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Environmental impact assessment of construction materials in a battery factory

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Abstract

This paper explores the environmental impact of construction materials in a battery factory, with a particular focus on their global warming potential, acidification, and eutrophication potential. The production of construction materials is found to contribute significantly to the overall environmental impact of a building, with steel and concrete identified as having the highest impact among the materials analyzed. The GWP of steel and concrete production can range from 100 to 200 kg CO_2eq/m^2 and 10 to 20 kg CO_2eq/m^2, respectively. However, initiatives such as HYBRIT and H2Green steel involving the use of hydrogen in the steelmaking process have the potential to reduce emissions by up to 95 percent. Moreover, the carbon footprint of battery cell production is another critical aspect to consider. Northvolt has set an ambitious target to decrease the carbon footprint of its cell fabrication from 33 kg to 10 kg CO_2eq./kWh by 2023. Additionally, in the product stage (A1-A3) when constructing the factory, a cell's energy storage capacity only accounts for significantly less than 1 kg CO_2eq./kWh. This means that Northvolt is heading in the right direction to achieve its goal. In conclusion, this paper highlights the urgent need for action in the building sector to reduce carbon emissions and promote greater sustainability. With greener initiatives, the steel industry can achieve significant reductions in greenhouse gas emissions, which can contribute to achieving global carbon emission targets. It is critical to continue researching and implementing sustainable practices in the building sector as it plays a crucial role in reducing overall carbon emissions.

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List of acronyms and abbreviations

CO_2 eq. carbon dioxide equivalent

EN European standard

EPD environmental product declaration

GWP global warming potential

AP Acidification

EP Eutrophication

ISO international organization for standardization

LCA Life cycle assessment

1. Introduction

1.1 Background

Global warming and climate change are some of the biggest threats human society is facing in this century. Carbon emissions from fossil fuel is the primary greenhouse gas emitted through human activities and it is the main cause of global warming. (Fang et al, 2011). The construction industry is a key contributor to these emissions with 40 percent of total energy resource accounting for more than 30 percent of global carbon dioxide (CO_2) emissions; materials such as concrete, steel and timber represent the major portion of material used entailing emissions hard to eliminate (Karlsson et al, 2020), therefore, they represent an important target that must be controlled throughout the building life cycle. (Chau et al, 2012). In recent years to achieve a reduction in carbon emissions, many countries have focus on choosing the adequate materials and methods which give a lower climate impact. Most of the industries nowadays including Northvolt are focusing on how to minimize the carbon footprint of its building. Northvolt was founded in 2016 and its goal and mission are to produce world's greenest battery cell with a minimal carbon footprint through the value chain and to enable the transition to renewable energy towards a more sustainable future (Northvolt, 2022). Therefore, the company place a lot of focus on the environmental impact of its products.

To overcome and mitigate global warming, a fundamental necessity is to quantify the environmental impact a material has in order to make a well-founded decision when choosing a material. A life cycle assessment (LCA) can be a useful tool to improve sustainability in the industry and will be required in the Swedish building sector starting in 2022 (Cheonghoon B et al, 2013). It evaluates and quantifies the environmental impact a product, service or building has from cradle to grave, meaning from the extraction of the raw material, manufacturing process, production, transportation, usage, waste treatment and final disposal or end of life.

Also, in order to promote products and services that causes less impact to the environment with verifiable information a powerful document that can be beneficial is the Environmental Product Declaration (EPDs). EPDs can be used to assess the environmental impact of any product and are a verified description of the environmental profile of any product, based on Life-cycle assessment calculations according to ISO 14040, ISO 14044 and EN 15804 standard for EU countries where about 18 environmental indicators are evaluated. (Bovea et al. 2014).

1.2 Problem

As the building sector is one of the biggest contributors, estimating and reducing carbon emissions is one of the main objectives and hot topics of the decade. Carbon emissions from this sector contribute significantly to climate change and global warming since buildings need a significant amount of heating, cooling, lighting among others to keep running. To generate this energy, the burning of fossil fuels is often needed, releasing carbon dioxide (CO_2) among other greenhouse gases to the atmosphere. Sweden has set up an objective to be fossil free by 2045 and The European Commission has established an objective to decrease carbon emissions in the building sector by 90 percent until 2050. LCA is one of the best tools to achieve and comply with these objectives. Therefore, the building sector can become more resource efficient through incorporating Life cycle assessment according to Petrovic et al. (2019)

According to statistical news from Statistics Sweden (2021) "emissions from the manufacturing industry decreased by 13 percent during 2020 compared with 2019, from 15.0 million tons of carbon dioxide equivalents in 2019 to 13.0 million tons of carbon dioxide equivalents in 2020". However, additional efforts are needed; implementation of energy efficient design strategies, such as renewable energy sources, energy-efficient building materials and smart buildings to optimize energy usage can also play a critical goal in achieving a more sustainable future.

1.3 Purpose and Research Questions

The purpose of this thesis is to conduct a life cycle assessment (LCA) of the environmental impact at the product stage (A1-A3) during the construction of "downstream" and "formation and aging" buildings in a Northvolt facility using Environmental Product Declarations (EPDs). The primary objective is to assess, rate, and certify the sustainability of the factory while mitigating environmental impact and providing sustainable solutions. The goal is to provide a comprehensive view of the potential environmental impact during the product stage, specifically in terms of global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP), with the aim of increasing awareness and visibility to achieve a greener and more sustainable project.

The thesis aims to address the following research questions:

Research Question 1 (RQ1): What is the environmental impact of construction materials used in the construction of "downstream" and "formation and aging" buildings, specifically in the product stage (A1-A3), in terms of GWP, AP, and EP impacts?

Research Question 2 (RQ2): How can the environmental impact of a building be reduced by using construction materials produced with novel production technologies?

The LCA will help to identify the construction materials with the highest environmental impact and help propose solutions to reduce such impact using innovative production technologies. The study will also provide insight into the effectiveness of using EPDs in assessing the environmental impact of construction materials during the product stage, which can help in the certification process of sustainable factories. By addressing these research questions, this thesis aims to contribute to the promotion of sustainability practices in the construction industry, as well as to support the achievement of global environmental targets.

2. Theoretical Framework

2.1 Building components

Typically, there are two major components when constructing a building, which are substructure and superstructure. Substructure can be defined as the lower part of building constructed below the ground level. Its main function is to transfer the loads from upper levels (superstructure) to the soil. It involves the foundation of the building.

On the other hand, superstructure is everything above ground level and serves the purpose of structure's intended use. It includes beams, columns, floor slabs and roof. Also, in the construction industry, it is often referring as architectural shell as the structural element that divides the inner space of the structure from the outside including external walls and external openings (windows and doors). Once this is complete, last step is the fit-out which refers to the process of transforming the interior space suitable for use and occupation contains interior walls and openings but also furnishing and other fitting-out work.

2.2 Construction materials and its effect in the environment

Construction is a key sector of the global economy. However, construction activities can also have significant environmental impacts, particularly in terms of resource consumption, waste generation and greenhouse emissions. Also, transporting materials from and to the construction site and producing these materials can generate significant amount of emissions. The production process of construction materials such as steel and concrete can have a significant impact on the environment throughout their lifecycle, from extraction of raw material to disposal (International Energy Agency, 2019).

Concrete is a vital component and widely used in the building construction today. It has many advantages such as durability, strength, fire resistant among others but its production process requires large number of natural resources and massive amount of energy consumption. The production of cement which is a key component of concrete entails grinding of the cement ingredients and heating to very high temperatures to form clinkers resulting in a major contributor to CO_2 and other greenhouse emissions in the atmosphere. Additionally, the extraction of raw materials used in its production have a negative impact on ecosystems and biodiversity resulting in habitat loss and destruction of natural landscapes. (Babor et al. 2009). According to the International Energy Agency (IEA), CO_2 emissions from 1 ton of concrete produced can vary between 0,7 to 1 ton into the atmosphere. To tackle this issue, the industry has been exploring different strategies such as using alternative fuels, improved energy efficiency and the development of low-carbon cement product.

Similar to concrete, the production of steel with the construction industry being the largest consumer, also requires large amounts of energy and raw materials, affecting and resulting in significant environmental impacts. Greenhouse gases emissions and other pollutants such as sulphur dioxide, nitrogen oxides, are produced when converting iron ore into steel involving the use of coal and other fossil fuels that can contribute to air pollution and negative impacts on human health. In addition, steel has significant impacts at the end of its life cycle; the disposal of steel waste can contribute to landfills that can lead to soil and groundwater contamination.

Mitigation measures

In recent years, there has been growing concern about the environmental impact of industrial production, particularly in industries such as steel manufacturing. As companies seek to reduce their carbon footprint and promote sustainability, efforts have been made to develop more eco-friendly products and processes. In Sweden, one of the EU's leading producers of ores and metals, companies like SSAB have been taking steps towards decarbonization by exploring new methods of production.

In particular, the use of hydrogen in the steelmaking process has gained traction as a promising alternative to coal and coke. SSAB's HYBRIT and H2Green Steel initiatives have already begun to demonstrate the potential for hydrogen-based steel production to significantly reduce the carbon footprint of the industry. By replacing traditional fossil fuels with hydrogen, steel producers can drastically reduce their carbon emissions and move closer to achieving carbon neutrality.

Another approach to reducing the environmental impact of industrial production is the use of recycled materials. Recycled steel and concrete can be used to avoid the need for new raw materials and energy-intensive processing, which can lead to significant reductions in carbon emissions. However, it's important to keep in mind that the recycling process itself requires energy, and the emissions associated with it will depend on the source of that energy.

Overall, the push for more sustainable industrial production has led to a wide range of initiatives and approaches to reducing carbon emissions and environmental impact. While there are many challenges and obstacles to overcome, the progress made by companies like SSAB and others is a positive sign that a more sustainable future for industry is possible.

Green concrete

Green concrete refers to concrete that is made using environmentally sustainable materials and/or processes, hence designed to reduce the environmental impact of traditional concrete production. This may include the use of recycled materials such as fly ash or slag in lieu of Portland cement since it is one of the primary sources of CO_2 emissions during concrete production. Some studies have shown that the use of fly ash could potentially reduce carbon dioxide emissions up to 27 percent while the use of slag up to 42 percent. Green concrete can also be made using alternative sources of energy, such as solar or wind power or through the use of more efficient manufacturing procedures that reduce the amount of energy required to produce this material. (Garg, C., & Jain, A, 2014). However, there are also some challenges associated with the production and use of green concrete, involving the availability of alternative cementitious materials and the need of specialized equipment and expertise. (Liew et al. 2017)

HYBRIT

HYBRIT is a Swedish initiative that aims to develop a fossil-free value chain for iron and steel production using fossil-free electricity and hydrogen, reducing carbon dioxide emissions. The project is a collaboration between SSAB, mining company LKAB and energy company Vattenfall. The project will produce approximately 1.2 Mt of crude steel annually, representing 25 percent of Sweden's overall production, with the potential to avoid 14.3 Mt CO_2 of greenhouse gas emissions over the first ten years of production (HYBRIT, 2022). This product is expected to be available in the market by 2026, therefore no precise figures in terms of costs and/or CO_2 reduction are available at this stage.

According to the project partners, this fossil-free steel could reduce carbon dioxide emissions up to 90 percent, potentially reducing Sweden's total carbon dioxide emissions by 10 percent. In regard to its cost an estimated total cost per tonne of crude steel has been calculated based on energy prices, the indication is that the production cost of HYBRIT is roughly 20 to 30 percent higher than the traditional steel in the market now. (HYBRIT, 2023)

H2Green steel

H2Green steel was founded in 2020 and aims to accelerate the decarbonization of the steel industry by using green hydrogen in its steel plant under development in Northern Sweden. By using green hydrogen as a substitute of coal, which is produced by using renewable energy sources such as wind and solar power. Based on the company's plans and projections it believes that carbon dioxide emissions could be reduced up to 95 percent compared to traditional steel making. (H2Green steel, 2023)

The company plants to scale up production to 20 million tons per year by 2030, making it one of the largest steel producers in Europe. However, the production of green hydrogen requires significant amounts of renewable energy and the availability, and the cost of renewable energy source may be a limiting factor in the widespread adoption of this technology. Since the production has not started, there isn't any information yet available on the cost of H2Green steel, even so the company aims to produce green steel at a competitive cost, which would be comparable to the cost of traditional steel.

2.3 Life Cycle Assessment, LCA

Although many definitions exist, according to Horne et al. (2009) life cycle assessment (LCA) "consist of a systematic evaluation of an environmental impacts arising from the provision of a product or service".

The International Organization of Standardization (ISO) 14040 distinguishes the methodological framework of LCA operating in four main phases as seen in figure 1 goal and scope definition, inventory analysis, impact assessment and interpretation. (Hauschild et al. 2018).

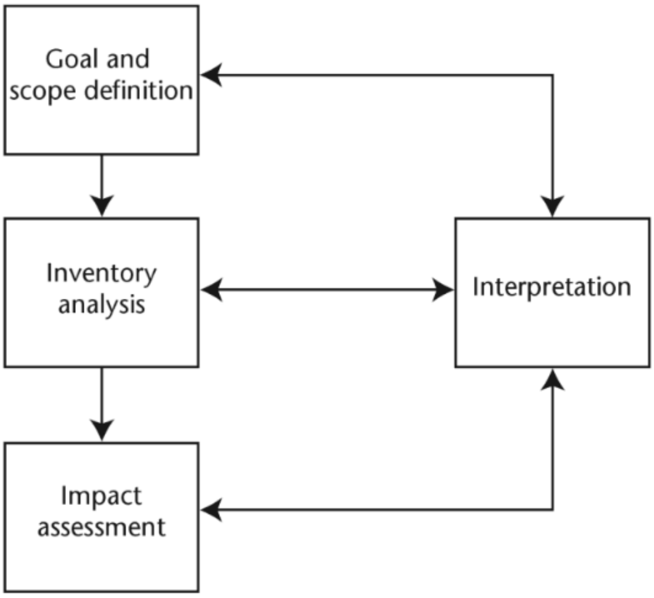


Figure 1. Framework of LCA from ISO 14040 standard

The first step of any LCA is the goal and scope definition where the assessment is framed out and outlined based on the goal of the study, it involves determining the system boundaries or limits of the analysis. In this phase the functional unit is also identified which can be defined as “a quantitative description of the function or service for which the assessment is performed” (Hauschild et al. 2018). According to Bahramian et al. (2020) two of the most popular unit are square meter (m^2) of floor area and kWh when the main focus of the study is energy usage in buildings.

Right after setting up the first phase, the inventory analysis forms the core of any LCA study, this is also known as a Life Cycle Inventory (LCI), it gathers the data collection, modelling and analysis while compiling all environmental flows, including resource inputs and waste or pollution outputs. This stage can be extremely complex because it can involve a full range of separate processes, therefore this is where most of the complexity of an LCA is involved (Horne et al. 2009). It often relies on generic data for many processes deriving from databases. The output of this inventory analysis provides a list of quantified physical elementary flows for the product system described by the functional unit (Hauschild et al, 2018).

The life cycle impact assessment phase (LCIA) is where the impacts on the environment are calculated, it evaluates the magnitude and significance of the potential environmental impacts for a product system throughout its life cycle by using category indicators (Heijungs et al, 2012). The impact assessment consists of five elements according to the ISO 14040 standard, two mandatory and three optional. The first element is the selection of impact categories representative of the assessment parameters (Table 1). “For each impact category, a representative indicator is chosen together with an environmental model that can be used to quantify the impact of elementary flows on the indicator” (Hauschild et al. 2018). The most common category to evaluate is the global warming potential, GWP, which takes into account the different greenhouse gases depending on their origin: GWP-fossil, GWP-biogenic, GWP-land use change and GWP total, the sum of the other three GWP indicators. (IPCC, 2013).

Table 1. Impact assessment categories

Impact Indicator	Unit
Global Warming Potential (GWP)	kg CO_2 eq.
Ozone Depletion Potential (OPD)	kg CFC 11 eq.
Acidification Potential of soil and water (AP)	kg SO_2 eq.
Eutrophication Potential (EP)	kg $PO_4{}^{3-}$
Photochemical Ozone Creation Potential (POCP)	kg C_2H_4 eq.
Abiotic Depletion Potential for non-fossil resources (ADP-E)	kg Sb eq.
Abiotic Depletion Potential for fossil-fuels (ADP-F)	MJ

The second mandatory element is the classification of elementary flows from the inventory by assigning them to impact categories according to their ability to contribute by impacting the chosen indicator. In additional to the previous steps, normalization, grouping and weighting may be included as optional steps to aid interpretation and draw conclusions. (Shaked et al, 2015)

The last step in an LCA study is the interpretation, it considers the results from the inventory analysis and the impact assessment phase. This step is done keeping in mind the goal and scope previously defined in the first step. To develop and strengthen conclusions while achieving accurate results sensitivity analysis, error calculations and uncertainty analysis have to be checked. (Klöpffer, 2014).

2.3.1 LCA of buildings

The increase in gross global energy and material consumption in the building sector for economic development and urbanization is one of the main concerns humankind is experiencing. LCA plays a significant role when it comes of improving future design for a more sustainable future. In order to reduce energy consumption additional materials and technologies are implemented during building design phase making LCA an appealing tool to evaluate the environmental impact it has. LCA provides a comprehensive evaluation of the environmental impact of buildings, including resource depletion and toxic substance while identifying areas for improvements. This has created an increasing interest over the years focusing on development of building sustainability certifications systems such as BREEAM, LEED. (Hauschild et al, 2018).

2.3.2 LCA stages

The life cycle of a building is typically divided into three major stages by the European Standard EN 15978:2011, A) the product stage and construction stage, B) operational stage and C) end of life (Figure 2). Each of these stages is further divided into substages. (Hauschild et al, 2018).

Life cycle stages A1-A5 consider all impacts in relation to raw material extraction, manufacture, deliver and construct the materials. Product/Manufacture stage (A1-A3) refers to the first three stages in a life cycle of a product, also referred as cradle to gate phase, which includes the extraction of the material (A1) from natural sources such as mining of ores, harvesting of timber among other. The environmental impact associated in this stage includes the depletion of natural resources, land-use changes and emissions of greenhouse gases and other pollutants. Stage A2 is the transportation of the raw material to the manufacturing site, the environmental impact during this stage includes the consumption of energy and the emissions of gases associated with the transportation. Last product stage is A3 which refers to the manufacturing process where the raw material is processed and transformed into the final product, besides environmental impact associated with greenhouse gases emissions and energy consumption, soil, air and water pollutants are also release during the manufacturing process.

B1-B7 considers those impacts associated with material use, it includes the operation, maintenance, repair and replace throughout the life cycle, environmental impact associated with this stage includes energy consumption and emissions of greenhouse gases and other pollutants during the use such as electricity, water and fuel. C stage refers to the end-of-life stage include impacts associated with how materials are treated or handled at the end of the life cycle. Benefits from reuse or recycle can be included but are taken into account under a separate module (D) that refers to beyond end-of-life stage. Roberts et al. (2020).

When conducting an LCA, typically all stages are taken into account, however there are cases depending on the objective that it can be useful to exclude some modules. By considering the entire life cycle of building, decision-makers can identify areas where environmental improvements can be made, such as using sustainable building materials, optimize the energy efficiency of a building and improving the end-of-life management of the building.

Additionally, LCA plays a crucial role in the identification of hotspots, which are key stages, processes, or activities within a product's life cycle that significantly impact the environment. The process of identifying hotspots is an indispensable step in conducting an LCA, as it enables the prioritization of environmental improvement efforts and guides decision-making processes aimed at reducing the overall environmental impact of a product. By focusing on these hotspots, organizations and policymakers can effectively allocate resources and implement targeted strategies to optimize specific stages or activities that contribute most significantly to the product's environmental footprint. The hotspots enclose areas where the product's life cycle makes the most substantial contribution to environmental burdens, such as greenhouse gas emissions, energy consumption, water use, or resource depletion.

The identification of hotspots is contingent upon the specific product or system being assessed, as each entails unique considerations. For instance, in the life cycle of an automobile, hotspots may comprise the extraction and processing of raw materials for manufacturing, vehicle assembly, fuel production and consumption, and end-of-life disposal. Thorough analysis of these hotspots empowers stakeholders to focus their efforts on improving energy efficiency, reducing emissions, promoting recycling practices, and exploring alternative materials or technologies. (Hauschild et al. 2018).

<table>
<tr><th colspan="3" rowspan="2">Product / Manufacture Stage [A1-A3]</th><th colspan="2" rowspan="2">Construction Process Stage [A4-A5]</th><th colspan="7">Use [B1-B7]</th><th colspan="4" rowspan="2">End-of-Life Stage [C1-C4]</th><th rowspan="2">Benefits & Loads Beyond [D]</th></tr>
<tr><th colspan="5">Building Fabric</th><th colspan="2">Operation of the Building</th></tr>
<tr><td>Raw Material Extract / Process / Supply</td><td>Transport</td><td>Manufacture</td><td>Transport to the Site</td><td>Assembly / Install in the building</td><td>Use / Application of Installed Products</td><td>Maintenance</td><td>Repair</td><td>Replacement</td><td>Refurbishment</td><td>Operational Energy Use</td><td>Operational Water Use</td><td>Deconstruction / Demolition</td><td>Transport to Waste Process</td><td>Reuse-Recovery-Recycle</td><td>Disposal</td><td>Reuse-Recovery-Recycle Potential</td></tr>
<tr><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td>A5</td><td>B1</td><td>B2</td><td>B3</td><td>B4</td><td>B5</td><td>B6</td><td>B7</td><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td>D</td></tr>
<tr><td colspan="3">Cradle-to-Gate</td><td colspan="13">Gate-to-Grave</td><td rowspan="2"></td></tr>
<tr><td colspan="16">Cradle-to-Grave</td></tr>
<tr><td colspan="17">Cradle-to-Cradle</td></tr>
<tr><td colspan="17">System Boundaries</td></tr>
</table>

Figure 2. Building Assessment Information

2.3.3. Uncertainties and limitations in LCA

Some of the concerns in relation to the implementation of an LCA are associated to potentially sources of uncertainty. These include poor data collection and quality, invalid or non-transparent assumptions and lack of sensitivity analysis.

LCA requires a significant amount of data, and the quality of this data will depend and vary on the source and availability of the information. For example, the data on a particular material or process may not be available, difficult to obtain or be outdated particularly for older buildings or unique materials, these data gaps and inconsistencies can lead to inaccurate results.

Also, LCA requires a number of assumptions and modelling choices, including choice of functional unit, system boundaries and impact categories. The assessment can include the entire life cycle of a product or covered only a portion of it. These choices will have a direct impact on the results of the assessment. Another source of uncertainty is that the environmental impact of a product can vary depending on factors such as location, climate and other location conditions. Last but not least the interpretation and communication of results may be subject to biases, depending on how these are presented, the audience and how the results are used. By acknowledging and addressing the uncertainties and uncertainties the quality and usefulness of LCA can be improved. (Hauschild et al, 2018).

2.4 Environmental product declaration

The broader implementation of LCA in the construction industry has caused companies to request product environmental information from the manufacturers. This data is provided in the form of an Environmental product declaration as known as EPD. The purpose of an EPD is to present quantifiable environmental information produced for an individual product in an independently verified systematic data based on a life cycle assessment in accordance with ISO 14040 and EN15804 (Marsh et al, 2022). This information can be used to make informed decisions on materials and systems and as an opportunity to cost savings through energy efficiency and reduction of waste.

The main existing programs to register EPDs in Europe are the Norwegian EPD Foundation, The International EPD System, German Institute of Construction and Environment and BRE Global Environment Profiles Scheme for construction products. All of them rely on a set of operating rules known as product category rules (PCR), these set up the specific guidelines and requirements for the development of the LCA study. (Del Borghi, A. 2013).

2.4.1 Impact indicators

Carbon footprint

Carbon footprint has become tremendously popular and a widely used term on the last decade. It can be defined as “a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product”. Wiedmann et al, (2008). Direct emissions can be defined as emissions produced during the construction phase on-site based on the amount of fuel and electricity consumed from resources (mainly equipment). These emissions also include those produced during the transportation (from gate to construction site), while indirect emissions are the ones produced offsite activities such as manufacturing and transportation. In this case, the transportation phase refers to the emissions produced during material transportation (from cradle to gate). Marzouk et al, (2017).

The calculation of carbon footprint can be approach by using two LCA methodologies: bottom-up, based on Process Analysis (PA) or top-down, based on Environmental Input-output (EIO) analysis. From a Process Analysis the environmental impact for an individual product is develop from cradle to grave. However, only on site and first, second order impacts are considered, which refer to the direct and immediate environmental consequences of a particular process or activity creating a system boundary issue. Wiedmann et al, (2008). For example the bottom-up approach in life cycle assessment focuses on assessing the environmental impact of building materials, like cement, by considering their entire life cycle. However, it has a system boundary issue because it typically only considers on-site and first and second-order impacts, overlooking upstream impacts from the entire supply chain. This limited boundary may exclude indirect environmental impacts, such as emissions from raw material extraction for production machinery or fuel transportation, leading to an incomplete assessment. On the other hand, Environmental input-output (EIO) is able to capture all supply chain impacts where transactions between the activities are measured in monetary units instead of physical units, For example, when assessing the carbon footprint of a building, EIO analysis would track the monetary flows between various sectors, such as cement production, steel manufacturing, transportation, and construction. These monetary flows represent the purchases and sales of goods and services between different sectors.

By quantifying the monetary transactions, EIO analysis can capture the indirect environmental impacts associated with the production and transportation of construction materials throughout the entire supply chain. It takes into account the interrelation and interdependencies between sectors, providing a comprehensive picture of the environmental impacts associated with the construction industry. However, this method has also been criticised for being too aggregated, causing the need to combine both methods in order to obtain a detailed and comprehensive analysis while mitigating uncertainty in compiling life cycle inventories. Kjaer et al, (2015)

Global warming potential

Environmental pollution is one of the main issues affecting climate change and construction site are typically associated with high quantities. These quantities need to be quantified since they affect human health. Global warming potential (GWP) can be defined as “the total energy that a gas absorbs over a certain period of time which is usually 100 years” (EPA, 2016a). Some of the major greenhouse gases are carbon dioxide (CO_2), methane (CH_4) nitrous oxide (N_2O) and fluorinated gases. These gases are trapped in the atmosphere as a result of human activities, making the one of the greatest contributors to climate change. Marzouk et al, (2017).

GWP is used as a instrument for comparing the climate impact of different greenhouse gases and developing new policies to mitigate climate change. The calculation process for comparing the climate impact of different greenhouse gases using global warming potential involves two key steps. Firstly, GWP values are assigned to each greenhouse gas, representing their warming potential compared to carbon dioxide (CO_2) over a specific time period. Secondly, the emissions of each greenhouse gas are measured and multiplied by its corresponding GWP value. This calculation yields the equivalent emissions in CO_2 units, enabling a meaningful comparison of the climate impact of different greenhouse gases. By accounting these gases policy makers can develop strategies to reduce emissions of those gases that have the greatest impact on the environment. Also, when comparing the GWP of different products or materials, stakeholders can make informed decisions about which products or materials to use in order to reduce the carbon footprint in projects. IPCC (2013)

The importance of the GWP in EPDs is also reflected in the growing trend towards low-carbon and carbon-neutral building design and construction. Many building codes and rating systems, such as LEED and BREEAM, prioritize low-carbon and carbon-neutral buildings. To meet these requirements, builders and architects need to carefully consider the GWP of the products and materials they use and select those with the lowest GWP.

Acidification

The acidification impact category is one of several environmental impact categories assessed in an EPD, it measures the emissions that refers to the potential of a material to contribute to the acidification of the environment, through the emissions of acid-forming pollutants, which measures a molecule's capacity to increase the hydrogen ion concentration in the presence of water, thus decreasing the pH value. When a product is manufactured, it may release substances such as sulphur dioxide (SO_2), nitrogen oxides (NOx) or other acidic gases that can lead to acid rain or acid deposition. These substances have harmful effects on the environment and human health including mortality, forest decline and the deterioration of building materials. Hauschild et al, (2018).

The acidification potential is expressed in terms of a unit of mass of a specific pollutant or a group of pollutants. The most commonly used unit is kilograms of sulphur dioxide equivalents (SO_2 eq.) per functional unit, or a material produced or used.

Eutrophication

According to Hauschild et al. (2018) eutrophication refers to excessive enrichment of the aquatic environment with nutrients particularly nitrogen and phosphorus, that leads to an increase of biomass production such as algae and other aquatic plants which results in the degradation of water quality (affecting appearance, colour, smell, taste) and ecosystem killing fish species and creating dead zones where aquatic life cannot survive. The release of these nutrients can come from various sources, such as agricultural or industrial activities, wastewater discharge or atmospheric deposition, materials contribute to this last one in the production and use of fertilizers and other chemical inputs.

In the context of LCA, eutrophication quantifies the potential impact of a product or material on aquatic ecosystems, through the release of nutrients into water bodies. It is usually expressed in terms of a unit of mas, such as kilograms of phosphorus equivalents (kg PO_4 eq.) per functional unit of the product.

2.5 Battery production

According to Väyrynen (2012) batteries are devices that convert stored chemical energy into electricity within a closed system. Lithium batteries (LIB), also known as lithium-ion batteries, are a type of rechargeable battery that uses lithium ions as the primary component for energy storage.These were developed in Japan and first introduced in the market by Sony Co in 1991. Lithium batteries have been widely used for electric vehicles, portable electronics especially cellular phones and notebook computers and grid storage. A LIB has different cell design including cylindrical and prismatic, but the cell manufacturing processes are very similar.

The manufacturing process includes three major parts (Liu et al, 20121): electrode preparation, cell assembly and battery electrochemistry activation.

2.5.1 Electrode preparation

The first step is the preparation of raw materials such as lithium, cobalt, nickel, manganese and others to make electrodes and electrolyte. The active material conductive additive, and binder are mixed to form a slurry with the solvent. For the cathode, N-methyl pyrrolidone is normally used to dissolve the binder, and for the anode, the styrene-butadiene rubber binder is dissolved in water with carboxymethyl cellulose. The slurry is then pumped into a die, where is coated on both sides and delivered to drying equipment to evaporate the solvent. In the case of cathode slurry since the organic solvent is toxic a solvent recovery process is necessary. For the anode slurry is step is skipped. Next step is calendering where the physical properties of the electrodes can be adjusted, this is where the anode and cathode are oven-dried before being pressed.

2.5.2 Cell assembly

At this point in the production process, the electrode rolls are fed into machines for cutting and further preparation. The electrodes are either rolled up (for cylindrical cells) or stacked (for prismatic cells) into small packages, which are then fitted into metal cans. Finally, the cells are filled with electrolyte and sealed.

2.5.3 Battery electrochemistry activation

Before delivering the cells to manufacturers, in order to enable operation stability electrochemistry activation steps are needed. The formation and aging process stars with charging the cells, followed by a rest session, this is also known as conditioning and is the last step in the production process. The cells are charged/discharged under a low rate and then the rate will be gradually increased to ensure stability. The gas generated from the formation process needs to be discharged for safety concerns. This is done to make sure that the battery works properly. After or during formation cycles, the cells are stored on aging shelves for complete electrolyte wetting and stabilization. Another degassing step is made before the cells are finally sealed for future applications. (Figure 3)

Testing and quality control is one of the final steps in the battery production to ensure that the batteries meet the required performance specifications and safety standards before these are packaged. This may include tests for capacity, voltage, temperature and durability, making packaging and distribution the last step.

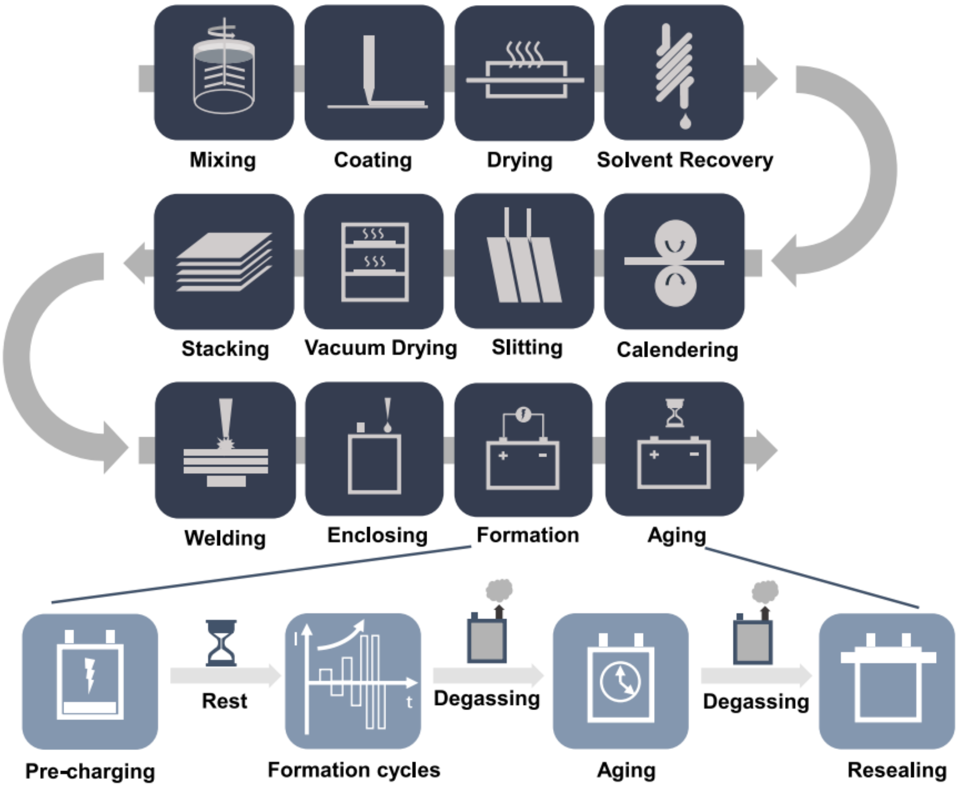


Figure 3. Lithium batteries manufacturing process

2.5.4 Downstream process

The downstream process in a battery factory is critical to the production of a high-quality product and typically involves a range of important activities.

In a battery factory, the downstream process typically involves the final stages of battery production, where the batteries are assembled and packaged for distribution. It includes the cell assembly, the cell formation where the batteries are charged and discharged to active the electrodes and determine battery's capacity, battery pack assembly, testing and quality control to ensure they meet the required performance specifications and safety standards and packaging and distribution to customers. Li, J., & Zhao, T. S. (2015). However, in some battery factories such as Northvolt AB, the downstream process may also include earlier stages of battery production such as slurry mixing process, coating, dry electrode and cell assembly which are crucial to ensuring the quality and consistency of the batteries throughout the production process. Formation and ageing are carried out in a separate building.

On the other hand, the upstream process involves the cathode active material production plant. It can be divided in two parts: precursor and calcination. In precursor, key materials such as nickel, manganese, lithium and cobalt are mixed and sent to calcination. The output is a fine powder which forms the basis for active cathode material. This material is the one that enables the battery to store energy (Northvolt AB, 2023)

2.5.5 Environmental impact of battery production

The growth in production of automotive battery cells has led to concerns about their environmental impact, energy consumption, and greenhouse gas emissions. One major environmental concern is related to the extraction and processing of lithium sources, which can have negative impacts on ecosystems and biodiversity. Additionally, the disposal of batteries containing heavy metals such as nickel and cobalt can result in pollution and pose risks to human health (Costa et al, 2021).

The environmental impact of battery production can vary depending on a variety of factors, such as the type of battery and the energy sources used in manufacturing. However, a common metric used to measure the carbon footprint of battery production is the amount of carbon dioxide equivalent emissions per kilowatt-hour of battery capacity (CO_2 eq./ kWh). This metric takes into account the emissions associated with the entire life cycle of a battery, including raw material extraction, processing, manufacturing, transportation, use, and disposal.

According to a study conducted by the European Environment Agency, a typical lithium battery produces around 60-106 kg CO_2 eq./kWh. This means that the production of a single battery with a range of 40 kWh, such as those used in Nissan vehicles, would emit approximately 2,920 kg of CO_2 eq. during its production. In comparison, the production of a 100 kWh battery used in Tesla vehicles would result in emissions of approximately 7,300 kg of CO_2 eq.

It is important to note that the carbon footprint of battery production can be reduced through various measures such as the use of renewable energy sources in manufacturing, more efficient production processes, and the recycling of batteries at the end of their useful life.

3. Methodology

3.1 Research Process

The research process is divided into five stages (Figure 4). First, the research topic was selected as being one the hot topics of interest for the company and initial research questions were developed. Secondly, a literature review was conducted to obtain a greater and broader understanding of a life cycle assessment framework. In the third stage, the case was investigated and data concerning GWP,AP and EP results were collected through external public sources such as Environmental Product Declaration (EPDs), climate database from Swedish National Board of Housing, Building and Planning (Boverket) and materials quantities given by the company. All collected information was then implemented in the case study (Downstream and formation and aging buildings). The research questions developed at the beginning were several times examined and adapted to the findings from literature and insights from the case study to provide conclusions.

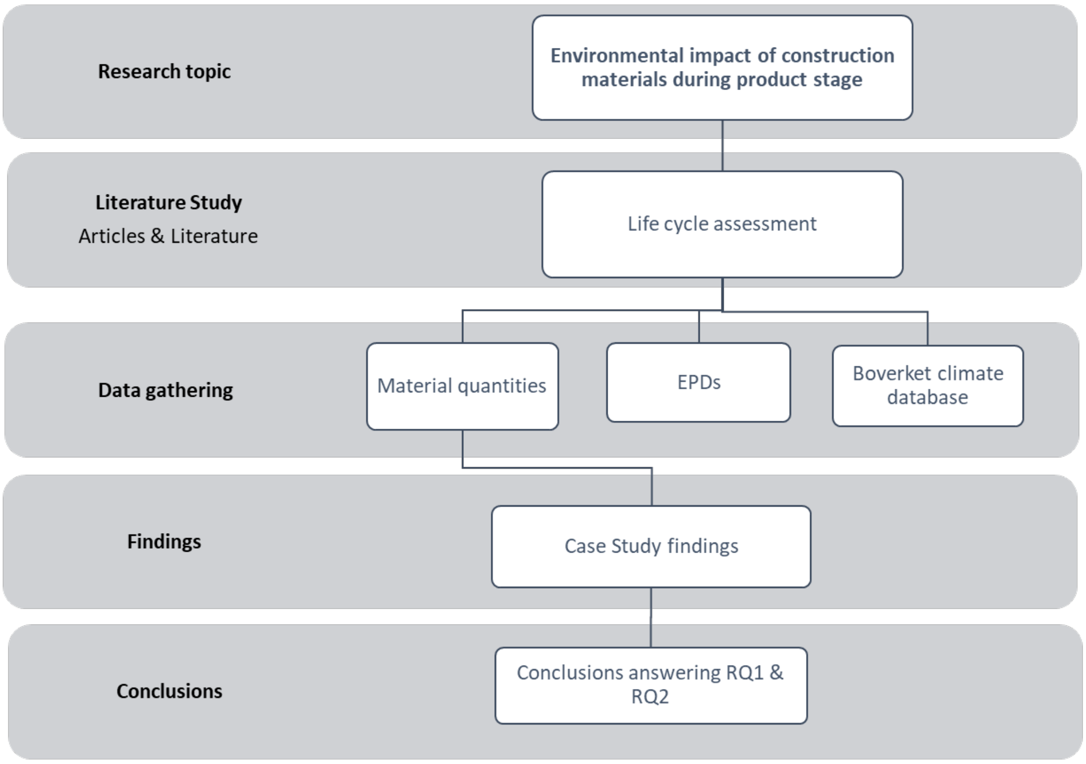


Figure 4. Methodology implemented

3.1.1 Literature review

A literature review was implemented to obtain a broad understanding of the current topic of research. It was conducted in Google Scholar and ScienceDirect using the terms “global warming potential”, “Life cycle assessment”, “environmental impact of construction materials” and “battery production”

First and foremost, the literature review was divided in two approaches to enable a deeper understanding and create a holistic picture on how to conduct a life cycle assessment, methodology, current challenges and limitations in relation to construction materials for the construction of a battery factory. The first approach was oriented in the construction sector (focusing on materials) based on this 8 papers were reviewed. The other focus was towards battery production, 2 papers were evaluated. All literature review is listed on Table 2 and was examined with regards to the following parameters:

Functional unit: what is the subject of study?

Data source: Which inventory was used to conduct the study?

LCA system boundaries: which stages were considered in the LCA?

Impact categories: Were all environmental impact categories considered?

Global warming potential: What is the global warming potential associated to main materials such as concrete and steel?

Table 2. Literature review

#	Authors	Year	Focus	Title
1	Kerr et al.	2022	Construction	Comparative Analysis of the Global Warming Potential (GWP) of Structural Stone, Concrete and Steel Construction Materials
2	Degen and Schuttte	2022	Battery Production	Life cycle assessment of the energy consumption and GHG emissions of state-of-the-art automotive battery cell production
3	Gebler et al.	2020	Battery Production	Life cycle assessment of an automotive factory: Identifying challenges for the decarbonization of automotive production - A case study
4	Häfliger et al.	2017	Construction	Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials
5	Sinha et al.	2016	Construction	Environmental footprint assessment of building structures: A comparative study
6	Martínez-Rocamora et al.	2016	Construction	LCA databases focused on construction materials: A review
7	Heinonen et al.	2016	Construction	Pre-use phase LCA of a multi-story residential building
8	Huijun et al.	2012	Construction	Life cycle energy consumption and CO_2 emission of an office building in China
9	Zabalza Bribián et al.	2011	Construction	Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential
10	Blengini, G.	2008	Construction	Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy

Functional unit: In regard to the functional unit this one varied between studies. Typically, it was expressed in kg or m^3, other studies identified it as 1 m^2 of floor area or energy reference area with a service life of XX years.

Data source: The study conducted by Martinez-Rocamora in 2016 facilities a state of art review of existing LCA databases concluding that GaBi and Ecoinvent as the most widely used databases for construction materials due to integrity and resources. Also, 2 of the studies used environmental product declarations already published on materials such as concrete and steel. Other studies relied on European public data sources such as ELCD (European Reference Life-Cycle Database). Heinonen study (2016) used ReCipe 2011 method.

LCA system boundaries: Entire life cycle of the building from production to demolition was set as system boundary for 6 out of 8 of the studies reviewed. The study of Heionen (2016) took into consideration in his study the pre-use stage.

Impact categories: All literature reviewed took into account global warming potential, making 2 studies only focusing on this parameter. The study made by Heinonen on the multi-story residential building considered all 18 impact categories provided by ReCipe. Zabalza Bribian et al (2011) considered in his study primary energy demand, GWP and water demand as impact categories to analyse due to their importance in reaching EU targets.

Global warming potential: GWP was indicated in all studies showing that materials used in construction, such as concrete and steel, also have a significant carbon footprint. The study conducted by Kerr (2022) showed in regard to materials that concrete can contribute during product stage (A1-A3) between 246 to 514 kg.CO_2/m^3, depending on the strength, while structural steel implemented for beams and columns can be accounted for 22,294 kg.CO_2/m^3 resulting in extremely high GWPs. Steel is a widely used construction material and so these findings indicate that it has an important role to play in the total carbon emissions attributed to the construction sector. In terms of building a factory, the greatest impact is allocated in the use phase representing a global warming potential with 77 percent of the total life cycle, on the other hand raw materials account for 17 perfect of the total life cycle GWP and construction phase to 6 percent. (Gebler et al. 2020)

In conclusion, the literature review indicated that constructions materials such as concrete and steel are a major contributor to carbon emissions and global warming, especially during the product phase. LCA studies have identified opportunities to reduce the environmental impact of buildings through the use of sustainable materials and energy-efficient designs. Additional investigation was made on alternative and/or greener materials in order to reduce the carbon emissions in this thesis.

3.1.2 Case study

The study was performed on 7 buildings located in Skellefteå, northern Sweden as part of the first giga-battery factory. 4 out of the studied building corresponded to the battery downstream production process (DS1,DS2,DS3 and DS4) and the other 3 related to formation and ageing process (FA1, FA2 and FA3). Due to the data gathering complexing other buildings part of this factory were not analysed. Also, due to confidentiality total gross area and kWh for each building are not disclosed.

3.1.3 Life cycle assessment

Goal

The main goal of this thesis is to answer to the following question: *What is the environmental impact of construction materials used in the structure and envelope of downstream and formation and aging buildings?* To account for major environmental concern, only three impact categories are evaluated: global warming potential (GWP), acidification (AP) and eutrophication (EP).

This study applied a cradle to gate LCA outlined by ISO 14040 standards series, the main focus of this work is on the embodied emissions also part of this goal is to identify hotspots materials implemented in civil, structural and architectural phase with a focus on GHG emissions. As the company is growing and expanding across Europe, this LCA is to inform the design team of the most significant aspects and potential material improvements to keep in mind during upcoming development.

Functional unit

To achieve the main goal described above and based on the literature review, *1 square meter of gross floor area* was chosen as the functional unit.

System boundaries

The overall LCA of a building, from cradle to grave approach, goes from the extraction of the raw material to demolition. However, in this study the LCA is conducted from cradle to gate, covering only product stage (A1 to A3) because it has the largest potential for revealing variations between material types and only focusing on civil, structural and architectural elements leaving aside mechanical, electrical and plumbing elements due its complexity and lack of data information. (Figure 5)

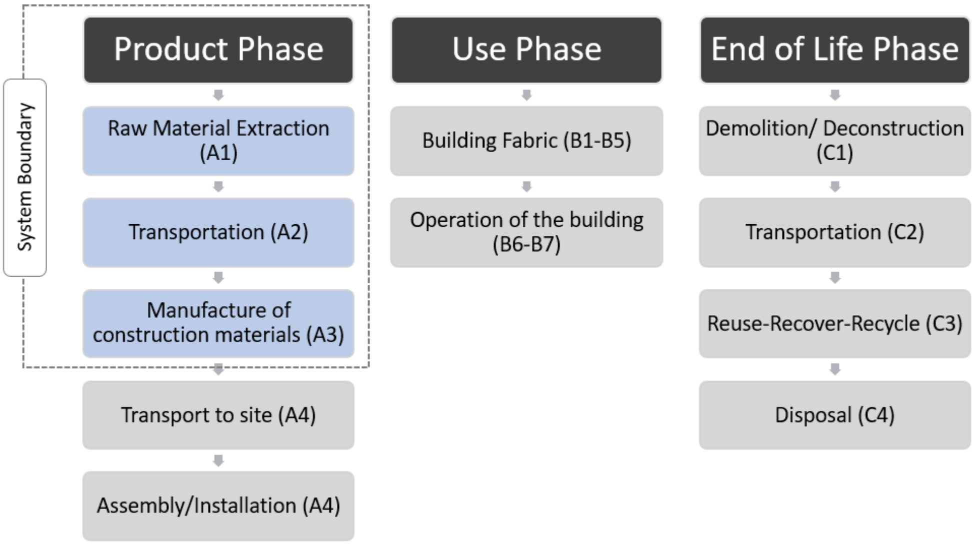


Figure 5. System boundaries

Building elements considered

The construction of any building requires a range of different materials and quantities. Due to the lack of data and its complexity, only essential components for construction and with a significant amount of material quantity were taken into account for the calculations. Table 3 gathers all elements. Same materials are applicable for both downstream and formation and ageing buildings.

Table 3. Building elements considered

Building envelope subsystems	Main materials
Substructure	
Floor Slabs & Foundations	Concrete, reinforcement, insulating materials
Structure	
Main support structure	Structural steel
Floors & Roof	Concrete / Steel
Architectural Shell	
Exterior Walls	Composite cladding
Doors & Windows	Glass, aluminium
Fit-out general	
Interior Walls	Mineral wool panels

The study period

According to Boverket report (2020) in Regulation on climate declarations for buildings, when calculating greenhouse gas emissions for use stage (B) it recommends a study period to be set at 50 years, which also aligns with what most Nordic and other European countries use. It is important to mention that this is not the same thing as the expected technical service life of the building, a period considered for the building to keep its shape and functions as original designed for. The reference study period refers to a delimited period of time for which the calculations are made. However, the scope of this thesis only accounts for the product stage, hence, no study period is needed. On the other hand, to assess the global warming potential per kilowatts hour of cell energy storage capacity the reference study period was 25 years set by Northvolt.

Impact categories and assessment method

The impact categories considered were global warming potential (also known as climate change) as the main interest impact category for the company. Acidification and eutrophication were also examined due to their importance in the product stage. The assessment method to calculate the impact categories for each element was the combination Swedish public data base and environmental product declaration, however the database given by Boverket only evaluated the global warming potential for modules A1 to A4.

To enable a systematic approach of EPDs used in the study, prioritization was created to obtain the most precise results, hence specific data for material used in the project was prioritized. If this type of data existed, EPDs verified by Sweden, Norway and German were preferred followed by the International EPD system. In cases where no specific data used was available, specific data from larger manufacturers, common in the Swedish market was used with the same priority given to verification system. Lastly, generic data from Boverket was used if no specific data was found.

Life cycle Inventory

Life cycle inventory as mentioned in section 2.3 describes the collection of the data necessary to achieve the goal of the study. The life cycle inventory compiled for this LCA is based on data provided by Northvolt. The quality and method behind collecting the data is varied, it is based on estimates and measurements from current existing buildings.

3.1.4 The calculation method

For each module of product stage, the basic principle for calculation of each environmental impact indicator previously discussed was to multiply material quantity of each building element considered in the system boundaries with its respective environmental indicator value (Figure 6). This required an initial conversion of some of the data so that all parameters (Global warming potential, acidification and eutrophication) were expressed in the same unit. The outcomes expressed in comparable units enables a preliminary assessment of the environmental impact resulting from using different products. These findings can then be extrapolated to predict the implications for the construction industry more generally if a large-scale shift in building materials occurs.

Figure 6. Calculation method for GWP

The calculations required for this analysis were performed in Excel. Additionally, the parameters considered can easily be modified to enable sensitivity analysis, allowing for a more detailed exploration of the potential environmental impacts of different building materials.

3.1.5 Uncertainties and assumptions

This study narrowed in on the building envelope, key construction elements and their environmental impact, only focusing on GWP, AP and EP at product stage. However, a building impacts the environment through more than the 3 categories evaluated and the entire life cycle of the building must be considered for a holistic picture and precise results.

Since a building is composed of many different components, obtaining data for each of the material resources may not always be feasible. Therefore, only essential construction materials with significant mass were evaluated, while finishes such as floor and paint were disregarded. However, due to varying degrees of data availability across all buildings, it is important to note that inherent uncertainty in the numbers and material sources may be predominant in some buildings. For instance, certain buildings lacked important material data, such as DS1, which was missing crucial elements. As a result, calculations were performed based on data availability, and it was acknowledged that this may affect the representativeness of the building. Additionally, there was limited information about the type and origin of concrete and/or steel used in some buildings, so the assessment relied on generic information from EPDs and the Boverket database.

Another main source of uncertainty is the actual amount of material for each element on each building, even though the quantities for an specific element did not change significantly, the sources used to get these quantities did not presented the same value throughout, therefore in some cases the mean of this value was used for a better assessment, keeping in mind that this could also potentially enlarge uncertainty and influence the conclusions drawn from the LCA.

4. Results

This section gathers the study results of the impact assessment of construction materials used for downstream and formation and ageing buildings for three modules (A1-A3) as defined in the standard EN 15804 in terms of global warming potential (GWP), acidification (AP) and eutrophication (EP). At the request of Northvolt, due to confidentiality and the preliminary nature of the assessment, not all results will be presented in absolute values but as relative values.

The results on overall environmental impacts are presented in section 4.1. while section 4.2 presents a detailed analysis of the DS3 building with a particular focus on the three parameters previously mentioned. Additionally, section 4.3 includes a sensitivity analysis that examines the global warming potential of different types of steel and manufacturing source.

4.1 Overall environmental impacts

Table 4 shows the overall environmental impact per one square meter of gross area by investigated impact categories for each building analysed.

Table 4. Environmental impact categories per one sqm by building

Building	**Global warming potential** (kg CO_2 eq./m^2)	**Acidification** (kg SO_2 eq./m^2)	**Eutrophication** (kg$(PO_4)^3$-eq./m^2)
DS1	162	0,55	0,33
DS2	379	1,24	0,62
DS3	**407**	**1,55**	**0,94**
DS4	474	2,04	1,12
FA1	307	1,09	0,08
FA2	432	1,93	1,06
FA3	438	1,96	1,04

When examining the outcomes, it was noted that DS1 and FA1 demonstrated the lowest values with regards to the three parameters assessed per square meter. This can be attributed to the fact that not all quantities were provided for each construction element in these buildings, which resulted in less precise evaluations. Despite not having the highest climate change impact, nor acidification and eutrophication, DS3 was selected as the baseline for further analysis due to the high accuracy of its material quantities in comparison to the other buildings. Hence, it will be scrutinized in more detail.

It can be challenging to draw definitive conclusions about the environmental performance of a building based solely on three parameters, as other factors such as energy efficiency, resource consumption, and waste management may need to be considered to provide a more holistic picture. Nevertheless, in general, lower values for global warming potential, acidification and eutrophication are considered more favorable, as they suggest a lower environmental impact. To provide a more comprehensive assessment of a building's environmental performance, it may be necessary to compare its performance to similar buildings or industry standards such as the references values from Boverket, taking into account a broader range of parameters.

To obtain a more comprehensive assessment of a building's environmental performance, it may be necessary to compare it to similar buildings or industry standards, taking into account a broader range of parameters. However, when comparing these results to a study conducted in a school in Iceland (Emami, 2016), where A1-A4 phases were evaluated with similar construction materials and a gross floor area of not even a quarter of these buildings, the results of the buildings gathered in the table above are not bad or abnormal for the size of the buildings on those phases. The GWP for the Icelandic school was approximately 300 kgCO_2 eq./m^2 which is comparable to the values presented in the table above. It is important to note that the study in Iceland also included transportation to the construction site in its results, highlighting the need to consider additional factors when comparing buildings' environmental performance.

4.1.1 Environmental impact per building element

The study presents material contribution results for all analyzed buildings in Figure 7. These results align with findings from the literature review, indicating that steel and concrete are the major contributors to global warming potential (GWP) among all buildings. The study found that steel accounts for 70 to 80 percent of the total GWP impact, while concrete accounts for between 10 to 30 percent.

The study also evaluated the impact of building materials on acidification and eutrophication. The results indicated that steel is the biggest contributor to acidification, followed by mineral wool for interior walls. This could be attributed to the manufacturing process of mineral walls, which may involve certain chemicals such as sulphur dioxide, whose impact on acidification potential can vary depending on the specific manufacturing process used. In terms of eutrophication, steel also represented the highest impact, followed by mineral wool.

Given that steel is the most significant contributor among all evaluated parameters, a sensitivity analysis was conducted to assess the impact of different types of steel. It should be noted that the study did not consider DS1 and FA1 materials in the results due to material inaccuracy.

Overall, these findings highlight the significant impact that building materials, particularly steel and concrete, have on the environment. The study underscores the importance of evaluating the environmental impact of building materials and considering alternative materials and manufacturing processes to mitigate these impacts.

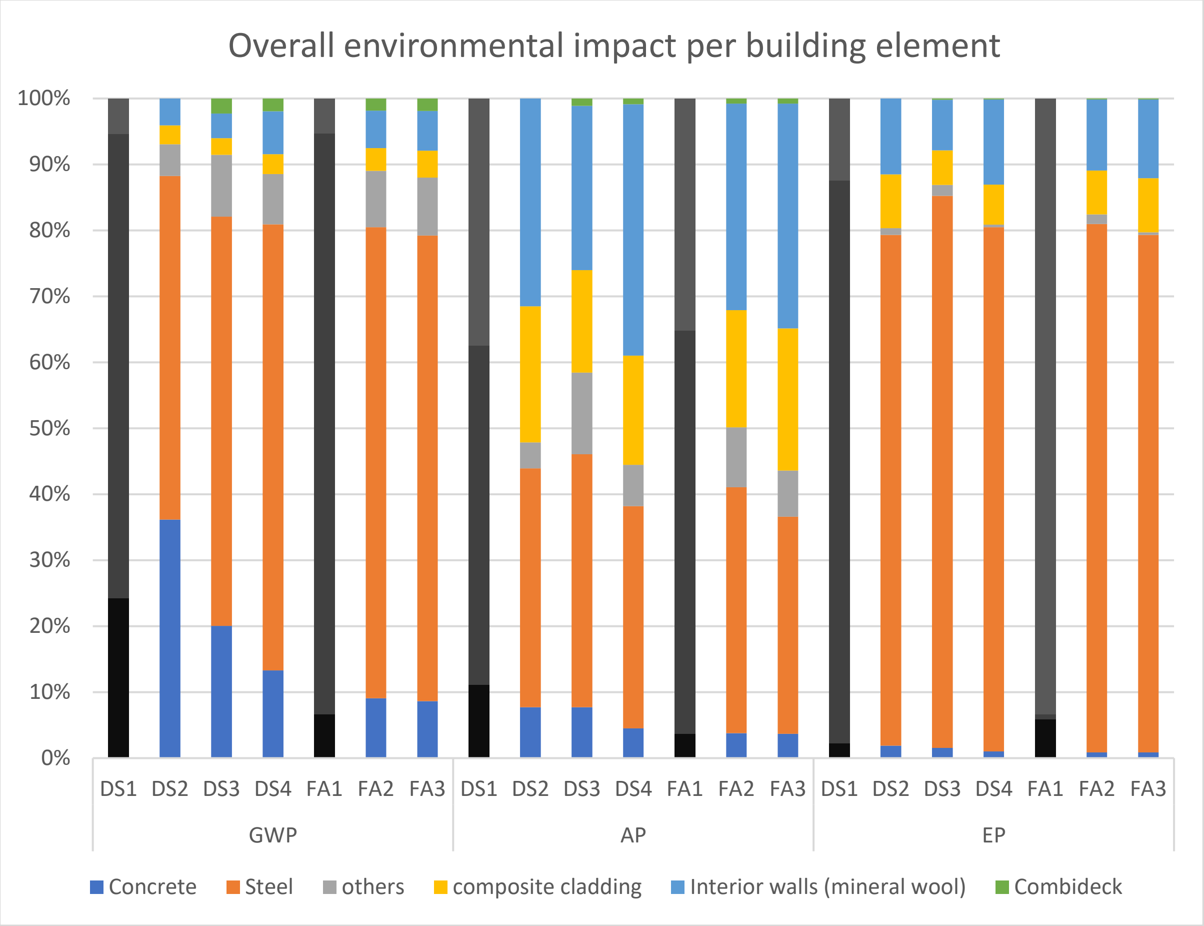


Figure 7. Overall environmental impact per building element

4.2 DS3 Analysis

As previously noted, DS3 building was selected as the baseline for this study due to the representative data it provided. The analysis of the DS3 building's environmental impact is divided into three distinct sections, each focused on evaluating a specific parameter: global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). This approach was adopted to provide a more comprehensive understanding of the building's overall environmental performance, taking into account the impact it has on various environmental factors. By evaluating each parameter separately, a more detailed picture of the building's environmental impact can be obtained, allowing for a more effective assessment of its sustainability.

4.2.1 Global warming potential

Figure 8 provides a comprehensive overview of the major contributors to global warming potential for different building components, with the structural steel frame being identified as the largest contributor, accounting for 63 percent of the total. The use of concrete for the substructure of the building ranks second, accounting for 12 percent of the total, while fit-out general and architectural shell make up only 4 percent and 3 percent, respectively. This is because as previously mentioned large amounts of energy are needed to produce steel, additionally, the production of steel often involves the use of fossil fuels, which release carbon dioxide into the atmosphere and contribute to climate change, while even though the production of concrete also requires a significant amount of energy, the process generally releases less carbon dioxide than steel production.

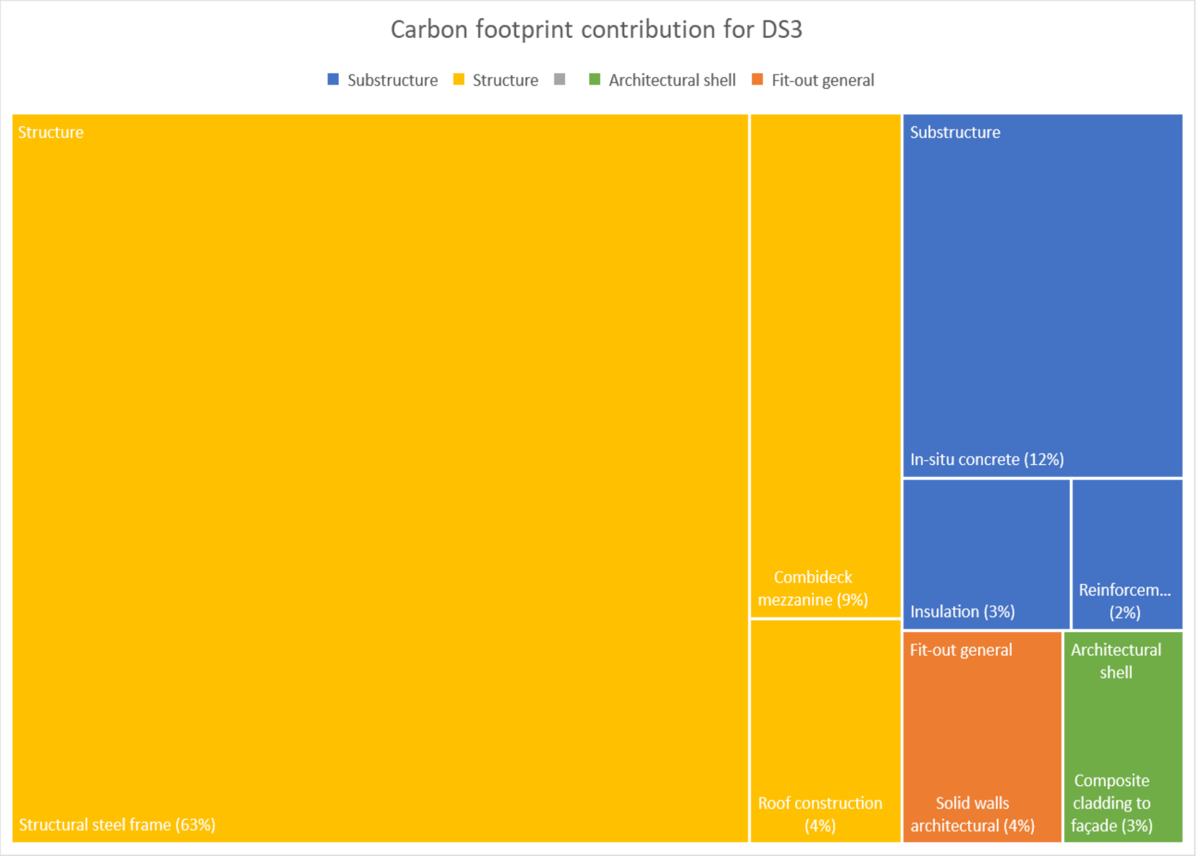
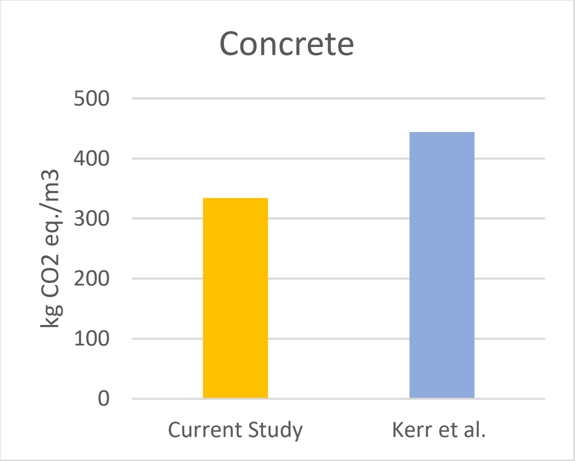


Figure 8. DS3: Global warming potential per building element

4.2.1.1 GWP impact assessment validation

Assessing the environmental impact of buildings is a complex process that requires careful consideration of a multitude of factors, one of which is global warming potential (GWP). As such, it was deemed necessary to conduct a comparison of the GWP impact of steel and concrete in the A1-A3 modules of the life cycle assessment (LCA) for the current study with prior research in order to validate the findings.

To accomplish this, it was important to take into account the system boundaries and functional unit of the previous studies. However, it should be noted that the system boundary for the current study was limited in comparison to existing literature. As a result, only one study was selected for the comparison, specifically the LCA conducted by Kerr et al. (2022) on construction materials, including concrete and steel. In the comparative assessment, data from 11 environmental product declarations (EPDs) were utilized, with the functional unit being m^3 and the system boundaries covering the complete life cycle from A1 to C4. The results of the study are presented in Figures 9 and 10.



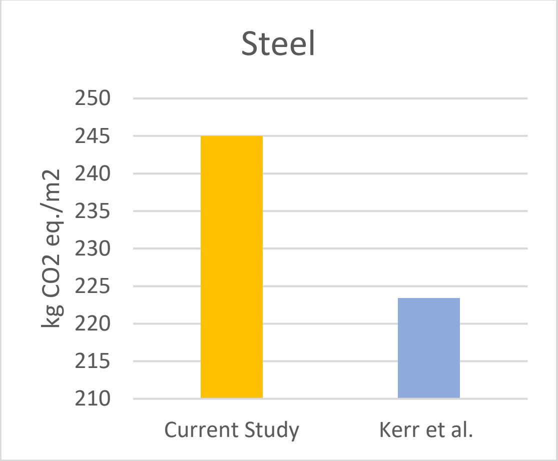


Figure 9. GWP (Concrete) for DS3 compared with similar LCA

Figure 10. GWP (Steel) for DS3 compared with similar LCA

Figure 9 and 10 demonstrate that the estimated GWP for DS3 and other buildings is consistent with the results from previous case studies, which helps to validate the methodology and assumptions used in the analysis. By conducting this comparison, it was possible to establish that the estimated GWP impact of steel per kg CO_2/m^2 and concrete per kg CO_2/m^3 in the current study was within the range of prior research. This lends credibility to the findings of the current study and underscores the importance of conducting sensitivity analysis and taking into account the system boundaries and functional unit of prior research when conducting LCAs.

4.2.2 GWP/kWh

The amount of carbon dioxide equivalent emissions produced per unit of energy storage capacity (kg CO_2eq./kWh) in batteries is a critical indicator generated during production. It holds significant importance in evaluating the environmental sustainability of batteries and their applications. It is noteworthy that Northvolt, in its annual report for the year 2022, has set an ambitious target to decrease the carbon footprint of its cell production from 33 kg to 10 kg CO_2e/kWh by the year 2023. This translates to 90 percent reduction in carbon emissions, surpassing the industry standard.

The carbon emissions resulting from production per unit of energy storage capacity (restricted to phases A1 to A3) for DS3 are measured at significantly lower than 1 kg CO2e/kWh, (the exact number cannot be shared due to confidentiality) and it therefore only contributes marginally to the carbon footprint of a battery.

4.2.3 Acidification

Acidification potential is an important parameter to consider when evaluating the environmental impact of building materials. The results from Figure 11 for the construction materials used in DS3 show that steel has the highest contribution to acidification potential at 38 percent, followed by mineral wool insulation for interior walls with 25 percent and composite cladding with 16 percent. Concrete, on the other hand, contributes a relatively small amount at 8 percent, while other components have an even lower contribution.

It is worth noting that the acidification potential of building components during the product stage is primarily determined by the manufacturing processes involved in their production as mentioned before. Steel and concrete, for example, require a significant amount of energy to produce, resulting in a higher acidification potential. On the other hand, composite cladding, which is typically made from a combination of materials such as plastics, metals, and wood, may have a higher acidification potential compared to concrete, despite concrete being used in larger quantities.

It is important to consider the potential impact of acidification, as it can lead to the acidification of soils and water bodies, which in turn can have harmful effects on ecosystems and human health. Therefore, reducing the acidification potential of building materials should be a key consideration in the selection and use of materials for construction.

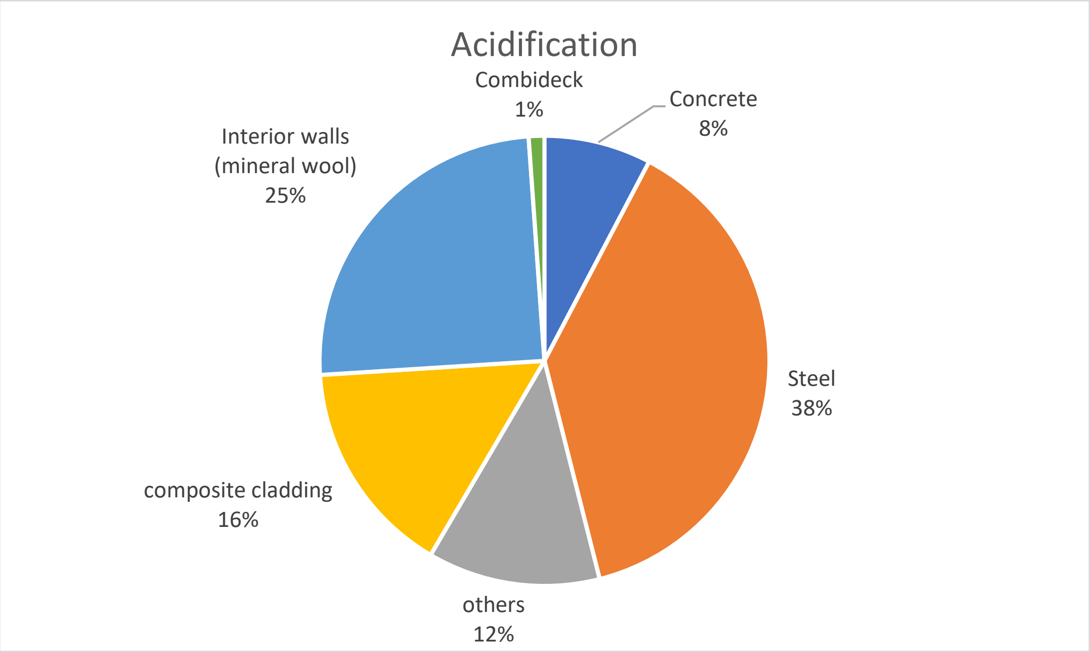


Figure 11. DS3: Acidification per building material

4.2.4 Eutrophication

It can be seen in figure 12 that steel has the highest contribution to eutrophication potential, accounting for 84 percent of the total impact in the product phase (A1-A3). Mineral wool has a relatively low contribution of 8 percent, followed by composite cladding at 5 percent, concrete at 1 percent, and others at 2 percent.

In the production of steel, the primary contributor to eutrophication potential is often associated with the extraction and processing of raw materials, particularly iron ore. Iron ore mining and processing involve activities that can release pollutants into water bodies, such as heavy metals and chemicals used in the extraction process. Additionally, steel production processes, such as iron and steel manufacturing, may generate wastewater containing high levels of nutrients, particularly nitrogen and phosphorus. When these nutrients enter water bodies, they can promote excessive algal growth and subsequent eutrophication These findings suggest that reducing the use of steel or shifting towards greener alternatives could potentially lead to significant reductions in eutrophication potential in building materials.

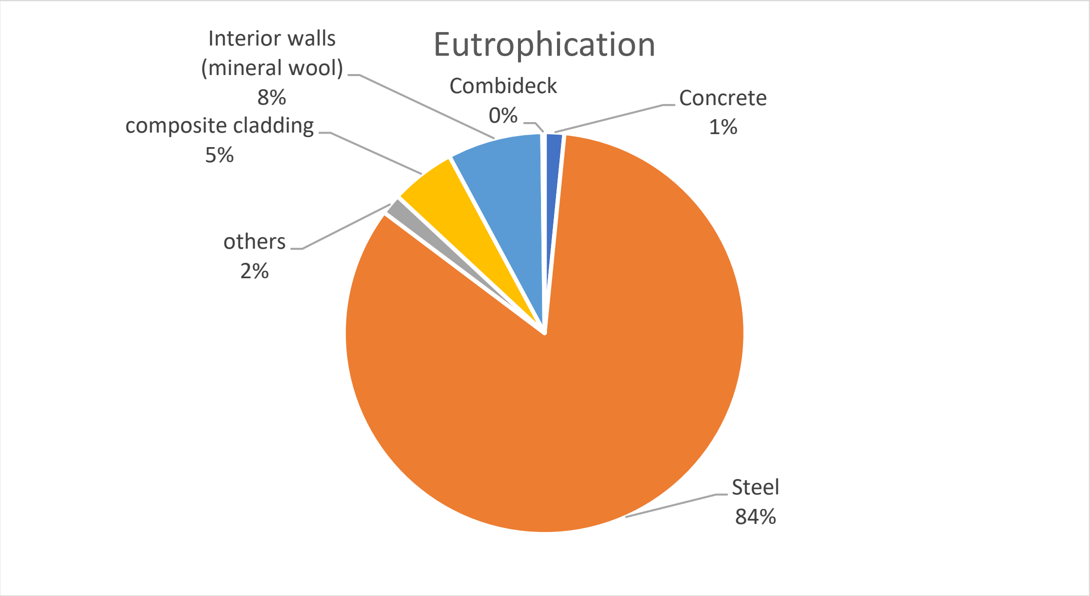


Figure 12. DS3: Eutrophication per building material

4.3 Sensitivity analyses

Sensitivity analysis is a crucial step in any life cycle assessment to ensure the reliability and validity of the results. In this case, the sensitivity analysis was carried out specifically for the parameter of steel, which was found to have the most significant impact on the environmental footprint of the building. The analysis was conducted in two parts to compare traditional structural steel from multiple manufacturers and greener alternatives such as HYBRIT and H2Green steel.

In the first analysis, traditional structural steel from multiple manufacturers was evaluated to assess if there were significant differences in the environmental impact depending on the manufacturer. This is an important consideration as different manufacturers may use different production processes, transportation methods, and energy sources, which can all influence the environmental footprint of the final product. The results of this analysis were examined to determine the impact of each manufacturer and to identify any significant variations in the environmental impact of the steel.

The second analysis focused on comparing traditional structural steel to greener alternatives, such as HYBRIT and H2Green steel. These greener alternatives have gained increasing attention in recent years as an effective means of reducing greenhouse gas emissions and minimizing the environmental impact of steel production. The aim of this analysis was to evaluate whether using greener alternatives to traditional structural steel could result in a significant reduction in the environmental footprint of the building.

4.3.1 Traditional structural steel impact from different manufacturers

In order to conduct a comprehensive evaluation of the environmental impact of structural steel, it was important to compare the results obtained with those from different manufacturers. This comparison would provide insight into whether or not the geographic origin of the steel had a significant impact on its overall environmental impact. To accomplish this, a sensitivity analysis was conducted to assess the impact of different manufacturers on the GWP of the steel used across all buildings.

The results, using EPDs from different manufacturers, indicated that while there were some differences in the GWP among the various manufacturers, these differences were relatively small and did not have a significant impact on the overall environmental impact of the steel used in the project (Figure 13). The findings of the analysis revealed that Peikko, a steel manufacturer from Finland but manufacturing steel in Lithuania, exhibited 32 percent less emissions compared to the baseline case (Nordec), a Finnish steel manufacturer. Steel fabricated in Sweden and Norway accounted for 9 and 10 perfect reduction compared to the baseline respectively.

It is worth noting, however, that the sensitivity analysis was limited in scope and further investigation may be necessary to fully understand the environmental impact of structural steel from different manufacturers. These results can be attributed to a number of factors, such as differences in production processes, the use of renewable energy, and the availability of raw materials. Additionally, other factors such as the transportation of the steel used by the manufacturers could also play a role in determining the overall environmental impact of the steel.

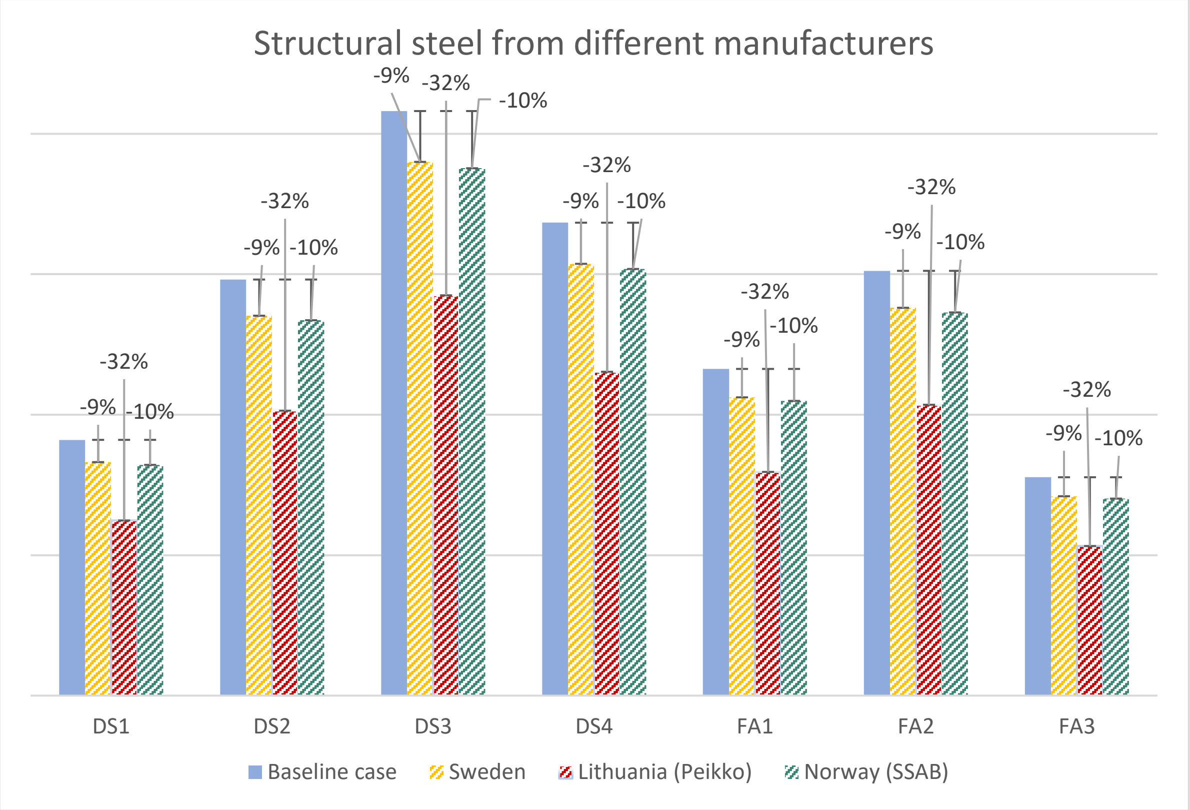


Figure 13. Structural steel impact from different manufacturers

4.3.2 Traditional steel vs. green steel

Regarding the analysis conducted on HYBRIT and H2green steel, it should be noted that due to the fact that these materials are still under development, no hard data was available. Therefore, assumptions were made based on information provided by the manufacturers on their respective websites. It was reported that HYBRIT has promised a 90 percent reduction in carbon emissions, which was used in the analysis. Similarly, H2Green steel is expected to achieve a 95 percent reduction in carbon emissions, according to the available information. (Figure 14). It is worth mentioning that including cost in the analysis of HYBRIT and H2Green steel was not possible as it is dependent on several factors such as the cost of producing hydrogen, the production processes involved, and the cost of renewable energy. These factors may vary from region to region, making it difficult to provide a standardized cost estimate. However, it is worth noting that the production of greener steel may currently incur a higher cost due to the need for new infrastructure and the development of new technologies. Nonetheless, as renewable energy and sustainable production methods become more widely adopted, it is expected that the cost of producing greener steel will decrease, making it more economically viable in the long run.

This analysis facilitates the inference of conclusions regarding the environmental impact of materials, highlighting the significant potential for emissions reduction associated with the utilization of greener alternatives. In particular, it is noteworthy that the adoption of such solutions can result in reductions of up to 95 percent in greenhouse gas emissions, thereby contributing to the mitigation of climate change. Additionally, with the increasing awareness and concern for climate change, the demand for sustainable materials is also likely to increase, making it necessary for companies to consider the use of greener solutions in their operations.

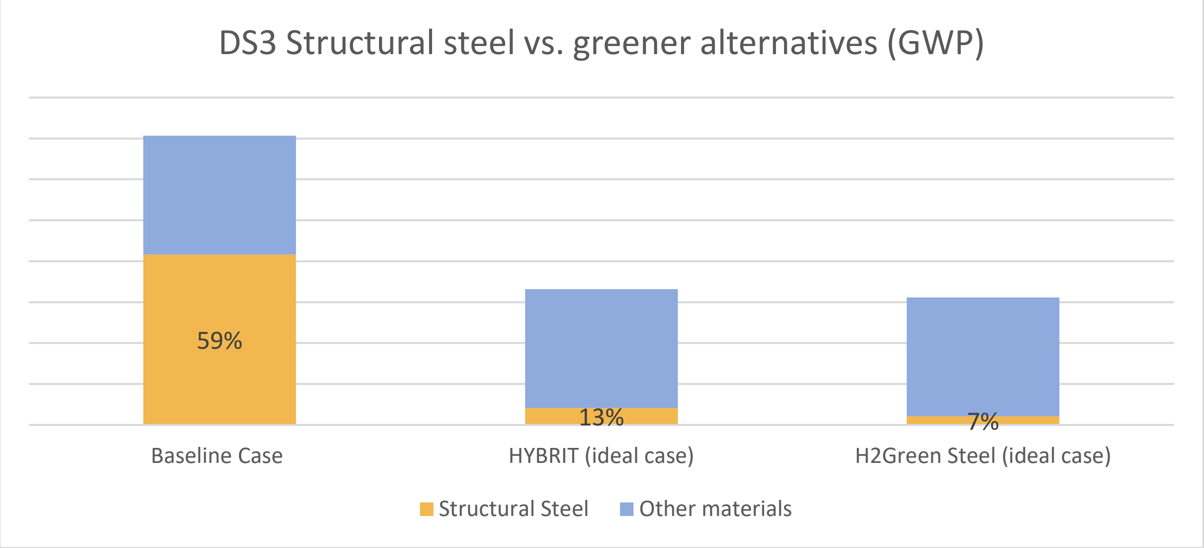


Figure 14. DS3 structural steel vs greener alternatives

Conclusions

After conducting a thorough analysis of the environmental impacts of construction materials in phases A1 to A3, with a focus on the indicators of GWP, AP, and EP, several key conclusions can be drawn.

Firstly, it is clear that the production of construction materials contributes significantly to the overall environmental impact of a building. This impact can be quantified using metrics such as kg CO_2eq/kg or kg CO_2eq/m^3, which provide a standardized means of comparing the environmental performance of different materials.

Secondly, among the materials analysed, steel and concrete were found to have the highest environmental impact. Steel production in particular was responsible for a significant portion of CO_2 emissions, with some companies such as HYBRIT and H2Green steel implementing innovative processes that involve the use of hydrogen in the steelmaking process, emissions can be reduced by up to 95 percent. These initiatives have great potential to drive the transition towards a more sustainable steel industry.

Thirdly, it is important to consider the entire life cycle of a building material when assessing its environmental impact. This includes not only the production phase, but also transportation, use, and end-of-life disposal or recycling. Careful consideration of each of these phases can help to identify opportunities for reducing environmental impact and improving overall sustainability.

Additionally, the amount of carbon dioxide equivalent emissions per unit of energy storage capacity in batteries is a crucial factor in assessing the environmental impact. Northvolt's ambitious target to reduce its cell production's carbon footprint from 33 kg to 10 kg CO_2eq/kWh by 2023 is a significant step towards promoting sustainability in the battery industry. This target translates to a 90 percent reduction in carbon emissions, which surpasses the industry standard. Carbon emissions resulting from production per unit of energy storage capacity were measured at significantly less than 1 kg CO_2eq/kWh, demonstrating that it is possible to achieve a low carbon footprint in battery production. These findings underscore the importance of companies setting ambitious targets for reducing carbon emissions in the production of batteries, and the potential for the industry to make significant strides towards greater sustainability.

Finally, the use of tools such as EPDs and databases like the Boverket Climate Database can be highly useful in quantifying the environmental impact of construction materials and identifying opportunities for improvement. By providing a standardized means of assessing environmental impact, these tools can help to promote greater transparency and accountability in the construction industry.

In conclusion, while the environmental impact of construction materials is significant, there are a variety of steps that can be taken to mitigate this impact and promote greater sustainability in the industry. By carefully considering the entire life cycle of materials and utilizing tools to measure and improve environmental performance, it is possible to reduce the impact of construction materials and create more sustainable buildings and infrastructure for the future.

Future studies

The findings of this study highlight the need for continued research and development in the field of sustainable construction materials. While this study only focused on the environmental impacts of construction materials in the A1-3 product stages, evaluating only three parameters, future research should aim to investigate the environmental impacts of different materials across the entire life cycle of buildings, including the in-use and end-of-life phases, while considering a broader range of environmental indicators. Additionally, the development of more accurate and reliable life cycle assessment methodologies for construction materials is needed, including refining existing models and data sources and exploring new approaches to data collection and analysis.

In terms of specific materials, steel and concrete were found to have the highest environmental impact. While the sensitivity analysis did consider potential improvements in using greener alternatives, further research is needed to investigate the potential of these approaches and other strategies for reducing the environmental impact of these materials. One area that deserves further exploration is the use of hydrogen in the steelmaking process, as companies such as HYBRIT and H2Green steel are already making strides in this area. It is important to continue researching the potential for using hydrogen as a means of reducing the CO_2 emissions associated with steel production. This could include assessing the scalability of hydrogen-based steel production methods and investigating the feasibility of using hydrogen as a fuel source for transportation and other industrial processes.

Another area of focus for future research could be the impact of cement on the environmental performance of concrete. Cement production is known to be a significant contributor to carbon emissions. Future research could explore alternative cement production methods that utilize more sustainable materials, such as calcined clays, and investigate the potential for increased use of alternative cementitious materials, such as fly ash and slag. Additionally, research could focus on optimizing concrete mix designs to reduce the overall amount of cement required while maintaining adequate strength and durability.

Overall, the findings of this study provide important insights into the environmental impacts of construction materials and highlight the need for continued research and development to support the transition towards a more sustainable built environment. Future studies should aim to investigate the environmental impact of materials across the entire life cycle of buildings while exploring potential strategies for mitigating the environmental impact of materials such as steel and concrete.

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