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# Life Cycle Assessment of a Medium Voltage Protection Relay

A case study

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**ABSTRACT:**
Sustainability is becoming increasingly important in today's business. Not only is there a pressure from governments and regulators, but also from other stakeholders. For example, customers are becoming increasingly concerned about sustainability when making purchasing decisions, and from ABB's point of view, both the company and their customers are now becoming more and more interested in Life Cycle Assessments (LCA) and Environmental Product Declarations (EPD) for their products. As a result, this thesis was commissioned by ABB ELDS.

The main purpose of this thesis is to address ABB ELDS's need for new LCA's and EPD's for their medium voltage protection relays, while also contributing to the literature. The main research question is "what are the potential environmental impacts of a medium voltage protection relay throughout its life cycle?". The study also aims to determine what are the most impactful life cycle stages and processes as well as to identify potential improvement opportunities.

A case study is conducted for two representative relay configurations of the Relion 615 series by adopting the internationally standardized method called LCA according to ISO 14040 and ISO 14044. The main intended application is for an EPD according to ISO 14025, and the adopted product category rules (PCR) is EPDItaly007, which is based on EN 50693. The LCA software used is SimaPro 9.3.0.2 with the database ecoinvent v3.8. The impact assessment is conducted according to the standard EN 15804:2012+A2:2019, as required by EPDItaly007.

The study shows that the most impactful life cycle stage of a relay is the use stage due to its power consumption. The second most impactful life cycle stage is the upstream manufacturing stage, mainly due to the production and use of integrated circuits and printed wiring boards. The use of precious metals and air freight was also found to have a significant impact on the environment. Finally, the study shows that the overall environmental impacts can be largely reduced by using renewable energy in different life cycle stages.

The study is significant from a managerial point of view because the results are used for developing and publishing an EPD, to satisfy the requests of the case company's customers. Also, because the results are interpreted to establish conclusions and recommendations, it provides value for product development and improvement. Finally, it provides novel contributions to the literature because current LCA studies of these types of products are scarce.

Note, the LCA has been internally reviewed by LCA experts of the case company. However, it has not been verified by an accredited third-party; the thesis was submitted during the same time as the audit process started. Thus, the results are subject to change from the official EPD.

**KEYWORDS:** Life cycle analysis, environmental declarations, case study, relays

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## Abbreviations

| | |
|---|---|
| BOM | Bill of materials |
| ELDS | Distribution Solutions, a division of ABB Electrification |
| EN | European Norm (European Standard) |
| EPD | Environmental Product Declaration |
| HSE | Health, Safety & Environment |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| PCR | Product Category Rules |
| PWB | Printed Wiring Board |
| PWBA | Printed Wiring Board Assembly |

# 1 Introduction

Sustainability is becoming increasingly important in today's business. Social and environmental issues of our time such as poverty, inequality, and climate change continue to exist (The World Bank, 2021a) due to an unsustainable globalization of business operations (Tang et al., 2020), the use of fossil fuels (United Nations, n.d.-b), and other consequential human activities (Singh & Singh, 2017). As a result, this is creating a pressure on companies to act (Haleem et al., 2022). Not only is there a pressure from governments and regulators, but also from the markets and from other stakeholders (Seuring & Müller, 2008; Wang et al., 2020). For example, customers are becoming increasingly concerned about sustainability when making purchasing decisions (Jančiauskaitė et al., 2019), and from ABB's point of view, customers are now becoming more and more interested in type III environmental declarations for their products.

A type III environmental declaration is an independently verified document, according to the international standard ISO 14025, which declares the environmental profile and the potential environmental impacts of a product throughout its life cycle (International Organization for Standardization, 2006a). This is also known as an environmental product declaration (EPD), and it is typically used for communication purposes. An EPD is essentially based on a life cycle assessment (LCA) study that is conducted according to a specific set of rules called product category rules (PCR).

Life cycle assessment or LCA is an internationally standardized environmental management tool according to the ISO 14040 series (International Organization for Standardization, 2006b). According to Klöpffer et al. (2014), it is "the only internationally accepted standardised method for analysing environmental aspects and potential impacts of product systems" (p. 17). According to the standards, LCA can be used in a wide range of different applications; from product design and improvement to public policy making, strategic decision making, and marketing. It is also considered an important tool in other areas such as sustainable supply chain management (Brömer et al., 2019; Seuring & Müller, 2008) and corporate sustainability (Witjes et al., 2018).

## 1.1 Background and purpose

ABB is a leading international technology company, which offers a wide range of technical products, solutions, and services, with over 100 000 employees in over 100 countries (ABB, 2020a). Sustainability is important to the company, and this is emphasized both on their website (ABB, n.d.-a) and in their annual report (ABB, 2020a). In fact, the company has developed a dedicated sustainability strategy for 2030 (ABB, n.d.-e), and they also publish a sustainability report yearly (ABB, 2020b).

The sustainability work at ABB started already decades ago. In the article by Allander (2001), the author discusses about LCA and EPD from ABB's point of view in the beginning of the 21st century. At this point, the company had just implemented the environmental management system ISO 14001 across most business units. The next step from here was to develop EPD's according to the ISO 14025 standard for all their core products and services. The LCA and EPD presented in the article by Allander (2001) was conducted for ABB, and it was the first EPD to be certified for any rotating electrical machine globally. Accordingly, over 60 different EPD's were published on the company's website between the years 2003–2009 (ABB, n.d.-c).

A decade after Allander (2001) published his article, Liimatainen (2012) did a bachelor's thesis for ABB within the same field of research. At this point, previous LCA's and guidelines were no longer up-to-date and valid due to significant changes over the past decade. For example, the earlier LCA's were conducted using an outdated software and database (p. 11). Also, none of the EPD's published between 2003–2009 adopted any PCR (ABB, n.d.-c), which is now a requirement according to ISO 14025. Thus, the aim of the thesis by Liimatainen (2012) was to develop new guidelines in the form of a PCR for ABB, and as an example, an LCA study was conducted for two different configurations of the Relion 615 series of medium voltage protection relays. The author also intended to develop an EPD based on the results; however, it is not mentioned if or where the EPD has been published. The validity of the study can neither be assured because it has not been verified by an accredited, independent third-party.

Currently, no EPD has been published on ABB's website since 2009 (ABB, n.d.-c), and the guidelines by Liimatainen (2012) are obsolete and no longer in use. Still, the need is clear, and ABB's division Distribution Solutions (ELDS) have now established a sustainability council to address this issue. In fact, they now have a dedicated team in Italy, which have over recent time developed a competence around LCA and EPD. Currently, they are in the process of sharing this competence to other local business units and dedicated teams globally. The team in Italy will remain as a global support team, and they will also be responsible for harmonizing the LCA practice within ELDS. Since 2021, the company has published at least 2 verified EPD's via P.E.P. Association (n.d.-a), and over 10 verified EPD's via EPDItaly (n.d.). In 2022, they also published an EPD via The Norwegian EPD Foundation (ABB Electrification Norway AS, 2022),

However, ABB ELDS in Vaasa, Finland, is still in need for new LCA's and EPD's for their medium voltage protection relays. As a result, this thesis was commissioned by ABB ELDS Vaasa. The purpose is to address these needs and to provide support for their sustainability work. This also presents an opportunity for research; while plenty of LCA studies exist in the literature of a variety of different electronic devices such as mobile phones and computers (Subramanian & Yung, 2016), the current literature on LCA studies of medium voltage protection relays is scarce. Searching the database *Scopus* with the key words "LCA" AND "relay" only gives 21 hits, of which none are actual LCA studies of medium voltage protection relays. Other than the bachelor's thesis by Liimatainen (2012), only few EPD's exist by for example Schneider Electric (2017b, 2018) and ABB (2006). Thus, the purpose is twofold, as it also aims to provide novel contributions to the literature.

## 1.2 Research questions and objectives

With respect to the background and purpose of this thesis, two primary goals were defined: 1) to conduct an LCA study of ABB's Relion 615 series of relays and 2) to develop an EPD based on the results. This will not only provide ABB ELDS Vaasa with an LCA and EPD for an important series of relays, but it will also provide them with an exemplary model for assessing other, similar products in the future. Accordingly, one primary research question and two secondary research questions were defined:

- "What are the potential environmental impacts of a medium voltage protection relay throughout its life cycle?"
    - "What are the most impactful life cycle stages and processes?"
    - "How can the most significant impacts be largely reduced?"

The research is designed as a mixed methods case study, and it adopts the internationally standardized method called LCA according to ISO 14040 and ISO 14044. A literature review is first conducted to establish a fundamental understanding of LCA, EPD, and the related standards and literature. An LCA study is then conducted for two representative relay configurations of ABB's Relion 615 series of medium voltage protection relays.

## 1.3 Scope and limitations

The thesis is limited to conducting only one LCA and developing only one EPD for only the Relion 615 series of relays. Because LCA and EPD are standardized according to the ISO 14040 series and the ISO 14020 series, the study is also limited to complying with these standards. A PCR is also adopted, as required by ISO 14025, and the case company has decided to use the PCR EPDItaly007 for all medium voltage protection relays. The PCR EPDItaly007 is based on the European standard EN 50693:2019, and these provide additional requirements on top of the ISO standards. The study is also limited to using the LCA software SimaPro 9.3.0.2 with the ecoinvent v3.8 database, because this is what the case company currently uses and has licenses for.

The Relion 615 series was chosen to be assessed in the LCA by request of the case company. The 615 series include numerous relays for different type of applications, and the relays are highly configurable in both hardware and software. Because it would be impracticable to assess every possible configuration separately, only two representative configurations are selected for the LCA. Extrapolation rules can then be established according to the European standard EN 50693:2019. Further details regarding the goal and scope of the LCA are found in chapter 5.1.

The primary research question, “what are the potential environmental impacts of a medium voltage protection relay throughout its life cycle?”, is answered through a life cycle impact assessment (LCIA) according to the standard EN 15804:2012+A2:2019, as required by the PCR EPDItaly007. This is declared in absolute terms in tables, and this is also the key results used for the EPD. The second research question, “what are the most impactful life cycle stages and processes?”, is answered through a process contribution analysis. This is discussed in relative terms by comparing the most significant processes in different impact categories. The third research question, “How can the most significant impacts be largely reduced?”, is answered by comparing how different assumptions to the model affect the final impacts. Only the most significant processes are investigated; no in-depth analysis is conducted. In addition, the constituent materials as well as the recyclability potential of the product are also assessed.

Finally, the LCA is evaluated with a completeness check, sensitivity check, and consistency check according to the guidelines and requirements provided by ISO 14044. However, no comprehensive uncertainty analysis is conducted because it is not required by the selected PCR. The study is also internally reviewed by LCA experts of the case company. However, due to time limitations, the results in this thesis are not verified by an accredited third-party; the thesis was submitted during the same time as the audit process started. Thus, the results are subject to change from the official EPD.

A literature review is also conducted, prior to the LCA study, which is limited to focusing on LCA, EPD, and the related standards and literature. The purpose of the literature review is to provide a fundamental understanding of the LCA methodology and the requirements for developing an EPD. It also discusses the background, concept, and need for sustainability, to establish a more holistic understanding of the subject. Also, an introduction to the case company ABB and their sustainability strategy is provided.

## 1.4 Structure of the thesis

Chapter 2 introduces the case company ABB and their sustainability strategy for 2030. Chapter 3 provides a literature review of LCA, EPD, and the related standards and literature. Chapter 4 discusses the research design and approach. It also discusses how the data was collected and analysed as well as how the reliability and validity was assessed. Chapter 5 describes the LCA study in detail, following a similar structure as an LCA report. Chapter 6 presents the results as well as discuss the reliability and validity. Finally, chapter 7 provides conclusions and a discussion. It also provides recommendations as well as suggestions for future research.

# 2 Case company

This chapter introduces the case company ABB and their sustainability strategy for 2030. ABB is a leading international technology company with over 100 000 employees in over 100 countries (ABB, 2020a). Their business is divided into four main business areas: Electrification, Process Automation, Motion, and Robotics and Discrete Automation. The company has a broad portfolio of technical products, solutions, and services. This includes for example switchgear, circuit breakers, propulsion, turbochargers, motors, generators, robotics, energy storage, smart systems, and automation solutions. The company serves a wide range of customers within utilities, industry, and infrastructure and transportation, and in 2020 the company had a revenue of 26,1 billion USD.

Distribution Solutions (ELDS) is one of the five divisions within the business area Electrification (ABB, 2020a). ELDS is also the division which has commissioned this thesis. ELDS serves to a large extent the power distribution sector and offers various low- and medium-voltage control and protection systems, products, automation, and service (ABB, 2020a).

ABB reckons the need to act and has adopted a dedicated sustainability strategy for 2030 (ABB, n.d.-e). With this, ABB (n.d.-b) aim to support all 17 sustainable development goals (SGDs) by the United Nations (2015) both directly and indirectly. The goals and targets of ABB's sustainability strategy for 2030 are as follows (ABB, n.d.-e):

1. **To enable a low-carbon society**: The company commits to support their customers in reducing their annual $CO_2$ emissions by at least 100 megatons per year, to achieve carbon neutral operations, and to engage with suppliers to reduce emissions across the entire supply chain. The targets have also been validated as in line with the 1.5 °C scenario of the Paris Agreement.
2. **To preserve resources**: The company commits to have at least 80 percent of their products covered by a circularity approach, to have at least 80 percent of supply spend in focus countries covered by a supplier sustainability framework, and to achieve zero waste disposed at landfills from their operations.

3. **To promote social progress**: The company commits to achieve yearly reductions in incidents, to double the number of women in senior management roles, achieve a top-tier employee engagement score, and to provide impactful support for community-building initiatives.
4. **To act with integrity and transparency**. The company commits to set yearly ESG targets for receiving bonus awards, to consistently adopt their code of conduct as a basis for interactions in projects and with counterparties, and to consistently adopt their supplier code of conduct in all procurement terms and conditions.

ABB also publishes a sustainability report yearly. According to the report from year 2020, the company has made significant progress (ABB, 2020b). Most of their sustainability targets have been met or surpassed so far; since 2013, ABB has successfully reduced their greenhouse gas (GHG) emissions by 58 percent, reduced water consumption in water stressed areas by 39 percent, and reduced employee injuries with 72 percent. Only a few targets have not been successfully achieved; for example, the amount of waste sent for disposal has only decreased by 3 percent despite a target of 20 percent.

# 3 Literature review

This chapter reviews the current literature related to life cycle assessment (LCA) and type III environmental declarations (EPD). It first introduces the background, concept, and need for sustainability as well as what strategies and tools organizations can adopt to improve their environmental performance. It then continues with discussing the latest international standards and literature regarding LCA and EPD. It also discusses the existing research regarding LCA studies of medium voltage protection relays and other electronic devices. Thus, the purpose of this chapter is not only to establish a theoretical framework for conducting the LCA study, but also to establish a holistic understanding of the subject and related research.

## 3.1 Sustainability

Our planet is currently facing serious threats due to the damage human activities are causing to the environment (NASA, n.d.; Singh & Singh, 2017; The World Bank, 2021a; United Nations, n.d.-b). For example, due to the vast amounts of greenhouse gas (GHG) emissions that have been released to the atmosphere due to human activities, our planet is now more than 1 °C warmer than it was in the late 1800s (NASA, n.d.; United Nations, n.d.-b). In fact, the concentration of GHG emissions is currently on the highest levels in over 800 000 years, and a primary reason is the increased use of fossil fuels such as oil, gas, and coal since the industrial revolution. As a result, this is contributing to severe effects of climate change such as more extreme weathers, more frequent wildfires, melting glaciers, rising sea levels, and an increasing acidity of the oceans (NASA, n.d.). Due to climate change, The World Bank (2021a) estimates that 132 million people will be pushed into poverty over the next 10 years.

Human activities are also causing other damages to the environment such as pollution, ozone depletion, and deforestation (Singh & Singh, 2017). The World Health Organization (2021) estimates that 7 million people die due to air pollution every year. Typical air pollutants include particulate matter, nitrogen dioxide and carbon monoxide, and common sources of pollution include combustion engines, industrial facilities, and forest fires. Another issue is also plastic pollution which, according to The World Bank (2021b), is “everywhere” today; it is in the air, in the water, and in the fish we eat. According to Ritchie & Roser (2018), it is estimated that over 60 million tons of plastic waste are mismanaged yearly, out of which 8 million tons enters the world’s oceans. This is not only disrupting marine wildlife, but the plastic also breaks down into microplastics over time, and this may have other unknown consequences in the long term.

In 1987, the World Commission on Environment and Development (WCED) published the report *Our common future* as a call for action. This is also recognized as “the Brundtland Report” (Elkington, 1997; Klöpffer et al., 2014; Seuring & Müller, 2008). In the report, WCED (1987) defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (p. 41). This set a foundation for the concept of sustainability, and later, Elkington (1997) elaborated on the concept and introduced the *triple bottom line* theory. According to the triple bottom line, there are three dimensions of sustainability: A social, economic, and environmental dimension, and all three dimensions are equally important (Elkington, 1997). Since then, the triple bottom line has become central in much sustainability related research (Haleem et al., 2022; Seuring & Müller, 2008; Witjes et al., 2018). It has also been further elaborated on by, for example, Dalibozhko & Krakovetskaya (2018) as illustrated in figure 1.

In 2015, members of the United Nations adopted a new plan of action titled *Transforming our world: The 2030 agenda for sustainable development* (United Nations, 2015). This includes 17 sustainable development goals (SDGs) and 169 specific targets to fight climate change, end poverty, achieve gender equality, and much more. During the same year, the Paris Agreement was also signed between 196 different nations, which is a legally binding contract to limit global warming to well below 2 °C and preferably below 1,5 °C relative to pre-industrial levels (United Nations, n.d.-a). Individual countries are also taking action; for example, Finland has in their program of prime minister Sanna Marin's government 2019 developed their own strategic goals for sustainable development (Finnish Government, n.d.-b). Not only is Finland committed to the Paris Agreement, but for example, the country has also committed to become carbon neutral by 2035 (Finnish Government, n.d.-a).

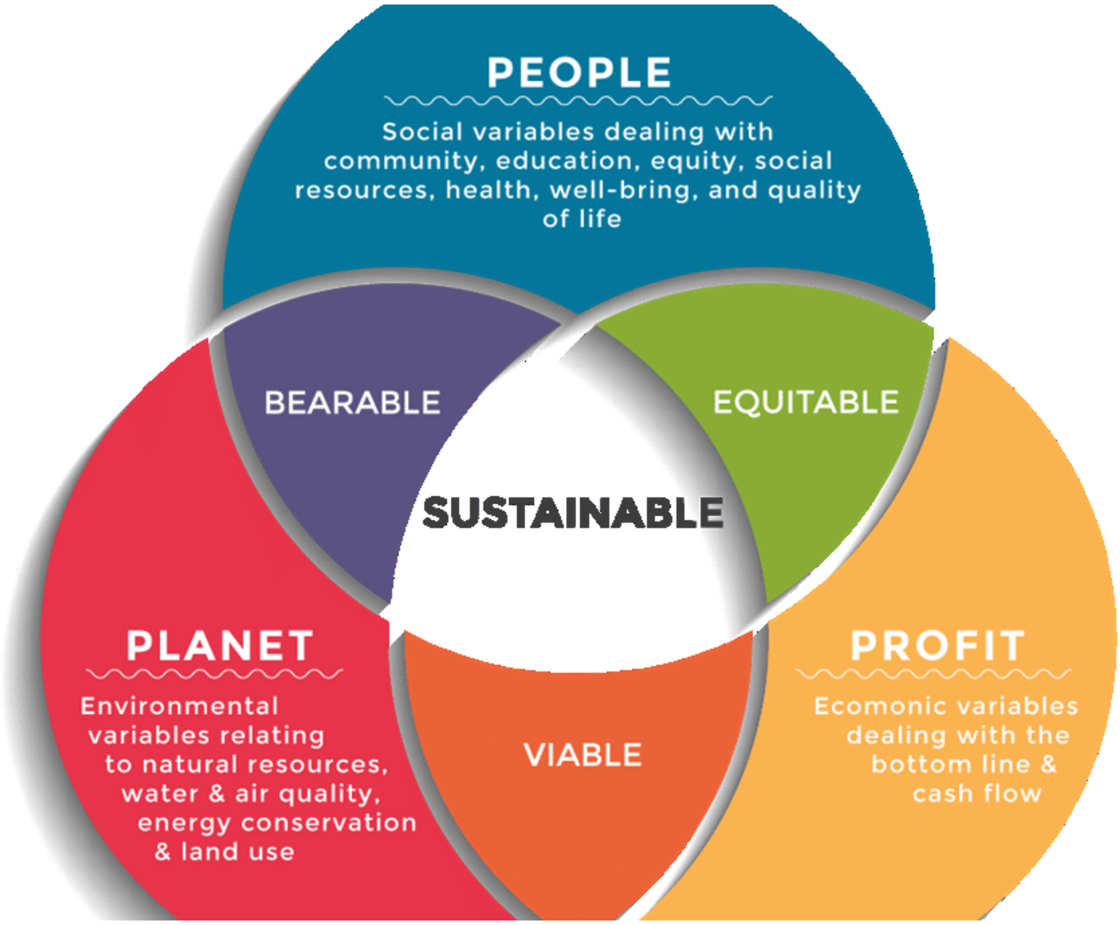



**Figure 1. The interconnected dimensions of the triple bottom line concept (Dalibozhko & Krakovetskaya, 2018)**

As the need for sustainability is becoming increasingly acknowledged (Jančiauskaitė et al., 2019), it is creating a pressure from regulators, markets, and other stakeholders for organizations to become more sustainable (Wang et al., 2020). Not only must organizations comply with laws and regulations, but according to Jančiauskaitė et al. (2019), corporate sustainability can also have significant effects on the overall corporate reputation and the customers' buying behaviours. Consequently, sustainability is only becoming more essential in today's business.

Haleem et al. (2022) suggest that stakeholder pressure is one of the most influencing factors for organizations to adopt sustainability management practices. The authors refer to stakeholders as “any individual or group that can affect, or be affected, by an organization” (p. 1). More specifically, the framework by Wang et al. (2020) describes the different stakeholder pressures that organizations are facing to adopt corporate environmental strategies (see figure 2). Similarly, Seuring & Müller (2008) suggest that the three most significant pressures for organizations to adopt sustainable supply chain management (SSCM) strategies are regulations, customer demands, and response to stakeholders. However, the relationship between stakeholder pressure and sustainability is not always apparent; there are also studies that suggest that the relationship is non-existent (Haleem et al., 2022).

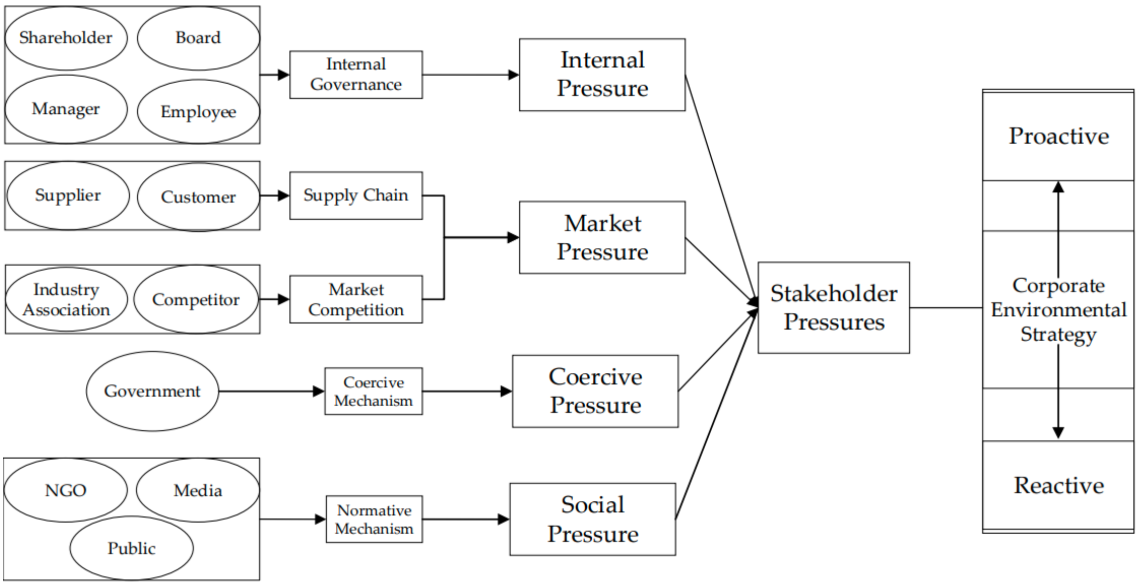



**Figure 2. Stakeholder pressures for corporate environmental strategy.** (Wang et al., 2020)

Environmental management strategies have evolved significantly over the last few decades (see table 1). What started as a focus on “End-of-Pipe Treatment” in the 1970’s evolved into a focus on waste reduction in the mid 1980’s, then cleaner production in the early 1990’s, and from there, life cycle assessment and sustainable development during 2000 and beyond (Curran, 2015). Thus, the strategies have evolved from being rather reactive responses to stricter regulations, to more proactive strategies for organizations to meet their sustainability goals and sustain a competitive advantage (Wang et al., 2020). While ABB's sustainability strategy for 2030 indicates a more proactive strategy (ABB, n.d.-e), this is not true for all companies (Wang et al., 2020).

**Table 1. The evolution of environmental management strategies.** (Curran, 2015)

| **Chronology** | **Strategy** |
|---|---|
| 1970's to 1980's | End-of-Pipe Treatment |
| Mid 1980's | Waste Minimization/Reduction |
| Early 1990's | Pollution Prevention/Cleaner Production |
| Mid 1990's | ISO Certification/Life Cycle Assessment |
| 2000 and beyond | Sustainable Development/Life Cycle Sustainability Assessment |

LCA is also considered an important tool for corporate sustainability (Witjes et al., 2018) and sustainable supply chain management (Brömer et al., 2019; Klöpffer et al., 2014). According to Witjes et al. (2018), corporate sustainability is something that requires full integration with a company's organizational system, from top management down to the operational level. This can be supported with tools, and the authors found that life cycle assessment (LCA) is one of the most prominent tools along with environmental management system (EMS) and sustainability reporting (SR). In terms of SSCM, Seuring & Müller (2008) similarly found LCA to be a central tool in supply chain management for sustainable products, and this also aligns with the findings by Brömer et al. (2019). Nevertheless, the tools and strategies discussed by Witjes et al. (2018) and Seuring & Müller (2008) are not mutually exclusive but rather complementary, and a key feature of LCA, according to Witjes et al. (2018), is that it is based on a bottom-up approach to support top-down strategic decisions. In the following chapter, LCA is discussed in more detail.

## 3.2 Life cycle assessment

Life cycle assessment or LCA is a method based on the international standards ISO 14040 and ISO 14044 for quantifying and analysing environmental aspects and potential environmental impacts of a product throughout its life cycle (Curran, 2015; International Organization for Standardization, 2006b, 2006c; Klöpffer et al., 2014). It is also known as a cradle-to-grave analysis as it considers all stages of the life cycle of a product; from raw material acquisition to production, use, distribution, and disposal (see figure 3). While other environmental management techniques exist (Curran, 2015; International Organization for Standardization, 2006b), LCA is the only internationally accepted and standardized method for these purposes (Klöpffer et al., 2014, p. 17)

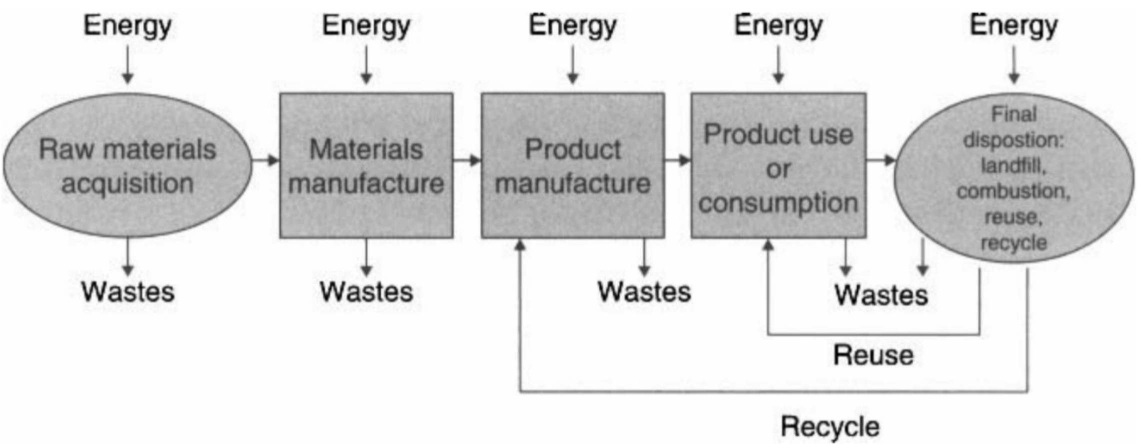



**Figure 3. Simplified flow chart of a products life cycle.** (Curran, 2012)

By considering the entire life cycle of a product, it is possible to identify trade-offs and the shifting of environmental burdens between different life cycle stages and processes (Curran, 2015; Klöpffer et al., 2014). This might not be recognized if the system boundaries are too restrictive or if the stages or processes are studied at an individual level. It is still possible to adopt the LCA framework in other types of studies such as cradle-to-gate or gate-to-gate studies (see figure 4); however, these are not considered valid LCA studies according to ISO 14040:2006.

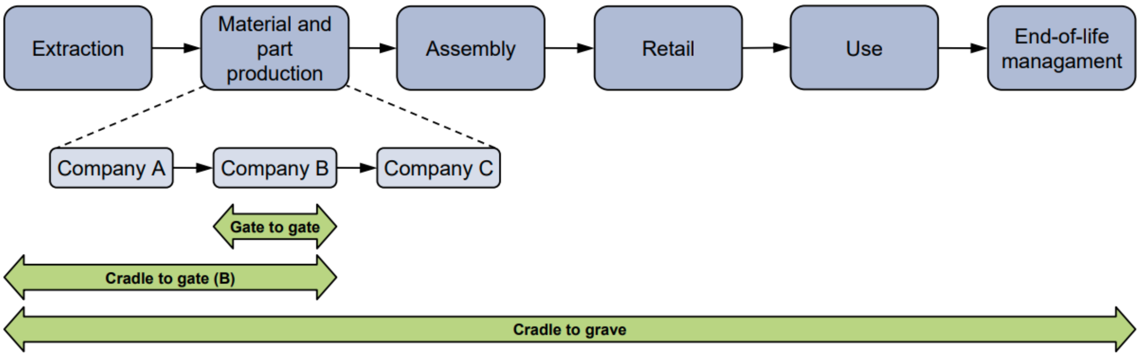



**Figure 4. Cradle-to-grave, cradle-to-gate, and gate-to-gate.** (Wolf et al., 2010)

Nevertheless, LCA offers a wide range of direct applications; from product development and improvement to strategic planning, public policy making, and marketing (International Organization for Standardization, 2006b). In this thesis, LCA is adopted for developing an EPD, that is, a type III environmental declaration in accordance with ISO 14020:2000 and ISO 14025:2006. This chapter thus concerns the background, concept, principles, framework, software, applications, and limitations of LCA. The following chapter 3.3 then discusses environmental labels and declarations and EPD's.

### 3.2.1 History and background

LCA is a technique that has gradually developed over the last few decades (Curran, 2015; Guinée et al., 2011). There are studies that can be considered precursors which date all the way back to the 1880's (Klöpffer et al., 2014); however, some of the first studies which are considered actual variants of LCA were conducted in the late 1960's and early 1970's (Curran, 2015). According to Klöpffer et al. (2014), the development of the modern LCA truly started in the early 1970's, and some of the main reasons were the increasing concerns about waste problems, bottlenecks in energy supply, and the acknowledgement of limited resources.

One of the first early LCA studies is an unpublished study from 1969 by the Midwest Research Institute (MRI), which concerns the quantification of resource use, emissions, and waste flows of different beverage containers for the Coca Cola Company (Curran, 2015; Guinée et al., 2011). In 1974, the MRI later conducted a follow-up study for the U.S. Environmental Protection Agency (Hunt et al., 1974). During the same year, a similar study was also conducted by Basler & Hofman (1974). These studies, among others, marked the beginning of modern LCA.

The MRI used the term Resource and Environmental Profile Analysis (REPA) for their studies (Curran, 2015; Guinée et al., 2011). These were, same as the modern LCA, based on a cradle-to-grave system analysis. However, most of the early LCA's were just inventory analyses without any impact assessment (Klöpffer et al., 2014). In a modern sense, this is known as a Life Cycle Inventory study or LCI study (International Organization for Standardization, 2006b, 2006c). Other terms for the early LCA studies are also proto-LCA (Klöpffer et al., 2014), or partial LCA (Curran, 2015). It took until the 1980's before the first impact assessments methods were published (Guinée et al., 2011), and this was first introduced in 1984 in a report by EMPA, that is, the Swiss Federal Laboratories for Materials Testing and Research (Bundesamt für Umweltschutz, 1984).

Thus, 1970-1990 are considered the decades of conception for LCA (Curran, 2015; Guinée et al., 2011). LCA as a methodology developed significantly during this time; from basic energy analyses and environmental burden analyses in the 1970's to comprehensive life cycle assessments in the 1980's (Guinée et al., 2011). However, according to Guinée et al. (2011) and Curran (2015), a major issue during this time were the inconsistencies in the methods and the lack of a more common theoretical framework. This resulted in significant variations in the results, even for studies conducted for the same product systems, and thus prevented LCA from becoming a more generally adopted technique.

In the beginning of the 1990's, the Society of Environmental Toxicology and Chemistry (SETAC) took a leading role in bringing LCA practitioners and scientists together through collaborations and workshops for developing a more harmonized framework for LCA (Curran, 2015; Guinée et al., 2011; Klöpffer et al., 2014). A key result was the SETAC

“Code of Practice” LCA guidelines. This was an important step for LCA, and it also set the foundation for the later standardization by ISO, that is, the International Organization for Standardization. During the years 1997–2000, ISO published the first four international standards for LCA: ISO 14040:1997, ISO 14041:1998, ISO 14042:2000, and ISO 14043:2000 (Curran, 2015; Klöpffer et al., 2014). Thus, the period of 1990–2000 is considered the decade of standardization (Curran, 2015; Guinée et al., 2011).

ISO is an international and independent non-governmental organization comprising of over 160 representative membership countries (International Organization for Standardization, 2019). The organization develops and publishes a variety of international standards for the benefit of different industries, regulators, and the society. An international standard can in simple terms be explained as “a document containing practical information and best practice. It often describes an agreed way of doing something or a solution to a global problem” (p. 4).

Currently, there are two international standards in effect for LCA: ISO 14040:2006 and ISO 14044:2006 (International Organization for Standardization, 2006b, 2006c). These two cancels and replaces the previous four standards, which have been technically revised. The main difference is that ISO 14040:2006 provides the framework and principles of LCA while ISO 14044:2006 provides requirements and guidelines for conducting an LCA. The core structure of the framework by SETAC has yet been maintained by ISO with only minor exceptions (Curran, 2015; Klöpffer et al., 2014).

Additional technical reports (TR) and technical specifications (TS) have also been published by ISO, including ISO/TR 14047:2012 titled *illustrative example on how to apply ISO 14044 to impact assessment situations* and ISO/TR 14049:2012 titled *Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis* (Klöpffer et al., 2014). However, the TR’s and TS’s are non-obligatory; they are mainly intended for additional help and support.

### 3.2.2 The concept of product systems

LCA is essentially based on a system analysis (Curran, 2015; Klöpffer et al., 2014). An LCA does not study just a product, but rather a product system. That is, the "collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product" (International Organization for Standardization, 2006b, p. 4). Thus, it allows quantifying an inventory of inputs and outputs, and based on the results, potential environmental impacts can then be estimated. An example of a product system is illustrated in figure 5.

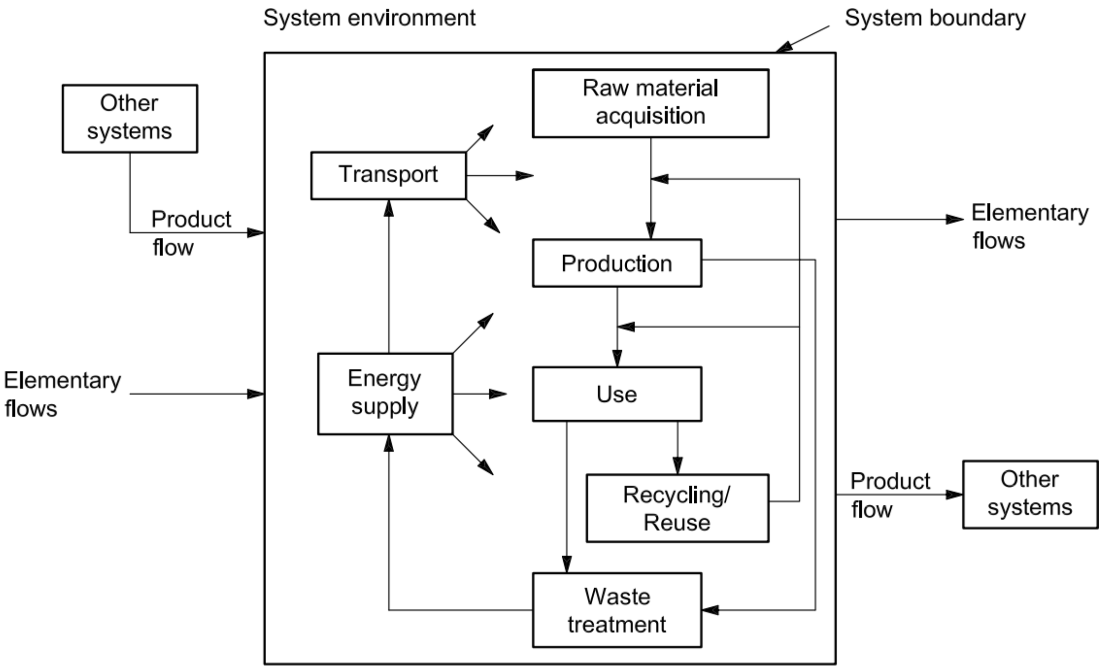



**Figure 5. An example of a product system according to ISO 14040:2006.**

Several different flows can be distinguished in figure 5. The product flows refer to the flow of products entering or leaving the product system such as recycled materials or components for reuse (International Organization for Standardization, 2006b). Inside the system, there are also intermediate product flows, and this refers to the flow of materials and subassemblies between individual unit processes (see figure 6). Finally, the elementary flows refer to the inputs and outputs of resources and energy such as the crude oil entering a process and the air polluting emissions leaving a process.

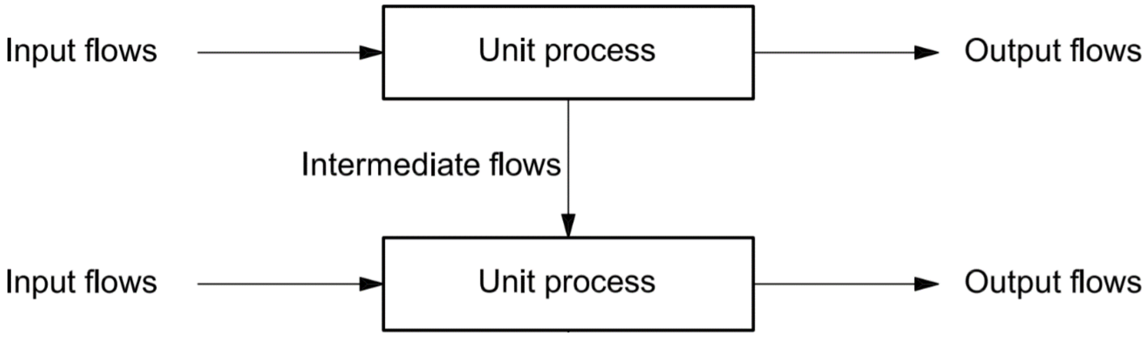



**Figure 6. Interconnected unit processes according to ISO 14040:2006.**

A unit process, as illustrated in figure 7, is the smallest element of a product system (International Organization for Standardization, 2006b). A higher resolution of data available allows unit processes to be more specific; for example, a metal deformation, a transportation procedure, or a single chemical reaction (Klöpffer et al., 2014). However, when there are less data available, a unit process can also represent an entire plant, a side chain, or the production of electricity. Other examples of unit processes are also coal mining, steel production, refining of oil, production of furniture, use of a television set, and recycling of wastepaper (Curran, 2015). Interconnected unit processes as in figure 6 thus form a product system as illustrated in figure 5.

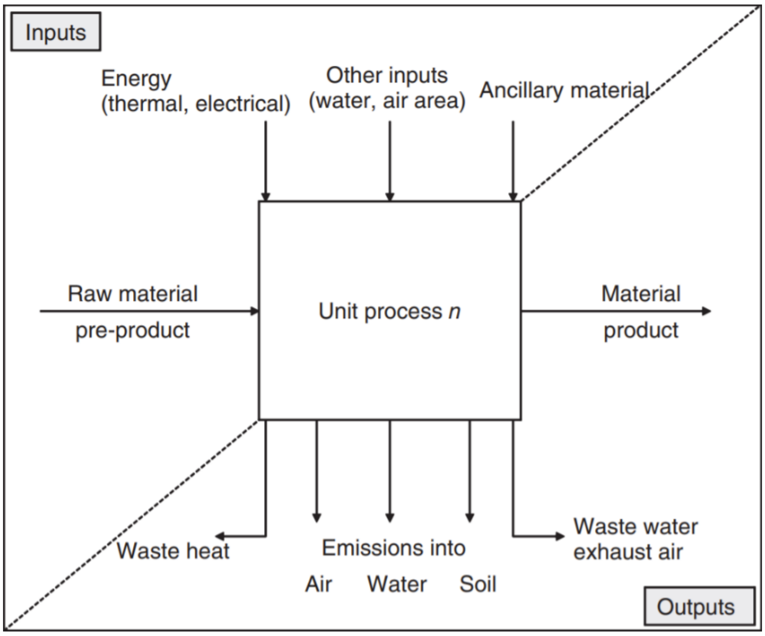



**Figure 7. An example of a unit process.** (Klöpffer et al., 2014)

### 3.2.3 Framework and guidelines

This section discusses the framework, guidelines, principles, and requirements for LCA according to the most recent international standards ISO 14040:2006 and ISO 14044:2006 and related literature. According to the standards, LCA comprises of four key phases: 1) goal and scope definition, 2) life cycle inventory analysis or LCI, 3) life cycle impact assessment or LCIA, and 4) interpretation of results. The general framework for LCA is illustrated in figure 8. However, the goal of an LCA can sometimes be satisfied without the LCIA phase, and that is called an LCI study. Additional requirements also apply if the LCA is conducted for a type III environmental declaration according to ISO 14025:2006 (see chapter 3.3).

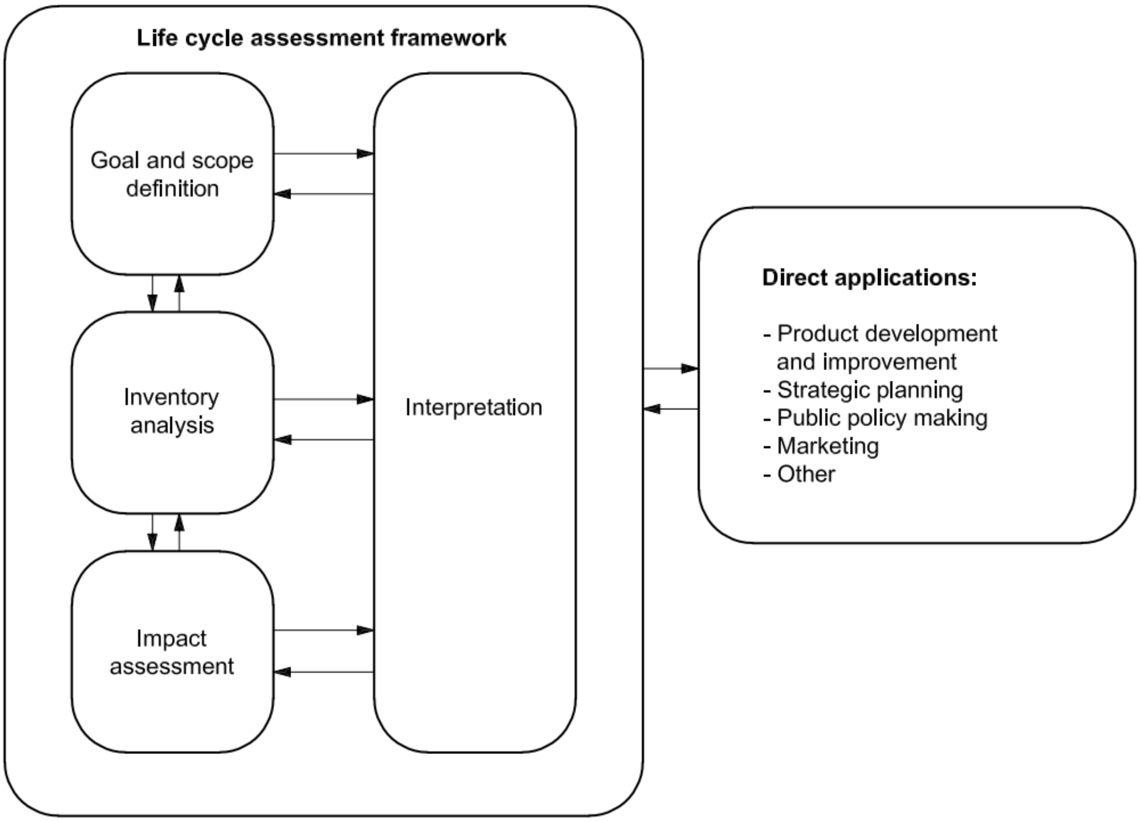



**Figure 8. LCA framework by ISO 14040:2006.**

The phases of LCA are related in an iterative nature (International Organization for Standardization, 2006b, 2006c). Aspects of each phase are subject to changes, depending on the results from the other phases, throughout the entire study. For example, the goal and scope may be revised or refined as the study progress and more data and information are revealed. After the first iteration it is also possible to identify which processes have the most significant inventories and impacts (Wolf et al., 2010). Some processes might even be more significant than expected. The quality of the data related to these processes may then be revised and improved in the next iteration. Thus, the iterative approach contributes to consistency and comprehensiveness of the LCA (International Organization for Standardization, 2006b) as well as to the overall quality, until the goals and requirements of the study are met (Wolf et al., 2010). The iterative nature of LCA is illustrated in figure 9.

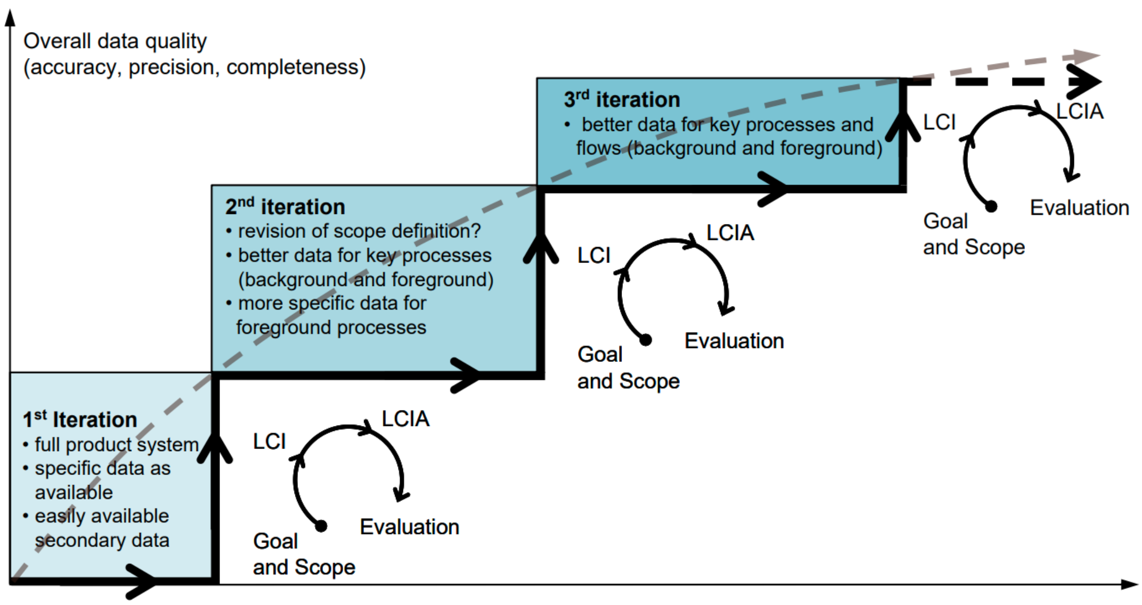



**Figure 9. The iterative nature of LCA** (Wolf et al., 2010)

LCA can also be distinguished between attributional LCA (ALCA) and consequential LCA (CLCA) (Curran, 2015). ALCA is the conventional approach in which "inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule" (p. 282). This is also the approach in focus in this thesis. CLCA is a different and more complex system modelling approach in which "activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit” (p. 282). Both approaches are legitimate but fundamentally different, and the choice of approach depends on the goal and scope. However, results are not comparable between an ALCA and a CLCA.

#### 3.2.3.1 Phase 1: Defining goal and scope

The first phase of an LCA is to define the goal and scope of the study (International Organization for Standardization, 2006c, 2006b). According to the standards, the goal and scope must be clearly defined as well as aligned with the intended application. The goal and scope may need to be revised or refined throughout the study, due to the iterative nature of LCA. Furthermore, there is no single method for conducting an LCA; the standards do not describe the method in detail. This means, an LCA is largely dependent on what is defined in this phase. Thus, the importance of this phase cannot be overstated (Curran, 2015).

ISO 14044:2006 specify a set of items that must be clearly described in terms of the goal and scope: (1) the intended application; (2) the reasons for conducting the study; (3) the intended audience; (4) if the results are intended to be used in comparative assertions and be disclosed to the public; (5) the product system to be studied; (6) the functions of the product system; (7) the functional unit; (8) the system boundary; (9) allocation procedures; (10) data requirements; (11) data quality requirements; (12) LCIA methodology and types of impacts; (13) value choices and optional elements; (14) interpretation to be used; (15) assumptions; (16) limitations; (17) type and format of the report; (18) type of critical review, if any (p. 7).

1–4 are directly related to the goal of the LCA (International Organization for Standardization, 2006c). This is relevant to be acknowledged as it directly affects the scope of the LCA. A well-defined goal also makes defining the scope easier (Curran, 2015). The applications themselves, however, are outside of the scope of ISO 14040:2006 and ISO 14044:2006. These are discussed in more detail in chapter 3.2.5.

5–18 are directly related to the scope of the study (International Organization for Standardization, 2006c). First, the product system (5) should be described, at least briefly, already from the beginning of the study (Klöpffer et al., 2014). The details can be refined as the study progress and more information is revealed (Wolf et al., 2010). Klöpffer et al. (2014) recommends using a system flow chart to illustrate the product system and all the unit processes to be considered, and this is also suggested by ISO 14044:2006. LCA software can also be used (Klöpffer et al., 2014), and these are discussed further in chapter 3.2.4.

A functional unit (7) must also be defined as LCA is a relative approach. A product system may have one or more functions (6), and the functional unit is a defined quantification of its performance as a unit of reference (International Organization for Standardization, 2006b). Thus, the functional unit determines the reference flow, which is the quantified number of products needed to fulfil the defined function of the product system. The functional unit is central as all calculations in the LCA are performed relative to this. A common functional unit is also necessary for LCA results to be comparable for product systems with matching functions (Klöpffer et al., 2014). For example, the functional unit for beverage packaging can be defined as "the provision of 1000 l liquid in a way to fulfil the technical aspects of the performance" (p. 3), and this is applicable to both the life cycle of 2000 x 0,5 l glass bottles and 500 x 2 l plastic bottles. Both product systems fulfil the same main functions, and by using a common functional unit, it allows for comparable results. Note, detailed comparisons can only be done through a comparative assertion, for which additional requirements apply.

A system boundary (8) must also be defined, and this essentially determines which unit processes are included in the LCA and to what level of detail they are studied (International Organization for Standardization, 2006c, 2006b). While it is required by the standards that all life cycle stages are considered, the interconnected processes and relationships of product systems can be highly complex in reality (Klöpffer et al., 2014). Thus, cut-off rules may be applied to exclude certain processes or flows based on mass, energy, and environmental significance (International Organization for Standardization, 2006c). However, nothing that can significantly impact the overall conclusions of the study may be excluded. For example, in some of the latest EPD's by ABB (2021a, 2021b), stickers and grease have been excluded as they have been considered negligible to the results. Nevertheless, the defining of the system boundaries is considered "one of the most important steps in an LCA" according to Klöpffer et al. (2014, p. 29).

Allocation procedures (9) then refer to the partitioning of inputs and outputs between different product systems (International Organization for Standardization, 2006b). This is necessary since industrial processes often are shared between different product systems. This is discussed further in the LCI phase in chapter 3.2.3.2.

Data requirements (10) and data quality requirements (11) are two other relevant aspect to consider (International Organization for Standardization, 2006c). There can be different types and sources of data, and the quality of the data can have a significant impact on the results. Also, the collection of data can be a resource-intensive process (International Organization for Standardization, 2006b), and according to Klöpffer et al. (2014), this is considered one of the most complex phases of LCA. Thus, practical limitations must also be considered.

The LCIA methodology and types of impacts (12) must also be determined (International Organization for Standardization, 2006c). This includes the selection of impact categories, category indicators, and characterization models to which the LCI results are assigned to in the LCIA phase (see chapter 3.2.3.3). The LCIA phase may also include optional elements based on preferences and value choices (13). Finally, the interpretation to be used (14) refers to how the results are to be interpreted for reaching conclusions and recommendations (see chapter 3.2.3.4).

An LCA is typically also based on a set of assumptions (15) (International Organization for Standardization, 2006c). Assumptions are sometimes necessary, for example, in terms of cut-off criteria, data calculations, and category indicator calculations. However, assumptions can have significant impact on the results, hence, they should always be transparently mentioned and justified. Also, a sensitivity analysis can help determine the influence of variations in the assumptions.

LCA studies also have limitations (16) due to, for example, limited data available (International Organization for Standardization, 2006c). Limitations can affect the study and the results and should therefore also be transparently described. Limitations of LCA are discussed further in chapter 3.2.6.

Lastly, ISO 14040:2006 and ISO 14044:2006 provide guidelines and requirements for the documentation and reporting (17) of an LCA study. The type and format depend on the intended application and audience, and this is determined in the scope of the study (International Organization for Standardization, 2006c). In any case, an LCA report must be transparent, accurate, and without bias. It should clearly describe the study, including the goal and scope, methods, assumptions, results, conclusions, and limitations. The exact requirements are specified in the standards. Finally, a critical review (18) may be conducted by internal or external experts, depending on the goal and scope, to verify that the LCA is valid and that it is consistent with the standards. According to ISO 14025:2006, verification is necessary if the intended application is for an EPD.

#### 3.2.3.2 Phase 2: Life Cycle Inventory analysis (LCI)

The second phase of an LCA is the Life Cycle Inventory analysis or LCI (International Organization for Standardization, 2006c, 2006b). This involves the collection of data and calculations for quantifying the inventory of inputs and outputs of the product system. The resulting inventory serves as a basis for the subsequent LCIA phase. While the goal and scope set the requirements and provide an initial plan for the LCI, figure 10 more specifically illustrates the specific steps necessary for achieving a completed inventory. Due to the iterative nature of LCA, the data collecting procedures, requirements, and limitations may need to be adjusted as the study progress.

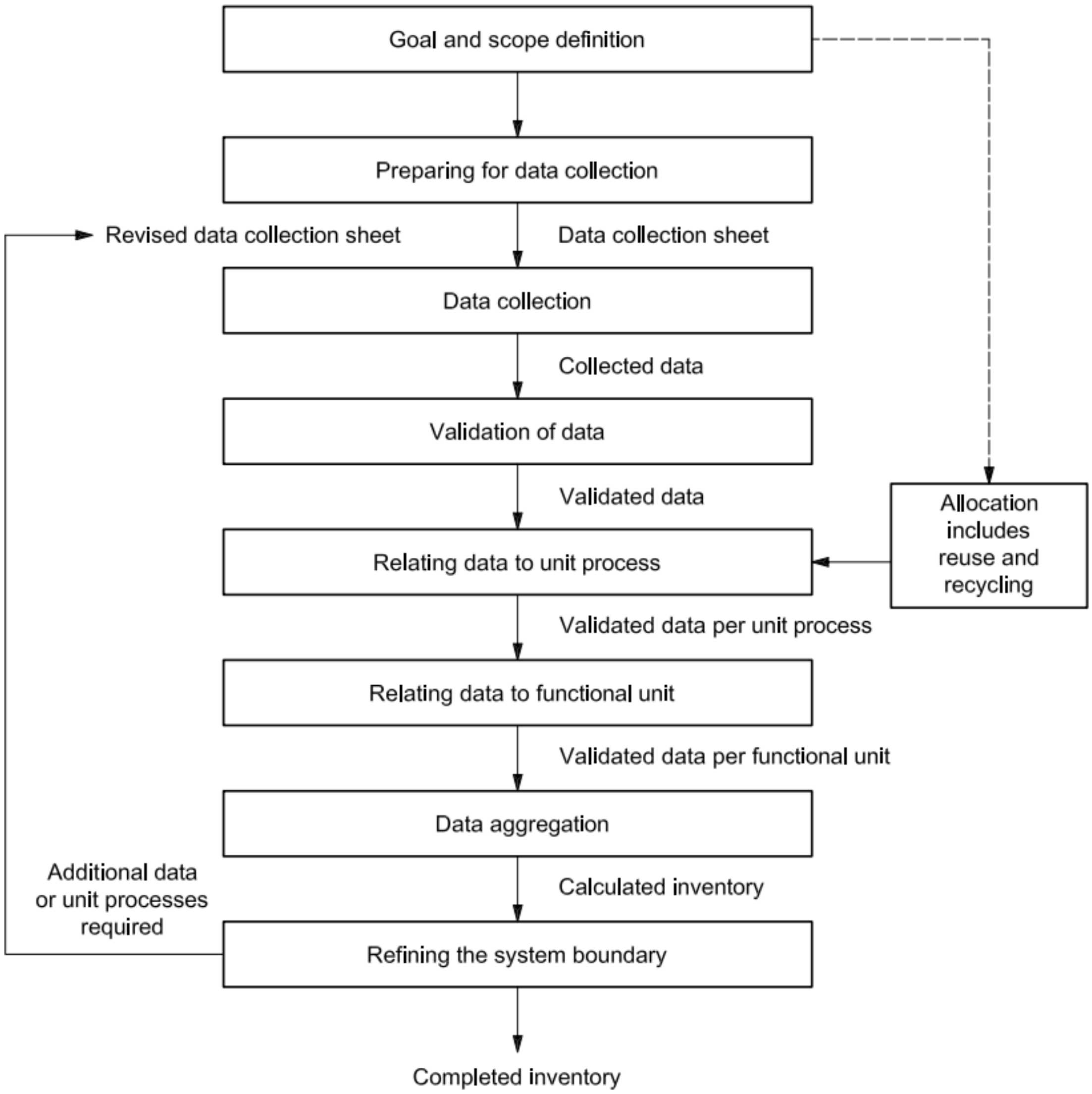



**Figure 10. Procedures for Life Cycle Inventory analysis (LCI) by ISO 14044:2006.**

Data must be collected for each unit process within the system boundary (International Organization for Standardization, 2006c). This means, all processes that assembles the system must first be identified (Wolf et al., 2010). These are initially identified when describing the product system in the goal and scope phase (Klöpffer et al., 2014), but further elaborated on throughout this phase (Wolf et al., 2010). ISO 14040:2006 suggests the following type of data to be considered for each unit process:

- Energy inputs, raw material inputs, ancillary inputs, other physical inputs
- Products, co-products, and waste
- Emissions to air, discharges to water and soil, and other environmental aspects

The data can either be obtained directly from the production sites or it may be collected or calculated from other sources (International Organization for Standardization, 2006c). In practice, the data can be a mix of measured, calculated, or estimated data. Wolf et al. (2010) and Curran (2015) also distinguish between primary data and secondary data. Primary data refers to the data that comes directly from the sources such as interviews, surveys, ERP systems, on-site measurements (Curran, 2015), and technical documents (Wolf et al., 2010). Secondary data refers to the data available from secondary sources such as third-party datasets, LCI databases (Wolf et al., 2010), and literature (Curran, 2015).

Wolf et al. (2010) and the standard EN 50693:2019 also distinguish between foreground processes and background processes. The former can be defined as “core processes in the product life cycle for which direct access to information is available”, and the latter as “processes in the product life cycle for which no direct access to information is possible” (European Standards, 2019, p. 32). On the other hand, Wolf et al. (2010, pp. 97–98) explain the former as “those that are under direct control of the producer of the good or operator of the service or user of the good or where he has decisive influence”, and the latter as “processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good (or operator of the service, or user of the good)”. Examples of foreground processes, according to Wolf et al. (2010), are in-house manufacturing processes, production of made-to-order products, and design-related use phase activities and end-of-life activities. On the other hand, background processes are, for example, the production of the electricity used, or the production of the steel used in steel parts.

The selection of data depends largely on the goal and scope (International Organization for Standardization, 2006c). It also depends on the data availability and its quality. Primary data or representative average data is always preferred for unit processes with the most significant inventories or environmental impacts. Generally, according to Wolf et al. (2010), primary data is always preferred for the foreground processes, while generic or average secondary data is typically used for the background processes. Although, generic data can sometimes still be preferred for a foreground process, if the quality of the primary data is insufficient.

As the data is collected, and necessary calculation and allocation procedures are performed, validation of the data is necessary (International Organization for Standardization, 2006c). Validating the data includes assessing the quality of the data and ensuring that it is valid. Procedures include checking mass and energy balances, checking for obvious anomalies, and treating incomplete data.

Finally, the flows of all unit processes must be established in relation to the functional unit (International Organization for Standardization, 2006c). Thus, the inputs and outputs of all unit processes are quantified in relation to the reference flow. The inventory can then be aggregated for the product system as a whole. The LCI results may be interpreted before proceeding with the LCIA phase. In turn, the system boundaries may be revised, and the quality of the data may be improved.

**Allocation procedures**

Allocation procedures are necessary when modelling with an attributional approach (ecoinvent, n.d.), because industrial processes often yield more than one product (International Organization for Standardization, 2006b). Such a process is called a multi-output process, and the additional products are called co-products (Klöpffer et al., 2014). However, it can be difficult to determine exactly which inputs and outputs are associated with which product (Curran, 2015). Allocation procedures aim to solve this by partitioning the inputs and outputs between the different product systems based on a set of rules. If possible, allocation should be avoided by dividing the unit process into separate sub-processes, or by further expanding the system boundaries to also include the co-products and their functions (International Organization for Standardization, 2006c). If allocation cannot be avoided, physical properties such as mass should be preferred as a basis for allocation. If this is not possible, allocation in proportion to economic value may be applied.

The choice of allocation procedure depends on the situation – there is no single procedure that is adequate in all cases (Curran, 2015). For example, in some of the most recent EPD's by ABB (2021a, 2021b), the yearly utility consumption and waste generation of the core manufacturing stage are first allocated to the production line based on its installed power and its surface area. This is then allocated to each unit by dividing it with the yearly output of products. The concept of co-product allocation is illustrated in figure 11.

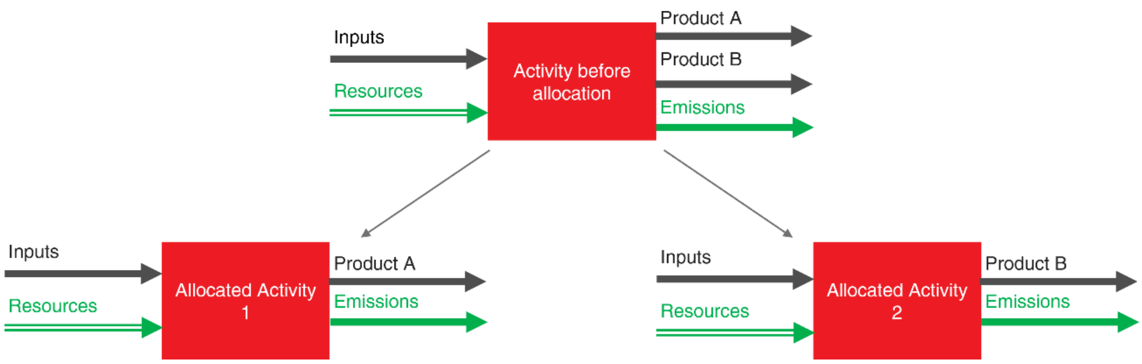
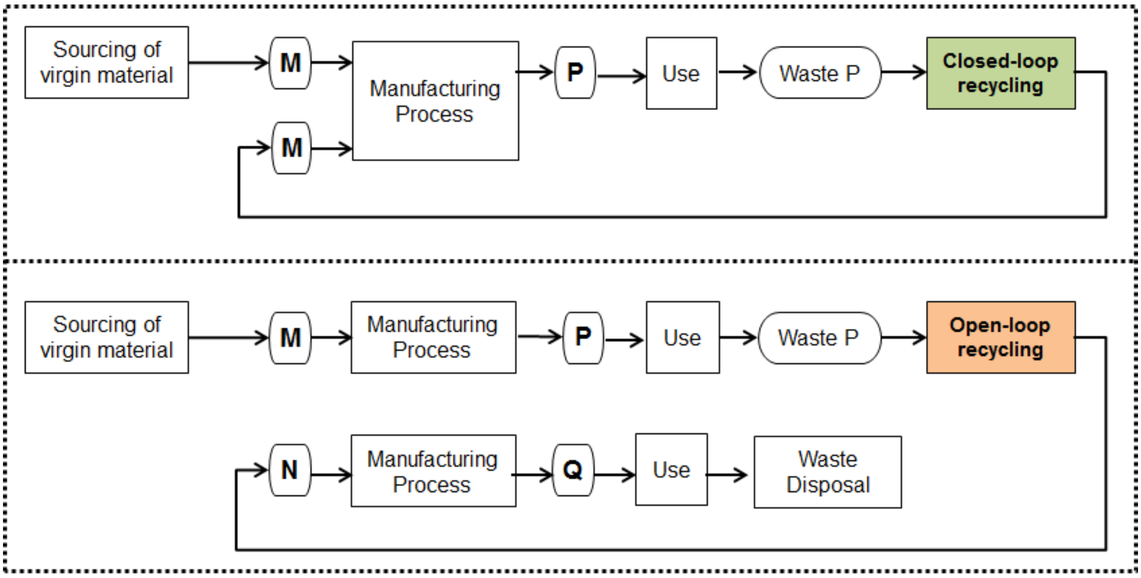



**Figure 11. Allocation of co-products.** (ecoinvent, n.d.)

Allocation must also be considered for reuse and recycling processes, since this can imply that the activities related to raw material extraction and waste treatment are shared with other product systems (International Organization for Standardization, 2006c). The selection of procedures depends largely on whether it is a closed-loop system where the waste is continuously recycled and reused in the same product system, or an open-loop system where the waste is recycled and reused in a different product system (see figure 12). Closed-loop recycling is generally more straightforward to model because all recycling activities occur within the same product system (Klöpffer et al., 2014). However, complete recycling is not possible in practice, and this creates other issues with this model (p. 105) such as determining the recycling rate and the amount of recycled content (Curran, 2015).




"M": material; "N": recycled material; "P": product; and, "Q": product from recycled material

**Figure 12. Closed-loop recycling and open-loop recycling.** (Abuabara et al., 2019)

Open-loop recycling can also be problematic since it requires determining a fair allocation of the environmental burdens between the interconnected product systems (Klöpffer et al., 2014). The authors suggest adopting a cut-off rule for determining the exact point of separation. A simple approach is the 50/50 method where burdens are allocated equally between the primary and secondary product system. Another approach is the polluter pays principle, adopted by for example the program operator EPDItaly (2020b) and in the standard EN 50693:2019, which means the environmental burdens of waste are allocated to "the product system that generates the waste until the end-of-waste state is reached" (p. 36). Also, the same principles apply if a waste treatment activity is shared in parallel with other product systems (International Organization for Standardization, 2006c); for example, multi-input allocation of burdens from the waste treatment activities at an incineration plant (Klöpffer et al., 2014).

Nevertheless, the LCA database ecoinvent offers already defined system models for both attributional and consequential modelling (ecoinvent, n.d.). It also offer system models with different allocation procedures and cut-off. The choice depends on the goal and scope; however, ecoinvent recommends the "cut-off system model" for beginners, which is based on an attributional approach.

### 3.2.3.3 Phase 3: Life Cycle Impact assessment (LCIA)

The third phase of an LCA is the life cycle impact assessment or LCIA (International Organization for Standardization, 2006b). The purpose of this phase is to assess the potential environmental impacts by associating the LCI results with specific impact categories and indicators. While the goal of an LCA in some cases can be satisfied through an LCI study without an LCIA (p. VI), this phase adds another valuable aspect because small emissions can sometimes have large effects on the environment (Klöpffer et al., 2014). Due to the iterative nature of LCA, the results of this phase may again influence the goal and scope as well as reveal key processes for which the data needs to be revised and further improved.

LCIA comprises of both mandatory and optional elements (International Organization for Standardization, 2006b). The first mandatory element (1) requires selecting a set of impact categories, category indicators, and characterization models, and these are initially selected in the goal and scope phase. The second mandatory element (2) requires assigning the LCI results to the selected impact categories, and this is called classification. The third and last mandatory element (3) requires calculating the category indicator results and this is called characterization. Existing LCIA methods are often used (see table 2); however, existing models are sometimes not sufficient, and this might require developing new ones according to ISO 14044:2006. Nevertheless, LCA software can facilitate the LCIA phase significantly and this is discussed further in chapter 3.2.4.

**Table 2. LCIA terms and examples by ISO 14044:2006.**

| **Term** | **Example** |
|---|---|
| Impact category | Climate change |
| LCI results | Amount of a greenhouse gas per functional unit |
| Characterization model | Baseline model of 100 years of the Intergovernmental Panel on Climate Change |
| Category indicator | Infrared radiative forcing (W/m2) |
| Characterization factor | Global warming potential (GWP100) for each greenhouse gas (kg CO2-equivalents/kg gas) |

| | |
|---|---|
| Category indicator result | Kilograms of CO2-equivalents per functional unit |
| Category endpoints | Coral reefs, forests, crops |
| Environmental relevance | Infrared radiative forcing is a proxy for potential effects on the climate, depending on the integrated atmospheric heat adsorption caused by emissions and the distribution over time of the heat absorption |

An impact category represents a class of environmental issues to which the LCI results are assigned, for example climate change (International Organization for Standardization, 2006c). The category indicator then refers to a quantifiable representation of that category, for example, infrared radiative forcing (W / $m^2$). Finally, a characterization factor is applied, and this converts the LCI results into a common unit of the category indicator, for example, global warming potential ($GWP_{100}$). Category indicators are based on a so-called environmental mechanism, and the concept is illustrated in figure 13. The category indicator can be chosen anywhere between the LCI results and the category endpoints.

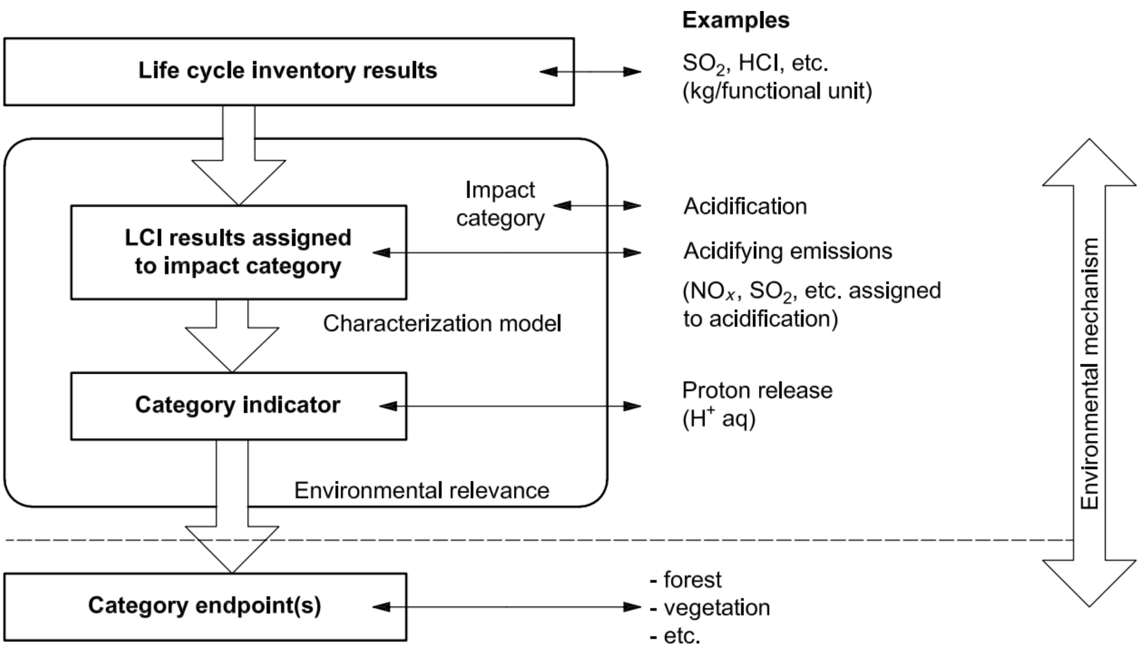



**Figure 13. The concept of impact category indicators according to ISO 14044:2006.**

Optional elements of LCIA include normalization, grouping and weighting (International Organization for Standardization, 2006c). Normalization refers to calculating the relative importance of each category indicator by dividing the results with a selected reference value. This can help create a better understanding of the relative significance for each indicator, and thus it can be useful for checking for inconsistencies. Grouping, on the other hand, refers to sorting and/or ranking the impact categories. Lastly, weighting refers to the process of converting results based on set of numerical factors. Note, both grouping and weighting are based on value-choices and are not scientifically based. Thus, full transparency is required if this is adopted.

Nevertheless, according to ISO 14040:2006, "there are no generally accepted methodologies for consistently and accurately associating inventory data with specific potential environmental impacts" (p. 16). Thus, the selection of LCIA methodology and types of impacts depend on the goal and scope. Modern LCIA methods have developed significantly since the first method was introduced by EMPA in 1984 (Guinée et al., 2011), and some examples of commonly used LCIA methods include IMPACT2002+, TRACI, CML-IA, ReCiPe, and ILCD (Curran, 2015). By considering a diverse set of impact categories, the overall impacts and potential trade-offs can be better understood (International Organization for Standardization, 2006b).

#### 3.2.3.4 Phase 4: Interpretation phase

The interpretation phase is the fourth and final phase of an LCA (International Organization for Standardization, 2006b). In this phase, the results of the LCI and LCIA are evaluated, presented, and discussed, in order to establish conclusions, limitations and recommendations with respect to the goal and scope of the study. Results may also be interpreted iteratively throughout the study due to the iterative nature of LCA. The interpretation phase is a systematic procedure comprising of three key elements: (1) identification of significant issues, (2) evaluation of results, and (3) the establishing of conclusions, limitations, and recommendations (International Organization for Standardization, 2006c). The results of the evaluation elements should be reflected in the results, as well as the fact that LCA is a relative approach and that results indicate potential impacts and not actual impacts (International Organization for Standardization, 2006b).

**1) Identification of significant issues**

The first element of the interpretation phase, according to ISO 14044:2006, is the identification of significant issues. This includes considering the implications of the methods used and the assumptions made in previous phases. Issues can be, for example, significant contributions from individual life cycle stages, from a group of processes, or from an individual unit process such as energy production or transportation. More specifically, issues can be related to inventory data such as energy, emissions, or waste. It can also be related to impact categories such as resource use and climate change. Accordingly, the data quality may need to be improved. This element is performed interactively with the evaluation element.

**2) Evaluation of results**

The second element of the interpretation phase, according to ISO 14044:2006, is the evaluation of the results. Evaluation techniques can include a completeness check, sensitivity check, consistency check, or any other validation that may be necessary with regard to the goal and scope of the study. It may also be supplemented with an uncertainty analysis and a data quality analysis. Thus, the main purpose is to establish a confidence in the results.

First, a completeness check is “the process of verifying whether information from the phases of a life cycle assessment is sufficient for reaching conclusions in accordance with the goal and scope definition” (International Organization for Standardization, 2006c, p. 6). This includes checking and ensuring that all relevant data and information that is needed is available and is complete (p. 26). Previous phases should be revisited if any relevant data or information is missing. Justifications should be made if any missing data or information is neglected.

Second, a sensitivity check is “the process of verifying that the information obtained from a sensitivity analysis is relevant for reaching the conclusions and for giving recommendations” (International Organization for Standardization, 2006c, p. 6). This includes assessing the reliability of the study by performing a sensitivity analysis, in order to determine how the results are affected by uncertainties in the data (p. 26). It may also include an uncertainty analysis. Nevertheless, LCA software can facilitate this significantly and this is discussed further in chapter 3.2.4.

Third, a consistency check is “the process of verifying that the assumptions, methods and data are consistently applied throughout the study and are in accordance with the goal and scope definition performed before conclusions are reached” (International Organization for Standardization, 2006c, p. 6). If relevant to the study, the following questions should be addressed (pp. 26–27):

- “Are differences in data quality along a product system life cycle and between different product systems consistent with the goal and scope of the study?”
- “Have regional and/or temporal differences, if any, been consistently applied?”
- “Have allocation rules and the system boundary been consistently applied to all product systems?”
- “Have the elements of impact assessment been consistently applied?”

**3) Conclusions, limitations, and recommendations**

The third and final element of the interpretation phase is, according to ISO 14044:2006, the establishing of conclusions, limitations, and recommendations. The findings should be established iteratively with the other elements of the interpretation phase. The following logical sequence is suggested in the standard (p. 27):

a) “Identify the significant issues”
b) “Evaluate the methodology and results for completeness, sensitivity and consistency”
c) “Draw preliminary conclusions and check that these are consistent with the requirements of the goal and scope of the study, including, in particular, data

quality requirements, predefined assumptions and values, methodological and study limitations, and application-oriented requirements”

d) “If the conclusions are consistent, report them as full conclusions; otherwise return to previous steps a), b) or c) as appropriate”

#### 3.2.4 Software and databases

Dedicated software is often used to facilitate the modelling and calculations due to the complex nature of LCA (Curran, 2015; Klöpffer et al., 2014). Features include the organizing of processes and data, aggregating inventory data, calculating category indicators, and illustrating system flow charts. Although software can facilitate LCA practice, a high degree of knowledge and expertise is still required by the practitioner (Curran, 2015).

LCA software has been developing for over 20 years, and this has allowed LCA to become a widely used tool with emphasis on data sharing and transparency (Curran, 2015). In fact, modern LCA relies heavily on both data and software. Klöpffer et al. (2014) still suggest that it is possible to use Microsoft Excel for calculations; however, the use of spreadsheet software is an outdated approach according to Curran (2015). Although, some working groups still utilize mathematical modelling software such as Matlab (p. 115).

The leading and most commonly used LCA software are GaBi by PE International and SimaPro by Pré Consultants (Curran, 2015; Herrmann & Moltesen, 2015). There is also open-source software that is available for free such as openLCA (Curran, 2015). According to some of the latest EPD’s by ABB (2021a, 2021b), the company has recently been using SimaPro. Earlier, GaBi has also been used by the company (Liimatainen, 2012). On the other hand, Schneider Electric (2017b, 2018) has used a software called EIME.

LCA software typically come with integrated databases (Klöpffer et al., 2014). These provide comprehensive background data which is commonly used for background processes as explained in chapter 3.2.3.2. Some of the most widely used LCI databases include ecoinvent and the GaBi database (Pauer et al., 2020). Note, GaBi is the provider of both software and database. Other databases are also the European Life Cycle Database (Kalverkamp & Karbe, 2019) and the Environmental Footprint Database (Pauer et al., 2020). ABB (2021a, 2021b) has recently been using the ecoinvent database, and Scheider Electric (2017b, 2018) has used EIME's own database.

Furthermore, numerous LCA software offer ready defined LCIA methods that can be easily applied to the LCI data (Curran, 2015; Klöpffer et al., 2014). These typically have all the mandatory phases of LCIA integrated to a large extent, including the selection of the impact categories, classification, and characterization (Klöpffer et al., 2014). While this offers a rather thoughtless way of conducting an LCIA, the mandatory elements should still be addressed in the goal and scope of the study (Klöpffer et al., 2014). It is still also possible to develop own LCIA methods according to ISO 14044:2006.

Research shows that the selection of software, database, and LCIA methods can have significant impact on the results (Curran, 2015; Pauer et al., 2020; Speck et al., 2016). The selection of software should typically not affect the results; however, Speck et al. (2016) found that variations may occur despite using the same database and methods, due to differences in the LCIA implementations. Different LCIA methods may likewise produce significantly different LCIA results for same impact categories due to differences in the characterization factors (Speck et al., 2016). Nevertheless, there is generally a divergence in databases (Curran, 2015). When comparing for instance ecoinvent and GaBi, sometimes the former yields more conservative results, and sometimes the latter yields more conservative results (Pauer et al., 2020).

LCA software can also facilitate a sensitivity analysis and an uncertainty analysis (Curran, 2015). For example, in SimaPro it is possible to define parameters in the data which allows for easily adjusting or switching between different system boundaries (PRé, 2016). Thus, it allows for semi-automated sensitivity analyses. Numerous software also support Monte Carlo analysis, which is a method that randomly calculates different possible scenarios for studying uncertainty (Curran, 2015). SimaPro also supports this feature, and it is possible for the user to define own uncertainty parameters such as type of distribution and standard deviation for each process (PRé, 2016).

Nevertheless, the use of software still requires manual input of data and modelling by the user before any calculations can be done (Klöpffer et al., 2014). Thus, the LCA modelling is still subject to errors by the practitioner – one must not blindly trust the software. Critical review with a system check is therefore important.

### 3.2.5 Applications

LCA offers a wide range of direct applications for both industry, government, and non-government organizations (International Organization for Standardization, 2006b). Generally, LCA is used as part of a more comprehensive decision-making process, for example, in product development, strategic planning, and public policy making. It is also considered an important tool for sustainable supply chain management (Brömer et al., 2019; Seuring & Müller, 2008) and for integrating corporate sustainability (Witjes et al., 2018). In fact, the method offers great flexibility, and according to ISO 14040:2006 (p. 19):

> *“There is no single solution as to how LCA can best be applied within the decision-making context. Each organization has to solve and decide that case by case depending (amongst others) on the size and culture of the organization, its products, the strategy, the internal systems, tools and procedures and the external drivers.”*

For example, in product design and improvement, LCA can help to identify opportunities for reducing the environmental impacts of a product in various stages of its life cycle (International Organization for Standardization, 2006b). There is also research, by for example Chang et al. (2014) and da Luz et al. (2018), that provide frameworks for how to integrate LCA in the product development process. Marks and Spencer, Nestle, Unilever, and Ikea are some examples of companies that rely on LCA for improving the sustainability of their products (FSLCI, 2015). United Plantations Berhad is another example, and the company has successfully been able to reduce their GHG emissions per kg of refined palm oil by 55 % from 2004 to 2019 (Schmidt & de Rosa, 2020).

Furthermore, in public policy making, LCA can support the development of regulations and setting environmental policies (Klöpffer et al., 2014). The author provides various examples, such as an LCA study of beverage packaging by Schmitz et al. (1995) for packaging regulation, and a cost-benefit analysis of environmental public procurement by Rüdenauer et al. (2007). Another example is also the article by i Palmer et al. (2011), in which the authors present "four models of options for the management of waste solvent to be addressed under Catalan industrial waste management regulation" (p. 458). In fact, Directive 2008/98/EC by the European Parliament (2008) requires all EU countries to develop comprehensive waste management plans, and the directive specifically states that "an approach that takes into account the whole life-cycle of products and materials and not only the waste phase" is necessary. i Palmer et al. (2011) point out that the Government of Catalonia has used LCA for various purposes already for many years.

Finally, LCA can be used for various marketing and communication purposes, such as ecolabelling or making environmental claims (International Organization for Standardization, 2006b). It can also be used for environmental product declarations (EPD), that is, type III environmental declarations according to ISO 14025:2006. Environmental labels and declarations are discussed in more detail in chapter 3.3.

### 3.2.6 Limitations

Despite LCA being a highly acknowledged technique for assessing environmental aspects and impacts of products, it is not perfect. According to Klöpffer et al. (2014), there are indeed limitations and numerous weak points with the method. In fact, LCA is one of many environmental management techniques among, for example, risk assessment and environmental performance evaluation (International Organization for Standardization, 2006b). There is also Environmental Impact Assessment (EIA), a method fundamentally different from LCA, which is commonly used for addressing local environmental impacts (Larrey-Lassalle et al., 2017). Thus, LCA might not be ideal or even appropriate in all situations (International Organization for Standardization, 2006b); however, methods can sometimes be combined for more extensive assessments (International Organization for Standardization, 2006b; Larrey-Lassalle et al., 2017).

First, LCA does not typically consider the economic or social aspects of a product; only the environmental aspect (International Organization for Standardization, 2006b). According to Klöpffer et al. (2014), this was intentional to avoid a method overload. The economic and social aspects must nonetheless be considered in the development of sustainable products, and according to ISO 14040:2006, it is entirely possible to apply LCA methods to these other aspects. A suggested approach is Life Cycle Sustainability Assessment (LCSA) which integrates Social Life Cycle Assessment (SLCA) and Life Cycle Costing (LCC) with conventional LCA (Curran, 2015; Klöpffer et al., 2014). SLCA and LCC is based on same principles as LCA, but instead address the social respective economic aspects of a product's life cycle.

Second, LCA does not aim to predict precise environmental impacts, but rather potential environmental impacts (International Organization for Standardization, 2006b). A reason for this is the fact that LCA is a relative approach. Results are always relative to a functional unit, and this is defined by the practitioner. For example, according to some of the latest EPD's by ABB (2021a, 2021b), the functional unit is based on a reference service life of 20 years. However, this does not reflect the reality; it is an assumption made for calculation purposes.

Third, there is an inherent uncertainty when assessing potential environmental impacts (International Organization for Standardization, 2006b). ISO 14040:2006 specifically states that "there are no generally accepted methodologies for consistently and accurately associating inventory data with specific potential environmental impacts" (p. 16). An inevitable issue is the lack of a spatial and temporal dimension in the LCI results, and the impacts that are addressed are often future impacts. Also, data quality and assumptions contribute to uncertainty, and this may likewise have a significant impact on the results (International Organization for Standardization, 2006c). At the same time, according to (Hertwich et al., 2000, p. 25):

> *"We are looking neither for universal agreement nor for perfect analysis that reflects the minute details of environmental processes, but for an improvement of the current decision-making process that often does not include environmental considerations."*

Fourth, conducting an LCA can be complex and typically requires a high degree of knowledge and expertise by the practitioner (Curran, 2015). Especially the process of collecting and managing the data can be resource intensive and time consuming (Curran, 2015). According to ISO 14040:2006, the level of detail and effort may vary to a large extent between different LCA studies, depending on the goal and scope. Simplifications can be done to facilitate LCA practice, and this is also the reason for using cut-off rules. At the same time, many issues with LCA can only be simplified with a loss of quality (Klöpffer et al., 2014). For example, a too restrictive system boundary might fail to consider significant impacts, or worse, it can invalidate the LCA according to the standards.

Finally, ISO never intended to standardize LCA in detail (Curran, 2015), and ISO 14040:2006 specifically states that there is no single method for conducting an LCA. The advantage is that organizations have the flexibility to adopt LCA according to its own goals and requirements (International Organization for Standardization, 2006b). The disadvantage is that it creates room for inconsistencies between studies, which in turn can makes studies of similar products incomparable. ISO 14025:2006 aims to address these issues by introducing product category rules and type III environmental declarations. This is discussed further in the following chapter.

## 3.3 Environmental labels and declarations

Environmental labels and declaration are, beside LCA, another tool for environmental management, which are internationally standardized according to the ISO 14020 series (International Organization for Standardization, 2000). The purpose is to transparently provide accurate and verifiable information about a products or services environmental profile. The overall goal is to encourage supply and demand for products and services with less environmental stress, and thus stimulate a market-driven, continuous improvement of environmental performance.

ISO 14020 is the first international standard in the ISO 14020 series that establishes the general principles (International Organization for Standardization, 2006a). The series further include three additional standards: (1) ISO 14024 for type I environmental labelling, (2) ISO 14021 for type II environmental labelling, and (3) ISO 14025 for type III environmental declarations. Curran (2015) distinguishes them simply as follows (p. 229):

> *"Typically Type I claims appear on a product as a stamp or seal of approval and similarly, Type II claims appear as a short statement calling out one attribute on a product. Contrarily, Type III product declarations are often a multi-page document outlining detailed environmental information."*

In this thesis, an LCA is conducted with the main intended application for a type III environmental declaration according to ISO 14025:2006. Thus, the following section focuses on this specific type and standard. Relevant EPD's and product category rules (PCR) from the industry are also discussed.

### 3.3.1 Type III environmental declarations

Type III environmental declarations are also known as Environmental Product Declarations or EPD (International Organization for Standardization, 2006a). This is a document that declares "quantified environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function" (p. V). Indeed, EPD’s are based on independently verified LCA data according to the ISO 14040 series. According to Curran (2015), this is the most comprehensive type within the ISO 14020 series. Typically, EPD’s are used by organizations for business-to-business communication (International Organization for Standardization, 2006a). However, they can also be used in business-to-consumer communication.

Conducting an LCA for an EPD adds additional requirements to consider. For example, ISO 14025:2006 requires adopting product category rules (PCR) when developing an EPD, and that is a set of rules, requirements, and guidelines that apply for a specific category of products (International Organization for Standardization, 2006a). However, ISO 14025:2006 does not provide any PCR’s; it only provides the principles and procedures for developing EPD’s, PCR’s, and EPD programs.

Instead, the PCR’s are developed and maintained by the program operators in accordance with their EPD programs (International Organization for Standardization, 2006a). A program operator can be, for example, “a company or a group of companies, industrial sector or trade association, public authorities or agencies, or an independent scientific body or other organization” (p. V). An EPD program is then a program, managed by a program operator, that guides the overall administration and operations based on a set of rules called general program instructions. EPD programs always have a defined scope, and these may be limited to, for example, a specific geographical area, industrial sector, or group of products. The overall purpose of EPD programs and PCR’s is to harmonize operations and methods in order to ensure comparability of EPD’s. It is voluntary to become a program operator, participate in a program, and to develop an EPD’s.

The scope of EPD programs and PCRs may sometimes overlap, and thus cooperation and harmonization between program operators is strongly encouraged in ISO 14025:2006. Mutual recognition of rules is important in terms of PCR development, review and verification procedures, and EPD formats. The purpose of the standard is nevertheless to achieve comparability of LCA results.

### 3.3.2 Program operators, product category rules and EPD's

In 2014, Hunsager et al. conducted a study in which they, among other things, mapped out existing PCR and EPD documents. Through an internet search and direct correspondence with program operators, Hunsager et al. (2014) found 27 EPD programs, 556 PCR documents, and 3614 EPD's across a variety of different sectors and geographical scopes. Later, Minkov et al. (2015) conducted a study about the status quo and practical challenges of EPD's and PCR's. The authors found 39 different EPD programs of which more than 75 % were fully ISO compliant. According to the authors, this was a five-fold increase since 2002.

PEP ecopassport is the only EPD program identified by Minkov et al. (2015) that is mentioned as directly related to electronics, and this is also mentioned by Hunsager et al. (2014). The scope of PEP ecopassport, according to the general program instructions by the P.E.P. Association (2017), is explicitly electrical, electronic, and HVAC-R equipment. Currently, there is only one PCR for the entire PEP ecopassport program, which is titled *Product category rules for electrical, electronic and HVAC-R products* by P.E.P. Association (2021). Instead of having different PCR's, they use product specific rules (PSR) to provide additional rules for specific types of products. According to their website (P.E.P. Association, n.d.-b), there are currently 18 different PSR available, for example, *PSR0001 - Wires, cables and accessories* and *PSR0005 - Electrical switchgear and controlgear solutions.*

Schneider Electronic is currently the only organization that can be found from the PEP ecopassport database that have published EPD's using the PEP ecopassport PCR for medium voltage protection relays (P.E.P. Association, n.d.-a). The company have several product series and families for both medium- and high-voltage protection relays (Schneider Electric, n.d.). However, they do not have separate EPD's for every relay product or configuration. For example, the company have only two public EPD's that represents the MiCOM 30 series; one that uses the P437 84TE relay to represent all 84TE devices (Schneider Electric, 2018) and one that uses the P139 40TE relay to represent all 24TE and 40TE devices (Schneider Electric, 2017b). Extrapolation rules are then provided to include other, similar relays of the product family.

Another program operator, which is not mentioned by Hunsager et al. (2014) or Minkov et al. (2015), is EPDItaly. In some of the most recent EPD’s by ABB (2021a, 2021b), the company has adopted PCR’s from this program operator. For example, in their EPD for the VD4 circuit breakers, both the PCR *EPDItaly007 – PCR for electronic and electrical products and systems* and *EPDItaly012 - electronic and electrical products and systems – switches* are adopted (ABB, 2021a). Like how PEP ecopassport use PCR and PSR, EPDItaly007 is here referred to as the core PCR and EPDItaly012 as a sub-PCR. This is further explained in the program instructions by EPDItaly (2020b). Note, no EPD’s can yet be found for medium voltage protection relays when searching the EPDItaly database (EPDItaly, n.d.).

The PCR by PEP ecopassport and EPDItaly007 both have a similar scope; both are international and both concern electrical products, systems, and equipment (EPDItaly, 2020a; P.E.P. Association, 2021). More importantly, both are largely based on the same European standard: *EN 50693:2019 – Product category rules for life cycle assessments of electronic and electrical products and systems*. EN 50693:2019 is a standardized PCR that provides harmonized rules for the product category in question. However, the main difference is that EN 50693:2019 provides more general rules while PEP ecopassport and EPDItaly provide additional and more specific rules. In fact, it is suggested in EN 50693:2019 that the standard should be complemented with separate PSR’s. The standard also provides guidance for how to develop a PSR.

## 3.4 LCA’s and EPD’s of relays and other electronic devices

LCA has become a well-established method within the electronics industry as well. According to the literature review by Subramanian & Yung (2016), numerous LCA studies have been published over the years of a variety of different electronic products. However, the current literature on LCA studies of medium voltage protection relays is still limited. For example, such devices are not even recognized by Subramanian & Yung (2016). Furthermore, searching the database *Scopus* with "TITLE-ABS-KEY ("medium voltage protection relay") AND TITLE-ABS-KEY ("LCA")" yields 0 results. Searching with "TITLE-ABS-KEY ("relay") AND TITLE-ABS-KEY ("LCA")" yields 21 results. However, none of the articles are actual LCA studies of medium voltage protection relays.

The only published LCA study found for medium voltage protection relays, prior to this thesis, is the thesis by Liimatainen (2012). This study was also conducted for ABB, for the same Relion 615 series of relays. Liimatainen (2012) conducted an LCA for two different configurations of the 615 series, and the aim was to produce an EPD based on the results. No existing PCR was adopted in the study; instead, a new PCR was developed. A summary of the results is found in table 3. Note, the functional unit used in the study is not specified. Also, the study by Liimatainen (2012) is a bachelor's thesis, and the results have not been verified by an independent third party. The reliability and validity of this study are therefore questionable.

**Table 3. LCIA results for the 615 series by Liimatainen** (2012)

| **A 615 series variant** | | | | |
|---|---|---|---|---|
| **Environmental Impact** | **Manufacture** | **Use** | **Total** | **Equivalent unit** |
| Acidification | 0.87 | 3.05 | 3.92 | $SO_2$ kg |
| Eutrophication | 0.05 | 0.16 | 0.22 | Phosphate kg |
| Global Warming | 120.39 | 715.58 | 835.97 | $CO_2$ kg |
| Ozone Layer Depletion | 0.00 | 0.00 | 0,00 | R11 kg |
| Photochemical Ozone Demand | 0.05 | 0.18 | 0.24 | Ethene kg |

The availability of EPD's for medium voltage protection relays is higher. Among the older EPD's published by ABB (n.d.-c), one example is the EPD for the REF 541/543/545 relays (ABB, 2006). A summary of the results is found in table 4. However, the functional unit is not specified in this study either. Although, a rated power between 17–27 watt is mentioned. It is neither stated if any product category rules have been adopted, or if the results have been verified by an accredited third party. Thus, the reliability and validity of this study are also questionable.

**Table 4. LCIA results for REF 54_ relays by ABB** (ABB, 2006)

| Environmental impact categories | Manufacturing phase | Usage phase | Disposal phase | Total | Equivalent unit * |
|---|---|---|---|---|---|
| Acidification | 195.42 | 581.34 | -0.03 | **776.73** | mol H+ |
| Global warming | 857.73 | 3828.59 | -0.64 | **4685.67** | kg $CO_2$ |
| Eutriphication | 53.60 | 45.57 | 0.03 | **99.21** | kg $O_2$ |
| Ozone depletion | 0.00 | 0.00 | 0.00 | **0.00** | kg CFC-11 |
| Photochemical oxidant formation | 0.51 | 0.73 | 0.00 | **1.24** | kg Ethylene |

More recent EPD's of medium voltage protection relays are found via P.E.P. Association (n.d.-a). This includes, for example, the EPD for the Easergy P3F30 relays by Schneider Electric (2017a). The company has adopted the PEP ecopassport PCR together with the PSR0005 for electrical switchgear and controlgear solutions. The functional unit is defined as the following: "Protect distribution and transmission networks and high voltage equipment (typically from 1 to 250 KV) like feeder, transformer, motor and generator against faults, (short circuit, over load …) 24h per day, for 10 years of continuous operations in Europe" (p. 2). The weight of the relay is ca 4,9 kg without packaging, and the rated power is assumed to be 8,89 W. This EPD has been verified by an accredited third party, and a summary of the impact assessment results is found in table 5.

**Table 5. LCIA results for the Easergy P3F30 relay by Schneider Electric** (2017a)**.**

| Impact indicators | Unit | Total | Manufacturing | Distribution | Installation | Use | End of Life |
|---|---|---|---|---|---|---|---|
| Contribution to mineral resources depletion | kg Sb eq | 3,06E-02 | 3,06E-02 | 0* | 0* | 3,32E-05 | 0* |
| Contribution to the soil and water acidification | kg $SO_2$ eq | 1,92E+00 | 3,20E-01 | 3,19E-03 | 0* | 1,59E+00 | 2,04E-03 |
| Contribution to water eutrophication | kg $PO_4^{3-}$ eq | 1,65E-01 | 6,75E-02 | 7,35E-04 | 3,94E-05 | 9,61E-02 | 8,78E-04 |
| Contribution to global warming | kg $CO_2$ eq | 5,24E+02 | 1,40E+02 | 6,99E-01 | 0* | 3,82E+02 | 2,54E+00 |
| Contribution to ozone layer depletion | kg CFC11 eq | 5,20E-05 | 2,71E-05 | 0* | 0* | 2,49E-05 | 9,58E-08 |
| Contribution to photochemical oxidation | kg $C_2H_4$ eq | 1,13E-01 | 2,53E-02 | 2,28E-04 | 0* | 8,75E-02 | 1,82E-04 |

However, it is critical to note that the results are not comparable between the Relion 615 series by Liimatainen (2012), the REF 541/543/545 relays by ABB (2006), and the

Easergy P3F30 relays by Schneider Electric (2017a). In fact, the first two studies do not even provide any functional unit, nor have they adopted any PCR. More importantly, LCA results can only be fully compared through a comparative assertion according to ISO 14040 and ISO 14044, for which additional requirements apply. Still, a common finding for all studies is that the use stage has the highest impacts, followed by the manufacturing stage, in most impact categories.

While the number of publicly available LCA studies and EPD's are limited for medium voltage protection relays, there are plenty of other LCA studies available. Subramanian & Yung (2016) conducted a literature review on LCA studies for various consumer electronic products. The authors reviewed a total of 134 journal articles and then organized the LCA studies into 10 main product categories including computers, mobile phones, and televisions. For computer related studies, the authors found that the use phase and the manufacturing stage were the most impactful life cycle stages. However, there is a contradiction in the literature which of the two has a higher impact. Discrepancies are also noted due to differences in functional units, usage, and assumptions.

Andersen et al. (2014) also compared several existing LCA studies for various electronic products. When comparing the global warming potential for mobile phones, the authors found that the manufacturing stage is the most impactful life cycle stage. On the other hand, when comparing laptop computers, the use stage is sometimes more impactful. The authors also found great inconsistencies between the studies; however, the degree of comparability between the selected studies is not addressed.

Similarly, Subramanian & Yung (2017) conducted a comparative study for desktop computers versus all-in-one computers. The authors used the SimaPro software with the ecoinvent v2.2 database, and the selected LCIA method was ReCiPe. As a result, the authors found that the use stage clearly has a higher impact, even when comparing different use case scenarios. The degree of comparability in this study is higher than in the one by Andersen et al. (2014), because the authors have used similar functional units and methods for both products. The authors also reckon that more detailed data is necessary for a more effective comparison.

Based on these findings, the use stage typically has the most significant impacts for a medium voltage protection relay, followed by the manufacturing stage. This is sometimes also true for computers, but there is a contradiction in the literature about which stage is more significant (Subramanian & Yung, 2016). Moreover, the modelling of the use stage for computers is not always obvious as it largely depends on how the user uses the device and how often (Subramanian & Yung, 2017). On the other hand, the use stage of relays is perhaps more straight forward to model since it can be assumed that they are always powered on in a standby mode (Schneider Electric, 2017a). The manufacturing stage is less dynamic but is instead largely affected by the quality of the data. According to Teehan & Kandlikar (2012), it is especially the production of integrated circuits and printed circuit boards that can contribute heavily to the results.

# 4 Methodology

This research is a case study, commissioned by ABB ELDS Vaasa, that adopts a standardized methodology called life cycle assessment (LCA) according to ISO 14040:2006 and ISO 14044:2006. The nature of the research is descriptive, and the method is based on mixed methods. This chapter describes and justifies the research methodology. The first section presents the research questions as well as the research design and approach. The following section discusses the data collection and how it was analysed. The last section discusses how the reliability and validity of the research were assessed.

## 4.1 Research design and approach

The purpose of this study was to address the needs of the case company for new LCA's and EPD's for their medium voltage protection relays, while also contributing to the literature. Two primary goals were defined: 1) to conduct an LCA study of ABB's Relion 615 series of relays and 2) to develop a compliant EPD based on the results. Accordingly, one primary research question and two secondary research questions were defined:

- "What are the potential environmental impacts of a medium voltage protection relay throughout its life cycle?"
    - "What are the most impactful life cycle stages and processes?"
    - "How can the most significant impacts be largely reduced?"

The research was designed as a case study in which an LCA was conducted for a selected product series by a case company, namely, the Relion 615 series by ABB. A case study can be defined as an in-depth exploration of a particular issue in a real-world context (Simons, 2009). LCA studies are case studies by nature, and they can also be used for comparative assertions (Heijungs et al., 2009). Moreover, the nature of this research can be considered descriptive because the main purpose was to describe a phenomenon using "what" and "how" questions (Saunders et al., 2016). In addition, since this was studied in a real-world context, it can be considered a descriptive case study (Yin, 2014).

The LCA study was conducted according to the international standards ISO 14040:2006 and ISO 14044:2006, and the choice of system modelling approach was attributional due to the goal and scope. Because the LCA was conducted for an EPD, ISO 14025:2006 also applies, which requires adopting a PCR with additional guidelines and requirements. The PCR adopted was EPDItaly007, which is based on the European standard EN 50693:2019, because this is the PCR the case company has decide to use for all LCA's of their medium voltage protection relays.

While the research approach was limited to the requirements of the case company, LCA is according to Klöpffer et al. (2014) "the only internationally accepted standardised method for analysing environmental aspects and potential impacts of product systems" (p. 17). Furthermore, the methodology is flexible and can be adopted in a variety of ways. ISO 14040:2006 explicitly states that "there is no single method for conducting LCA" (p. 9). A priority of scientific approach is yet provided (p. 7):

> *"Decisions within an LCA are preferably based on natural science. If this is not possible, other scientific approaches (e.g. from social and economic sciences) may be used or international conventions may be referred to. If neither a scientific basis exists nor a justification based on other scientific approaches or international conventions is possible, then, as appropriate, decisions may be based on value choices."*

This means, an LCA can be conducted using both quantitative and qualitative methods, and this is also suggested by Heijungs et al. (2009). The main difference is that quantitative research deals with measurable, numeric data; qualitative research deals with non-numeric data such as words and meanings (Saunders et al., 2016). ISO 14044:2006 still suggests that both quantitative and qualitative data is necessary in an LCA, and according to Hochschorner & Finnveden (2003), "it is not possible to quantify everything, so qualitative data and estimations are therefore necessary to create a comprehensive picture even in a quantitative LCA" (p. 119).

This research was based on both quantitative and qualitative data and methods, and thus it can be considered mixed methods research (Saunders et al., 2016). More specifically, because it was designed as a case study, it can be considered mixed methods case study research (Creswell & Plano Clark, 2018). On one hand, the core analysis was quantitative based on large amounts of numeric data using a state-of-the-art LCA software and database. On the other hand, it also included qualitative elements; for example, the selection of background processes in the LCA software was based on a qualitative assessment of technical drawings and documents for each part and component of the relay regarding type of material, production process, and surface treatment. The data quality was also assessed and characterized by both qualitative and quantitative aspects as required by ISO 14044:2006 (p. 10).

## 4.2 Data collection and analysis

Both qualitative and quantitative data was collected and analysed in this research. This section gives a brief overview of the data while further details are found in chapter 5. The data was analysed using the LCA software SimaPro 9.3.0.2, and the data was collected from the following sources:

1. **SAP** – the case company's enterprise resource planning system: From here, the bill of materials (BOM) of individual relay configurations were extracted. The level of detail in these BOM's were low as they only tell which hardware modules, packaging materials, and accessories that are used in the final assembly.
2. **GreenData Manager (GDM)** – a software used by the case company for managing environmental compliance data and documents: From here, more detailed BOM's were extracted for each hardware module. The level of detail in these BOM's were higher as they include the assembly hierarchy, quantity, weight, and primary supplier for even the smallest parts and sub-assemblies.
3. **SmarTeam** – the case company's product data management system: From here, technical drawings and documents were extracted for each part and sub-assembly. This allowed to obtain information related to material types, production processes, surface treatments, and surface areas.
4. **Ecoinvent database v3.8** – a life cycle inventory database: All background data used in the LCA were obtained from this database.

5. **Internet:** Road and ferry transport distances between indirect suppliers, direct suppliers, and ABB's production plants were estimated using Google Maps. Air transport distances were estimated using the website www.distance.to.
6. **Employees within the company:** Data about ABB's utility consumption and waste generation were provided by contact persons in various managerial positions. The treatment of incomplete data was consulted, when necessary, with people in both managerial and expert positions.

## 4.3 Reliability and validity

The reliability and validity of this research were assessed according to the requirements of ISO 14040:2006 and ISO 14044:2006 as well as the PCR EPDItaly007. Both of these are important aspects to the quality of the research (Saunders et al., 2016). The reliability and validity were specifically assessed through the following measures:

- **Completeness check**: A qualitative assessment to ensure that the data and information were sufficient for reaching conclusions according to the goal and scope.
- **Sensitivity check**: A sensitivity analysis to determine how changes in data and assumptions affected the final impacts. This was also important for the iterative process of improving data quality. However, no comprehensive uncertainty analysis was conducted because it is not required by the PCR.
- **Consistency check**: A qualitative assessment to ensure that data, assumptions, and methods were consistent and according to the goal and scope.
- **Data quality assessment**: The data quality was assessed and characterized by both quantitative and qualitative aspect, as required by ISO 14044:2006. However, due to confidentiality reasons, the assessment is not publicly disclosed.
- **Internal review**: Because the main intended application was for an EPD, the study must be independently verified according to ISO 14025:2006 and the adopted PCR. To prepare for the verification, an internal review was conducted with some of ABB's own multidisciplinary LCA experts. However, due to time

limitations, the verification was not completed when this thesis is submitted. Thus, the results are subject to change from the official EPD.

Nevertheless, a highly structured methodology is essential to facilitate replication, and this is important to ensure reliability of the research (Saunders et al., 2016). Due to the complex nature of LCA, transparency is also critical according to ISO 14040:2006. In fact, the PCR EPDItaly007 requires a comprehensive LCA report according to the European standard EN 50693:2019. Accordingly, a dedicated LCA report was developed; however, this report contains confidential information and is not disclosed to the public. Instead, the LCA is described in detail in chapter 5, following a similar structure of the LCA report, in which confidential information has been excluded.

# 5 Life cycle assessment study

This LCA study is conducted according to the international standards ISO 14040:2006 and ISO 14044:2006 for LCA as well as ISO 14025:2006 for EPD. ISO 14025 also requires developing or selecting a PCR when conducting an LCA for an EPD, and in this assessment, EPDItaly007 by the program operator EPDItaly is selected as PCR. EPDItaly007 is based on the European standard EN 50693:2019, and the case company has decided to use this PCR for all medium voltage relays. In terms of LCA software, SimaPro 9.3.0.2 is used with the database Ecoinvent v3.8, because this is what the case company currently uses and has licenses for. The modelling approach is attributional; thus, the ecoinvent system model "allocation, cut-off by classification" is used. Finally, the impact assessment method is conducted according to the standard EN 15804:2012+A2:2019, as required by EPDItaly007. This chapter explains each step of the LCA in detail, following a similar structure as the LCA report. However, confidential information is excluded.

## 5.1 Part 1: Goal and scope

This section concerns the first phase of the LCA, that is, the defining of the goal and scope. The goal in this LCA is to assess the potential environmental impacts of the Relion 615 series of medium voltage protection relays based on two selected, representative product configurations. The main intended application is for an EPD based on the PCR EPDItaly007, and the selected EPD type is "the average manufacturing of a product at different plants, by a specific manufacturer" according to EPDItaly (2020b). The purpose is to produce a compliant and verified EPD for the Relion 615 series, in order to satisfy the requests of the case company's customers, that is, the main intended audience. However, results are also interpreted to identify environmental hotspots and improvement opportunities for the case company.

Finally, the study is internally reviewed by some of ABB's own multidisciplinary LCA experts. However, due to time limitations, the official verification is completed after this thesis is submitted. Thus, the results are subject to change from the official EPD.

### 5.1.1 Product family and reference products

The product family in the scope of this LCA is the Relion 615 series of relays of medium voltage protection relays (see figure 14). The 615 series are used in utility, industrial, and transport and infrastructure applications for protection, control, measurement, and supervision of power systems (ABB, 2019).

**Figure 14. The Relion 615 series of relays.** (ABB, 2019)

The 615 series include the following relays: RED615 for line differential protection, REF615 for feeder protection, REG615 for generator protection, REM615 for motor protection, RET615 for transformer protection, REU615 for voltage protection, and REV615 for capacitor bank protection (ABB, n.d.-d). The relays are available in ready-made configurations but can also be tailored to meet customer specific requirements (ABB, 2019). An overview of the general technical specifications according to the technical manual is found in table 6 and table 7.

**Table 6. Dimensions and weights of the Relion 615 series.** (ABB, 2018b)

| Description | Value | |
|---|---|---|
| Width | Frame | 177 mm |
| | Case | 164 mm |
| Height | Frame | 177 mm |
| | Case | 160 mm |
| Depth | | 201 mm |
| Weight | Complete relay | 4,1 kg |
| | Plug-in unit only | 2,1 kg |

**Table 7. Rated voltage and nominal power of the Relion 615 series.** (ABB, 2018b)

| | Power supply, type 1 | Power supply, type 2 |
|---|---|---|
| Nominal auxiliary voltage Un | 100, 110, 120, 220, 240 V AC, 50 and 60 Hz | 24, 30, 48, 60 V DC |
| | 48, 60, 110, 125, 220, 250 V DC | |
| Burden of auxiliary voltage supply under quiescent (Pq) / operating condition | AC < 16,0 W (nominal) / 21,0 W (max.) | DC < 13,0 W (nominal) / 18,0 W (max.) |
| | DC < 13,0 W (nominal) / 18,0 W (max.) | |

Relion 615 relays are highly configurable in terms of in both hardware and software, depending on the required functions by the customer (ABB, 2013, 2015, 2018b). The configurations are distinguished by ordering codes, and these can be selected in ABB's product selection tool (see figure 15). Thus, the ordering code determines the specific functions of a relay, which means the exact combination of hardware and software.

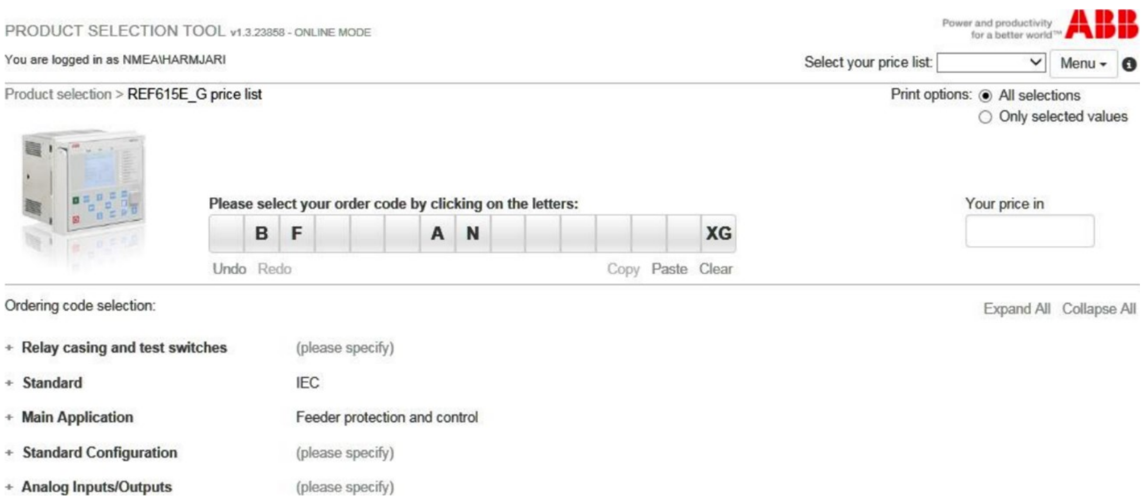



**Figure 15. ABB's product selection tool.** (ABB, 2015)

According to the technical manual by ABB (2018b), the 615 series yet offer the same main functions and are built on the same underlying technology. More specific functions, such as arc protection and autoreclosing, depend on the product configuration and application. The ordering code system that is explained in the REF615 product guide by ABB (2013) indicates over thousands of different ordering code combinations (p. 73). However, the number of possible hardware configurations is certainly less.

The configurable nature of the product implies that there can be significant variations in terms of both weight and power consumption. In turn, this can contribute to significant variations in the environmental impacts within the series. Two representative relay configurations are therefore selected by the case company as reference products for the LCA: 1) HBFCACABNNA1BNN11G and 2) HBFNAEAGNEA1BNA11G. Configuration 1 is a minimum version in terms of hardware, which has three module slots empty. Configuration 2 is a maximum version in terms of hardware, which has all module slots filled. (See table 8)

**Table 8. Representative product configurations selected for the LCA study**

| **Slot** | **Module** | **Reference product 1 (Minimum hardware)** | **Reference product 1 (Maximum hardware)** |
|---|---|---|---|
| X000 | Communication module | - | COM0037 |
| X100 | Power supply module | PSM0004 | PSM0004 |
| X110 | Binary input/output module | - | BIO0005 |
| X120 | Analogue input module 1 | AIM0016 | AIM0016 |
| X130 | Analogue input module 2 | - | AIM0006 |
| XBPL | Backplane module | BPL0001 | BPL0001 |
| XCPU | CPU module | CPU0007 | CPU0007 |
| XDIS | Display module | DIS0012 | DIS0012 |
| **Product ID** | | REF615E_1G | REF615E_1G |
| **Product Version** | | 5.0 FP1 | 5.0 FP1 |
| **Average nominal power (measured)** | | 5 W | 9,5 W |
| **Weight (excl. packaging)** | | 3,7 kg | 4,1 kg |
| **Ordering code** | | HBFCACABNNA1BNN11G | HBFNAEAGNEA1BNA11G |

The nominal power consumptions are physically measured for both configurations by the case company's research and development department. However, the presented weights are the results of the LCA. These are 3–4 % higher than the relays' actual weights, and this is due to uncertainties in the data. Nevertheless, by assessing two different but representative reference products, it is possible to establish extrapolation rules according to EN 50693:2019. The extrapolation rules are provided together with the results in chapter 6.6.

### 5.1.2 Functional unit

The functional unit is a defined quantification of a products performance as a unit of reference (International Organization for Standardization, 2006b). The main functions of all relays within the scope of the EPD are the same: Protection, control, measurement, and supervision of power systems (ABB, 2018b). The functional unit is defined as the following:

> *"a single medium voltage protection relay, which protects a power system against faults such as short circuit and overload, during a service life of 10 years and with a use rate of 100 %, including related accessories and packaging."*

A use rate of 100% is assumed because under normal operational circumstances, the relay is always powered on in a "normal mode" (ABB, 2018b, p. 463). Thus, variations in power consumption from other modes are considered negligible. The functional unit is defined so that it is consistent with some of the most recent EPD's by ABB (2021a, 2021b) and compliant with EPDItaly007 and EN 50693:2019.

Note, the reference service life (RSL) of 10 years is a theoretical period selected for calculation purposes only. This is not representative for the minimum, average, nor actual service life of the product. EPDItaly007 and EN 50693:2019 do not provide any specific values to be used. This was selected because an RSL of 10 years is suggested for active products that "consume energy for their main function" in a corresponding PSR titled *PSR0005 - Electrical switchgear and controlgear solutions* by P.E.P. Association (2016). Thus, the choice of RSL is aligned with others in the industry.

### 5.1.3 System boundaries and life cycle stages

According to EPDItaly007, the installation method of the product determines which standard to refer to for defining the system boundaries. Because the Relion 615 series of relays are easily removed or replaced according to the installation manual by ABB (2018a), the system boundaries are defined according to EPDItaly007, which is based on EN 50693:2019. The product system considers the entire value chain from cradle to grave, including both upstream, core, and downstream activities (see figure 16):

- The upstream manufacturing stage: This includes the acquisition of raw materials as well as production and transportation of semifinished parts, components, and subassemblies from both direct and indirect suppliers to ABB.
- The core manufacturing stage: This includes the final assembling and testing at ABB's manufacturing sites. It also includes the utility consumptions and the waste generated at the sites as well as the production and use of packaging materials.
- The distribution stage: This includes all activities related to the distribution and transportation of the final product to the site of installation.
- The installation stage: This includes the end of life of the packaging materials.
- The use stage: This includes the power consumption throughout the reference service life of the product.
- The end-of-life stage: This includes all activities related to waste treatment and disposal of the product at the end of its service life.

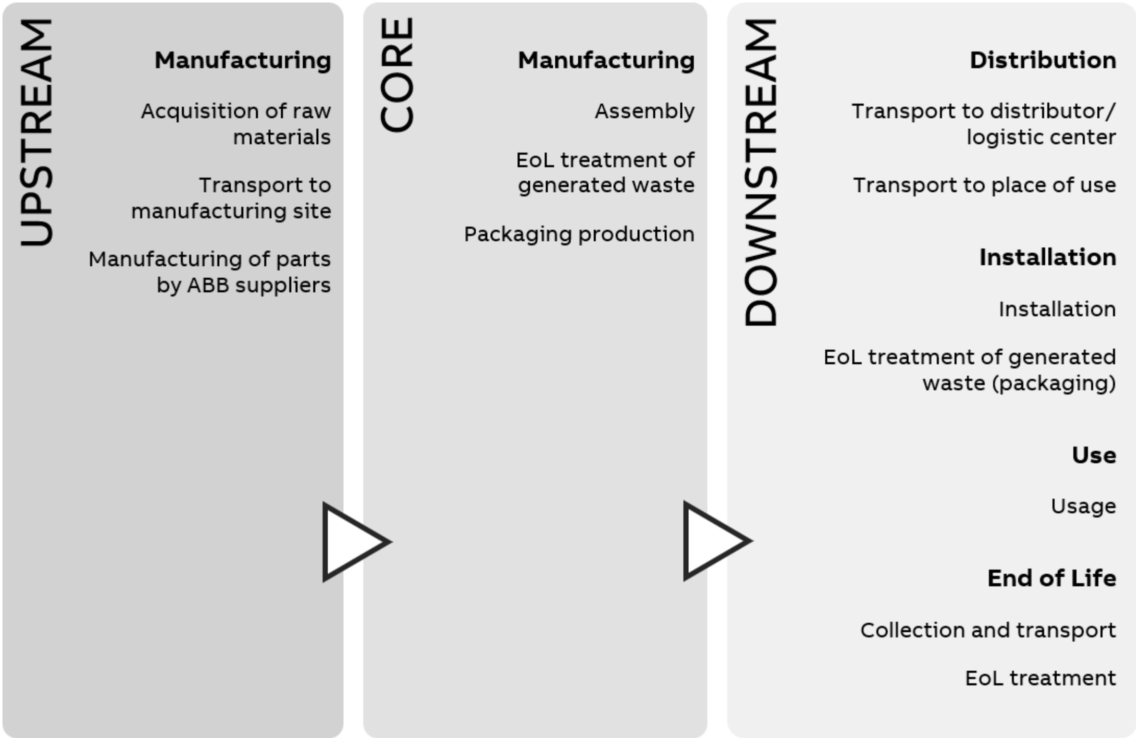



**Figure 16. Life cycle stages of the LCA according to EPDItaly007.** (ABB, 2021b)

### 5.1.4 Temporal and geographical boundaries

In terms of temporal boundaries, all primary data collected from ABB are from 2021, which is considered a representative year for the company. Secondary data are provided by ecoinvent v3.8, which was also released in 2021.

In terms of geographical boundaries, the materials and components used in the production of the Relion 615 relays are globally sourced. The supply chains are often complex and can extend across multiple countries and continents. Therefore, background processes with global representativeness are selected from ecoinvent due to the unclear origin of each material. Thus, a conservative approach is adopted.

Furthermore, the Relion 615 relays are produced in three different geographical locations (i.e., Finland, India, and China), and this is also accounted for. Each plant is modelled separately based on the primary data available. Background processes with matching geographical representativeness are selected accordingly from ecoinvent. A weighted average is then used in the LCA, according to the production volumes from 2021. A weighted average is also used for the transportation distances between all direct suppliers and ABB's three production plants, and the same approach is also adopted to account for the differences in the packaging materials used.

### 5.1.5 Exclusions from the system boundary

In accordance with EPDItaly007 and EN 50693:2019, capital goods such as machinery, tools, buildings, infrastructure, packaging for internal transports, and administrative activities, which cannot be allocated directly to the production of the reference product, are excluded. However, what is automatically included in the background processes from the ecoinvent database are not excluded.

### 5.1.6 Data quality

Both primary and secondary data are used. The main sources for primary data are the bill of materials (BOM) as well as technical drawings and documents. This is mainly extracted from: 1) SAP – the enterprise resource planning system, 2) GreenData Manager (GDM) – a software used for managing environmental compliance data and documents, and 3) SmarTeam – the product data management system. Site specific foreground data for the production plant in Finland are mainly provided by the Production Manager and the Health, Safety & Environment (HSE) Manager. Site specific foreground data for the production plants in India and China are provided by contact persons of respective plant.

For all other processes for which primary data are not available, generic data from the ecoinvent v3.8 database is used. The ecoinvent database is available in SimaPro 9.3.0.2, which is the LCA software used for the calculations. The treatment of occasional incomplete data is documented separately and consulted with employees of the case company in various managerial and expert positions.

### 5.1.7 Allocation rules

The utility consumption and waste generation of ABB's production plants are allocated to the production of one relay by using allocation rules. Because all plants are focused on relay production, the total utility consumption and waste generation for 2021 is simply divided by the total output of relays during the same year. This means, utility consumption and waste generation deriving from offices and administrative activities are not excluded, because it is not possible to accurately allocate the inventory only for the production. Thus, a conservative approach is adopted. Finally, each production plant is modelled separately in the LCA, after which a weighted average is adopted according to the production volumes from 2021.

Concerning the allocation procedures related to waste and recycling activities, the *Polluter Pays* principle is adopted as required by EPDItaly007. The ecoinvent system model "allocation, cut-off by classification" is therefore applied in the LCA as it is based on the same principle (ecoinvent, n.d.). For recyclable materials, this means they are available burden-free to recycling at the end-of-life stage. The use of recycled materials instead bears the impacts of the recycling efforts. The same approach has likewise been adopted in some of the recent EPD's by ABB (ABB, 2021a, 2021b). Note, the system model "Allocation, cut-off, EN 15804" is also based on the Polluter Pays principle, but with different cut-off points (ecoinvent, n.d.). However, this is not applicable in this LCA, because EN 15804 only applies to products that are permanently installed in buildings and which cannot be separated (EPDItaly, 2020a).

### 5.1.8 Cut-off criteria

The PCR EPDItaly007 does not provide any details about cut-off criteria; it refers to chapter 4.2.3.3 in the standard EN 50693:2019. According to EN 50693:2019, the cut-off criteria can be set to a maximum of 5 % of the overall environmental impacts given by the LCIA results. The standard also suggests developing and adopting more detailed cut-off criteria in a PSR. However, in this case, a more specific PSR is not available.

Due to vague guidelines and requirements provided by the PCR EPDItaly007 and the standard EN 50693:2019, only stickers have been excluded as they are considered negligible to the overall environmental impacts. Thus, a conservative approach is adopted.

## 5.2 Part 2: Life cycle inventory analysis

This section concerns the second phase of the LCA, that is, the life cycle inventory analysis (LCI). More specifically, it describes the collection of data as well as the modelling in SimaPro. Each life cycle stage is addressed separately and with respect to the requirements provided by the PCR EPDItaly007 and the standard EN 50693:2019.

A bill of materials (BOM) is essentially a list of all the parts and components used in a product assembly; thus, it serves as a basis for identifying all materials and processes in the manufacturing stage. A master BOM is first extracted from SAP which includes a list of all hardware modules used in the final assembly as well as the related accessories and packaging materials. More detailed BOMs are then extracted separately from GDM for each module. The BOMs are organized in hierarchy levels, and each item is matched with its material code, quantity, weight, and name of the primary supplier. The level of detail is such that every single component that is mounted on the printed wiring boards (PWB), including resistors and transistors, are distinguished with specific weights provided. Mechanical assemblies are also typically divided into the smallest parts with specific weights provided.

Additional data are manually added to the BOM's regarding the manufacturing process, type of material, surface area, and surface treatments. Generally, this information is obtained from technical drawings and documents from GDM and SmarTeam. Furthermore, road and ferry distances between indirect suppliers, direct suppliers, and ABB are obtained from Google Maps. Air distances are instead obtained from www.distance.to, and a distance correction of 95 km is added as suggested by the European standard EN 16258:2012.

### 5.2.1 Manufacturing stage

The manufacturing stage is modelled in two parts according to the PCR EPDItaly007: The upstream manufacturing stage and the core manufacturing stage. The upstream manufacturing stage is first modelled according to the BOM's. The core manufacturing stage is then modelled according to the site-specific data provided by ABB.

The constituent materials are presented with the results in chapter 6. Steel and electronics are the most frequently used materials, followed by aluminium and polycarbonate. The following types of steels are mainly used from ecoinvent: "Steel, low-alloyed {GLO}| market for" and "Steel, chromium steel 18/8 {GLO}| market for". A custom alloy is created based on primary data for the aluminium, because the impacts vary significantly between the alloys available from ecoinvent. To account for the production efforts of mechanical parts, "metal working, average"-processes are most commonly used, followed by "injection moulding" and "wire drawing"-processes.

The printed wiring boards (PWB) are modelled on a component level. Empty PWB's are first modelled as "printed wiring board, for surface mounting, PB free surface {GLO}| market for". Every single component, such as resistors, transistors, etc., is then categorized and grouped into the most corresponding processes found in ecoinvent. Finally, the production efforts are accounted for by using the process "Mounting, surface mount technology, Pb-free solder {GLO}| market for". Because primary data are available, the soldering material is excluded from the ecoinvent's mounting process and added separately with specific weights. Also, due to the high impacts of gold, primary data are used to model the specific amounts of gold used in each connector.

The transport distances of raw materials to the manufacturing site of the first known supplier in the supply chain are assumed to be included in ecoinvent's "market for"-processes. Additional transport between indirect suppliers, direct suppliers, and ABB's production plants are then added separately. The following rules are adopted:

- Only the transport distances from and between primary suppliers are considered. Secondary suppliers are not considered due to the complexity of modelling.
- Intracontinental transports are assumed to be by road and ferry, and the distances are obtained from Google Maps.
- Intercontinental transports are assumed to be by air, which is the most conservative option, and the distances are found from www.distance.to. A distance correction of 95 km is added as suggested by the European standard EN 16258:2012. Road transport distances are also added between the manufacturing sites and the airports according to Google Maps.
- If a supplier is an international broker, the transport is assumed to be by road from the closest warehouse. Additional transports within the supply chain are assumed to be already included in ecoinvent's "market for"-processes.
- A weighted average is calculated separately for each direct supplier to ABB's three production plants.

Then, for the core manufacturing stage, all data about utility consumption and waste generation are first aggregated into separate Excel-files for each plant. The plants are then modelled separately in the LCA, after which a weighted average is adopted according to the production volumes from 2021. The packaging materials and accessories associated with the products are also included in the study. Table 9 compares the greenhouse gas (GHG) emissions per kWh for the energy mixes used by each plant.

**Table 9. GHG emissions per kWh for the energy mixes used by each ABB plant (EN 15804:2012+A2:2019 method, GWP indicator).**

| Electricity mix | Data source | Amount | Unit |
|---|---|---|---|
| ABB FI – custom: 50 % wind + 50 % hydro | Ecoinvent v3.8 | 0,0259 | kg CO2-eq/kWh |
| ABB IN – custom: 98,5 % national energy mix + 1,5 % photovoltaic | Ecoinvent v3.8 | 1,36 | kg CO2-eq/kWh |
| ABB CN – 100 % national energy mix | Ecoinvent v3.8 | 1,05 | kg CO2-eq/kWh |

### 5.2.2 Distribution stage

The relays are generally delivered directly to the customer, and the most common type of transport is by road and air. ABB does not have any additional distribution centres. The relays are neither repacked throughout the distribution stage.

A distribution scenario is developed for the LCA based on delivery statistics from the plant in Finland from 2021. However, the data only tells the means of transport between the country of origin and the country of destination. Therefore, the distances are estimated using the following approach:

- In the cases of air transports or road and air combined, it is first assumed that the relay is transported 370 km domestically by air from Vaasa to Helsinki. The remaining air transports from Helsinki to each capital of the destination countries are then added. All air distances are taken from www.distance.to. A distance correction of 95 km is added as suggested by the European standard EN 16258:2012. Finally, an additional 300 km road transport is assumed to the site of installation.
- In the cases of road transport exclusively, it is assumed that the relay is transported directly from Vaasa, Finland, to the capital of the destination country. The distances are taken from Google Maps. An additional 100 km sea transport with ferry is assumed, except when the destination country is Finland.

Note, the scenario is exclusively based on delivery data from the production plant in Finland. Yet, it is considered a conservative approach because the relays sold from Finland are sold globally while the relays sold from India and China are sold domestically.

### 5.2.3 Installation stage

The installation phase only requires manual work; no energy is consumed. Therefore, this phase in the LCA includes the end-of-life of the packaging materials and manuals that are discarded after installation.

Statistical data are adopted from Eurostat (2018) to create an end-of-life scenario, which is representative for Europe (see table 10). A transport distance of 100 km is assumed because the actual location of disposal is unknown.

**Table 10. End-of-life scenario for packaging materials and accessories.** (Eurostat, 2018)

| **Material** | **Recycling** | **Incineration with energy recovery** | **Incineration without recovery** | **Landfill** |
|---|---|---|---|---|
| Paper and cardboard | 99 % | 1 % | 0 % | 0 % |
| Plastic | 74 % | 19 % | 1 % | 6 % |
| Wood | 46 % | 49 % | 4 % | 1 % |

### 5.2.4 Use stage

The use phase considers the power consumption over the reference service life of 10 years as defined in the functional unit. A use rate of 100 % is assumed because under normal operational circumstances, the relay is always powered on in a normal mode. Variations in power consumption from other modes are therefore considered negligible. Finally, because this product is sold globally and is not limited to any specific country, the latest energy mix of the European Union is adopted as suggested by the standard EN 50693:2019 (see table 11).

**Table 11. GHG emissions per kWh for the European energy mix (EN 15804:2012+ A2:2019 method, GWP indicator).**

| **Electricity mix** | **Data source** | **Amount** | **Unit** |
|---|---|---|---|
| European energy mix | Ecoinvent v3.8 | 0,40 | kg CO2-eq/kWh |

Maintenance is not considered because the Relion 615 does not have any required maintenance within its service life. There is no planned or preventive maintenance for this product. The only maintenance that is performed is corrective maintenance if, for example, something breaks or stops working. However, corrective maintenance is unusual, and thus considered negligible.

### 5.2.5 End-of-life stage

The end-of-life stage for the reference product is modelled according to the guidelines provided in the technical report IEC/TR 62635 by the International Electrotechnical Commission (2012). This is because EPDItaly007 refers to EN 50693:2019, and according to EN 50693:2019, an end-of-life scenario should be modelled according to the selected PSR. However, if no PSR is available, a representative scenario should be defined. As an example, EN 50693:2019 (Annex F) suggests adopting the guidelines by IEC/TR 62635, and this is also adopted in some of the most recent EPD's by ABB (2021a, 2021b).

More specifically, the percentages between recycling, incineration, and landfill are adopted from example 2 in Annex D by G-SCOP Laboratory in IEC/TR 62635:2012 (pp. 29–30). This is because the data in example 2 has European representativeness while example 1 has Korean representativeness. European representativeness is also used in the end-of-life scenario for the packaging waste, and for the electricity used in the use phase. In addition, it is assumed that all parts go through a separation process; thus, a conservative approach is adopted. Corresponding processes are selected from ecoinvent for each waste type and waste treatment. The recycling processes are burden free due to the adopted system model. Finally, the transport distances from the place of use to the site of disposal are assumed to be 100 km because the actual location of disposal is unknown. The end-of-life scenario is presented in table 12.

**Table 12. End-of-life scenario for the product, adopted from IEC/TR 62635 (Annex D.3)**

| Material | Table | Recycling | Incineration (energy recovery) | Landfill |
|---|---|---|---|---|
| Electronics (PWB – intermediate) | D.5 | 17 % | 43 % | 40 % |
| Cables (cable, low current) | D.5 | 24 % | 0 % | 76 % |
| Recyclable polymers (PP, PP+EPDM, PP-GF, PE) | D.8 | 90 % | 1 % | 9 % |
| Non-recyclable polymers (all other polymers except ABS and HIPS) | D.8 | 0 % | 5 % | 95 % |
| Steel | D.8 | 94 % | 0 % | 6 % |
| Aluminium | D.8 | 91 % | 0 % | 9 % |
| Copper | D.8 | 85 % | 0 % | 15 % |
| Other non-ferrous metals | D.8 | 70 % | 0 % | 30 % |

## 5.3 Part 3: Life cycle impact assessment

This section concerns the third phase of the LCA, which is the life cycle impact assessment (LCIA) phase. The impact assessment is conducted according to the standard EN 15804:2012+A2:2019, as required by the PCR EPDItaly007. The results are divided into three categories: (1) *Core environmental impact indicators*, which concerns for example climate change and ozone depletion, (2) *Parameters describing resource use*, which concerns for example the net use of fresh water and non-renewable primary energy resources, and (3) *Parameters describing waste production*, which concern for example the amount of hazardous and non-hazardous waste disposed. All impact assessment results are presented in tables in appendix 1 and 2. However, only the most important findings are presented in chapter 6 together with the other results.

## 5.4 Part 4: Interpretation of results

This section concerns the fourth and final phase of the LCA, which is the interpretation phase. The results have been interpreted iteratively throughout the entire study, until the overall data quality have been considered sufficient according to the goal and scope. The results are presented in chapter 6, together with an evaluation of the reliability and validity. Finally, the conclusions, limitations, and recommendations are presented in chapter 7.

# 6 Results

In this chapter, the results of the LCA study are presented. These are not only used for later developing an EPD, but they are also interpreted to identify environmental hotspots and improvement opportunities. First are the constituent materials of the reference products presented, then the recyclability potentials, and finally key findings from the impact assessment results and a process contribution analysis. The complete impact assessment results are found in appendix 1 and 2. The results can be extrapolated for other relay configurations according to the extrapolation rules provided in chapter 6.6.

## 6.1 Constituent materials

Table 13 and table 14 present the constituent materials of reference product 1 and reference product 2. Steel, low-alloyed steel in particular, and electronics are the most frequently used materials, followed by aluminium and polycarbonate. Due to the complex nature of the electronics, these are presented as a separate category which includes printed wiring boards, electronic components, connectors, and cables. Electronics are typically composed of various plastics, copper, and precious metals.

**Table 13. Constituent materials of reference product 1 (min. hardware).**

| Materials | Name | Weight [kg] | Weight % |
|---|---|---|---|
| Plastics | Polycarbonate | 0,36 | 10 |
| Metals | Steel, low-alloyed | 1,02 | 28 |
| | Steel, stainless steel | 0,23 | 6 |
| | Aluminium | 0,58 | 16 |
| | Other metals | 0,18 | 5 |
| Others | Electronics (PWB’s, components, connectors, cables) | 1,23 | 33 |
| | Others | 0,08 | 2 |
| Total | | 3,68 | 100 |

**Table 14. Constituent materials of reference product 2 (max. hardware).**

| Materials | Name | Weight [kg] | Weight % |
|---|---|---|---|
| Plastics | Polycarbonate | 0,36 | 9 |
| Metals | Steel, low-alloyed | 0,98 | 24 |
| | Steel, stainless steel | 0,24 | 6 |
| | Aluminium | 0,58 | 14 |
| | Other metals | 0,20 | 5 |
| Others | Electronics (PWB’s, components, connectors, cables) | 1,68 | 41 |
| | Others | 0,08 | 2 |
| Total | | 4,11 | 100 |

Note, the weights are the result of the LCA. The relays and each sub-assembly have also been weighed separately to ensure that the LCA is consistent with the actual weights. The final weight difference was only 3–4 %, and the LCA is on the conservative side. No obvious error was found, and the difference is likely due to uncertainties in the data.

## 6.2 Recyclability potential

The recyclability potentials of the reference products are presented in table 15. This is calculated in SimaPro based on the end-of-life scenario adopted from IEC/TR 62635, Annex D, example 2, which is representative for Europe. The scenario is based on the rates given for materials that go through a separation process, and thus a conservative approach is adopted. The recyclability potential is higher for reference product 1, and this is because the portion of electronics is lower while the portion of metals and plastics are higher.

**Table 15. Recyclability potentials of the reference products.**

| Product | Recyclability potential |
|---|---|
| Reference product 1 (min. hardware) | 56 % |
| Reference product 2 (max. hardware) | 51 % |

## 6.3 Impact assessment

In this section, the most important findings of the impact assessment are presented. The complete results are found in appendix 1 and 2. Figure 17 and figure 18 compare the total impacts per life cycle stage for both reference products. The most contributing life cycle stage is the use stage, which contributes to roughly 2/3 of the total impacts in most impact categories. In fact, the total impact, over a service life of 10 years, is 59–66 % on climate change. Similar figures also show for other impact categories. Exceptions include resource use of minerals and metals and hazardous waste disposed, which are only a few percentages of the total impact. The second most contributing life cycle stage is the upstream manufacturing stage. This stage contributes to roughly 1/3 of the total impacts in most impact categories. Exceptions include resource use of minerals and metals (82–86 %) and hazardous waste disposed (98–99 %).

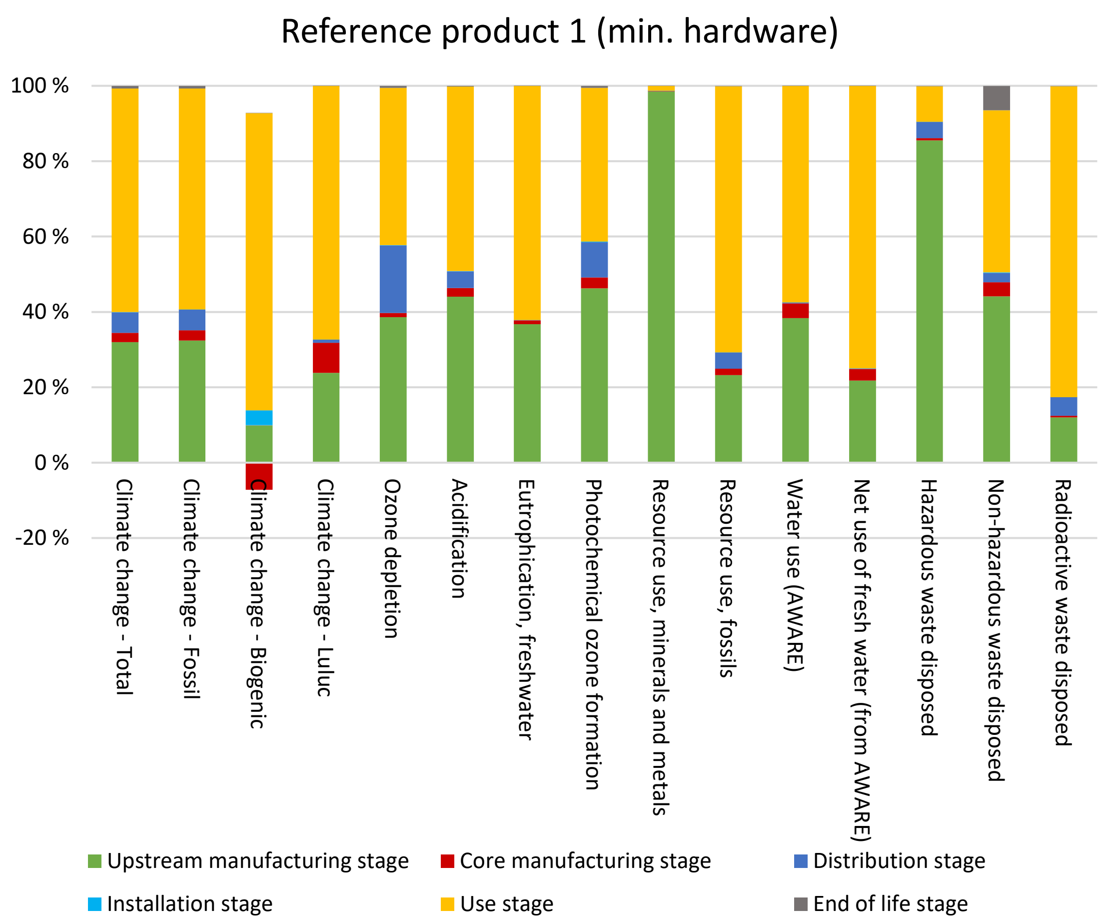



**Figure 17. Impact assessment results for reference product 1.**

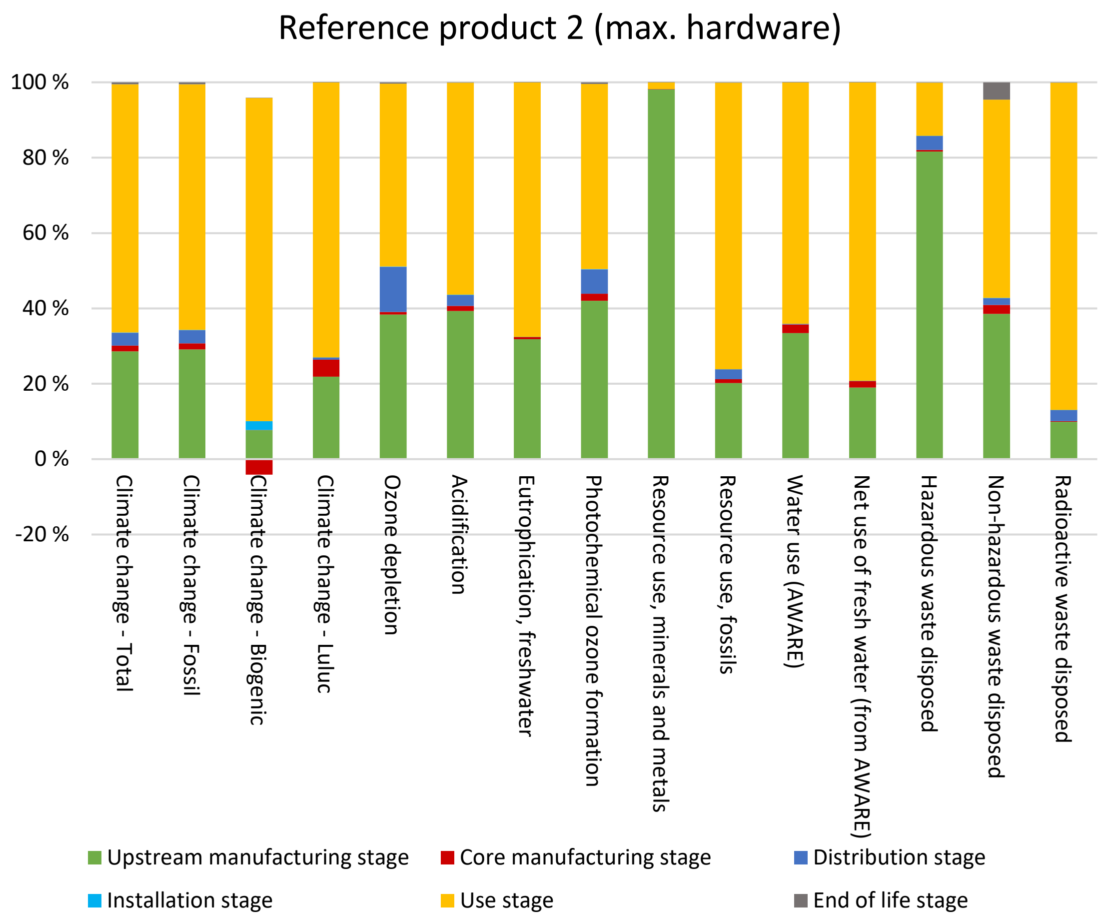



**Figure 18. Impact assessment results for reference product 2.**

Note, there is a negative impact in the impact category “climate change – biogenic”, in the core manufacturing stage. This is mainly due to the production and use of bio-based packaging materials such as wooden pallets, cardboard, and paper. The uptake of biogenic $CO_2$ during forest growth is simply calculated as negative emissions in the LCA. The $CO_2$ is later released in the end-of-life stage unless the materials are recycled.

## 6.4 Process contributions

This section presents the results of a process contribution analysis. Figure 19 and figure 20 compare the impacts on climate change for the top contributing processes. The process “Electricity, medium voltage {RER}” is by far the most contributing process to climate change. This is due to the consumption of the European energy mix in the use stage. This is then followed by the production and use of integrated circuits, empty printed wiring boards (PWB's), and air freight.

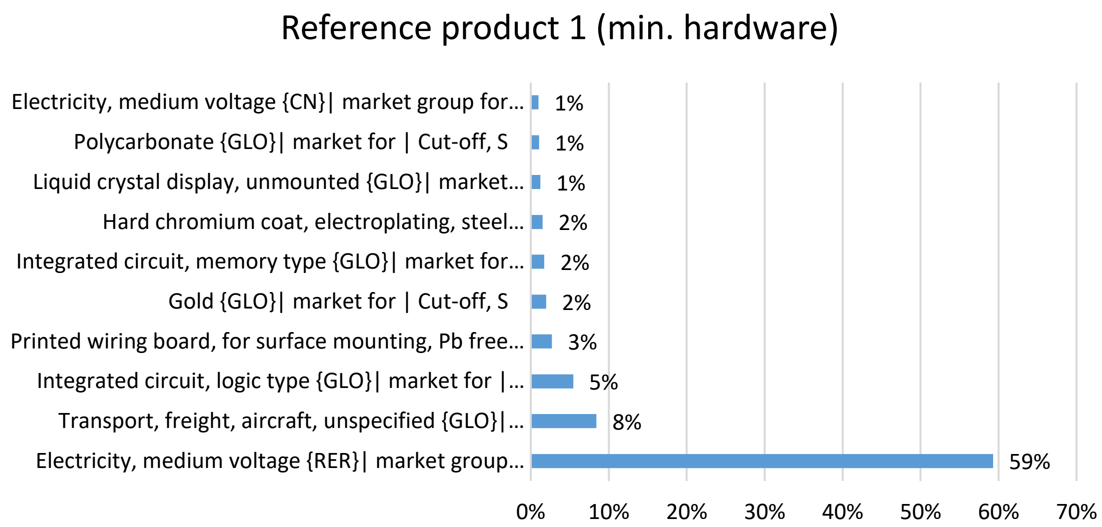



**Figure 19. Process contribution analysis, % of total impact, GWP indicator (1/2).**

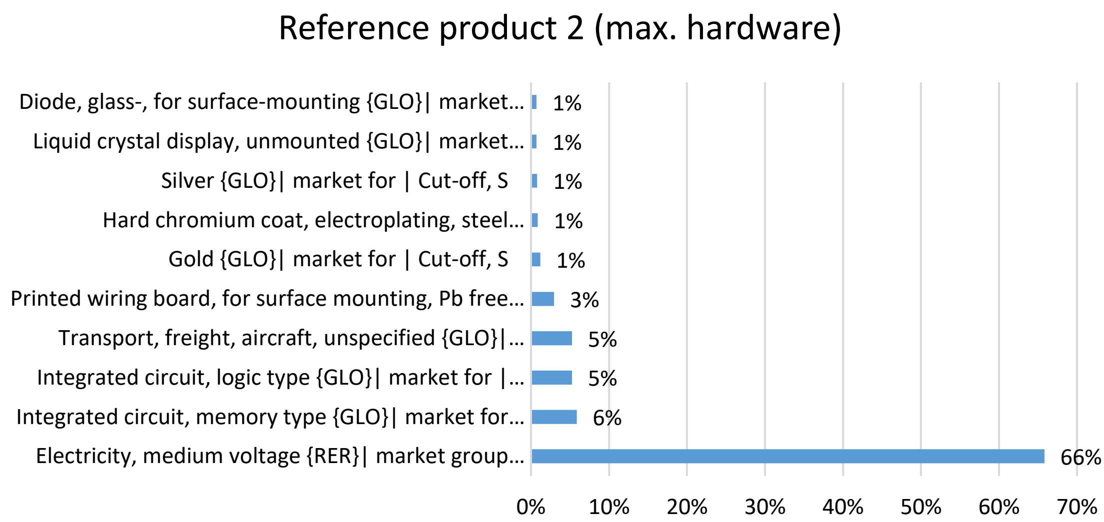



**Figure 20. Process contribution analysis, % of total impact, GWP indicator (2/2).**

Figure 21 and figure 22 also compare the top contributing processes, but in different impact categories. Again, the consumption of the European energy mix in the use stage has the largest impact in almost all impact categories, except in resource use of minerals and metals and hazardous waste disposed. Instead, the main contributing processes to the use of minerals and metals are the integrated circuits (25–33 %) and the use of gold in the connectors (19–26 %). It can also be noted that the use of air freight, in the upstream stage and distribution combined, has a significant impact on both ozone depletion (18–28 %) and photochemical ozone formation (10–15 %).

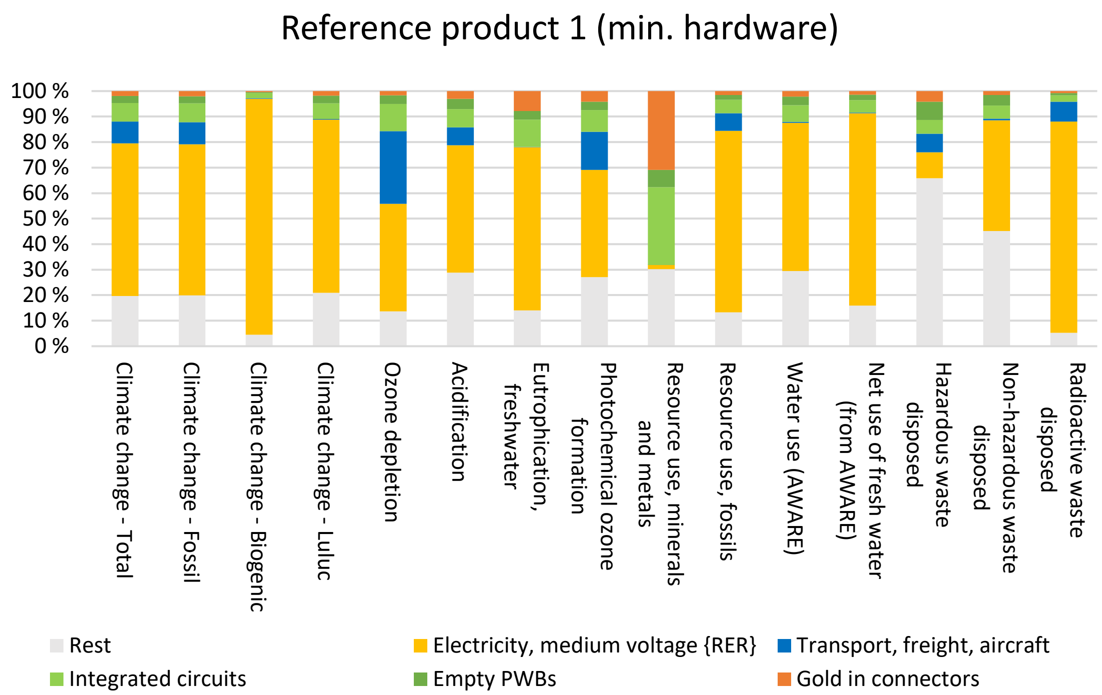



**Figure 21. Process contribution analysis, % of total impact, different indicators (1/2).**

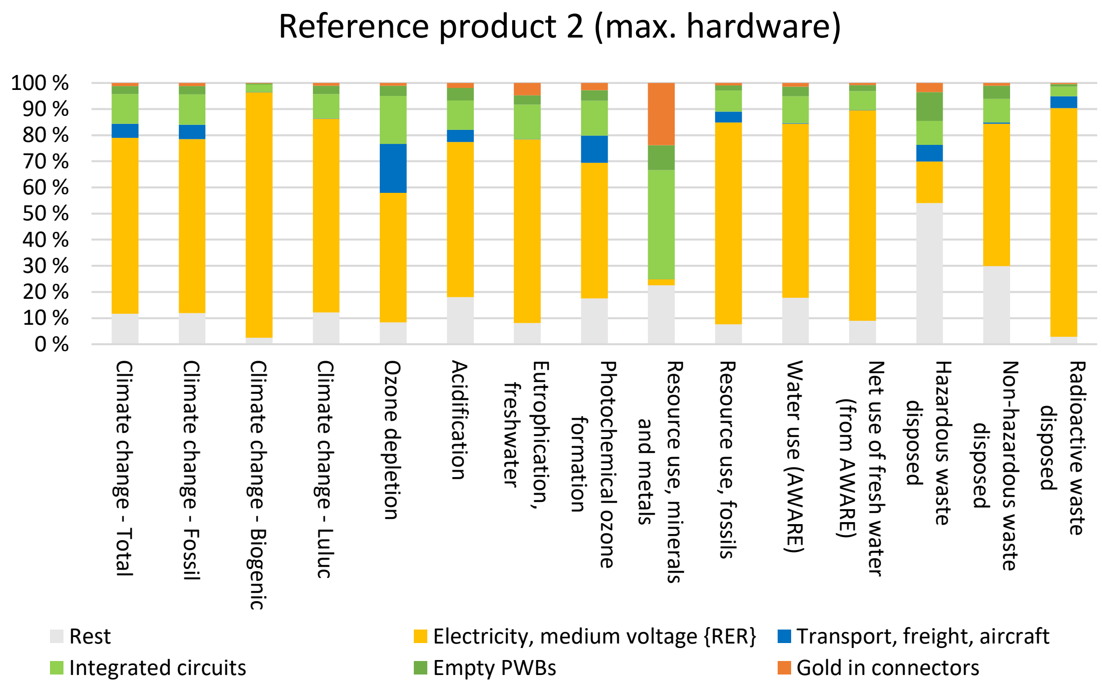



**Figure 22. Process contribution analysis, % of total impact, different indicators (2/2).**

## 6.5 Additional findings

Figure 23 compares the impacts on climate change per relay produced by each ABB factory. The comparison shows that the impact on climate change by the plant in Finland is 83 % lower than the plant in India, and 86 % lower than the plant in China. The main reason is due to the differences in the energy mixes used by each plant. In fact, the study shows that the plant in Finland has successfully reduced their impact on climate change by 60 %, by using 50/50 mix of wind and hydro instead of the national energy mix. If the plant in India and China would also use the same energy mix of wind and hydro, their impacts would both decrease by 67 %.

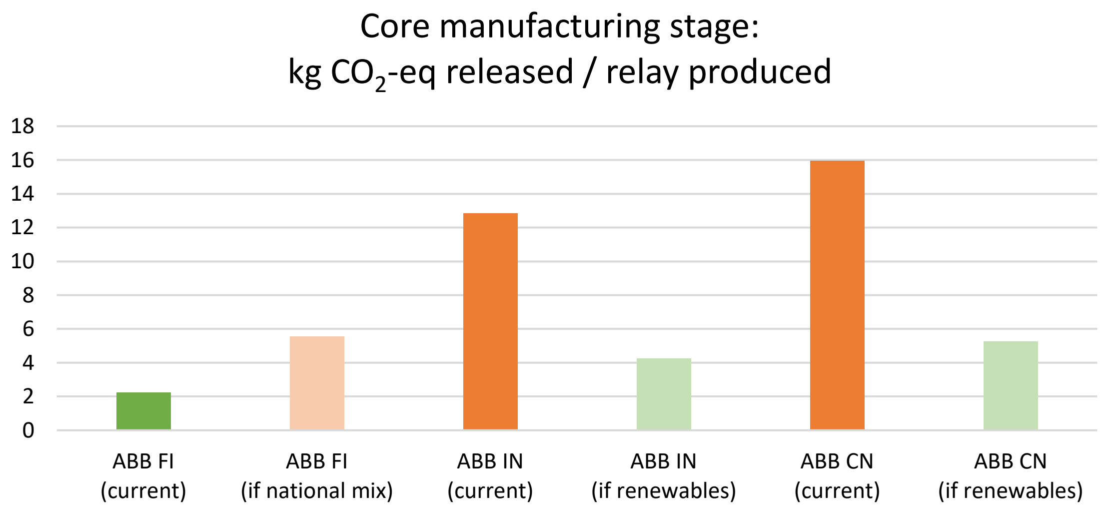



**Figure 23. Impact on climate change per relay produced, ABB plants compared.**

Finally, figure 24 shows how different impact categories change if the same energy mix of 50/50 wind and hydro is also used in the use stage. In fact, the total impact on climate change would decrease by 55–62 % for the entire LCA. Similar improvements also show in other impact categories. However, an exception is the slight increase by 2–3 % in resource use of minerals and metals. Also, hazardous and non-hazardous waste remain almost unchanged. This is likely due to the increased need for metals and minerals to produce the wind turbines and hydroelectric power stations.

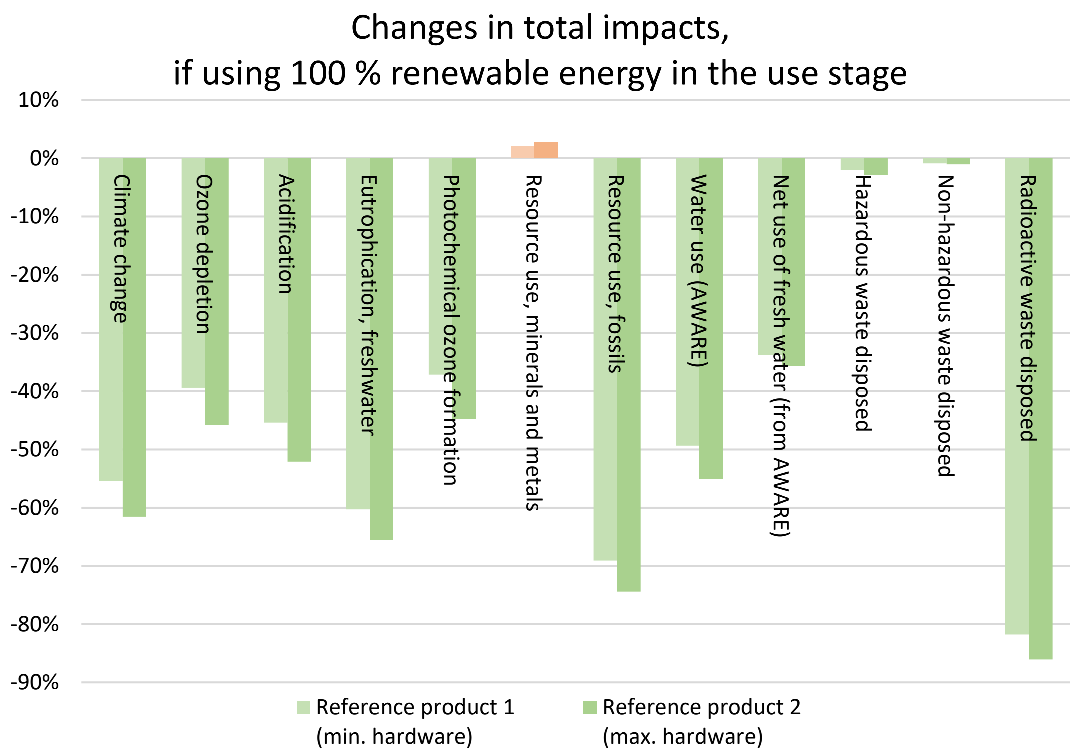



**Figure 24. Changes in total impacts, if using 100 % renewable energy in the use stage.**

## 6.6 Extrapolation rules

According to the findings of this study, the weight of a Relion 615 relay can range between ca 3,7 kg and ca 4,1 kg depending on the hardware used. According to internal and external test reports, the nominal power consumption can range from ca 5 W up to ca 16 W depending on the relay configuration and type of auxiliary voltage used.

Due to the large variations present in the series, extrapolation rules are established according to EN 50693:2019. This allows for estimating more precise impacts of other relay configurations. The following extrapolation rules are defined:

- The manufacturing stage, distribution stage, and end-of-life stage as well as the recyclability potential can be linearly extrapolated for other product configurations based on weight or number of hardware modules.
- The use stage may be linearly extrapolated based on the actual, measured nominal power consumption.

## 6.7 Reliability and validity

The LCA has been carefully evaluated with a completeness check, sensitivity check, and consistency check according to the guidelines and requirements provided by ISO 14044. It has also been internally reviewed by LCA experts of the case company. However, it has not been verified by an accredited third-party. Due to time limitations, the thesis was submitted during the same time as the audit process started. Thus, the results are subject to change from the official EPD. Specific numbers or percentages may deviate, although, the overall conclusions should not.

First, occasional incomplete data have been mapped out and treated. The treatment of incomplete data has been consulted with employees of the case company in various managerial and expert positions, and most often the data has been found from alternative sources. When data has not been available, it has been approximated. However, the approximated materials contribute to less than 1 % of the total impacts in all impact categories. Also, the plant in China is partially approximated by data from Finland and India, and this contributes to 1 % or less in almost all impact categories.

Second, whenever there has been significant uncertainty in the data, a sensitivity analysis has been conducted to ensure that it does not have a significant impact on the results. For example, this is why it was decided to declare two representative product configurations and establish extrapolation rules; modelling one average product to represent the entire series was not an option due to the large variations within the series. It is also the reason why the PWB's were modelled on a component level, and why the constituent materials of the aluminium alloy were modelled manually.

Third, a consistency check has been carried out to ensure that data quality, allocation rules, and ecoinvent processes have been consistently applied throughout the entire model. Also, the relays and each sub-assembly have been weighed separately to ensure that the LCA is consistent with the actual weights. The final weight difference was only

3–4 %, and the LCA is on the conservative side. No obvious error was found, and the difference is likely due to uncertainties in the data.

Nevertheless, no comprehensive uncertainty analysis is conducted because it is not required by the selected PCR. Yet, according to both internal and external test reports, the power consumption for a specific relay configuration can vary roughly ± 10 %, depending on the type of auxiliary voltage used. The power consumption in the use stage is also the most significant process by far. In addition, there is an inevitable uncertainty in both the processes adopted from ecoinvent and in the impact assessment method. Thus, the overall uncertainty in the results is likely greater than ± 10 % when speaking of the individual reference products. However, variations within the series are far larger, and hence the establishment of extrapolation rules. If the extrapolation rules are correctly applied, they eliminate the uncertainty in power consumption. In that case, the overall uncertainty in the primary data is well within ± 10 %, and that is also the limit for what is allowed according to the general program instructions by EPDItaly (2020b).

# 7 Conclusions

The goal of this research was to conduct an LCA study for the Relion 615 series of relays, and to develop an EPD based on the results. A case study was carried out with the main research question “what are the potential environmental impacts of a medium voltage protection relay throughout its life cycle?”. The study also aimed to determine what are the most impactful life cycle stages and processes as well as to identify potential improvement opportunities.

## 7.1 Summary of findings

The LCA was successfully conducted, and the potential environmental impacts are presented in appendices 1 and 2. The study found that the most impactful life cycle stage is the use stage due to the power consumption, which contributes to roughly 2/3 of the impacts in most impact categories. More specifically, the total impact on climate change, over the reference service life of 10 years, is 59–66 %. The results were similar in most other impact categories, except in resource use of minerals and metals which was only 1–2 %, and hazardous waste disposed which was 9–14 %.

The second most impactful life cycle stage is the upstream manufacturing stage, which contributes to roughly 1/3 of the impacts in most impact categories. This is mainly due to the manufacturing of electronic components and printed wiring boards. For example, the total impacts on climate change are 7–11 % from all integrated circuits combined, and 3 % from the empty PWB’s. The impacts were similar in most other impact categories, except in resource use of minerals and metals, which had 25–33 % from the integrated circuits.

The use of precious metals and air freight was also found to have a significant impact on the environment. For example, the use of gold only in the connectors contributes to 1 % of the total impact on climate change, and 19–26 % on resource use of minerals and metals. Furthermore, the use of airfreight in the upstream manufacturing stage and distribution stage combined contribute to 5–8 % of the total impact on climate change, 10–15 % on photochemical ozone formation, and 18–28 % on ozone depletion.

Furthermore, the study shows that the overall environmental impacts can be largely reduced by using renewable energy in different life cycle stages. For example, by using a 50/50 mix of wind and hydro energy in the core manufacturing stage instead of the national energy mix, the impact on climate change by ABB's factories decrease 60–67 %. Similarly, by using the same energy mix in the use stage, the total impact on climate change of the entire LCA can decrease by 55–62 %. Many other impact categories also decrease to the same extent. Thus, if all suppliers would use 100 % renewable energy as well, it can be assumed that the total impacts from the upstream manufacturing stage can decrease to the same extent. Also, using renewable energy in the transportation may have a benefit to the same extent as well.

Finally, the overall findings are aligned with previous research. The use stage had the most significant impact, followed by the manufacturing stage, and this is often also found in other LCA studies of various electronic devices (ABB, 2006; Schneider Electric, 2017a; Subramanian & Yung, 2016). Also, the production of integrated circuits and printed wiring boards had some of the most significant impacts on the manufacturing stage, and this is aligned with the findings by Teehan & Kandlikar (2012).

## 7.2 Discussion

The study is significant from a managerial point of view because the results are used for developing and publishing an EPD, to satisfy the requests of the case company's customers. Also, because the results are interpreted to establish conclusions and recommendations, it provides direct value for product development and improvement. It may further provide value in other areas such as supply chain management, and therefore contribute to ABB's sustainability strategy for 2030. Finally, it provides novel contributions to the literature because current LCA studies of such particular products are scarce. This is likely the first LCA study ever that is conducted according to the PCR EPDItaly007 for a medium voltage protection relay.

In terms of reliability and validity, the LCA has been carefully evaluated with a completeness check, sensitivity check, and consistency check according to the guidelines and requirements provided by ISO 14044. The overall findings are aligned with previous studies of similar devices. The study has also been internally reviewed by LCA experts of the case company, which further strengthens the quality of the research. However, the results presented in this thesis have not been verified by an accredited third-party. The thesis was submitted during the same time as the audit process started. Thus, the results are subject to change from the official EPD, and this is a limitation of this study. The exact numbers and percentages may deviate; although, the overall conclusions should not.

Finally, the uncertainty in the results for each reference product is at least ± 10 %, mainly because the power consumption depends on the type of auxiliary voltage used, but also due to the underlying uncertainty in the ecoinvent processes and in the impact assessment method. More importantly, variations within the series are far larger, and hence the establishment of extrapolation rules. However, if the extrapolation rules are correctly applied, they eliminate the uncertainty in power consumption. In that case, the overall uncertainty in the primary data is well within ± 10 %, and that is also the limit for what is allowed according to the general program instructions by EPDItaly (2020b). However, these numbers have not been scientifically proved through a comprehensive uncertainty analysis; these are qualified estimates based on the reasoning in chapter 6.7.

## 7.3 Future research

The study has successfully determined the potential environmental impacts of the Relion 615 series of medium voltage protection relays based on two representative reference products, and this provides a basis for developing and publishing an EPD. It has also identified the most important environmental hotspots and improvement opportunities. However, this is not enough to realize actual improvements; future work is necessary.

From ABB's point of view, cost-benefit analyses must be conducted in order to understand which areas of improvement that should be focused on first. For example, it must be determined how much it would cost to also start using 100 % renewable energy at other production plants. This may further require the quality of the data related to each plant to be improved.

Likewise, similar assessment should be made for key suppliers. It is a fact that most of the impacts from manufacturing derive from the upstream manufacturing stage. Thus, it might be worth for ABB to carry out joint development projects with those suppliers, to help improve their environmental performance. As a result, it would decrease the environmental stress of ABB's products.

A deeper analysis is required to identify more specific improvement opportunities. This includes, for example, to investigate possibilities for replacing the gold in the connectors with alternative metals such as silver alloys or recycled gold. Another suggestion is to make a more detailed comparison of the packaging materials used by each plant, and then reconsider current choices. What is more, the possibilities for using renewable energy sources in transportation, alternatively $CO_2$ compensated transportations, may also be investigated. Another suggestion is to investigate opportunities for improving the recyclability potential of the relays; for example, by replacing current plastics with more recyclable plastics. Most importantly, possibilities for improving the energy efficiency should be investigated. The product is likely optimized already to a large extent; however, this study might reveal new trade-offs in the product design that are worth taking from an LCA point of view.

Nevertheless, it is recommended to carry out more LCA studies of these type of products. By adopting the same PCR and method, it allows for more rightful comparisons, and this in turn may reveal more improvement opportunities. Different product designs may have different trade-offs, and to understand these from an LCA point of view can be valuable for future product design and improvement. For example, ABB (2021c) claims that their SSC600 devices can now handle the tasks of up to 30 protection relays, thus, a comparative assertion might reveal interesting facts about in which case which solution is better from an LCA point of view.

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# Appendices

## Appendix 1. Impact assessment results for reference product 1

Product ID: REF615E_1G
Product version: 5.0 FP1
Ordering code: HBFCACABNNA1BNN11G
Hardware: Minimum (3 slots empty)
Nominal power: 5 W (measured, average)

**Table 16. Environmental impact indicators of reference product 1.**

| Impact category | Unit | Total | UPSTREAM | CORE | DOWNSTREAM | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Manufacturing | | Distribution | Installation | Use | End-of-life |
| GWP - total | kg CO2 eq. | 2,95E+02 | 9,43E+01 | 7,44E+00 | 1,59E+01 | 4,03E-01 | 1,75E+02 | 2,13E+00 |
| GWP - fossil | kg CO2 eq. | 2,88E+02 | 9,35E+01 | 7,91E+00 | 1,58E+01 | 1,22E-01 | 1,69E+02 | 2,13E+00 |
| GWP - biogenic | kg CO2 eq. | 6,12E+00 | 7,06E-01 | -5,17E-01 | 6,60E-03 | 2,82E-01 | 5,64E+00 | 3,65E-04 |
| GWP - luluc | kg CO2 eq. | 5,91E-01 | 1,41E-01 | 4,69E-02 | 4,92E-03 | 1,30E-05 | 3,98E-01 | 1,02E-04 |
| ODP | kg CFC-11 eq. | 2,01E-05 | 7,76E-06 | 2,22E-07 | 3,59E-06 | 2,36E-08 | 8,38E-06 | 1,07E-07 |
| AP | mol H+ eq. | 1,86E+00 | 8,19E-01 | 4,26E-02 | 8,25E-02 | 7,16E-04 | 9,10E-01 | 3,52E-03 |
| EP - fresh-water | kg P eq. | 2,72E-01 | 1,00E-01 | 2,75E-03 | 2,44E-04 | 3,26E-06 | 1,69E-01 | 2,89E-05 |
| POCP | kg NMVOC eq. | 9,19E-01 | 4,25E-01 | 2,67E-02 | 8,58E-02 | 1,10E-03 | 3,75E-01 | 5,25E-03 |
| ADP – minerals and metals | kg Sb eq. | 3,00E-02 | 2,95E-02 | 3,00E-05 | 5,89E-06 | 1,02E-07 | 4,01E-04 | 5,40E-07 |
| ADP – fossil | MJ, net calorific value | 5,12E+03 | 1,19E+03 | 8,67E+01 | 2,23E+02 | 1,50E+00 | 3,61E+03 | 7,06E+00 |
| WDP | m3 eq. | 6,83E+01 | 2,62E+01 | 2,65E+00 | 1,96E-01 | 4,13E-05 | 3,92E+01 | 4,47E-02 |

GWP-fossil: Global Warming Potential fossil; GWP-biogenic: Global Warming Potential biogenic; GWP-luluc: Global Warming Potential land use and land use change; ODP: Depletion potential of the stratospheric ozone layer; AP: Acidification potential; EP-freshwater: Eutrophication potential-freshwater compartment; POCP: Formation potential of tropospheric ozone; ADP-minerals & metals: Abiotic Depletion for non-fossil resources potential; ADP-fossil: Abiotic Depletion for fossil resources potential, WDP: Water deprivation potential.

### Table 17. Resource use parameters of reference product 1.

| Resource use parameters | Unit | Total | UPSTREAM | CORE | DOWNSTREAM | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Manufacturing | | Distribution | Installation | Use | End-of-life |
| PENRE | MJ, low cal. value | 5,09E+03 | 1,16E+03 | 8,56E+01 | 2,23E+02 | 1,50E+00 | 3,61E+03 | 7,06E+00 |
| PERE | MJ, low cal. value | 8,18E+02 | 1,15E+02 | 5,89E+01 | 8,30E-01 | 6,46E-03 | 6,43E+02 | 5,65E-02 |
| PENRM | MJ, low cal. value | 3,14E+01 | 3,04E+01 | 1,03E+00 | 0 | 0 | 0 | 0 |
| PERM | MJ, low cal. value | 1,34E+01 | 0 | 1,34E+01 | 0 | 0 | 0 | 0 |
| PENRT | MJ, low cal. value | 5,12E+03 | 1,19E+03 | 8,66E+01 | 2,23E+02 | 1,50E+00 | 3,61E+03 | 7,06E+00 |
| PERT | MJ, low cal. value | 8,31E+02 | 1,15E+02 | 7,23E+01 | 8,30E-01 | 6,46E-03 | 6,43E+02 | 5,65E-02 |
| FW | m3 | 4,10E+00 | 8,94E-01 | 1,24E-01 | 7,36E-03 | 3,79E-05 | 3,08E+00 | 1,46E-03 |
| MS | kg | 9,21E-01 | 8,42E-01 | 7,89E-02 | 0 | 0 | 0 | 0 |
| RSF | MJ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NRSF | MJ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

PENRE: Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw material; PERE: Use of renewable primary energy excluding renewable primary energy resources used as raw material; PENRM: Use of non-renewable primary energy resources used as raw material; PERM: Use of renewable primary energy resources used as raw material; PENRT: Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials); PERT: Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials); FW: Net use of fresh water; MS: Use of secondary materials; RFS: Use of renewable secondary fuels, NRSF: Use of non-renewable secondary fuels.

### Table 18. Waste indicators of reference product 1.

| Waste production indicators | Unit | Total | UPSTREAM | CORE | DOWNSTREAM | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Manufacturing | | Distribution | Installation | Use | End-of-life |
| HWD | kg | 1,36E-02 | 1,17E-02 | 7,80E-05 | 5,92E-04 | 4,02E-06 | 1,28E-03 | 1,87E-05 |
| NHWD | kg | 2,78E+01 | 1,23E+01 | 1,03E+00 | 7,04E-01 | 3,40E-02 | 1,20E+01 | 1,79E+00 |
| RWD | kg | 3,23E-02 | 3,90E-03 | 1,30E-04 | 1,57E-03 | 1,04E-05 | 2,67E-02 | 4,73E-05 |
| MER | kg | 1,03E+00 | 0 | 3,21E-01 | 0 | 1,82E-01 | 0 | 5,28E-01 |
| MFR | kg | 4,41E+00 | 4,68E-01 | 1,24E+00 | 0 | 6,43E-01 | 0 | 2,05E+00 |
| CRU | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| ETE | MJ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EEE | MJ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

HWD: hazardous waste disposed; NHWD: non-hazardous waste disposed; RWD: radioactive waste disposed; MER: materials for energy recovery; MFR: material for recycling; CRU: components for reuse; ETE: exported thermal energy; EEE: exported electricity energy.

## Appendix 2. Impact assessment results for reference product 2

Product ID: REF615E_1G
Product version: 5.0 FP1
Ordering code: HBFNAEAGNEA1BNA11G
Hardware: Maximum (all slots filled)
Nominal power: 9,5 W (measured, average)

**Table 19. Environmental impact indicators of reference product 2.**

| Impact category | Unit | Total | UPSTREAM | CORE | DOWNSTREAM | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Manufacturing | | Distribution | Installation | Use | End-of-life |
| GWP - total | kg CO2 eq. | 5,05E+02 | 1,45E+02 | 7,44E+00 | 1,74E+01 | 4,03E-01 | 3,32E+02 | 2,79E+00 |
| GWP - fossil | kg CO2 eq. | 4,93E+02 | 1,43E+02 | 7,91E+00 | 1,73E+01 | 1,22E-01 | 3,21E+02 | 2,78E+00 |
| GWP - biogenic | kg CO2 eq. | 1,15E+01 | 9,66E-01 | -5,17E-01 | 7,23E-03 | 2,82E-01 | 1,07E+01 | 4,44E-04 |
| GWP - luluc | kg CO2 eq. | 1,04E+00 | 2,27E-01 | 4,69E-02 | 5,39E-03 | 1,30E-05 | 7,57E-01 | 1,24E-04 |
| ODP | kg CFC-11 eq. | 3,28E-05 | 1,26E-05 | 2,22E-07 | 3,94E-06 | 2,36E-08 | 1,59E-05 | 1,21E-07 |
| AP | mol H+ eq. | 3,07E+00 | 1,21E+00 | 4,26E-02 | 9,04E-02 | 7,16E-04 | 1,73E+00 | 4,05E-03 |
| EP - fresh-water | kg P eq. | 4,75E-01 | 1,51E-01 | 2,75E-03 | 2,68E-04 | 3,26E-06 | 3,21E-01 | 3,71E-05 |
| POCP | kg NMVOC eq. | 1,45E+00 | 6,09E-01 | 2,67E-02 | 9,40E-02 | 1,10E-03 | 7,12E-01 | 6,00E-03 |
| ADP – minerals and metals | kg Sb eq. | 4,28E-02 | 4,20E-02 | 3,00E-05 | 6,45E-06 | 1,02E-07 | 7,61E-04 | 6,27E-07 |
| ADP – fossil | MJ, net calorific value | 9,03E+03 | 1,83E+03 | 8,67E+01 | 2,44E+02 | 1,50E+00 | 6,87E+03 | 8,00E+00 |
| WDP | m3 eq. | 1,16E+02 | 3,89E+01 | 2,65E+00 | 2,14E-01 | 4,13E-05 | 7,44E+01 | 5,67E-02 |

GWP-fossil: Global Warming Potential fossil; GWP-biogenic: Global Warming Potential biogenic; GWP-luluc: Global Warming Potential land use and land use change; ODP: Depletion potential of the stratospheric ozone layer; AP: Acidification potential; EP-freshwater: Eutrophication potential-freshwater compartment; POCP: Formation potential of tropospheric ozone; ADP-minerals & metals: Abiotic Depletion for non-fossil resources potential; ADP-fossil: Abiotic Depletion for fossil resources potential, WDP: Water deprivation potential.

**Table 20. Resource use parameters of reference product 2.**

| Resource use parameters | Unit | Total | UPSTREAM | CORE | DOWNSTREAM | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Manufacturing | | Distribution | Installation | Use | End-of-life |
| PENRE | MJ, low cal. value | 8,99E+03 | 1,79E+03 | 8,56E+01 | 2,44E+02 | 1,50E+00 | 6,86E+03 | 8,00E+00 |
| PERE | MJ, low cal. value | 1,47E+03 | 1,85E+02 | 5,89E+01 | 9,09E-01 | 6,46E-03 | 1,22E+03 | 6,96E-02 |
| PENRM | MJ, low cal. value | 3,73E+01 | 3,63E+01 | 1,03E+00 | 0 | 0 | 0 | 0 |
| PERM | MJ, low cal. value | 1,34E+01 | 0 | 1,34E+01 | 0 | 0 | 0 | 0 |
| PENRT | MJ, low cal. value | 9,03E+03 | 1,83E+03 | 8,66E+01 | 2,44E+02 | 1,50E+00 | 6,86E+03 | 8,00E+00 |
| PERT | MJ, low cal. value | 1,48E+03 | 1,85E+02 | 7,23E+01 | 9,09E-01 | 6,46E-03 | 1,22E+03 | 6,96E-02 |
| FW | m3 | 7,38E+00 | 1,40E+00 | 1,24E-01 | 8,06E-03 | 3,79E-05 | 5,84E+00 | 1,86E-03 |
| MS | kg | 9,21E-01 | 8,42E-01 | 7,89E-02 | 0 | 0 | 0 | 0 |
| RSF | MJ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NRSF | MJ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

PENRE: Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw material; PERE: Use of renewable primary energy excluding renewable primary energy resources used as raw material; PENRM: Use of non-renewable primary energy resources used as raw material; PERM: Use of renewable primary energy resources used as raw material; PENRT: Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials); PERT: Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials); FW: Net use of fresh water; MS: Use of secondary materials; RFS: Use of renewable secondary fuels, NRSF: Use of non-renewable secondary fuels.

**Table 21. Waste indicators of reference product 2.**

| Waste production indicators | Unit | Total | UPSTREAM | CORE | DOWNSTREAM | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Manufacturing | | Distribution | Installation | Use | End-of-life |
| HWD | kg | 1,73E-02 | 1,41E-02 | 7,80E-05 | 6,49E-04 | 4,02E-06 | 2,43E-03 | 2,11E-05 |
| NHWD | kg | 4,33E+01 | 1,67E+01 | 1,03E+00 | 7,71E-01 | 3,40E-02 | 2,27E+01 | 2,00E+00 |
| RWD | kg | 5,83E-02 | 5,77E-03 | 1,30E-04 | 1,72E-03 | 1,04E-05 | 5,07E-02 | 5,31E-05 |
| MER | kg | 1,22E+00 | 0 | 3,21E-01 | 0 | 1,82E-01 | 0 | 7,21E-01 |
| MFR | kg | 4,46E+00 | 4,67E-01 | 1,24E+00 | 0 | 6,43E-01 | 0 | 2,11E+00 |
| CRU | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| ETE | MJ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EEE | MJ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

HWD: hazardous waste disposed; NHWD: non-hazardous waste disposed; RWD: radioactive waste disposed; MER: materials for energy recovery; MFR: material for recycling; CRU: components for reuse; ETE: exported thermal energy; EEE: exported electricity energy.