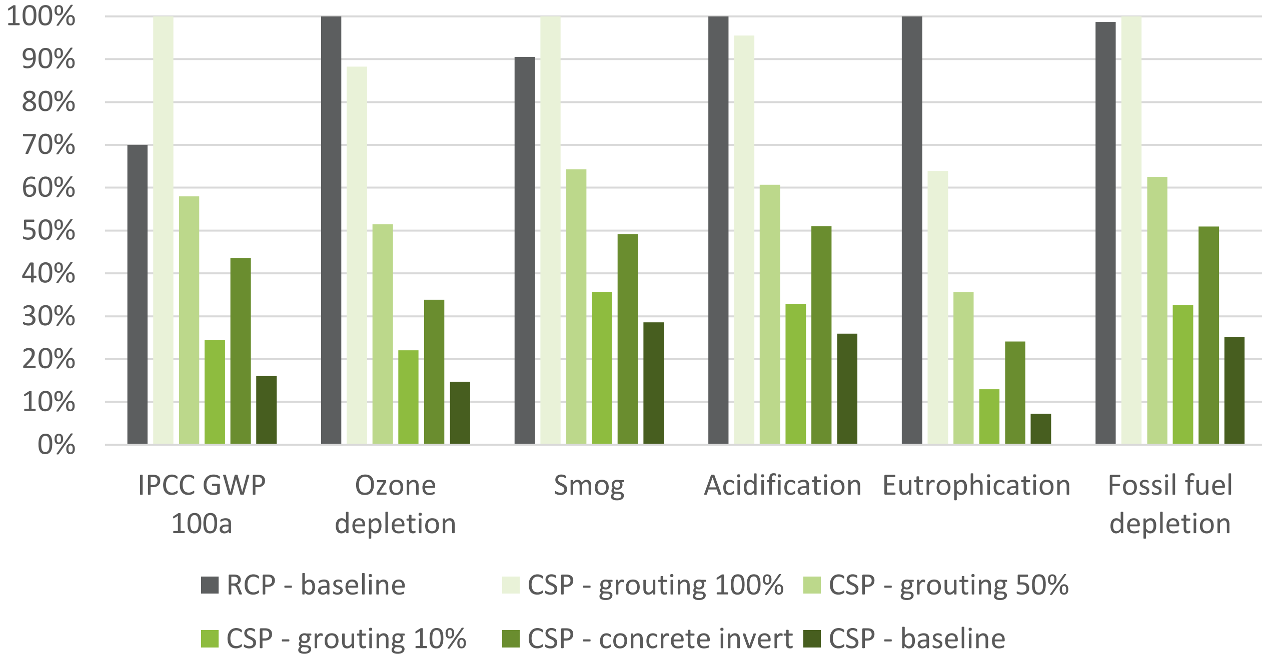


**Figure 6-7: Results for sensitivity analysis on the repair activities of the CSP per life cycle stage**

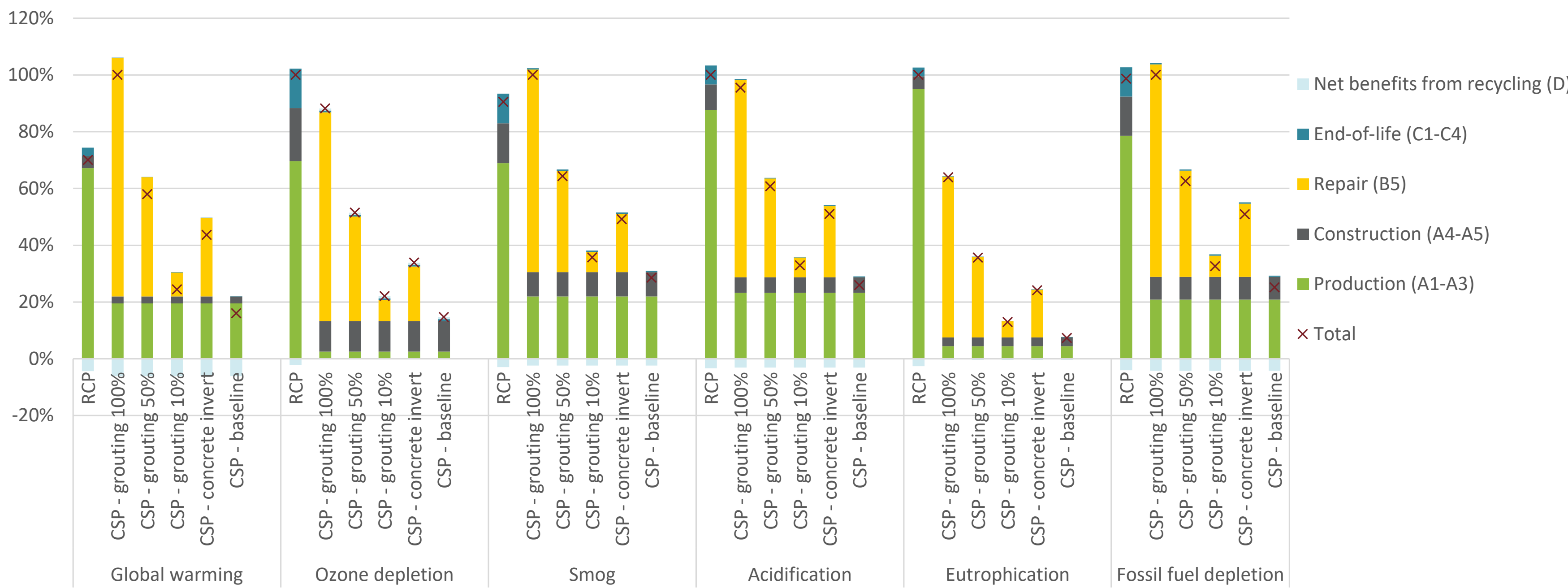


**Table 6-13: Life cycle results of the sensitivity analysis on the repair activities of the CSP**

| Indicator | Unit | RCP | CSP - grouting 100% | CSP - grouting 50% | CSP - grouting 10% | CSP - concrete invert | CSP - basline | CSP - grouting 100% | CSP - grouting 50% | CSP - grouting 10% | CSP - concrete invert | CSP - basline |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Per FU | | | | | | Difference with RCP (%) | | | | |
| **Global warming** | kg $CO_2$ eq. | 8.75E+03 | 1.25E+04 | 7.25E+03 | 3.05E+03 | 5.45E+03 | 2.00E+03 | 43% | -17% | -65% | -38% | -77% |
| **Ozone depletion** | kg CFC-11 eq. | 6.87E-04 | 6.06E-04 | 3.53E-04 | 1.51E-04 | 2.33E-04 | 1.01E-04 | -12% | -49% | -78% | -66% | -85% |
| **Smog** | kg $O_3$ eq. | 8.00E+02 | 8.84E+02 | 5.68E+02 | 3.16E+02 | 4.35E+02 | 2.53E+02 | 10% | -29% | -61% | -46% | -68% |
| **Acidification** | kg $SO_2$ eq. | 4.78E+01 | 4.56E+01 | 2.90E+01 | 1.57E+01 | 2.44E+01 | 1.24E+01 | -5% | -39% | -67% | -49% | -74% |
| **Eutrophication** | kg N eq. | 1.49E+01 | 9.50E+00 | 5.29E+00 | 1.92E+00 | 3.59E+00 | 1.08E+00 | -36% | -64% | -87% | -76% | -93% |
| **Fossil fuel depletion** | MJ surplus | 8.24E+03 | 8.35E+03 | 5.22E+03 | 2.72E+03 | 4.25E+03 | 2.10E+03 | 1% | -37% | -67% | -48% | -75% |

### 6.6.4 SCENARIO ANALYSIS ON THE COMPOSITION OF RCP

Concrete composition was based on the North American average composition of underground precast products. A scenario analysis was conducted with the **composition of industry-average Canadian precast pipes** manufactured by members of the Canadian Concrete Pipe & Precast Association (CCPPA, 2015). Overall, the composition indicated in both the North American and the Canadian EPDs for underground precast products are relatively similar. Results presented in Table 6-14 show that the differences in composition **do not change the conclusion of this study**: the RCP remains with higher potential environmental impacts than CSPI's CSP on all indicators.

**Table 6-14: Life cycle results of the sensitivity analysis on the RCP composition**

| Indicator | Unit | RCP | CSP | Difference with new composition (%) | Difference with current composition (%) |
|---|---|---|---|---|---|
| | | Per FU | | | |
| **Global warming** | kg $CO_2$ eq. | 8.6E+03 | 2.0E+03 | -77% | -77% |
| **Ozone depletion** | kg CFC-11 eq. | 6.2E-04 | 1.0E-04 | -84% | -85% |
| **Smog** | kg $O_3$ eq. | 8.3E+02 | 2.5E+02 | -70% | -68% |
| **Acidification** | kg $SO_2$ eq. | 5.0E+01 | 1.2E+01 | -75% | -74% |
| **Eutrophication** | kg N eq. | 1.0E+01 | 1.1E+00 | -90% | -93% |
| **Fossil fuel depletion** | MJ surplus | 7.7E+03 | 2.1E+03 | -73% | -75% |

### 6.6.5 SENSITIVITY ANALYSIS ON THE ALLOCATION OF THE DECONSTRUCTION WORK

In the baseline scenario, it was assumed that at the end of their reference service lives, pipes are being replaced and the excavation, backfilling, compaction, etc. and other machinery work were allocated to the pipe replacing the installed pipe. However, the excavation and backfilling of pipes at the end-of-life of the studied system contributes to the life cycle of the pipe being uninstalled as well as the future pipe being installed. Table 6-15 shows the results when this machinery work is attributed to the life cycle of the current pipes. As the deconstruction work is similar for the two products, the differences between the two products is slighty decreased, however, **the conclusion of this study is not affected by the allocation of the deconstruction work.**

**Table 6-15: Life cycle results of the sensitivity analysis on the allocation of the deconstruction work**

| Indicator | Unit | RCP | CSP | Difference with deconstruction (%) | Difference without deconstruction (%) |
|---|---|---|---|---|---|
| | | Per FU | | | |
| **Global warming** | kg $CO_2$ eq. | 8.9E+03 | 2.2E+03 | -76% | -77% |
| **Ozone depletion** | kg CFC-11 eq. | 7.2E-04 | 1.4E-04 | -81% | -85% |
| **Smog** | kg $O_3$ eq. | 8.4E+02 | 2.9E+02 | -65% | -68% |
| **Acidification** | kg $SO_2$ eq. | 4.9E+01 | 1.4E+01 | -72% | -74% |
| **Eutrophication** | kg N eq. | 1.5E+01 | 1.3E+00 | -92% | -93% |
| **Fossil fuel depletion** | MJ surplus | 8.5E+03 | 2.4E+03 | -72% | -75% |

### 6.6.6 SCENARIO ANALYSIS ON THE END-OF-LIFE MANAGEMENT FOR THE RCP

The current model used the assumption that both products are managed at the end of their reference service life. Due to the economic value of steel scrap, it is unlikely that steel pipes would be left in place. However, due to the low content of high value material in the RCP, **a scenario was studied in which the RCP is left in place**. Table 6-16 shows that the **conclusions of the study are not affected** by the end-of-life management choice for the RCP. Overall, the RCP impacts are not affected by the end-of-life management scenario due to a balance between end-of-life management impacts and recycling benefits. When the RCP is left in place, there are lower potential impacts since the product does not have to be crushed nor transported, however, the product is not recycled, therefore, there is no credit associated with other functions fulfilled by the RCP beyond system boundaries.

**Table 6-16: Life cycle results of the scenario analysis on the end-of-life management for the RCP**

| Indicator | Unit | RCP | CSP | Difference with leave-in-place (%) | Difference without leave-in-place (%) |
|---|---|---|---|---|---|
| | | Per FU | | | |
| **Global warming** | kg $CO_2$ eq. | 9.1E+03 | 2.0E+03 | -78% | -77% |
| **Ozone depletion** | kg CFC-11 eq. | 6.8E-04 | 1.0E-04 | -85% | -85% |
| **Smog** | kg $O_3$ eq. | 7.6E+02 | 2.5E+02 | -67% | -68% |
| **Acidification** | kg $SO_2$ eq. | 4.7E+01 | 1.2E+01 | -74% | -74% |
| **Eutrophication** | kg N eq. | 1.5E+01 | 1.1E+00 | -93% | -93% |
| **Fossil fuel depletion** | MJ surplus | 8.4E+03 | 2.1E+03 | -75% | -75% |

### 6.6.7 Sensitivity analysis on the LCIA method

The sensitivity analysis on the selection of LCIA methods was performed on both storm drainage pipe models. **The alternate LCIA method is CML** (baseline), as it is a method displayed in construction EPDs due to PCR's requirements. Correlation between LCIA methods for each indicator is presented in Table 6-17. Results presented in Table 6-18 show that the differences between CSPI's CSP and the RCP are in the same order of magnitude for all studied indicators and that the conclusions of this study remain unchanged.

**Table 6-17: Indicator match between LCIA methods**

| TRACI 2.1 indicator | Unit | CML indicator | Unit |
|---|---|---|---|
| **Global warming** | kg $CO_2$ eq. | **Global warming (GWP100a)** | kg $CO_2$ eq. |
| **Ozone depletion** | kg CFC-11 eq. | **Ozone layer depletion (ODP)** | kg CFC-11 eq. |
| **Smog** | kg $O_3$ eq. | **Photochemical oxidation** | kg $C_2H_4$ eq. |
| **Acidification** | kg $SO_2$ eq. | **Acidification** | kg $SO_2$ eq. |
| **Eutrophication** | kg N eq. | **Eutrophication** | kg $PO_4^{3-}$ eq. |
| **Fossil fuel depletion** | MJ surplus | **Abiotic depletion (fossil fuels)** | MJ |

**Table 6-18: Life cycle results of the sensitivity analysis on the LCIA method**

| TRACI 2.1 indicator | Alternate indicator (CML) | Unit | RCP | CSP | Difference between the pipes[1] | |
|---|---|---|---|---|---|---|
| | | | Results with alternate indicators | | Alternate indicators | TRACI 2.1 indicators |
| **Global warming (GWP100a)** | Global warming (GWP100a) | kg $CO_2$ eq. | 8.8E+03 | 2.0E+03 | -77% | -77% |
| **Ozone depletion** | Ozone layer depletion (ODP) | kg CFC-11 eq. | 5.3E-04 | 7.7E-05 | -86% | -85% |
| **Smog** | Photochemical oxidation | kg $C_2H_4$ eq. | 1.9E+00 | 3.7E-01 | -81% | -68% |
| **Acidification** | Acidification | kg $SO_2$ eq. | 4.6E+01 | 1.1E+01 | -76% | -74% |
| **Eutrophication** | Eutrophication | kg $PO_4^{3-}$ eq. | 9.8E+00 | 1.6E+00 | -84% | -93% |
| **Fossil fuel depletion** | Abiotic depletion (fossil fuels) | MJ | 7.7E+04 | 1.7E+04 | -78% | -75% |

[1] *A negative result means that CSPI's pipe has a lower result.*

### 6.6.8 SENSITIVITY ANALYSIS ON THE ALLOCATION METHOD FOR RECYCLING (CUT-OFF)

Although the main function of each product system is identical (i.e. providing a storm drainage system), the different product systems also play secondary functions. In order to capture the secondary functions of these two product systems, system expansion was used to include processes that are displaced by these secondary functions. For the recycled CSP, it was assumed that recycling displaces the production of virgin steel. For the RCP, it was assumed that the amount of concrete that is recycled will displace the production of aggregates (US EPA, 2020b) and that the amount of steel that is recycled will displace the production of virgin steel. The impact of additional steel and aggregate production was subtracted from the RCP and CSP systems in the form of "credits". Overall, the difference between products is increased as the secondary function of steel leads to much larger credits than the ones for concrete recycling since concrete is downcycled as an aggregate.

This approach does not account for efforts from the concrete industry to increase the recycled content of its products by integrating Supplementary Cementing Materials (SCM) such as fly ash and steel slag. The cut-off allocation method was applied in this sensitivity analysis. Using the cut-off approach, deconstruction and transport to the recycling facility are the only processes considered when materials are recycled at the end-of-life stage. There is no credit attributed to the materials under study for recycling, as the impacts of the recycling process, including sorting of the waste, will be allocated to the next systems using the recycled materials and no credit for substituting virgin material is accounted for. As such, in the resource production stage, only the potential environmental impacts generated by the recycling of scrap at the steel mills are included in the scope of the system.

Table 6-19 presents the results with the cut-off approach for both products. Overall, the differences between products decreased as the steel scrap value is not accounted for and because the RCP impacts are slightly decreased when the recycled content is accounted for. However, **the choice of allocation methodology does not affect the conclusion of this study**.

**Table 6-19: Life cycle results of the sensitivity analysis on the allocation method for recycling**

| Indicator | Unit | RCP | CSP | Difference with cut-off (%) | Difference with system expansion (%) |
|---|---|---|---|---|---|
| | | Per FU | | | |
| **Global warming** | kg $CO_2$ eq. | 8.6E+03 | 2.8E+03 | -68% | -77% |
| **Ozone depletion** | kg CFC-11 eq. | 6.9E-04 | 9.6E-05 | -86% | -85% |
| **Smog** | kg $O_3$ eq. | 7.7E+02 | 2.7E+02 | -65% | -68% |
| **Acidification** | kg $SO_2$ eq. | 4.5E+01 | 1.4E+01 | -69% | -74% |
| **Eutrophication** | kg N eq. | 1.4E+01 | 1.1E+00 | -92% | -93% |
| **Fossil fuel depletion** | MJ surplus | 8.4E+03 | 2.4E+03 | -71% | -75% |

## 6.7 Data and Dataset Quality Assessment

This section addresses the data quality and uncertainty assessment. Overall, efforts have been made to enables the reproducibility of this study by referring to internationally recognized standards such as ISO and EN standards, being transparent in the life cycle inventory and datasets used which are detailed along this report.

### 6.7.1 Data Quality Assessment

Data quality was evaluated on the basis of the reliability and completeness of the data itself, combined with assessment of their temporal, geographical and technological representativeness. The significance of the data quality scores are presented in Table 4-1. The data quality evaluation is presented in Table 6-20 and Table 6-21. The importance of data on the potential life cycle impacts was also evaluated based on contribution analysis and sensitivity analyses. In the framework of this LCA, data with high importance means that its relative contribution to the potential impacts for more than one indicator was the highest. Data with moderate importance means that its relative contribution to the potential impacts was among the highest for at least one indicator. Data with low importance means that its relative contribution to the potential impacts was never among the highest. The influence of the precision of the data used was evaluated by conducting sensitivity analyses on parameters which have a major influence on results. Also, it is considered that methodological choices (sections 3 and 4) and data values (section 5, Appendix A and Appendix B) have been presented in this report in a way that allows for reproducibility.

#### Primary Activity Data

For CSPI's CSP, this analysis shows that the primary activity data quality is considered to be reliable. They are also representative of the temporal, geographical and technological contexts. The completeness of the data is considered acceptable. Activities with high and moderate importance in terms of potential environmental impacts are mostly modelled using primary data which make data uncertainties less significant. Data uncertainty regarding the use stage was studied in a sensitivity analysis and uncertainty is therefore considered acceptable as results are not affected by the value of this data. All processes over which CSPI's members can have influence are modelled with primary data. As plants participating in data collection were of similar sizes, data collected was validated by confronting collected data on the three sites to the production volumes of each site.

No primary activity data was collected for the generic North American RCP.

#### SECONDARY ACTIVITY DATA

For CSPI's CSP, secondary activity data was used mainly for the installation, use and end-of-life stages. The reliability and representativeness of this data are considered to be good considering the efforts made to ensure the comparability with the CSP.

For the RCP, secondary activity data was provided by the LCA report for underground precast products manufactured in North America in 2014. Their reliability, temporal and geographical quality are therefore considered good. The data related to the precast products is representative of less than 10% of the total annual production of precast products in North America. The completeness and technological correlation of this data is considered to be acceptable as technology and manufacturing practices for precast underground products are considered to be of similar across plants and products.

Secondary activity data was used for the end-of-life stage for both products. Their reliability and representativeness are variable. Efforts were made to increase modelling quality using findings from literature. In the context of a comparative analysis, data gaps were reduced by applying the same assumptions to both products.

### 6.7.2 DATASET QUALITY ASSESSMENT

As the modelling was done with processes from the *ecoinvent* 3.4 database, the data behind these processes were mostly European and thus not necessarily representative of the North American context. However, the use of processes representative of the Canada or US context when possible improved the scores for these secondary data. All datasets used were reliable (score of 1 on the pedigree matrix) and from identical technologies (score of 2 on the pedigree matrix). Datasets used were either representative of the considered geography (score of 1 on the pedigree matrix) or from area with similar production systems (score of 3 on the pedigree matrix). The temporal correlation and completeness assessments were set to default, according to Weidema's matrix (score of 5 on the pedigree matrix) for ecoinvent processes as they are highly variable (score of 1 to 5 on the pedigree matrix depending on the dataset) but their value do not affect the result of the dataset quality assessment. As shown in Table 6-20 and Table 6-21, the quality of the datasets is acceptable or high for both studied product. More details on the *ecoinvent* datasets used are in Appendix A. See section 4.3 for a description of the data quality assessment criteria.

### 6.7.3 RESULTS OF DATA AND DATASET QUALITY ASSESSMENT

Detailed results of both data and dataset quality assessments are presented in Table 6-20 and Table 6-21.

### Table 6-20: Data and dataset quality assessment for CSPI's CSP

| Data | Source[1] | Importance[2] | Data quality assessment | | | | | Dataset quality assessment | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Reliability | Completeness | Temporal correlation | Geographical correlation | Further technological correlation | Datasets used | Datasets quality |
| **Raw material supply (A1)** | | | | | | | | | |
| **HDG coil** | 1 | Red | 1 | 3 | 2 | 1 | 1 | Worldsteel data for North American hot-dip galvanized coil production | High |
| **Transport to manufacturer (A2)** | | | | | | | | | |
| **Transport** | 1 | Green | 1 | 4 | 2 | 1 | 1 | customized dataset with ecoinvent unit processes for North American truck transport (Transport, 53' dry van) | Acceptable |
| **Manufacturing (A3)** | | | | | | | | | |
| **Fuel use** | 1 | Yellow | 1 | 3 | 2 | 1 | 1 | ecoinvent unit processes not adapted (CA-QC, RER, GLO) | Acceptable |
| **Electricity** | 1 | Yellow | 1 | 3 | 2 | 1 | 1 | ecoinvent unit processes adapted to CA | Acceptable |
| **Packaging** | 1 | Green | 1 | 3 | 2 | 1 | 1 | ecoinvent unit processes not adapted (GLO, CH) | Acceptable |
| **Couplers** | 1 | Green | 1 | 4 | 1 | 1 | 1 | Worldsteel data for North American hot-dip galvanized coil production | Acceptable |
| **Waste treatment** | 1 | Green | 1 | 3 | 2 | 1 | 1 | ecoinvent unit processes not adapted (GLO) | Acceptable |
| **Construction (A4 -A5)** | | | | | | | | | |
| **Transport** | 2 | Yellow | 4 | 5 | 1 | 1 | 1 | customized dataset with ecoinvent unit processes for North American truck transport (Transport, 53' dry van) with truckload adjusted | High |
| **Machinery** | 2 | Yellow | 1 | 4 | 1 | 1 | 3 | ecoinvent unit processes not adapted (GLO) | Acceptable |
| **Waste treatment** | 1 | Green | 1 | 3 | 2 | 1 | 1 | ecoinvent unit processes not adapted (CH) | Acceptable |
| **Use stage (B1)** | | | | | | | | | |
| **Coating oxidation** | 2 | Green | 4 | 5 | 1 | 1 | 1 | substance in SimaPro software | High |
| **End-of-life stage (C1-C4)** | | | | | | | | | |
| **Machinery** | 2 | Green | 3 | 4 | 1 | 1 | 3 | ecoinvent unit processes not adapted (GLO) | Acceptable |
| **Transport to treatment facility** | 2 | Green | 4 | 5 | 1 | 1 | 1 | customized dataset with ecoinvent unit processes for North American truck transport (Transport, 53' dry van) | Acceptable |
| **Waste treatment** | 2 | Green | 1 | 1 | 1 | 1 | 4 | ecoinvent unit processes not adapted (GLO) | Acceptable |
| **Recycling benefits stage (D)** | | | | | | | | | |
| **Steel recycling** | 2 | Yellow | 1 | 1 | 2 | 1 | 3 | Worldsteel data for steel scrap (global) | Acceptable |

[1] 1 - specific (primary) data; 2 – generic (secondary) data. [2] **Red** – high; **Yellow** – moderate; **Green** – low. [3] *The significance of data quality scores is detailed in Table 4-1*

**Table 6-21: Data and dataset quality assessment for the RCP**

| Data | Source[1] | Importance[2] | Data quality assessment[3] | | | | | Dataset quality assessment | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Reliability | Completeness | Temporal correlation | Geographical correlation | Further technological correlation | Datasets used | Datasets quality |
| **Raw material supply (A1)** | | | | | | | | | |
| **Cement** | 2 | | 1 | 3 | 2 | 1 | 3 | ecoinvent unit processes adapted to CA and the USA | High |
| **Aggregates** | 2 | | 1 | 3 | 2 | 1 | 3 | ecoinvent unit processes not adapted (CH) | Acceptable |
| **Steel** | 2 | | 1 | 3 | 2 | 1 | 3 | Worldsteel dataset for rebar production (global) | Acceptable |
| **Chemicals** | 2 | | 1 | 3 | 2 | 1 | 3 | ecoinvent unit processes not adapted (GLO) | Acceptable |
| **Plastic** | 2 | | 1 | 3 | 2 | 1 | 3 | ecoinvent unit processes not adapted (RER) | Acceptable |
| **Transport to manufacturer (A2)** | | | | | | | | | |
| **Transport** | 2 | | 1 | 3 | 2 | 1 | 3 | customized dataset with ecoinvent unit processes for North American truck transport (Transport, 53' dry van) | Acceptable |
| **Manufacturing (A3)** | | | | | | | | | |
| **Fuel use** | 2 | | 1 | 3 | 2 | 1 | 3 | ecoinvent unit processes not adapted (CA-QC, RER, GLO) | Acceptable |
| **Electricity** | 2 | | 1 | 3 | 2 | 1 | 3 | ecoinvent unit processes adapted to CA and USA | Acceptable |
| **Water use** | 2 | | 1 | 3 | 2 | 1 | 3 | substance in SimaPro software | High |
| **Couplers** | 2 | | 4 | 5 | 1 | 1 | 1 | ecoinvent unit processes not adapted (CA-QC, RER, GLO) | Acceptable |
| **Waste treatment** | 2 | | 1 | 3 | 2 | 1 | 3 | ecoinvent unit processes not adapted (GLO) | Acceptable |
| **Construction (A4 -A5)** | | | | | | | | | |
| **Transport** | 2 | | 4 | 5 | 1 | 1 | 1 | customized dataset with ecoinvent unit processes for North American truck transport (Transport, 53' dry van) with truckload adjusted | High |
| **Machinery** | 2 | | 1 | 4 | 1 | 1 | 3 | ecoinvent unit processes not adapted (GLO) | Acceptable |
| **End-of-life stage (C1-C4)** | | | | | | | | | |
| **Machinery** | 2 | | 3 | 4 | 1 | 1 | 3 | ecoinvent unit processes not adapted (GLO) | Acceptable |
| **Transport to treatment facility** | 2 | | 4 | 5 | 1 | 1 | 1 | customized dataset with ecoinvent unit processes for North American truck transport (Transport, 53' dry van) | Acceptable |
| **Waste treatment** | 2 | | 1 | 1 | 1 | 1 | 4 | ecoinvent unit processes not adapted (GLO) | Acceptable |
| **Recycling benefits stage (D)** | | | | | | | | | |
| **Concrete recycling** | 2 | | 1 | 1 | 2 | 1 | 1 | ecoinvent unit process not adapted (CH) | Acceptable |
| **Steel recycling** | 2 | | 1 | 1 | 2 | 1 | 3 | Worldsteel data for steel scrap (global) | Acceptable |

[1]1 - specific (primary) data; 2 – generic (secondary) data. [2]**Red** – high; **Yellow** – moderate; **Green** – low. [3]*The significance of data quality scores is detailed in Table 4-1*

## 6.8 UNCERTAINTY ANALYSIS

There are two types of uncertainty related to the LCA model:

- Inventory data uncertainty;
- Characterization model uncertainty, which translates inventory into potential environmental impacts.

### 6.8.1 INVENTORY DATA UNCERTAINTY ANALYSIS

Quantitative analyses of the uncertainty due to the variability and data quality of inventory data have been performed within the Monte-Carlo simulation module in SimaPro software. This discussion is based on the outputs of the Monte-Carlo analyses conducted between compared systems with 1,000 iterations. Monte Carlo results are presented in Appendix C. Results did not reveal any case for which there was more than a 1 in 2 chance (50% or more chance) for an increase in impact to become a reduction (and vice versa) because of inventory uncertainty. Therefore, the comparison was declared of high confidence regarding inventory uncertainty.

The uncertainty on inventory data is considered small enough to conclude that this aspect does not compromise the comparative conclusions on all of the indicators assessed.

Note that this inventory uncertainty analysis does not include an analysis of the uncertainty related to the primary activity data (i.e. quantities of inputs and outputs provided by CSPI) since it is unknown. This kind of uncertainty was treated through the numerous sensitivity analyses and the data quality assessment.

### 6.8.2 CHARACTERIZATION MODEL UNCERTAINTY

In addition to the inventory data uncertainty described above, there is an uncertainty related to the characterization of the LCI results into midpoint indicators. The uncertainty ranges associated with characterization factors vary from one mid-point indicator to another. The accuracy of characterization factors depends on the ongoing research in the many scientific fields behind life cycle impact modelling, as well as on the integration of current findings within operational LCIA methods. This type of uncertainty is not yet well understood by the LCA community. The scientific consensus on this sensitive topic, as well as the grouping methodology, is still under revision in order to better assess these ranges of uncertainty (European Commission, 2011).

Quantification of inventory uncertainties using Monte-Carlo is considered acceptable, in the current state of knowledge, to draw conclusion from obtained results. As described in section 6.2, a minimum difference threshold of 10% was used to consider any comparison between products as significant. This is consistent with many sources, such as the IPCC and also LCA in the green building sector.

# 7. Conclusions, limitations and recommendations

## 7.1 Conclusions

This study presented the cradle-to-grave profile of the potential life cycle environmental impacts of CSPI’s 1,800 mm diameter corrugated steel pipes used for storm water drainage. The environmental profile was compared to a reinforced concrete pipe representative of the North American market in 2016. The stages contributing the most to the potential impacts of CSPI’s CSP are **HDG coil production and construction. The net recycling benefits, which acknowledge the value of steel scrap, enable the corrugated steel pipes to significantly reduce its impacts.**

The comparative analysis with the RCP showed that **CSPI’s 1,800 mm diameter CSP has lower potential environmental impacts on all studied indicators:** global warming, ozone depletion, smog, acidification, eutrophication, and fossil fuel depletion. The significant lower weight of the CSP accounts for its better performance on most indicators.

## 7.2 Limitations

Life cycle impact assessment results present potential and not actual environmental impacts. They are relative expressions, which are not intended to predict the final impact or risk on the natural environment or whether standards or safety margins are exceeded. Additionally, the indicators studied do not cover all the environmental impacts associated with human activities. Impacts such as noise, odours, electromagnetic fields, the accumulation of plastic in the environment and others are not included in the present assessment. The methodological developments regarding such impacts are not sufficient to allow for their consideration within the life cycle assessment.

The results for CSPI’s 1,800 mm diameter CSP are specific to the 1,800 mm diameter CSP manufactured by CSPI’s members and cannot be used as generic LCA results for CSP.

## 7.3 Recommendations

This section presents the recommendations to improve the environmental performance of CSPI’s CSP and maintain their competitive position:

- **Promote the use of coatings improving durability.** Results highly depend on the difference of durability between the two products. As long as CSPI can maintain the durability of its pipe, CSPI’s 1,800 mm diameter steel pipes will remain competitive.
- **Increase CSPI’s members participation in data collection.** Practices vary from one plant to another depending on the suppliers, loss and energy use. By improving the sample representativeness, CSPI can have a better understanding of its members’ plants performance and work to improve it.
- **Work with HDG suppliers to improve HDG environmental performance.** Since HDG coil production is responsible for most of the CSP potential impacts, this will help CSPI keep their competitive position on the long term.

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# APPENDIX A

## ECOINVENT DATASETS USED FOR MODELLING

## APPENDIX A – ECOINVENT DATASETS USED FOR MODELLING

### Table A.1: Datasets for CSPI's CSP

| Process | Datasets |
|---|---|
| **Raw material supply (A1)** | |
| **HDG coil** | • Worldsteel data for North American hot-dip galvanized coil production (Steel Recycling Institute, 2017) |
| **Packaging** | • Steel, chromium steel 18/8 {GLO}\| market for \| Cut-off, U |
| **Transport to manufacturer (A2)** | |
| **Transport** | • Customized dataset with the following *ecoinvent* unit processes:<br>o Lorry, 28 metric ton {RoW}\| production \| Cut-off, U<br>o Maintenance, lorry 28 metric ton {RoW}\| processing \| Cut-off, U<br>o Road {RoW}\| road construction \| Cut-off, U<br>o Road maintenance {RoW}\| road maintenance \| Cut-off, U<br>o Diesel, low-sulphur {RoW}\| market for \| Cut-off, U<br>The emissions from diesel combustion are modelled with substances included in the SimaPro software. |
| **Manufacturing (A3)** | |
| **Fuel use** | • Diesel, burned in building machine {GLO}\| processing \| Cut-off, U<br>Heat, district or industrial, natural gas {CA-QC}\| market for \| Cut-off, U<br>Heat, district or industrial, other than natural gas {CA-QC}\| heat production, propane, at industrial furnace >100kW \| Cut-off, U |
| **Consumables** | • Lubricating oil {RER}\| production \| Cut-off, U |
| **Scrap transport** | • Municipal waste collection service by 21 metric ton lorry {CH}\| processing \| Cut-off, U |
| **Electricity** | • Electricity, medium voltage {CA}\| market group for \| Cut-off, U |
| **Packaging** | • Sawnwood, beam, hardwood, dried (u=10%), planed {CH}\| planing, beam, hardwood, u=10% \| Cut-off, U |
| **Couplers - connecting band** | • Worldsteel data for North American hot-dip galvanized coil production for production; customized dataset with *ecoinvent* unit processes for North American truck transport (Transport, 53' dry van) for transport; manufacturing datasets from CSPI's data |
| **Couplers - rubber gasket** | • Synthetic rubber {GLO}\| market for \| Cut-off, U |
| **Construction (A4 -A5)** | |
| **Transport** | • Customized dataset with the following *ecoinvent* unit processes:<br>o Lorry, 28 metric ton {RoW}\| production \| Cut-off, U<br>o Maintenance, lorry 28 metric ton {RoW}\| processing \| Cut-off, U<br>o Road {RoW}\| road construction \| Cut-off, U<br>o Road maintenance {RoW}\| road maintenance \| Cut-off, U<br>o Diesel, low-sulphur {RoW}\| market for \| Cut-off, U<br>The emissions from diesel combustion are modelled with substances included in the SimaPro software.<br>The dataset was adapted to the average truck load reported by CSPI. |
| **Machinery** | • Excavation, hydraulic digger {GLO}\| market for \| Cut-off, U |
| **Waste transport** | • Municipal waste collection service by 21 metric ton lorry {CH}\| processing \| Cut-off, U |
| **Waste treatment** | • Waste wood, untreated {CH}\| treatment of, sanitary landfill \| Cut-off, U<br>Waste polyurethane {CH}\| treatment of, sanitary landfill \| Cut-off, U |
| **Use stage (B1)** | |
| **Coating oxidation** | • Zinc to water |
| **End-of-life stage (C1-C4)** | |
| **Machinery use** | • Excavation, hydraulic digger {GLO}\| market for \| Cut-off, U |

| | |
|---|---|
| **Transport to treatment facility** | • Customized dataset with the following *ecoinvent* unit processes:<br>o Lorry, 28 metric ton {RoW}\| production \| Cut-off, U<br>o Maintenance, lorry 28 metric ton {RoW}\| processing \| Cut-off, U<br>o Road {RoW}\| road construction \| Cut-off, U<br>o Road maintenance {RoW}\| road maintenance \| Cut-off, U<br>o Diesel, low-sulphur {RoW}\| market for \| Cut-off, U<br>The emissions from diesel combustion are modelled with substances included in the SimaPro software. |
| **Waste treatment** | • Scrap steel {CH}\| treatment of, inert material landfill \| Cut-off, U |
| **Recycling credit stage (D)** | |
| **Steel recycling and benefits** | • Worldsteel data for steel scrap as compiled by SimaPro in its Industry Data 2.0 database |

### Table A.2: Datasets for the RCP

| Process | Datasets |
|---|---|
| **Raw material supply (A1)** | |
| **Cement** | • Cement, Portland {US}\| production \| Cut-off, U, adapted with cement composition and $CO_2$ emissions |
| **Aggregates** | • Gravel, round {CH}\| gravel and sand quarry operation \| Cut-off, U<br>Gravel, crushed {CH}\| production \| Cut-off, U |
| **Steel** | • Worldsteel data for global rebar production as compiled by SimaPro in its Industry Data 2.0 database, excluding end-of-life recycling |
| **Chemicals** | • Non-ionic surfactant {GLO}\| market for non-ionic surfactant \| Cut-off, U<br>Chemical, organic {GLO}\| production \| Cut-off, U<br>Silicone product {GLO}\| market for \| Cut-off, U<br>Fatty acid {GLO}\| market for \| Cut-off, U<br>Polystyrene foam slab {RER}\| production \| Cut-off, U<br>Titanium dioxide {RER}\| market for \| Cut-off, U |
| **Plastic** | • Polypropylene, granulate {RER}\| production \| Cut-off, U<br>Polystyrene foam slab {RER}\| production \| Cut-off, U |
| **Other** | • Expanded clay {RoW}\| production \| Cut-off, U<br>Lubricating oil {RER}\| production \| Cut-off, U<br>Glass fibre {RER}\| production \| Cut-off, U |
| **Transport to manufacturer (A2)** | |
| **Transport** | • Customized dataset with the following *ecoinvent* unit processes:<br>o Lorry, 28 metric ton {RoW}\| production \| Cut-off, U<br>o Maintenance, lorry 28 metric ton {RoW}\| processing \| Cut-off, U<br>o Road {RoW}\| road construction \| Cut-off, U<br>o Road maintenance {RoW}\| road maintenance \| Cut-off, U<br>o Diesel, low-sulphur {RoW}\| market for \| Cut-off, U<br>The emissions from diesel combustion are modelled with substances included in the SimaPro software. |
| **Manufacturing (A3)** | |
| **Fuel use** | • Diesel, burned in building machine {GLO}\| processing \| Cut-off, U<br>Heat, district or industrial, natural gas {CA-QC}\| market for \| Cut-off, U<br>Heat, district or industrial, other than natural gas {CA-QC}\| heat production, propane, at industrial furnace >100kW \| Cut-off, U<br>Transport, freight, lorry, unspecified {RER}\| transport, freight, lorry, all sizes, EURO6 to generic market for \| Cut-off, U<br>Heavy fuel oil, burned in refinery furnace {CH}\| processing \| Cut-off, U<br>Propane, burned in building machine {GLO}\| propane, burned in building machine \| Cut-off, U |

| Process | Datasets |
|---|---|
| **Electricity** | • Electricity, medium voltage {US}\| market group for \| Cut-off, U<br>Electricity, medium voltage {CA}\| market group for \| Cut-off, U |
| **Waste transport** | • Municipal waste collection service by 21 metric ton lorry {CH}\| processing \| Cut-off, U |
| **Waste treatment** | • Hazardous waste, for underground deposit {DE}\| treatment of hazardous waste, underground deposit \| Cut-off, U<br>Hazardous waste, for incineration {CH}\| treatment of hazardous waste, hazardous waste incineration \| Cut-off, U<br>Inert waste, for final disposal {CH}\| treatment of inert waste, inert material landfill \| Cut-off, U<br>Waste plastic, mixture {CH}\| treatment of, municipal incineration \| Cut-off, U |
| **Couplers - rubber gasket** | • Synthetic rubber {GLO}\| market for \| Cut-off, U |
| **Construction (A4 -A5)** | |
| **Transport** | • Customized dataset with the following *ecoinvent* unit processes:<br>o Lorry, 28 metric ton {RoW}\| production \| Cut-off, U<br>o Maintenance, lorry 28 metric ton {RoW}\| processing \| Cut-off, U<br>o Road {RoW}\| road construction \| Cut-off, U<br>o Road maintenance {RoW}\| road maintenance \| Cut-off, U<br>o Diesel, low-sulphur {RoW}\| market for \| Cut-off, U<br>The emissions from diesel combustion are modelled with substances included in the SimaPro software.<br>The dataset was adapted to the average truck load reported by CSPI. |
| **Machinery** | • Excavation, hydraulic digger {GLO}\| market for \| Cut-off, U |
| **End-of-life stage (C1-C4)** | |
| Machinery use | • Excavation, hydraulic digger {GLO}\| market for \| Cut-off, U<br>Waste reinforced concrete {CH}\| treatment of, recycling \| Cut-off, U |
| Transport to treatment facility | • • Customized dataset with the following ecoinvent unit processes:<br>o Lorry, 28 metric ton {RoW}\| production \| Cut-off, U<br>o Maintenance, lorry 28 metric ton {RoW}\| processing \| Cut-off, U<br>o Road {RoW}\| road construction \| Cut-off, U<br>o Road maintenance {RoW}\| road maintenance \| Cut-off, U<br>o Diesel, low-sulphur {RoW}\| market for \| Cut-off, U<br>The emissions from diesel combustion are modelled with substances included in the SimaPro software. |
| Waste treatment | • Waste concrete {CH}\| treatment of, inert material landfill \| Cut-off, U<br>Scrap steel {CH}\| treatment of, inert material landfill \| Cut-off, U |
| **Recycling credit stage (D)** | |
| **Concrete benefits** | Gravel, crushed {CH}\| production \| Cut-off, U |
| **Steel recycling and benefits** | Worldsteel data for steel scrap as compiled by SimaPro in its Industry Data 2.0 database |

**Table A.3: Electricity mixes modelled**

| Electricity mixes | Data source | Coal | Oil | Gas | Other Fossil | Nuclear | Hydro | Biomass | Wind | Solar | Import | Geothermal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| US | ecoinvent | 40% | 1% | 26% | 0% | 20% | 6% | 1% | 5% | 0% | 1% | 0% |
| CA | ecoinvent | 10% | 0% | 6% | 0% | 15% | 64% | 0% | 2% | 0% | 2% | 0% |

*Note: Numbers may not add up due to rounding.*

**Table A.4: Main modifications made to *ecoinvent* processes**

| Activity | | | Original value from *ecoinvent* | Value used in the model | Unit |
|---|---|---|---|---|---|
| **$CO_2$ emissions from clinker production** | USA | | 0.839 | 0.868 | kg $CO_2$ eq./kg clinker |
| | Canada | | 0.839 | 0.782 | |
| **Portland cement production** | USA | | | | |
| | - | Clinker | 90% | 85% | |
| | - | Gypsum | 5% | 5% | |
| | - | Limestone | 5% | 2% | |
| | Canada | | | | |
| | - | Clinker | 90% | 92% | |
| | - | Gypsum | 5% | 5% | |
| | - | Limestone | 5% | 3% | |
| **Portland limestone cement production** | USA and Canada | | | | |
| | - | Clinker | 90% | 83% | |
| | - | Gypsum | 5% | 5% | |
| | - | Limestone | 5% | 12% | |

# APPENDIX B
# LCI AND LCIA RESULTS

(Refer to Excel file: CSPI_LCA _AGECO_AppendixB_LCIandLCIAresults.xlsx)

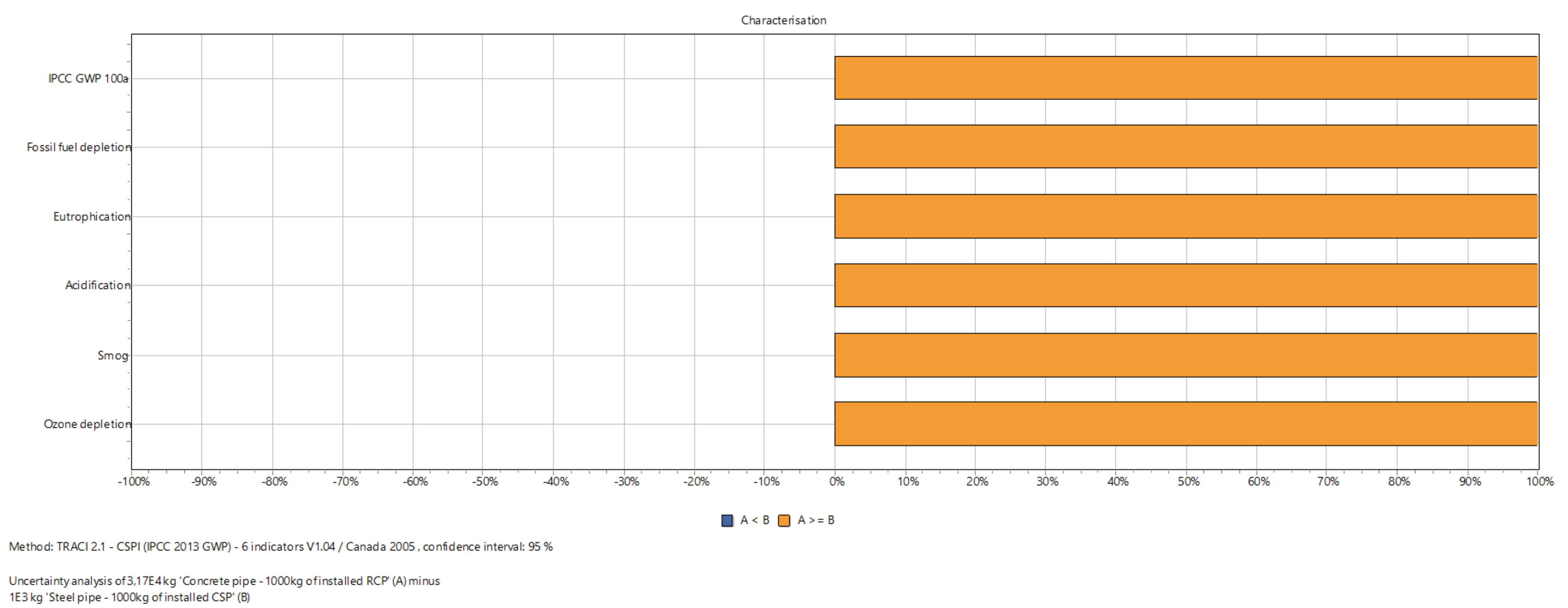
# APPENDIX B – LCI AND LCIA RESULTS

Refer to Excel file: CSPI_LCA _AGECO_AppendixB_LCIandLCIAresults.xlsx

# APPENDIX C
# UNCERTAINTY ASSESSMENT – MONTE-CARLO SIMULATIONS

## APPENDIX C – UNCERTAINTY ASSESSMENT – MONTE-CARLO SIMULATIONS

**Figure C.1: Occurrence probability for the results of the subtraction system A (RCP) – system B (CSP)**



# APPENDIX D
# CRITICAL REVIEW STATEMENT

## APPENDIX D – CRITICAL REVIEW STATEMENT

Detailed comments are presented in the document titled "Critical review SteelvsConcrete Pipe 14040-44 20.10.16 ack signed.pdf".

***Industrial Ecology Consultants***

October 19, 2020

**Madavine Tom, ing.**
Analyste principale | Senior Analyst
Groupe AGÉCO
25, avenue Mozart Est, bureau 310
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**Verification Report: Comparative LCA of Corrugated Steel vs. Reinforced Concrete Pipes**

The LCA Practitioner, Groupe AGÉCO, commissioned Industrial Ecology Consultants to perform an external independent verification of the **Comparative Life Cycle Assessment (LCA) study of CSPI's 1,800mm Corrugated Steel Pipes with North American Reinforced Concrete Pipes, September 2020.** Groupe AGÉCO completed the Life Cycle Assessment (LCA) study on behalf of the commissioning organization, the **Corrugated Steel Pipe Institute (CSPI)**.

**The review of the study was performed to demonstrate conformance** with the following standards:

- International Organization for Standardization. (2006). Environmental management -- Life cycle assessment – Principles and framework (ISO 14040:2006).
- International Organization for Standardization. (2020). Environmental management -- Life cycle assessment -- Requirements and guidelines (ISO 14044:2006/Amd.1:2017/Amd.2:2020)
- International Organization for Standardization. (2014). Environmental management -- Life cycle assessment -- Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006. (ISO/TS 14071:2014)

The independent third-party verification was conducted by an external panel of experts per ISO 14044 Section 6.2: Critical review by internal or external expert:

Thomas P. Gloria, Ph.D.
Founder, Chief Sustainability Engineer
Industrial Ecology Consultants

Brandie M. Sebastian, LCA-CP
Sustainability Practice Co-lead
John Beath Environmental, LLC

Jeremy Gregory, Ph.D.
Research Scientist acting as an independent consultant
Executive Director, Concrete Sustainability Hub
MIT Civil and Environmental Engineering Department

***Industrial Ecology Consultants***

REVIEW SCOPE

The intent of this review was to provide an independent third-party external verification of a completed comparative LCA study report to be communicated externally. Specifically, per ISO 14044, the review was performed to determine the following:

- Are the methods used to carry out the study consistent with the ISO 14040/14044 standards?
- Are the methods used to carry out the study scientifically and technically valid?
- Are the data used appropriate and reasonable in relation of the goal of the study?
- Do the interpretations reflect the limitations identified and the goal of the study?
- Is the report transparent and consistent?

REVIEW PROCESS

The review involved verification of conformance of the LCA project report based on the requirements set forth by the applicable ISO standards. A formal review matrix was developed for the LCA report based on the applicable standards. All comments were successfully addressed by the LCA practitioner, Groupe AGECO. This review did not include an assessment of the Life Cycle Inventory (LCI) model, however, it did include a detailed analysis of the individual datasets used to complete the study.

VERIFICATION STATEMENT

Based on the independent verification objectives, the **Comparative Life Cycle Assessment (LCA) study of CSPI's 1,800 mm Corrugated Steel Pipes with North American Reinforced Concrete Pipes, September 2020,** was verified to be ***in conformance*** with the applicable ISO standards referenced above. The plausibility, quality, and accuracy of the LCA-based data and supporting information are confirmed.

As the External Independent Third-Party Review chair, I confirm that members of the review panel have sufficient knowledge and experience of building products, steel and concrete pipe technology, the relevant ISO standards and the geographical areas intended to carry out this verification.

Sincerely,

Thomas P. Gloria, Ph.D.
Founder, Chief Sustainability Engineer
Industrial Ecology Consultants