Life cycle assessment of a CAV, a VAV, and an ACB system in a modern Swedish office building.

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Lund University

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Energy use in buildings contributes significantly to the global energy demand and environmental impacts. Among all building services, heating, ventilation, and air conditioning (HVAC) systems consume the most energy. HVAC systems are as well one of the largest consumers of natural resources and materials in the building sector. Studies have shown that the manufacturing and operation of HVAC systems have a significant impact on the environment. With a constant growing awareness towards thermal comfort and energy use, the question remains, which HVAC system has a better environmental performance. This thesis presents a comparison between the life cycle impacts of three different HVAC systems — constant-air volume, variable-air volume, and active climate beam systems — designed for a Swedish modern office building. The system boundary of the life cycle assessment was set to be cradle-to-grave with options, over a 20-year period. SimaPro software was used for the life cycle assessment (LCA) of the systems. The CML IA (baseline) method was used for the life cycle impact assessment and the results were weighted based on the shadow cost Dutch method. Initially, a base case scenario was set for all three HVAC systems, using Copper material for the hydronic system and using Swedish electricity mix. Varying the material used for the hydronic system and the electricity type, a parametric study was then conducted comparing the environmental impacts of the systems.

The results of the Base case scenario showed that, from a life cycle perspective, the ACB and VAV systems have similar environmental performance. During the life cycle of the CAV and VAV systems, the operational phase showed to have the highest environmental impact. Whereas, for the life cycle of the ACB system, the manufacturing phase exhibited the highest environmental impact. The biggest reduction in environmental impacts was observed when PVC pipes were used instead of copper pipes, in the ACB system. A slight reduction was seen when 100 % renewable based electricity was used by the systems instead of the Swedish electricity mix. Under all case-scenarios, the CAV system showed to have the highest environmental impacts. Further research regarding the impacts of the maintenance phase and life span of the systems would be relevant for the comparison of life cycle impacts of the systems.

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List of Abbreviations

ACB	Active chilled beam
ADPE	Abiotic depletion of natural resources potential
ADPF	Abiotic depletion of fossil fuels potential
AHU	Air handling unit
AP	Acidification potential
APOS	Allocation at point of substitution
BBR	Boverkets byggregler
BOQ	Bill of quantities
CAV	Constant-air volume
CED	Cumulative energy demand
COP	Coefficient of performance
DH	District heating
EP	Eutrophication potential
EPD	Environmental product declaration
FAETP	Fresh water aquatic ecotoxicity potential
GWP	Global warming potential
HTP	Human toxicity potential
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
ILCD	International Reference Life Cycle Data System
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MAETP	Marine aquatic ecotoxicity potential
NREL	National Renewable Energy Laboratory
ODP	Ozone layer depletion potential
POCP	Photochemical oxidation potential
PVC	Polyvinyl chloride
TETP	Terrestrial ecotoxicity potential
UAD	Under air floor distribution system
UN	United Nations
UNEP	United Nations Environment Programme
VAV	Variable-air volume

1 Introduction

1.1 Background

The built environment is a major contributor to green-house gas emissions (Khasreen et al., 2009). Studies have shown that buildings, on a global level, are responsible for 30−40 % of the energy used and 40−50 % of the global carbon dioxide emissions (Bribián et al., 2009). In the European Union, the building sector is accountable for approximately 40 % of the total environmental burden (UNEP, 2003). As a result, the European commission has set targets to reduce green-house gases by at least 20 % by the year 2020 and at least 40 % by the year 2030, compared to 1990 emission levels (Climate Action - European Commission, 2019).

In buildings, heating, ventilation, and air conditioning (HVAC) systems consume the most energy, representing approximately 50 % of the building's total energy (Pérez-Lombard et al., 2008). Nonetheless, the HVAC system has become one of the essential building service elements in modern buildings (Chen, 2011). Recently, the number of HVAC systems installed has increased dramatically (BSRIA, 2009; Coletti & Fano, 2008). This is mainly due to an increase in demand for thermal comfort and thermal comfort standards, specifically in developed countries. With a focus on reducing energy consumption during the operational phase while maintaining good indoor air quality (IAQ), new systems such as chilled beams have been introduced (Chen, 2011).

Globally, emissions caused by a building during the operational phase are mostly due to non-renewable energy such as fossil fuel burned to heat and cool the building. However, this is not the case in Sweden due to the district heating network which is powered mainly by renewable energy (Di Lucia & Ericsson, 2014). Figure 1 shows the CO_2 emissions from Swedish district heating systems from 1970–2016 (Werner, 2017).

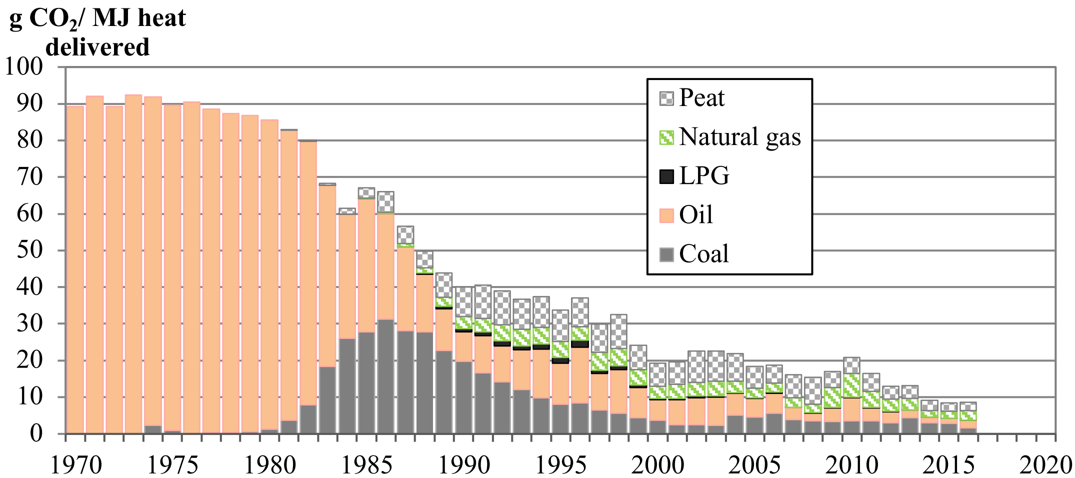

Figure 1: Specific carbon dioxide emissions from Swedish district heating systems (Werner, 2017).

Due to the utilization of renewable energy, the environmental impacts of HVAC components can be equal to or greater than that associated with the operational phase (Pehl et al., 2017; Di Lucia & Ericsson, 2014). This increases the significance of decreasing the life cycle energy use and total emissions of HVAC systems. According to Chen (2011), the manufacturing and transportation of HVAC materials, along with the installation and construction of HVAC components, consume large quantities of energy and have a significant environmental impact. Moreover, the extraction of minerals, such as iron ore, aluminum and copper, all of which are commonly used in HVAC systems, causes a significant reduction in the planet's natural resources (Bribián et al., 2009).

Studies evaluating the environmental impacts of HVAC systems usually only focused on the operational phase while disregarding other life cycle phases that can as well have high environmental impacts (Chen, 2011). The majority of studies conducted in the building sector have focused on the environmental impact of the exterior envelope, structural system on the life cycle of buildings, and the energy usage during the operational phase (Yang et al., 2008). Moreover, only a few studies have discussed the environmental impacts of HVAC systems not only from a carbon footprint perspective, but also the impact HVAC systems can have on human health and natural resources, as seen in the literature review section.

Overall, increased awareness toward environmental issues has led countries to implement strict building codes and energy criteria (Sartori & Hestnes, 2007). Consequently, several standardized environmental assessment methods have been developed to provide building designers with better comprehension and estimation of a product's life cycle impact (Prek, 2004). Currently, LCA is one of the leading methodologies for facilitating more environmentally friendly decisions in the building sector.

In this study, the environmental impacts of the life cycles of a Variable air volume (VAV) system, a Constant air volume (CAV) system and, an Active chilled beams (ACB) system are evaluated and compared, for a modern office building in Sweden. Three different case scenarios were analyzed using different materials and energy mix

1.2 Objectives

The overall aim of the thesis is to study the environmental impacts of a VAV system, a CAV system and, an ACB system designed for a modern Swedish office building. Part of the aim is to show the major factors influencing the environmental impacts of each system, in addition to providing distinct evaluation and comparison of the three systems. This comparison could facilitate, in the future, the selection of HVAC systems and can be used to contribute to the development and improvement of the systems examined. The thesis also aims to answer the following questions:

- *Does the HVAC system with the lowest operational energy usage has also the lowest environmental impact?*
- *Which life cycle phase in a system has the most environmental impact and why?*
- *What are the major factors influencing the environmental impacts of the CAV, VAV, and ACB systems?*
- *How can the environmental impacts of the life cycles of the CAV, VAV, and ACB systems be reduced within the current scope of the study?*

- *How sensitive are the LCA results of the CAV, VAV, and ACB systems to different scenarios of energy mix?*

1.3 Scope and limitation

The study is based on a hypothetical building located in Malmo, Sweden. The comparison is based on three different HVAC systems: CAV, VAV, and ACB. The systems were originally designed in a research done by Abugabbara et al. (2017) for a modern office building. For this study, AutoCAD and CADvent plugin were used to extract BOQ of the HVAC systems developed by Abugabbara et al. (2017). SimaPro is used for the life cycle assessment (LCA) of the systems (PRé Sustainability, 2019). The CML IA (baseline) method is used for the impact assessment, in addition to the Cumulative energy demand (CED) method.

In order to evaluate the sensitivity of the results, different scenarios, in which the electricity mix as well as the material for water connections are varied, were examined. The LCA study is based on average global market data. In the life cycle inventory only materials that make up components within the building's boundary are taken into account, as shown in Figure 2. Materials that were stated to make up less than 1 % of a component and their percentages were not specified were not taken into account. For example, it was listed in the Building product declaration (BPD), obtained from the manufacturer of the AHU units, that gold made up less than 1 % of the AHU unit, but the exact percentage of the gold content was not specified, and therefore, gold was not taken into account in the life cycle inventory (Lindab AB, 2019).

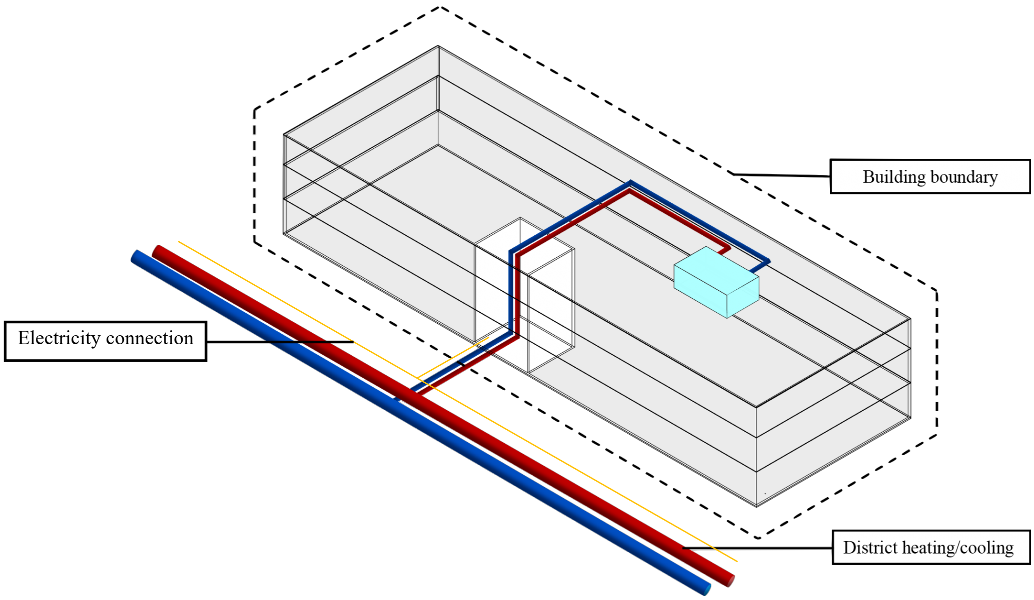

Figure 2: System boundary for material and energy flow.

The LCA study is conducted within a cradle-to-gate system boundary with options. The extraction of materials, transportation to the production site, and manufacturing energy need was included. The energy consumption during the operational phase due to heating, cooling, and running fans and pumps was also taken into account. Transportation from site to waste treatment facilities was taken into account, using average data from Ecoinvent database (Ecoinvent v3, 2019). Energy used in the process of recycling and waste treatment was also included. Environmental impacts due to transportation from the production site to the building and the maintenance of the systems were excluded due to lack of data. Moreover, the end-of-life phase and impacts due to labor were excluded. Environmental quality such as indoor air quality is not taken into account in the LCA study but was previously examined by Abugabbara et al. (2017). Energy consumed during the operational phase was not calculated in this thesis but obtained from Abugabbara et al. (2017) and was used as an input for the study.

1.4 Deposition of report

Chapter 1 introduces the background of the topic, objectives, and the scope and limitations. *Chapter 2* discusses the background of LCA and summarizes various methods and tools that can be used for the environmental assessment. *Chapter 3* presents the literature review of case studies related to the built environment, LCA of HVAC systems, and different Life cycle impact assessment (LCIA) methods and approaches. *Chapter 4* discusses the details of the methodology used in this study. *Chapter 5* presents the results obtained. *Chapter 6* summarizes and concludes the study, and gives recommendations for further research.

2 Life cycle assessment

2.1 LCA Background

LCA is a standardized methodology for assessing environmental impacts associated with the stages within a product's life, from raw material acquisition, to manufacturing, distribution, usage, maintenance, and disposal. An LCA may encompass all of these stages or may cover a subset of a stage(s) in a product's life, depending on the system boundary (Hollerud et al., 2017).

Nowadays, two ISO standards are available for conducting an LCA. The ISO 14040 outlines the key principles and framework of how an LCA should be conducted, while ISO 14044 provides specifies details and guidance on how the procedure of evaluating an LCA should be conducted. Further requirements can be found within the ISO 14 000 series (Olsson & Steko, 2015; ISO, 2006).

2.2 Framework

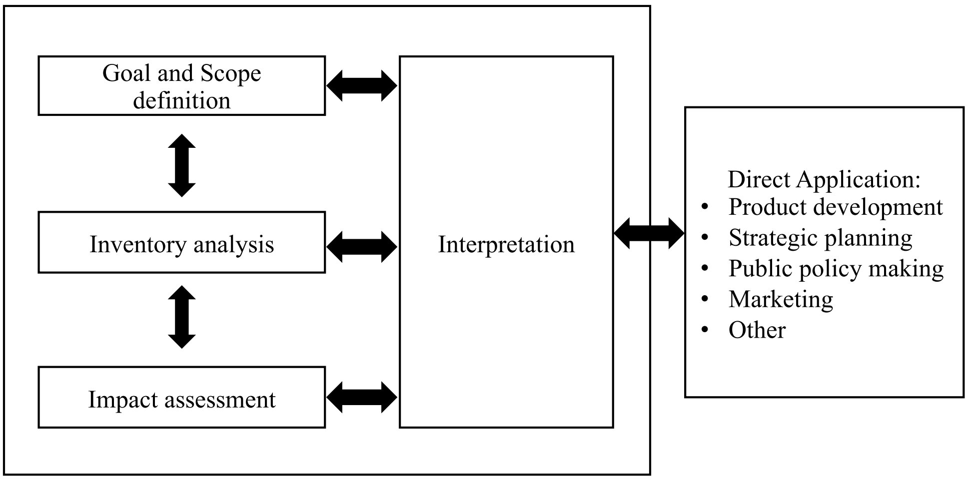

Figure 3: Phases of an LCA according to ISO 14040 (2006).

The framework set by ISO 14040 (2006) is an iterative process which includes four main phases, shown in Figure 3. The goal and scope are defined in the first phase. The aim of the study is defined as the goal. The functional unit and system boundaries are determined for the scope. The functional unit defines the analyzed specific function in the study. This is crucial when comparing two systems to ensure an equal comparison (Borg, 2016). The system boundaries include what processes will be taken into account and what type of data will be collected. This, for instance, can be cradle-to-grave or cradle-to-gate. In the second phase, an inventory of the product's relevant inputs and outputs within the system boundaries is assembled. This could either be done manually or with a help of an established database (Olsson & Steko, 2015). This is then called a life cycle inventory (LCI). Please refer to *Section 2.8* for more information on different LCA databases. The impact assessment phase includes a number of sub-steps, starting from choosing and defining relevant impact categories. This is followed by classifying LCI results into environmental impacts (Pennynck, 2016). Characterization factors are then used to model the impacts within the impact categories (Khasreen et al., 2009). An optional step, involving weighting and normalizing the results of the impacts, enables the comparison of potential impacts. Finally, in the interpretation phase, the results are analyzed with respect to the goal of the study.

2.3 Variants of LCA

Each LCA study has a specified system boundary. According to the ILCD handbook (2010), a system boundary can be *cradle-to grave*, *cradle-to-gate*, or *gate-to-gate*.

Cradle-to-grave LCA deals with a product's life cycle from the manufacturing phase to the operational phase, then finally to the end-of-life phase (Karim, 2011).

Cradle-to-gate LCA deals mainly with the manufacturing phase of a product (Joshi, 2009). In case of building materials, this can be the manufacturing of a material starting from raw material acquisition, transportation to the production site, production process and transportation to the construction site.

Gate-to-gate LCA takes into account one life cycle phase of a product. This can be, for instance, analyzing the environmental effects of a material in the end-of-life phase (Karim, 2011).

2.4 LCA Modelling systems

According to Shonan guidance on LCA, there are two main modelling systems for LCA: Attributional and consequential modelling systems (UNEP, 2003; Sonnemann & Vigon, 2011). Shonan defines the systems as follows:

Attributional approach: System modelling 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.

Consequential approach: 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.

Please refer to *Section 3.3* for more information on LCA modeling systems.

2.5 Environmental impact categories

In order to comprehend the outcomes of flows and emissions due to a life cycle phase of a product, these flows and emissions need to be converted into environmental impacts. This is done by assigning quantities of emissions and resource consumption to the environmental impacts that are caused by these emissions (Joshi, 2009). For example, inventory flows such as "methane emissions to air" are assigned to the environmental impact "Global warming potential (GWP)" (ARENA, 2016). This is obtained through steps called Classification and

Characterization, as seen in Figure 4. Initially, all the inventory flows are categorized according to the impact they have on the environment. Secondly, the impact of the inventory flows is multiplied by a characterization factor which represents its input to the environmental impact (Golsteijn, 2014).

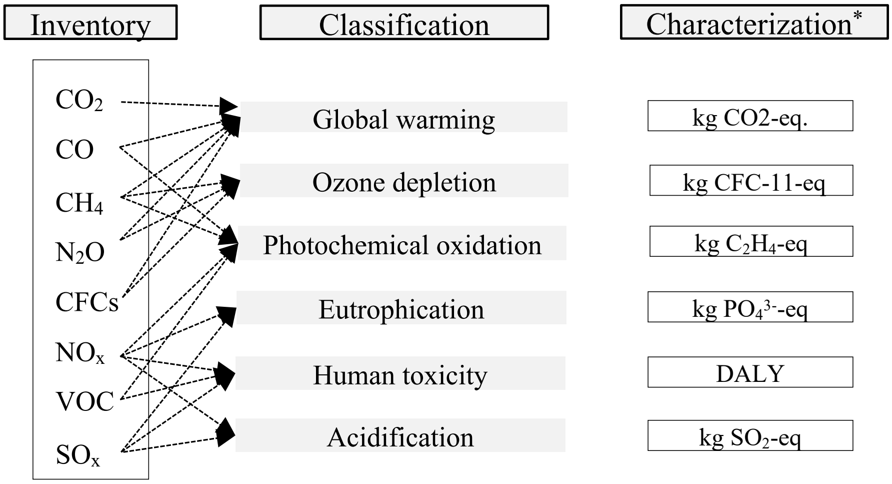

Figure 4: Inventory flows classification and characterization (Lee & Inaba, 2004).
** Depends on the model*

Furthermore, there are two types of impact indicators: Midpoint and Endpoint indicators. Midpoint indicators are problem-oriented while Endpoint indicators are damage-oriented (Frenette et al., 2010). Endpoint indicators basically reflect the consequences of the midpoint indicators ("LCIA: The ReCiPe model" 2018). Some examples of Midpoint and Endpoint indicators can be seen in Table 1.

Table 1: Examples of midpoint and endpoint indicators.

Type	Impact Indicator	Unit
Midpoint	Global warming potential	kg CO_2-eq
	Freshwater Eutrophication	kg PO_4-eq
	Non-renewable energy	MJ Primary
	Acidification potential	kg SO_2 -eq
Endpoint	Ecosystem diversity	species·yr
	Human health damage	Disability Adjusted Life Year (DALY)
	Resource availability	-----

2.6 Life cycle impact assessment

There are a variety of Life cycle impact assessment (LCIA) methods available that differ in indicator type, characterization model, etc. Some LCIA methods use both midpoint and endpoint indicators while other LCIA methods use either midpoint or endpoint indicators.

For instance, **ReCiPe**, an LCIA method developed by RIVM, Radboud University, Norwegian University of Science and Technology and PRé Consultants, uses both midpoint and endpoint indicators ("ReCiPe - PRé Sustainability," 2010). ReCiPe includes a wide variety of midpoint categories and uses impact mechanisms that have a worldwide range. Midpoint and endpoint indicators used in ReCiPe are available within three different cultural perspectives: *individualist, hierarchist and egalitarian* (Andersson & Listén, 2014). Each perspective represents similar assumptions and choices categorized together (Zelm, 2009). A user can choose the perspective that conforms with the type of study being conducted. Table 2 presents impact categories offered in ReCiPe "Individualist".

Table 2: Impact categories available in the ReCiPe method "Individualist" (Rivm.nl, 2019).

Type	Impact category	Unit
Midpoint	Global warming	kg CO_2-eq
	Stratospheric ozone depletion	kg CFC11-eq
	Ionizing radiation	kBq C-60 eq
	Ozone formation, Human health	kg NO_x -eq
	Fine particulate matter formation	kg $PM_{2.5}$ -eq
	Ozone formation, Terrestrial ecosystems	kg NO_x -eq
	Terrestrial acidification	kg SO_2 -eq
	Freshwater eutrophication	kg P -eq
	Marine eutrophication	kg N-eq
	Terrestrial ecotoxicity	kg 1.4-DCB
	Freshwater ecotoxicity	kg 1.4-DCB
	Marine ecotoxicity	kg 1.4-DCB
	Human carcinogenic toxicity	kg 1.4-DCB
	Human non-carcinogenic toxicity	kg 1.4-DCB
	Land use	m^2a crop-eq
	Mineral resource scarcity	kg Cu-eq
	Fossil resource scarcity	kg oil-eq
	Water consumption	m^3
Endpoint	Damage to Human health	DALY
	Damage to ecosystem	species•yr
	Damage to resource availability	USD2013

Impact 2002+ is a method that also combines mid-point and end-point level impacts, as seen in Table 3. Impact 2002+ combines four different LCIA methods: IMPACT 2002 (Pennington et al. 2005), Eco-indicator 99 (Goedkoop & Spriensma. 2000, 2nd version, Egalitarian Factors), CML (Guinée et al. 2002) and IPCC (Humbert et al., 2012). Compared to ReCiPe, the end point level impacts include *Climate change*, in addition to *Ecosystem diversity, Human health damage* and, *Resource availability.* In order to develop non-spatial, spatial-European and global versions of the environmental profile for other categories, additional modifications were introduced regarding the assessment of some impact categories (Frenette et al., 2010; Rochat et al., 2006; Karim, 2011)

Table 3: Impact categories available in the Impact 2002+ method (Humbert et al., 2012).

Type	Impact category	Unit
Midpoint	Carcinogens	kg C_2H_3Cl-eq
	Non-carcinogens	kg C_2H_3Cl-eq
	Respiratory inorganics	kg $PM_{2.5}$-eq
	Ionizing radiation	Bq C-14-eq
	Ozone layer depletion	kg CFC-11-eq
	Respiratory organics	kg C_2H_4-eq
	Aquatic ecotoxicity	kg TEG water
	Terrestrial ecotoxicity	kg TEG soil
	Terrestrial acid/nitrification	kg SO_2-eq
	Land occupation	m^2.org.arable
	Aquatic acidification	kg SO_2-eq
	Aquatic eutrophication	kg PO_4 P-lim
	Global warming	kg CO_2-eq
	Non-renewable energy	MJ primary
	Mineral extraction	MJ surplus
Endpoint	Human health	DALY
	Ecosystem quality	PDF•m^2•yr
	Climate change	kg CO_2 eq
	Resources	MJ primary

IPCC 2013 is a Life cycle impacts assessment (LCIA) methodology developed by the United Nations Environment Program (UNEP) that specifically deals with climate change and evaluates its consequence on human health, ecosystem, and availability or resource (Karim, 2011; UN Environment, 2019). The method is constantly updated with the most recent, global scientific research, for a better comprehension of climate change. In this method, climate change is characterized as GWP and can be evaluated within three different time horizons: 20, 100 and 500 years. In addition, the method is regularly updated with recent scientific discoveries regarding climate change.

Table 4: Impact categories available in the IPCC 2013 method.

Impact category	Impact Indicator	Unit
Global warming potential	IPCC GWP 20a	kg CO_2-eq
	IPCC GWP 100a	kg CO_2-eq

CML-IA (baseline) is an LCIA methodology developed the University of Leiden in the Netherlands in 2001(Acero et al., 2014). According to Van Oers (2012), CML-IA (baseline) is a midpoint-oriented method that includes the characterization factors for all baseline characterization methods mentioned in the Handbook of LCA. Indicators included in this method can be seen in Table 5. Normalization factors for EU and the World are available in the CML-IA (baseline) method (Van Oers, 2012). The impact categories used in the CML methodology are based on global region, excluding *Acidification potential (AP)* and *photooxidant chemical formation potential* (POCP), which are derived from average European values (Commission, 2010; Guinée, 2002). Furthermore, the global warming potential indicator is developed according to the IPCC 5th Assessment Report model, based on a 100-year time horizon (Stocker et al., 2013). EN 15804 standard recommends the use of CML IA impact assessment method.

Table 5: Impact categories available in the CML-IA (baseline) method (Acero et al., 2014).

Type	Impact category group	Unit
Midpoint	Acidification	kg SO_2-eq
	Climate change	kg CO_2-eq
	Depletion of abiotic resources	kg Sb-eq/ MJ
	Ecotoxicity	kg 1.4-DB-eq
	Eutrophication	kg PO_4-eq
	Human toxicity	kg 1.4-DB-eq
	Ozone layer depletion	kg CFC-11-eq
	Photochemical oxidation	kg C_2H_4-eq

Cumulative energy demand (CED) is based on the method published by Ecoinvent version 2.0 and broadened by PRé Consultants for SimaPro 7 (PRé Sustainabilty, 2019). The CED method is used to quantify the usage of primary energy through a life cycle of a product, in units of MJ (Acero et al., 2014). This includes indirect and indirect uses of energy, and the type of energy used. It as well includes energy utilized during extraction, manufacturing, construction, usage, and disposal phases (Huijbregts et al., 2010). For weighting purposes, a primary energy conversion factor can be assigned to different types of energy.

Table 6: Impact categories available in the Cumulative Energy Demand methods (Acero et al., 2014).

Impact category group	Impact	Unit
Non-renewable resources	Fossil	MJ
	Nuclear	MJ
	Primary forest	MJ
Renewable resources	Biomass	MJ
	Geothermal	MJ
	Solar	MJ
	Wind	MJ
	Water	MJ

2.7 Normalization and weighting factors

Normalization is an approach in which impact indicators that are of different units are converted into unit-less values (Joshi, 2009). This enables the comparison between different impact indicators (Karim, 2011). Normalization is attained by dividing the value of each impact category by a reference value. According to the ILCD handbook (2010), a reference value can be the impact or damage due to the total annual environmental impacts of a country, region, globally, or per capita. For example, this can be the annual environmental impacts of a specific impact category per person in Sweden.

Weighting is achieved by multiplying each indicator result by a specific weighting factor and the values obtained are then summed up to a total environmental score (Joshi, 2009). A weighting factor is based on subjective assessment reflecting political, social, or ethical aspect (Karim 2011). An example of this, given by Karim (2011), is that an impact category such as *Water consumption* would have a significant importance in countries suffering from drought, where its relevance in countries with ample water supplies is lower. Weighting can be applied to some LCIA methods. It can also be applied to both normalized and non-normalized values (Joshi, 2009).

An example of a weighting method is the Shadow cost method. The shadow cost is a Dutch method that represents the cost needed to mitigate damages due to the environmental impacts of a material or system. It represents the highest monetary amount a society should pay to obtain environmental equality (De Bruyn et. al., 2010; Chevalerias, 2015)

According to ISO 14044 (2006), normalization and weighting are optional steps.

2.8 LCA databases

LCA databases provide life cycle inventory based on different sources. There are several databases available ranging from regional to international databases. There are more databases that are under development all around the world.

CPM LCA database was established by the Swedish Life cycle center, in 1995. The database presents reviewed data that are categorized as follows: Sufficient, Acceptable, or Unsatisfying (Hollerud et al., 2017). A validity timeframe is also assigned to the datasets. Three different formats of data sets are provided. The first format is developed by Sustainable Product Information Network for the Environment (SPINE), while the second format, compliant with ISO 14040/44 standards, is developed by International Reference Life Cycle Data System (ILCD, 2010). The third format offers ISO/TS 14048 report. Most of the data are only applicable in Sweden and neighboring areas.

U.S. Life Cycle Inventory Database (USLCI) is a free public database that was developed through a collaboration between the National Renewable Energy Laboratory (NREL) and the Athena Institute, directed by the U.S. Department of Energy (U.S. Life Cycle Inventory Database, 2012; Hollerud et al., 2017). The database provides two types of inputs: elementary flows and unit processes. Transparency is a crucial element in this database; therefore, data providers are stated under the Modeling section. The database also undergoes regular updates.

Ecoinvent database was established by the Swiss Centre for Life Cycle Inventories (Martínez-Rocamora et al., 2016). The database provides thousands of documented process data for a wide variety of products. Due to its transparent and consistent life cycle inventory databases, Ecoinvent has been included in LCA programs like SimaPro and GaBi. A thorough review procedure is applied to all new datasets, to ensure a high level of data quality throughout the entire database (Ecoinvent Database, 2018). All the data related to LCA are ISO 14040/44 compliant.

Ecoinvent also offers three different system models: *Allocation at point of substitution (APOS)*, *Consequential* and *Cut-off* (Ecoinvent 3, 2018). According to Ecoinvent 3, in the *APOS* model, burdens are allocated relative to a particular process, following the attributional method. The *cut- off system model* is based on the concept that a producer is fully responsible for the material's waste disposal, and that he or she does not gain any points for the supply of any recyclable materials (Ecoinvent 3, 2018). This means that recyclable materials come with no burden. However, for secondary recyclable materials, only the impacts of recycling are taken into account. In the *consequential system model*, the consequences of a change in a system is evaluated by using different assumptions (Ecoinvent 3, 2018). This can be applied when conducting an overview study and forecasting future changes. The theory behind the modeling systems varies in several characteristics of the attributional approach that the cut-off model is based on. Please refer to *Section 3.3* for more information on the different system models

2.9 LCA tools

There are several numbers of tools available for conducting an LCA. Each tool differs in accessibility, datasets, and interface. The following are some common LCA tools used nowadays.

OpenLCA is an open source LCA software, created by Green Delta in 2006 (Green Delta| OpenLCA, 2018). OpenLCA offers both commercial and free databases. Transparent calculation methods for inventory and impact assessment are offered in the software. The software has a user-friendly interface and allows for the examining of Life Cycle Costing (LCC) and social assessment.

SimaPro is developed and distributed by PRé Sustainability Consultants, based in the Netherlands (Hollerud et al., 2017). On a global level, SimaPro is one of the two most utilized popular LCA programs. The software provides multiple versions, suitable for different needs. A license is required to be able to use a software. SimaPro offers a variety of databases such as Ecoinvent, USLCI, etc. SimaPro is compliant with ISO 14000. The software also offers the possibility of conducting uncertainty analysis.

GaBi, another popular software, is one of the most used LCA software tools. The software is developed by a German company called PE INTERNATIONAL (Herrmann & Moltesen, 2015). It is designed to perform environmental assessment analysis as well as LCC and social assessment (Augustsson, 2014). The software offers a total of 19 different databases, two of which are the main databases: Lean and Professional. All LCA data are in accordance with ISO 14040/ 44 (Hollerud et al., 2017).

3 Literature review

3.1 Built environment

In developed countries, the construction sector is responsible for a high percentage of the total environmental impacts (Cabeza et al., 2014). Building construction and operation represent, globally, 40 % of raw materials usage, 40 % of total energy usage, and 13 % of total water consumption (Burgan & Sansom, 2006). Furthermore, a building's embodied environmental impact throughout its life cycle can be equal to or more than that associated with the operational phase (Khasreen et al., 2009). This can be the case, especially in recently built buildings, as they have lower operational energy and use more materials, allowing for the embodied energy to have a higher impact (Ramírez-Villegas et al., 2019). This is due to the increase in the use of materials for insulation and building services (Sartori & Hestnes, 2007). A study conducted on a hypothetical zero-emission office building showed that the embodied energy of the materials accounted for 66 % of the total energy, taking into account a building lifespan of 60 years (Dokka et al., 2013). This was due to the use of renewable energy which resulted in lower emissions during the operational phase. Monahan & Powell (2011) analyzed the embodied carbon and energy of modern construction methods and found that choosing more environmentally friendly material and construction methodologies can significantly reduce the environmental impact in residential buildings.

3.2 Life cycle assessment of HVAC systems.

The life cycle of an HVAC system can make up a large percentage of the overall environmental impacts and the primary energy need of a building. In a study conducted by Scheuer et al (2003), the LCA of a six-story building in the US was evaluated, with a building life span of 75 years. The building's structure, envelope, interior structure, and finishes along with the utility and sanitary systems were taken into account. The system boundary included production and transportation of the building materials as well as the construction and demolition of the building. The primary energy intensity of the building's life cycle was estimated to be 316 GJ/ m^2. Around 94 % of the estimated primary energy was associated with HVAC and electricity use. A study conducted by de Klijn-Chevalerias and Javed (2017) assessed the environmental impacts of different building materials using the Dutch method approach. It was indicated in the results that environmental impacts and embodied energy of the HVAC system accounted for approximately 20−25 % of the overall shadow cost of the building in the base case and modified case scenarios. In all cases, HVAC systems were the major contributors to the total shadow cost of the building.

The environmental impacts of a building or a system vary with each life cycle phase. The assigned regional climate and energy mix in a study can as well have a direct influence on the environmental impacts associated with a specific life cycle phase of a building or a system. A study performed by Shah et al. (2008) evaluated the LCA of a heating and a cooling system in four US regions. It was concluded in the study that the operational phase consumed the most energy. It was also found that the environmental impacts of the heating and cooling system are dependent on the local climate and energy type. In a study conducted by Wallhagena et al. (2011), the LCA of an office building in Sweden was evaluated. Unlike previous literature, the results showed that the operational phase did not contribute as much in terms of emissions. This was due to district heating use in Sweden that is mainly based on renewable energy. This places a significant emphasis on environmental impacts that arise from other life cycle phases of the building. Another study analyzed the environmental impacts of a new high-end office building in Finland, with a 50-year lifespan (Junilla & Horvath, 2003). The results indicate that the impacts were mainly related to the manufacturing of building materials and electricity usage. Electricity used for building services and the production and maintenance of steel, concrete and paint, show to have the highest impact. Based on a previous study carried out in 1999, Nyman & Simonson (2005) assessed the environmental impacts of building services in Finland, with a 50-year life span. The results show that the use of heat recovery can aid in reducing the environmental burdens of HVAC system. Additionally, results indicated that bigger AHUs have lower impact due to smaller flow resistance. As shown in the literature cited previously, it was also concluded that the energy mix and local climate along, with the air flow rate set, play a major role on the environmental impact that an HVAC system will have. It should be noted that energy for heating the air and the ductwork was not considered in the study as opposed to this thesis.

HVAC systems vary in functions, efficiency, and environmental impact. A variety of factors can influence the environmental impacts of an HVAC system during its lifecycle. These factors range of materials used, energy type, system boundary, etc. A study done by Chen et al., (2013) compared three different ventilation systems: VAV, ACB, and Under air floor distribution (UAD) systems. It was found that, compared to air conditioning systems, the ACB system has more energy saving potential, although it has the highest embodied energy during the manufacture stage amongst all the system. Overall, the ACB's life cycle has the least environmental impact over a span of 50 years, while the VAV system has the highest impact, out of the three systems evaluated. In another study, Chau et al., (2007) assessed the environmental impacts of building materials and building services components for commercial buildings in Hong Kong, with a building life span of 50 years. The system boundary included extraction, production, transportation of materials and components, and construction process. Although they accounted for 2 % of the building's total weight, building services components made up 27 % of the total environmental impacts. This is compared to concrete which made up 74 % of the total weight but contributed 14 % of the total environmental impacts. Another study highlight that ventilation ducts contribute highly to the impact of the system due to fossil fuel used for their production (Borg, 2016). In this study, the LCA of a ventilation system is evaluated from cradle to grave, varying the time horizon. It was found that the AHU contributed highly to the human toxicity impact category more than the climate change impact category. This was due to the sulfide disposed resulting from copper production. In a study conducted by Prek (2004), the environmental impacts of three different heating systems, including a radiator system, a floor heating system, and a fan coil convector system, were evaluated. The results show that copper pipes used in the radiator heating system have three times the environmental impacts exhibited by steel pipes. If no additional building construction is taken into account, the floor heating system would have the lowest environmental impacts.

There is a significant potential of lowering the primary energy need of an HVAC system through the use of recycled materials. As steel is one of the main materials in HVAC systems, it is important to note the effect of using recycled steel. A study conducted by Kofoworola & Gheewala (2009), assessing the LCA of office buildings in Thailand, showed that the manufacturing of steel and concrete along with the electricity usage of HVAC and lighting systems have a significant impact on the life cycle of the building. It was concluded that the use of recycled materials can lower the overall environmental impact of a building. Bribián et al., (2009) found that the use of recycled materials, such as steel and aluminum, can reduce the embodied energy up to 50 %. Thormark (2002) assessed the recycling potential on the embodied energy and energy need in low energy building and found that, through recycling, around 40 % of the embodied energy can be recovered.

3.3 Choosing an LCA Modelling system

LCA modelling systems fall into two main categories as discussed in *Section 8.4*: Attributional and consequential. Attributional system model is characterized by their aim to describe the physical flows that are environmentally admissible in a life cycle. Consequential system model is characterized by its focus on outlining how environmentally relevant flows will vary with respect to potential decisions (Curran, 2007; Finnveden et al., 2009). When used for decision making, consequential LCA should be conducted. However, only when the results of attributional and consequential LCA differ considerably and there are more insights gained than uncertainties (Ciroth, Huppes, & Lundie, 2008). According to Weidema (2003), consequential LCA can be admissible when it comes to decision-making, however, it is more admissible when it comes to comprehending the product chain and identifying the processes and relations that are essential to improve. Nonetheless, Ekvall et al. (2005) mention that attributional and consequential LCA modeling systems can both be used for learning purposes and also for decision-making. Attributional LCA is valid for the aim of bypassing connections with systems exhibiting large environmental impacts. On the other hand, Consequential LCA is viable when evaluating the environmental consequences of individual decisions or rules. Therefore, both of these purposes are appropriate. According to Ekvall & Weidema (2004), the modelling systems are based on different choices between average and marginal data. The Attributional modelling system encompasses average data that depict the average environmental burdens associated with a specific process in a system. Consequential modeling system encompasses marginal data that depicts the effects of minor changes in the output process of a system on the environmental burdens of that system (Ekvall & Weidema, 2004).

The ILCD handbook identifies three main scenarios where the choice between attributional and consequential LCA is advised for each one (Brown et al., 2011):

1- Attributional LCA is recommended when the decision-making is at a micro- level. For instance, the effects due to one building will not have significant consequences on the background system.

2- Decision making based on a macro-level such as implementing a building sector policy might have a significant consequence on the background system and therefore consequential LCA is recommended.

3- The use of LCA for accounting, with or without system-external interactions.

3.4 Life cycle impact assessment

There is a wide variety of impact assessment method and each depends on the type of study being conducted. Each impact assessment method can as well yield different results due to the use of different characterization factors and, therefore, direct comparison between methods might not be applicable. For instance, a study that investigated the impacts related to the manufacturing of cylinder heads for a diesel and a petrol automotive powertrain used three different environmental impact assessment methods: ReCiPe, Eco-indicator 99, and Impact 2002+ (Stavropoulos et al., 2016, p. 630). The impact categories investigated were Human health, Resource consumption and Ecosystem quality. Following the Eco-indicator 99 method, the ReCiPe method showed the highest environmental impact values. However, a negative score representing the environmental impacts was observed when using the Eco-indicator method. Out of the three methods used, the Impact 2000+ method provided the lowest values. This was due to the fact that each method uses different weighting factors. Therefore, it was concluded in the paper that a direct comparison amongst these methods is not valid. However, petrol head showed to have the highest environmental impact, regardless of which method was used. In another study, Pizzol et al. (2010) investigated the impacts of a variety of metals on human health and human toxicity, comparing nine methodologies of LCIA. It was found that there was a discrepancy between the values obtained when using the ReCiPe LCIA method and EPS 2000 LCIA method. EPS showed notably lower values compared to ReCiPe. Pizzo et al. attributed this to the absence of characterizations factor for metals in the EPS method (Andersson & Listén, 2014). Another study compared three different impact assessment methods: EDIP97, CML2001 and Eco-indicator 99, using the same life cycle inventory from a study of a water-based UV-lacquer. The results showed that for human toxicity the CML2001 score was dominated by the input of metal, while the EDIP97 score was affected by solvent and nitrogen oxides (Dreyer et al., 2003). Furthermore, in terms of Aquatic ecotoxicity, metals were the main contributors for both methods, but while it was vanadium in CML2001, it was strontium in EDIP97. The study concluded that what matters when choosing an impact assessment method is whether the chemical impacts on human health and ecosystem health are essential for the study or not.

3.5 Overview

In terms of HVAC systems, many studies have focused on the operational phase of the system. However, existing studies have shown that HVAC systems can cause a building to have a high environmental burden, especially during the manufacturing phase. Several works of literature have as well agreed that the environmental impacts of an HVAC system are highly dependent on the energy mix and local climate. Wallhagena et al., (2011) showed that when the energy utilized in the operational phase is based on renewable energy, other life cycle phases can have a more significant environmental impact. Moreover, most of the studies done on the LCA of HVAC systems focused mainly on carbon-foot print and embodied energy. While these are essential indicators, there is a need to explore other indicators such as acidification and photochemical oxidation, etc., especially when looking at materials such as steel and copper. Existing studies have also highlighted the importance of using secondary materials, where its shown that the environmental impacts of a system decrease when recycled materials were used instead.

When performing an LCA study, several impact assessment methods can be used. The selection of the impact assessment method will depend on its relevance to the study's background and regional validity. Some commonly used impact assessment methods found in literature are Eco-indicator 99, ReCiPe, CML IA and IMPACT 2002+.

When choosing a modelling system for an LCA study, it can be seen that the methodological approach and data selection of the life cycle inventory and impact assessment are highly influenced by the goal definition (Finnveden et al., 2009). As mentioned by Curran (2013), Consequential LCA is theoretically complex as it encompasses economic concepts that are based on previous trends in prices and consumption, etc. There is an added risk of insufficient assumptions that can have a drastic effect on the results. Therefore, it is crucial to make certain that there is plausible reasoning behind the results obtained. However, it is challenging to specify which approach is the most legitimate as its dependent on the study's scope and the researcher's point of view.

4 Methodology

The building and systems presented in the following subsections were initially designed for a previous research carried out by Abugabbara et al. (2017) and used as a base case in the LCA study conducted in this thesis.

4.1 Building description

This study assessed three HVAC systems in a hypothetical modern office building located in Malmö, Sweden. The building consists of three stories and their floor areas can be seen in Table 7. According to Abugabbara et al. (2017), the building is divided into six thermal zones. An occupancy pattern based on Halvarsonn (2012) was adopted. The U-value of the thermal envelope was set based on the latest requirement set by BBR (Boverkets byggregler, 2018). The operative temperature was set to not exceed 22 *°C* in winter and 26 *°C* in summer. The building was assumed to have a set-back operative temperature of 18 *°C* in winter and 28 *°C* in summer.

Table 7: Building area per floor.

Level	Area/ m^2
Ground floor	418
First floor	514
Second floor	359

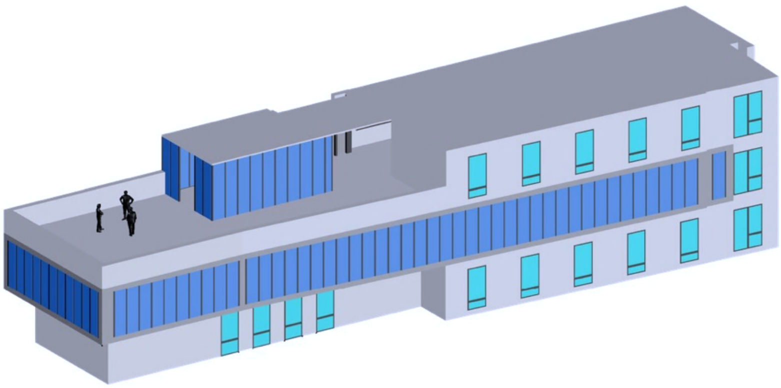

Figure 5: Building 3D Model (Abugabbara et al., 2017).

4.2 HVAC systems

The LCA was conducted for a CAV, a VAV, and an ACB system. The systems were designed in a research carried out by Abugabbara et al. (2017), using CADvent, a plugin for AutoCAD. The CAV system operates in two modes. When the building is occupied, the system supplies the maximum air volume and when there is no occupancy the system supplies only the required hygienic air flow. The VAV and ACB regulate the air and water volume rates depending on the occupancy pattern. The energy use of the CAV, VAV, and ACB systems were calculated by Abugabbara et al. (2017) and modified to be used as an input for the LCA study conducted. The calculated annual energy consumption, given at kWh/ m^2, can be seen in Figure 6.

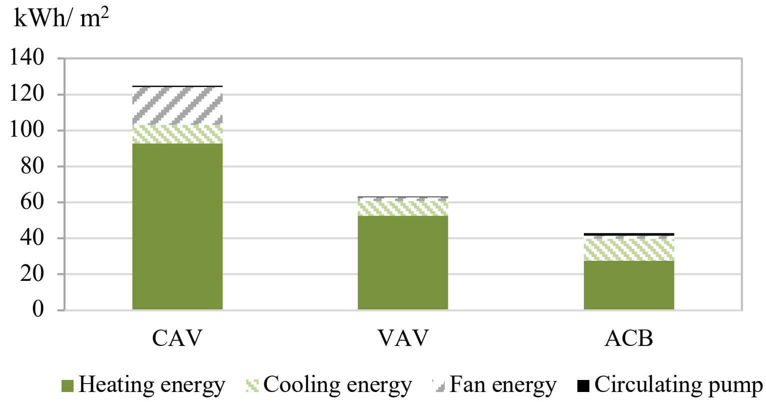

Figure 6: Annual energy consumption per HVAC system (Abugabbara et al., 2017)- Modified.

4.3 Goal and scope

The goal of the LCA was to calculate and analyze the environmental impact relative to the life cycle phases of a CAV, a VAV, and an ACB system. The LCA was cradle-to-grave. The LCA was conducted using SimaPRO software and Ecoinvent 3 database. The LCA system model chosen was Allocation at point of substitution (APOS) which is based on the attributional approach. Market values were chosen for the materials used for the manufacturing of HVAC components. From Ecoinvent database, the waste treatment and recycling scenario ware set to the Netherlands and modified to fit Sweden's recycling rate (FTI AB, 2018). Heating energy used during the operational phase was set based on energy sources used for district heating in Sweden. Initially, the electricity used during the operational phase was set to electricity mix used in Sweden. Different electricity mixes were chosen for energy consumed during manufacturing and operational phase. The CML-IA (Baseline) method was used for the life cycle impact assessment. The Cumulative energy demand (CED) was also estimated for the three systems. Normalizing factors based on EU 25+ 3 200 reference values were used (Van Oers, 2012). The shadow cost approach was used for weighting the results (De Bruyn et. al., 2010). A parametric analysis was then conducted comparing PVC pipes to copper pipes and 100 % clean electricity to the Swedish electricity mix.

4.4 Functional unit

In this study, the function of the HVAC systems was to provide space heating and cooling for a modern office building in Sweden, while maintaining a minimum airflow rate of 0.35 l/ s/ m^2 and 7 l/ s/ person. Therefore, the functional unit was defined to be 20 years of heating and cooling to maintain an indoor temperature of 26° C and 22° C in summer and winter, respectively, while providing a minimum airflow of 0.35 l/s/ m^2 and 7 l/s/ person.

4.5 System boundary

The system boundary of the LCA study included extraction of raw materials, production of the materials, manufacturing of the components, and usage during the operational phase. Available data from the manufacturer allowed for the evaluation of the manufacturing and operational phase of the HVAC components (Lindab AB, 2019). Energy needed for waste treatment and recycling of materials was taken into account. The demolition phase, maintenance phase, and transportation to the construction site of the components were not included due to lack of data. Transportation to Waste treatment and recycling facilities was taken into account; therefore, the system boundary was set to cradle to grave (with options), as seen in Figure 7.

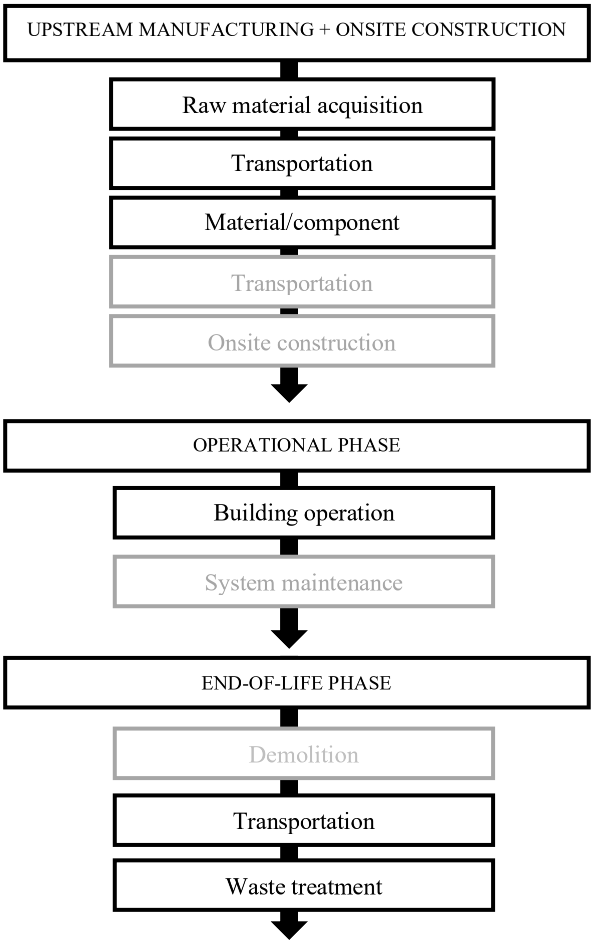

Figure 7: System boundary of the LCA study.

4.6 Life cycle inventory

4.6.1 Materials

A bill of quantity (BOQ) of all the components of the HVAC systems analyzed was obtained from the manufacturer of the HVAC systems, through AutoCAD and CADvent plug-in. The material content of each HVAC component, seen in Figure 8, was then obtained through building product declaration (BPD), along with the weight of each component (Lindab AB, 2019). Components that were not included in BOQ such as pipes and pumps were obtained through environmental product declarations (EPDs) or set according to data found in the Ecoinvent database (Grundfos Holding A/S, 2018; Ecoinvent v3, 2019). Please refer to *Appendix I* and *Appendix II* for more detailed information on the materials and components making up the systems. Market data, within Ecoinvent 3 database, was used for the processing of materials. Market data includes all the environmental impacts associated with extraction of raw materials, transport to production site, energy used for production, etc. (Lindvall, 2018). Market data are based on average data from Europe, Asia, Africa, etc. Market data were chosen to give a fair comparison between materials and to represent the worst-case scenario.

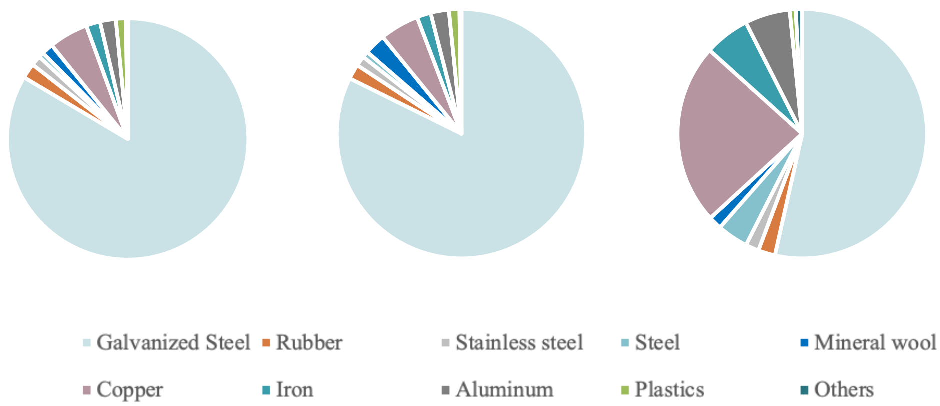

Figure 8: Materials making up the HVAC systems used for the base case in the following order: CAV, VAV, and ACB [1].

4.6.2 Energy

For electricity used during the manufacturing of HVAC components and the operational phase, the Swedish electricity mix was chosen from Ecoinvent 3 database. Figure 9 shows the different energy types based on Sweden's district heating that was used as an input for heating energy. For the cooling energy, a COP of 3 was assumed.

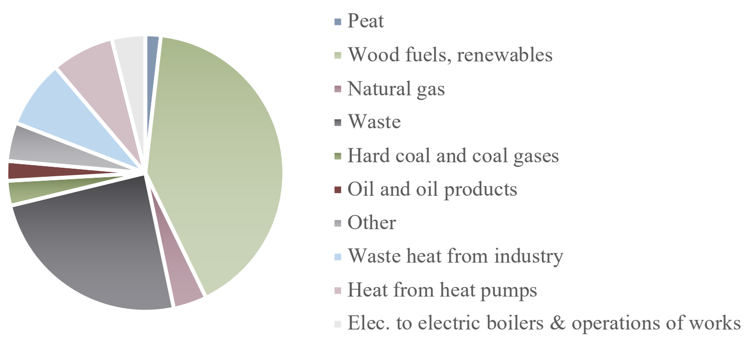

Figure 9: Total energy input for District heating (SCB, 2017).

[1] Materials categorized as others can be seen in Appendix I.

4.7 Life cycle impact assessment

The CML IA (baseline) method, discussed in *Section 2.6*, was used to assess the potential environmental impacts of each system. Normalization based on reference values from EU25+3 2000 was applied to the results (Van Oers, 2012). Initially, for each case scenario, the total environmental impacts of each system were calculated separately. Secondly, the potential environmental impacts per life cycle phase of the CAV, VAV, and ACB systems were compared to each other. The Cumulative energy demand LCIA method was then used to calculate the total life cycle energy use of each system. The shadow cost was then calculated for each system. Reference values from Table 8 were used for the weighting method.

Table 8: Weighting factors based on the shadow cost method (De Bruyn et. al., 2010).

Impact category	Equivalent unit	Weighting factors / (€ / kg eq)
Depletion of abiotic resources	Sb eq	€ 0.16
Depletion fossil fuels – ADP	MJ	€ 0.16
Global warming – GWP 100	CO_2 eq	€ 0.05
Depletion ozone layer – ODP	CFC-11 eq	€ 30
Photochemical oxidant creation – POCP	C_2H_4 eq	€ 2
Acidification – AP	SO_2 eq	€ 4
Eutrophication – EP	PO_4 eq	€ 9
Human toxicity – HTP	1,4-DCB eq	€ 0.09
Fresh water aquatic eco toxicity – FAETP	1,4-DCB eq	€ 0.03
Marine aquatic eco toxicity - MAETP	1,4-DCB eq	€ 0.0001
Terrestrial eco toxicity – TETP	1,4-DCB eq	€ 0.06

After obtaining the results, the environmental impacts due to the life cycle of each system were compared to each other.

4.8 Parametric study

4.8.1 Copper pipes vs. PVC pipes

A parametric study was conducted in which the pipe material is switched from copper (used in the base case) to PVC, in all the HVAC systems. Initially, the analysis was done for each system, assuming the use of PVC pipes for water connections, to show the relationship between that manufacturing, the operational phase, and the recycling & waste treatment phase. Secondly, the life cycle impacts of a system, when PVC pipes are used and when copper pipes are used, were compared to each other. Finally, a comparison of the life cycle impacts of the CAV, VAV, and ACB system was conducted. The results were also weighted based on the Dutch method mentioned in *Section 4.7.* It should be noted that the CAV and VAV systems had pipe connections only between DH connections in the mechanical room and the AHU. On the other hand, the ACB system had pipes for hot and cold-water connections to the beams, in addition to the pipes running between the mechanical room and the AHU.

4.8.2 Swedish electricity mix vs. 100 % renewable electricity

Under the base case scenario, a Swedish electricity mix was set form Ecoinvent database (Ecoinvent V3, 2018). A parametric study was then conducted comparing the potential environmental impacts of the HVAC systems when the Swedish electricity mix is switched to 100 % renewable electricity. The same evaluation steps mentioned in *Section 4.8.1* were followed.

4.9 Assumptions

The lifespan of the systems was assumed to be 20 years. The hypothetical building was assumed to be located in Malmö, Sweden. This assumption was made to enable an accurate comparison, without any difference in climate conditions. The lifetime of the HVAC system was assumed to be 20 years. The electricity used during the operational phase of the building was assumed to be based on Swedish electricity mix for the base case. The building was assumed to be heated by district heating. Due to simplicity reasons, the maintenance of HVAC components was assumed to be similar, therefore not included. It was assumed that the efficiency of the HVAC systems remains the same throughout their life span. Some parts of the HVAC systems were not included due to lack of data. The emissions due to the HVAC systems were assumed constant throughout the life cycle phases. This means that the techno-sphere was assumed to have no changes throughout the life span of the systems. Assumptions made for the waste treatment phase were based on Sweden's recycling rate and transportation assumptions were based on average data obtained through the Ecoinvent database.

5 Results

5.1 Base case

Life cycle impacts of the three HVAC systems, in which copper pipes and Swedish electricity mix are used, are presented in the following section.

5.1.1 Life cycle impacts per system

Figure 10 and Figure 11 present the potential environmental impacts of the life cycle of the CAV and the VAV systems. It can be observed that the operational phase is the dominant contributor to the total environmental impacts of both the systems. One exception is the Abiotic depletion potential in which the manufacturing phase of the VAV system contributes more to the indicator than the operational phase does. Furthermore, recycling & waste treatment phase shows to have slightly lowered the environmental impacts of the systems. Please refer to the *Appendix VI* for more detailed information on what material and/or process are affecting each phase.

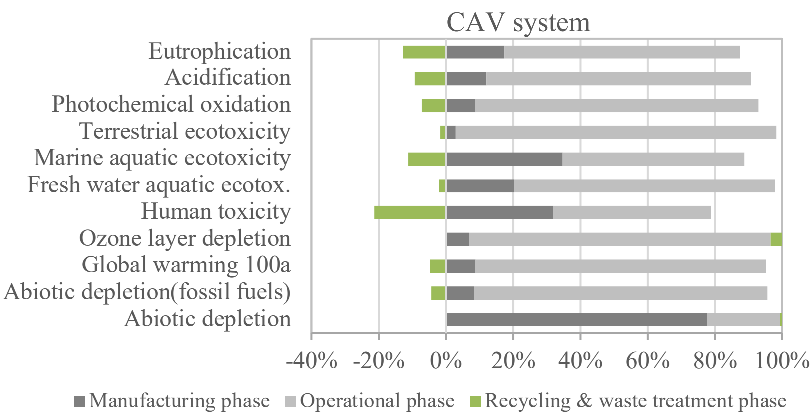

Figure 10: Potential environmental impacts of the life cycle of the CAV system (Base case).

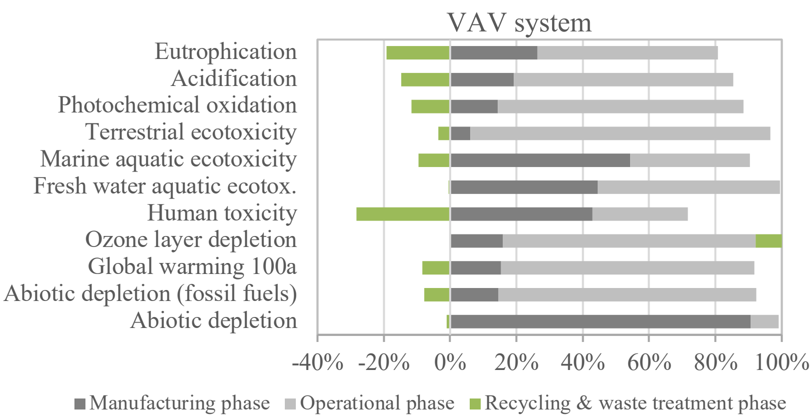

Figure 11: Potential environmental impacts of the life cycle of the VAV system (Base case).

The potential environmental impacts of the life cycle of the ACB system are shown in Figure 12. Unlike the CAV and the VAV systems, the manufacturing phase of the ACB system contributes to the majority of the environmental impacts. Although the recycling and waste treatment phase showed to have relatively mitigated the environmental impacts of the system, it still showed to have an influence on the Ozone layer depletion potential indicator. Please refer to the *Appendix VI* for more on information on what material and/ or process is affecting each phase.

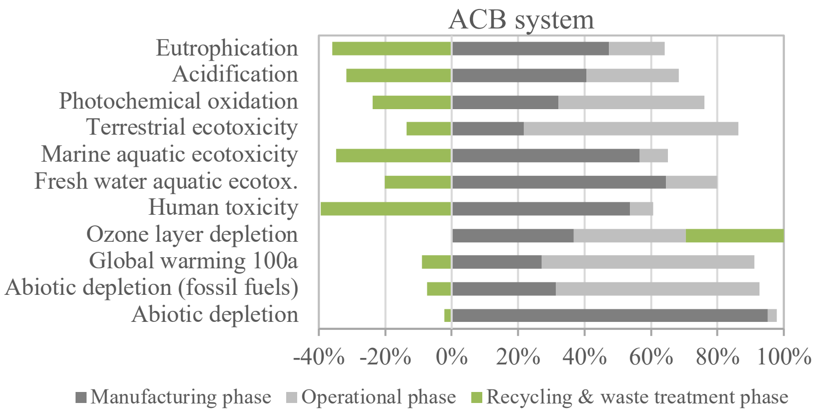

Figure 12: Potential environmental impacts of the life cycle of the ACB system (Base case).

5.1.2 System life cycle phase comparisons

Comparison of the environmental impacts due to the manufacturing phase and the recycling phase of each system is shown in Figure 13. It can be observed that the relative difference of the CAV system to the VAV system is minimal. On the other hand, the relative difference of the VAV and CAV systems to the ACB system is more than 50 %, for the majority of indicators.

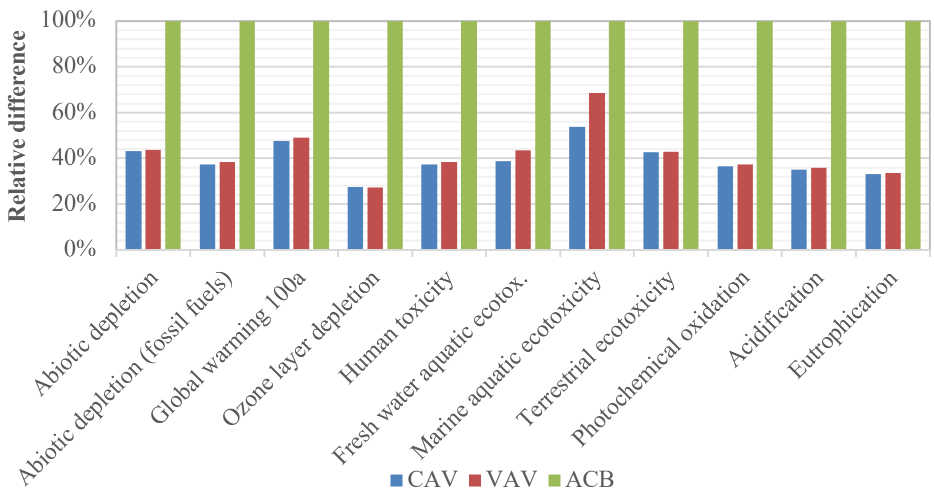

Figure 13: Relative difference between the environmental impacts of the manufacturing & recycling phases of CAV, VAV, and ACB systems (Base case).

When comparing the impacts due to the operational phase of the systems, as seen in Figure 14, it can be observed that the operational phase of the ACB system has the lowest environmental impacts. On the other hand, the CAV system has the highest environmental impacts.

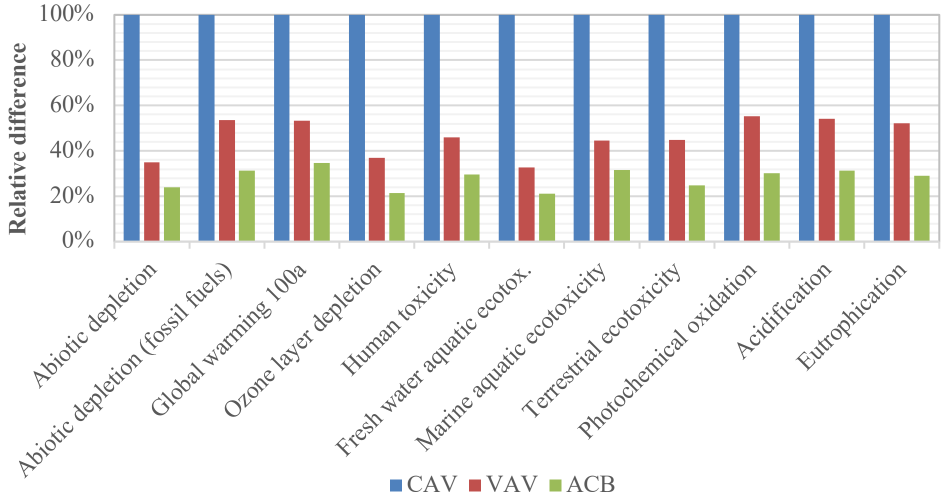

Figure 14: Relative difference between the environmental impacts of the operational phase of CAV, VAV, and ACB systems over 20 years (Base case).

In Figure 15, the relative difference between the life cycle impacts of the CAV, VAV, and the ACB systems vary depending on the environmental indicators. However, the CAV system remains to have the highest environmental impacts for most of the indicators, compared to the VAV and the ACB systems. An exception to this can be seen for the Abiotic depletion of natural elements indicator in which the ACB system show to have the highest environmental impact.

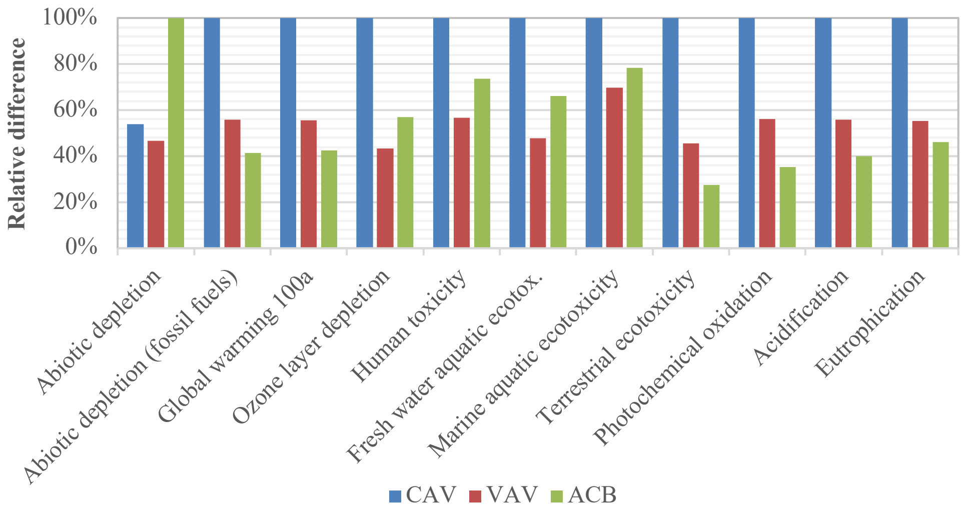

Figure 15: Relative difference between the environmental impacts of the life cycle of CAV, VAV, and ACB systems (Base case).

5.1.3 Cumulative energy demand

The cumulative energy demand shown in Figure 16 indicates that the highest amount of energy is based on biomass, while an adequate amount is based on fossil fuel and nuclear energy. Moreover, a small amount of energy is based wind, solar, geothermal, and water sources. Overall, the life cycle of the CAV system has the highest cumulative energy demand while the life cycle of the ACB system has the lowest cumulative energy demand.

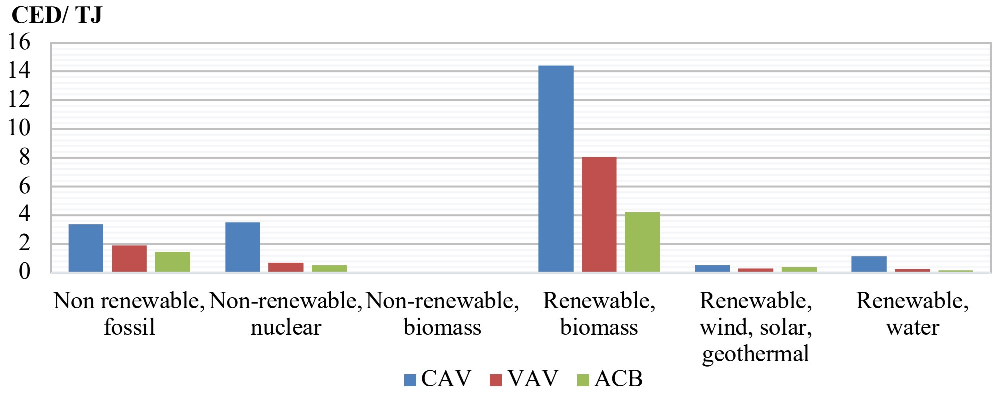

Figure 16: Weighed Cumulative energy demand needed for the extraction, transportation, manufacturing and operation of materials per system (Base case).

5.1.4 Weighting- Shadow cost method

After weighting the results, it can be seen in Figure 17 that the CAV system has the highest shadow cost out of the three systems. Moreover, the VAV system provides a 38 % reduction in shadow costs compared to that of the CAV system. The difference in shadow cost between the VAV and ACB systems is minimal, with a 5 % increase in shadow costs of the ACB system. Nonetheless, the shadow cost of the ACB system remains lower than that of the CAV system.

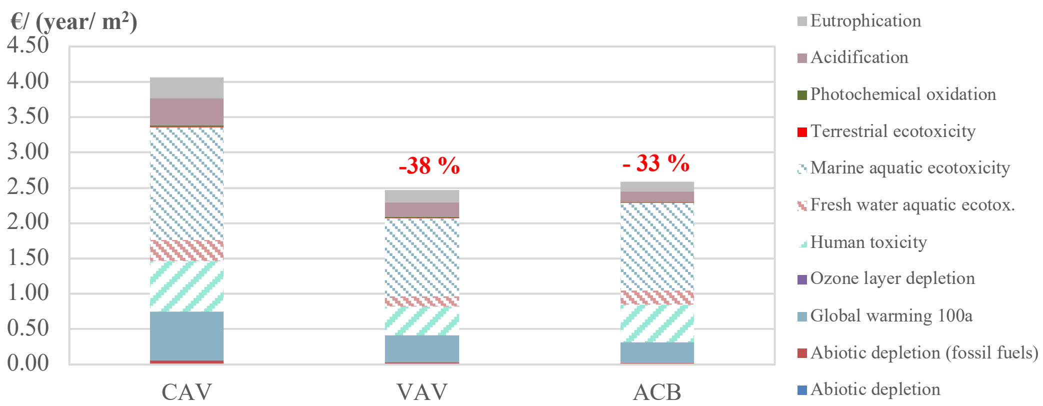

Figure 17: Total shadow cost of the CAV, VAV, and ACB systems (Base case).

5.2 Parametric study

5.2.1 Life cycle impacts per system (Water connection: PVC pipes)

As shown in Figure 18 and 19, with the use of PVC pipes, the impacts due to the operational phase becomes very minimal compared to other life phases of the CAV and VAV systems. Nonetheless, the manufacturing phase of the CAV and VAV systems is still the main contributor to the Abiotic depletion of natural elements.

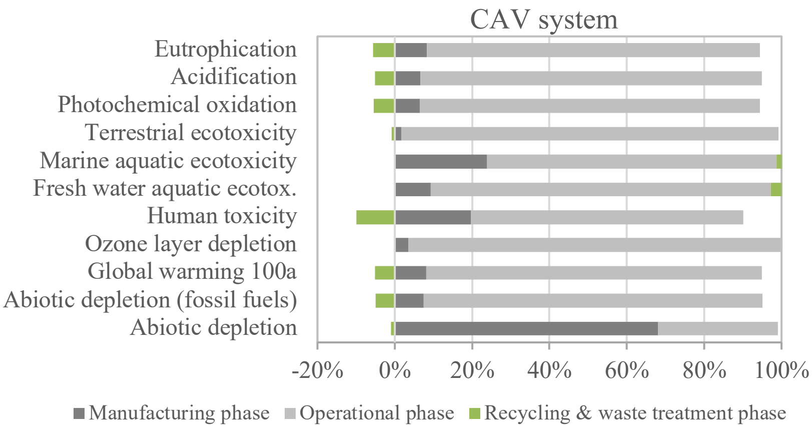

Figure 18: Potential environmental impacts of the life cycle of the CAV system (when PVC pipes are used).

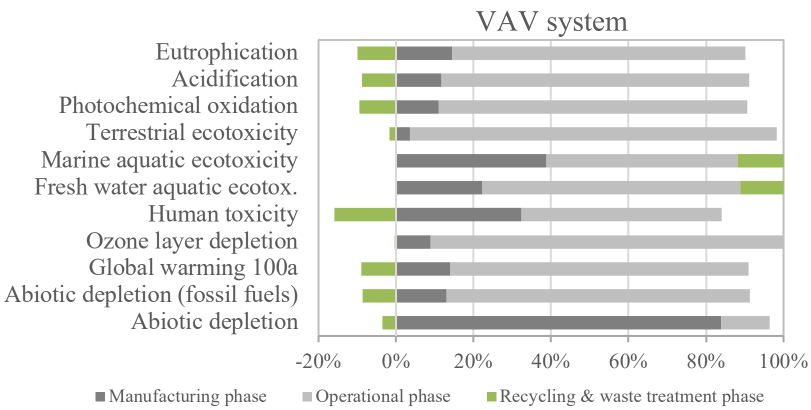

Figure 19: Potential environmental impacts of the life cycle of the VAV system (when PVC pipes are used).

In Figure 20, it can be observed that the environmental impacts due to the manufacturing phase of the ACB system have decreased with the use of PVC pipes. However, Marine and freshwater aquatic ecotoxicity indicator, along with the indicator of Abiotic depletion of natural resources are still highly affected by the manufacturing phase.

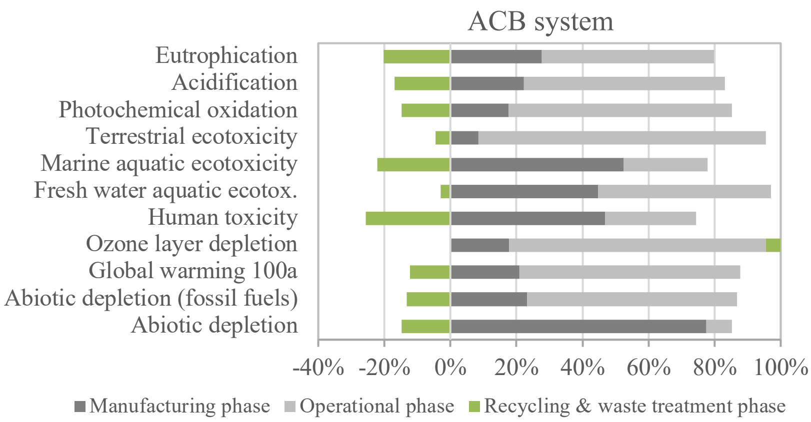

Figure 20: Potential environmental impacts of the life cycle of the ACB system (when PVC pipes are used.

5.2.2 Life cycle comparison per system (Copper pipes vs. PVC pipes)

Figure 21 shows that the relative difference between the life cycle of the CAV system, when copper pipes are used to when PVC pipes are used, is very minimal. However, for the Abiotic depletion indicator, the CAV system, when copper is used, show to have a higher relative difference compared to when PVC pipes are used. This is due to the fact that abiotic depletion of natural resources is highly affected by the use of copper.

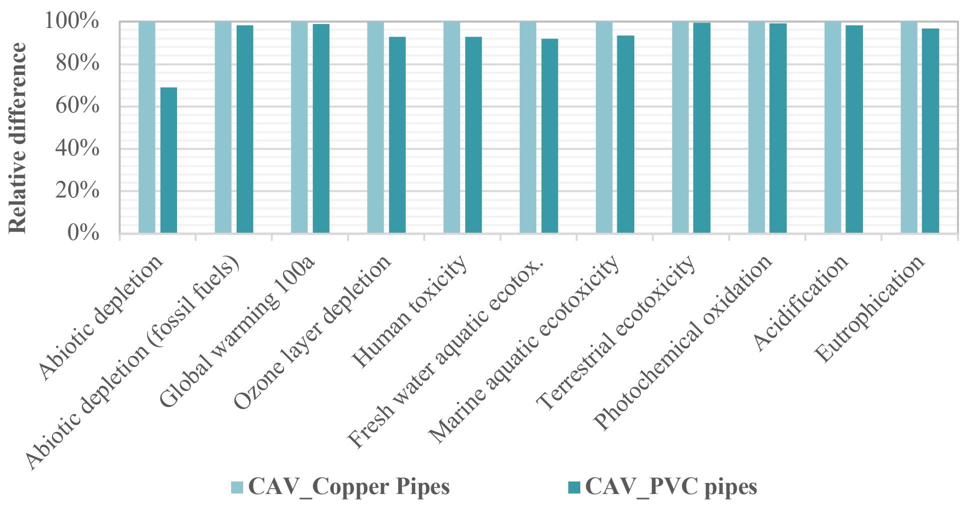

Figure 21: Relative difference between the environmental impacts of the CAV system when Copper and PVC pipes are used.

The same behavioral pattern exhibited by the CAV system can be seen for the VAV system in Figure 22; there is a very minimal change when PVC pipes are used instead of copper pipes.

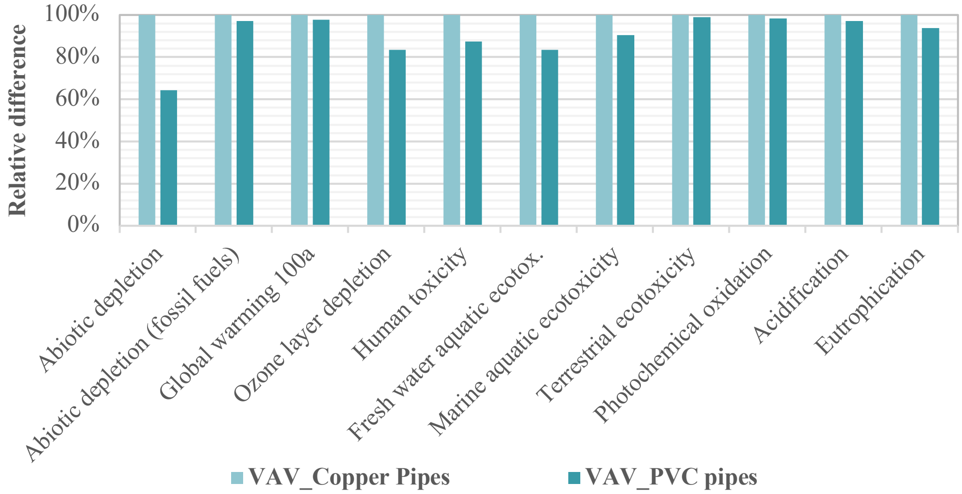

Figure 22: Relative difference between the environmental impacts of the VAV system when Copper and PVC pipes are used.

When the life cycle of the ACB system is compared when using copper pipes to when using PVC pipes, shown in Figure 23, it can be observed that there is a visible decrease in the overall environmental impacts.

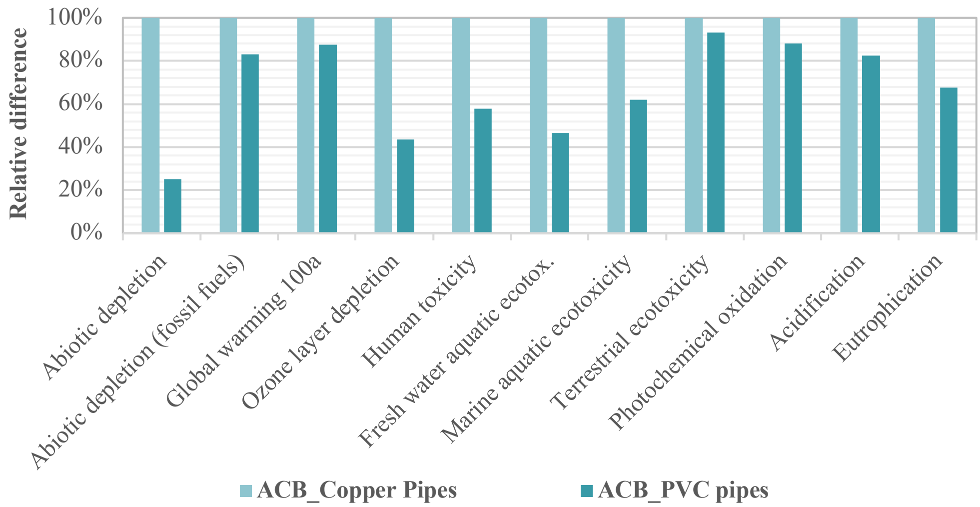

Figure 23: Relative difference between the environmental impacts of the ACB system when Copper and PVC pipes are used.

The life cycle of the ACB system, indicated in Figure 24, has the overall best performance when PVC pipes are used instead of copper pipes. On the other hand, the life cycle of the CAV system remains to have the worst environmental performance compared to the life cycles of the VAV and ACB systems.

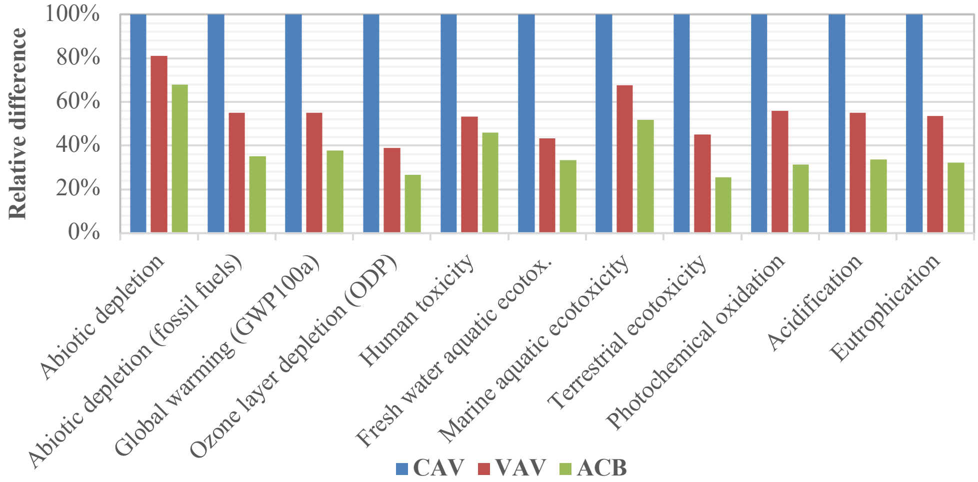

Figure 24: Relative difference between the environmental impacts of the life cycle of CAV, VAV, and ACB systems when using PVC pipes.

Figure 25 shows that the total shadow costs of the ACB system is the lowest compared to the that of the VAV and CAV systems, as opposed to the base case, seen in Figure 17. Nonetheless, the shadow costs of the CAV system decrease slightly compared to the base case, but the CAV system still remains to have the highest shadow cost out of the three systems.

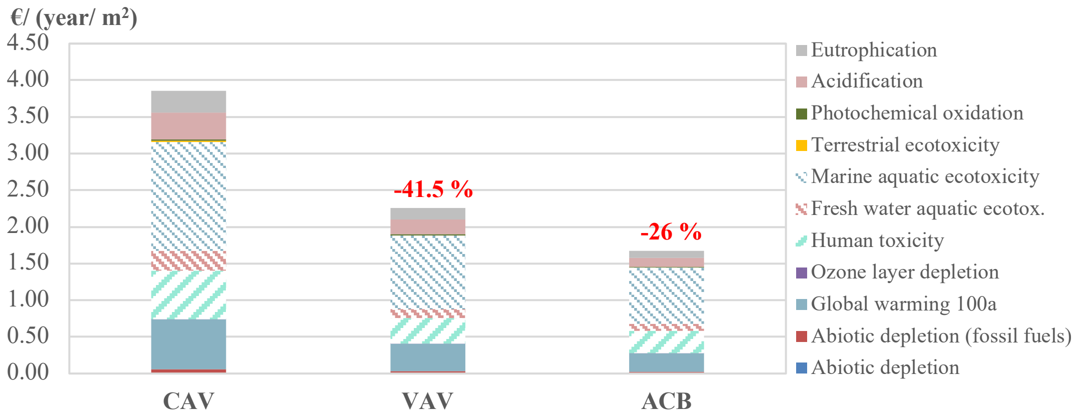

Figure 25: Total shadow cost of the CAV, VAV, and ACB systems when using PVC pipes.

5.2.3 Life cycle impacts per system (Electricity type: 100 % clean)

The operational phase of the CAV and VAV systems remains to be the main contributors to the total environmental impact of the systems, in Figures 26- 27. However, the environmental impacts due to the manufacturing phase becomes slightly emphasized when compared to that of the manufacturing phase, in the base case.

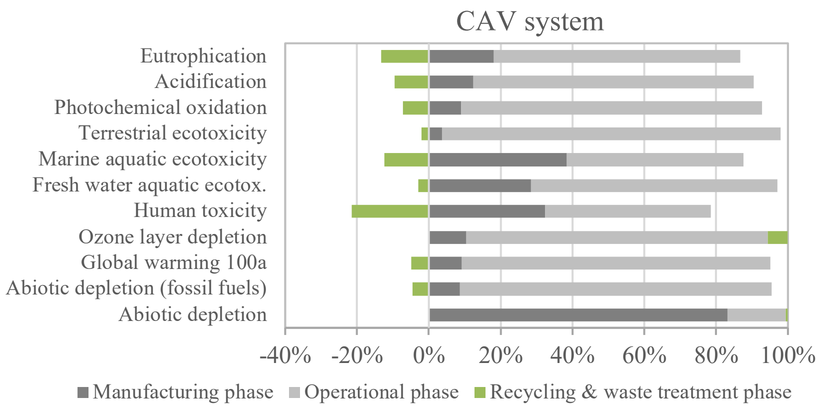

Figure 26: Potential environmental impacts of the life cycle of the CAV system (when 100 % clean electricity is used).

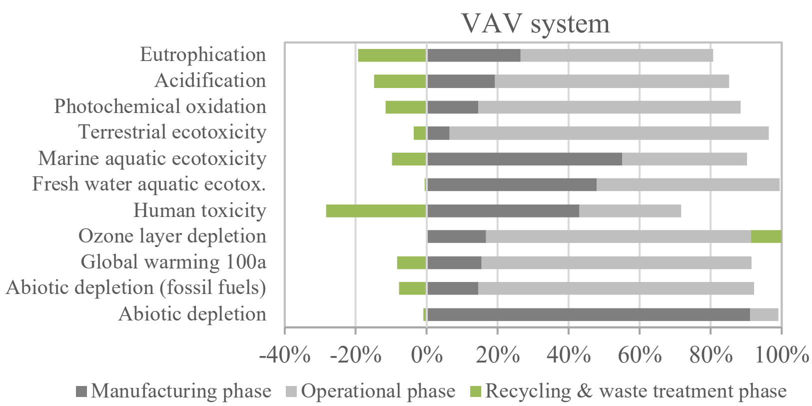

Figure 27: Potential environmental impacts of the life cycle of the VAV system (when 100 % clean electricity is used).

The manufacturing and operational phases of the ACB system, seen in Figure 28, remain to contribute highly to the total environmental impacts.

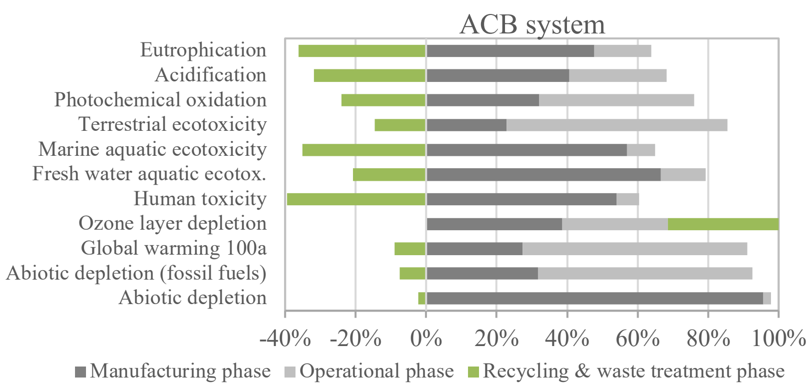

Figure 28: Potential environmental impacts of the life cycle of the ACB system (when 100 % clean electricity is used.

5.2.4 Life cycle comparison per system (Swedish electricity mix vs. 100 % renewable electricity)

Figure 29 presents the relative difference of the CAV system when using Swedish electricity compared to when using 100 % clean electricity. It can be observed that there is a reduction in the relative difference between the environmental impacts of the system, however, it is not very prominent.

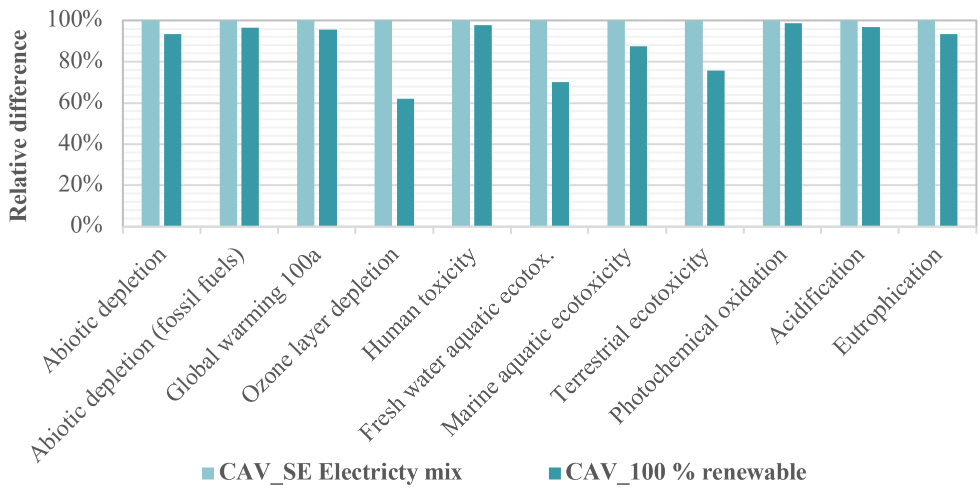

Figure 29: Relative difference between the environmental impacts of the CAV system when Swedish electricity mix is used and when 100 % renewable electricity is used.

When comparing the life cycle of the VAV system when different energy types are used, a minimal to no difference can be seen from Figure 30.

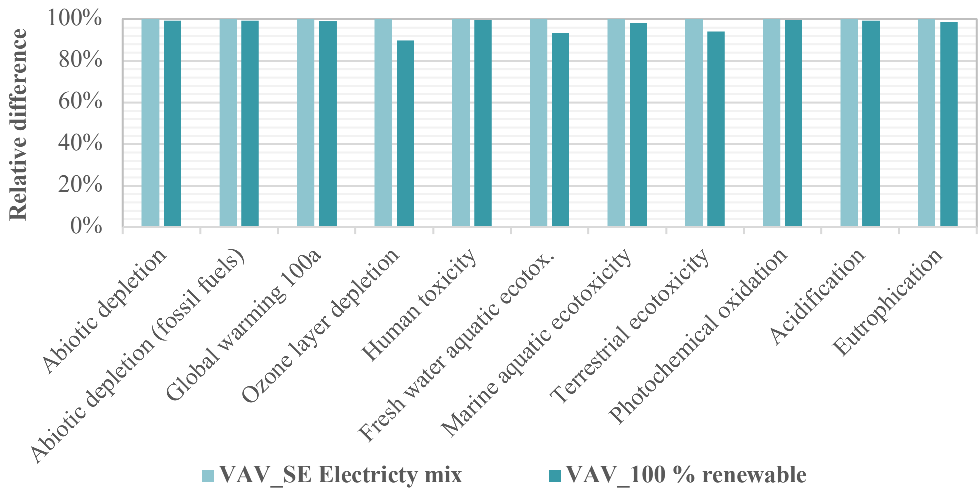

Figure 30: Relative difference between the environmental impacts of the VAV system when Swedish electricity mix is used and when 100 % renewable electricity is used.

In Figure 31, the same pattern seen for the VAV system is observed for the ACB system in which cleaner electricity source does not considerably lower the environmental impacts of the ACB system.

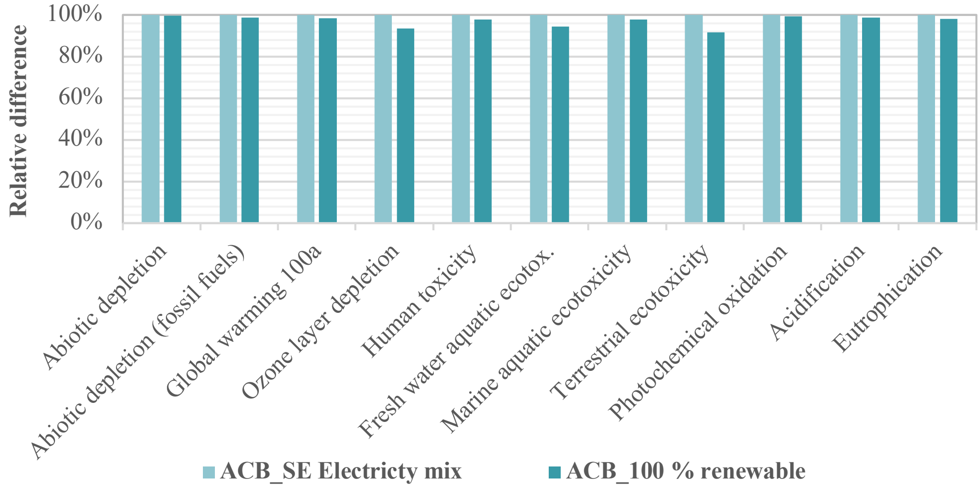

Figure 31: Relative difference between the environmental impacts of the ACB system when Swedish electricity mix is used and when 100 % renewable electricity is used.

It is notable that the life cycle of the CAV system continues to have the worst overall environmental performance compared to that of the ACB and VAV systems, when looking at the relative difference between the environmental impacts of the life cycle of the HVAC systems when 100 % renewable electricity is used, seen in Figure 32.

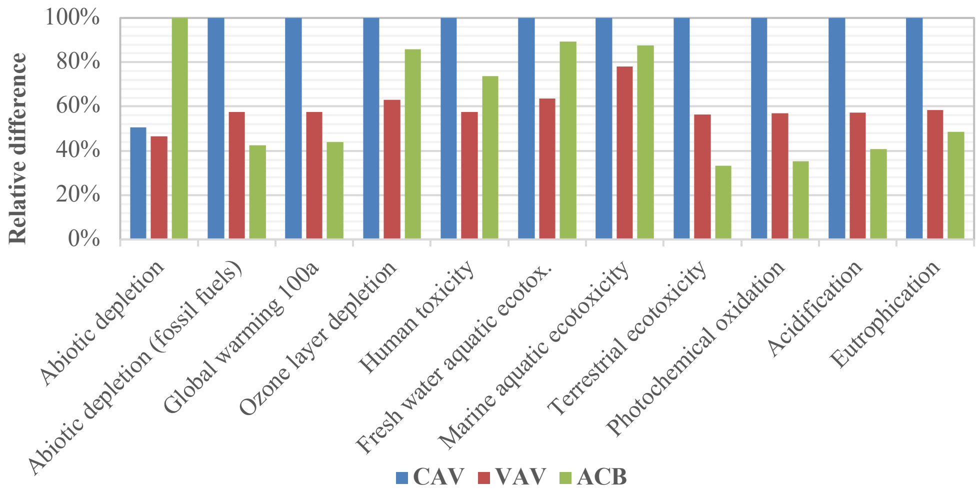

Figure 32 Relative difference between the environmental impacts of the life cycle of CAV, VAV, and ACB systems when 100 % renewable electricity is used.

It can be seen in Figure 33 that the system with the lowest shadow cost becomes the VAV system, with a 4.5 % reduction in shadow costs, compared to the shadow cost of the ACB system. The relative difference of the CAV system to the VAV system decreases slightly from 38 %, seen in Figure 17, to 34 %. Nonetheless, the CAV system remains to have the highest shadow cost.

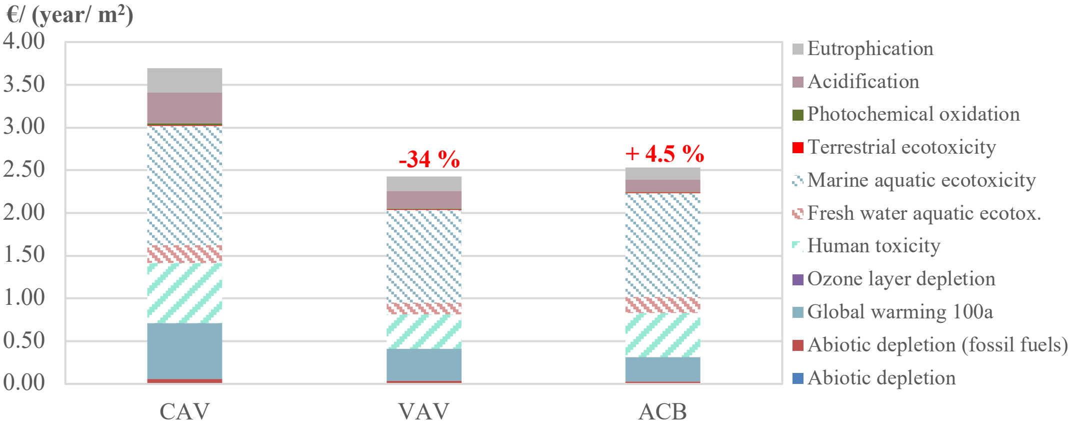

Figure 33 Total shadow cost of the CAV, VAV, and ACB systems when 100 % renewable electricity is used.

6 Discussion and Conclusion

6.1 Discussion

In this thesis, the CML IA life cycle impact assessment method and the Cumulative energy demand method have been used to evaluate the life cycle of each HVAC system. A parametric study has been done changing two parameters in the VAV, CAV, and ACB systems; the material used for pipes and energy source for electricity used by the systems. The shadow cost method has been used to weight the results.

It is clearly indicated from the results that impacts due to the operational phase and manufacturing phase vary depending on the system. When looking at the base case, in which copper pipes are used in the HVAC system, the operational phase of the CAV and the VAV systems contributes to the majority of the total life cycle impact. Nonetheless, the manufacturing phase of the ACB system exhibits the highest environmental impacts compared to those of the CAV and the VAV systems, as was expected from the literature review. However, the environmental impacts due to the operational phase of the ACB system are lower than those of the CAV and VAV systems. This is due to the high amount of energy that the CAV and VAV consume during their operational phase compared to the ACB system.

When comparing the use of PVC pipes to copper pipes in the HVAC systems, seen in Figures 18−25, a slight decrease in impacts can be observed in the life cycles of the CAV and VAV systems. This is because the CAV and VAV systems use pipes only between DH connections within the building and the AHU. This is unlike the ACB system which uses pipes for hot and cold-water connections to the beams, in addition to pipes between the mechanical room and the AHU. Therefore, with PVC pipes, a significant reduction is seen especially in the manufacturing phase of the ACB system, since it uses the highest amount of copper. This is also due to the intense energy needed for the production of copper compared to PVC pipes. Although recycling does mitigate the impacts due to the production of copper, melting and reshaping copper scrap still consume a high amount of energy. Consequently, the main phase contributing to the total environmental impact of the ACB system shifts from the manufacturing phase to the operational phase.

The use of 100 % renewable electricity has a slight influence on the environmental impacts of the three systems. However, while it reduces the impacts due to the operational phase of the VAV and CAV systems, the largest reduction in impacts is noted during the manufacturing phase of the ACB system. This can be justified since the electricity needed for the manufacturing of the ACB system is higher than that used by the CAV and VAV systems. On the other hand, fans and pumps have higher electricity use during the operational phase of the CAV and VAV systems compared to that of the ACB system.

It is noticeable that the recycling process helps mitigate the environmental impacts of the ACB system the most. The recycling of materials, mainly metals, plastic, and electronic components shows a positive effect on most of the environmental indicators. This is especially true in the case of recycling copper since it is one of the main contributors to the environmental impacts of the ACB system. However, recycling does not decrease the environmental impacts of the manufacturing phase of the ACB system enough to be lower than those of the manufacturing phase of the CAV and VAV systems. This is attributed to the substantial amount of energy needed for the manufacturing of the beams themselves. It is also assumed to be due to the complexity of electronic waste recycling, as the ACB system has the highest amount of electronic components compared to the VAV and CAV systems. Moreover, even when copper pipes are not used in the water connections of the ACB system, the system still has a higher copper content in its components(beams) compared to that in the CAV and VAV systems. It is also observed that waste treatment contributes slightly to the ozone layer depletion potential of the systems. This indicates that there are some emissions produced due to the process of waste treatment.

Overall, the same pattern was observed for all the cases. For the CAV system, most indicators are influenced by the operational phase. An exception to this is the Abiotic depletion indicator since it accounts for the natural resources that each system has used during the manufacturing process. The VAV system is mainly influenced by the operational phase, however, its manufacturing phase has a higher impact than that of the CAV, due to its higher total weight – more components make up the VAV system. In all three cases, the manufacturing phase of the VAV system has an equal or higher Marine aquatic ecotoxicity potential (MAETP) and Abiotic depletion potential (ADPE) than the operational phase does. This is also attributed to the fact that MAETP indicator is highly affected by metal production than energy use. Overall, the manufacturing phase of the ACB system has a substantially higher influence in all three scenarios analyzed, compared to the VAV and CAV systems.

The cumulative energy demand, seen in Figure 16, indicates that the life cycle of the ACB system has the lowest total energy use, while the life cycle of the CAV system has the highest. A small part of the total energy used by the systems is shown to be based on fossil fuels. This is attributed to the production of metals that is mainly based on fossil fuels. As Sweden's electricity is partially based on nuclear, a small part of the cumulative energy demand of the systems is shown to be based on a nuclear energy source. Energy based on biomass represents the majority of the cumulative energy demand. This is attributed to the fact that Sweden's district heating system is around 41 % based on biogas, as seen in Figure 9. It was also noted that heat from waste incineration, which represents around 24.5 % of the energy sources used in Sweden's district heating system, is characterized as biomass energy in the Cumulative energy demand method.

Utilizing the shadow cost method provides a different perspective on the environmental performance of the three systems analyzed. The life cycle of the CAV system has the overall worst environmental performance compared to the life cycles of the ACB and VAV systems, in all three cases, prior to weighting. This difference in environmental performance is also highlighted when the shadow cost method is used; the CAV system having the highest shadow cost. It is also interesting to see that the shadow cost of the VAV system is the lowest compared to that of the CAV and ACB systems, for the Base case and 100 % clean electricity scenario. Nonetheless, the ACB system has the lowest shadow cost, when PVC pipes are used instead of copper pipes. This indicates that the VAV system could have a better environmental performance than that of the ACB system, which is contrary to the results prior to weighting.

When PVC pipes are used, the life cycle of the ACB system has the lowest environmental impacts and the lowest shadow cost. In the base case, the lifecycle of the CAV and VAV systems behaves very similarly in terms of environmental impacts. This can also be observed from the results after implementing the shadow cost weighting method.

Contrary to what was mentioned in the literature review, the operational phase of all systems remains to have a high impact even with the use of 100 % renewable electricity. This is assumed to be because the energy needed for heating is vastly higher than the electricity needed by the system and that Swedish electricity mix is based on approximately 50 % renewable energy, while the other 50 % is based on a non- renewable source. Moreover, it is recognized that energy based on a renewable source still comes with certain environmental burdens due to the LCA modelling system chosen from Ecoinvent database.

6.2 Conclusion and future work

In this study, all efforts were made to obtain as viable information as possible, however, several assumptions had to be made due to the lack of data.

It was recognized from the literature review that not one case reviewed was comparable due to the use of different scopes. Therefore, more standardization of LCA is needed in order to have similar goals and scopes that would make the studies more comparable.

According to the BPDs obtained from the manufacturer, the energy needed for the production of the components of the ACB system is higher than that needed for the production of the components of the CAV and VAV systems. Additionally, even though the environmental impacts due to the operational phase of the systems are substantial, the environmental impacts due to the manufacturing phase are not insignificant.

According to the LCA results, the majority of the impacts were mainly due to either the manufacturing of the ACB system or the operation of the CAV and VAV systems. It is also observed that the system performing worst in terms of environmental impacts, which is the CAV system, shows to have the highest Cumulative energy demand.

The biggest reduction in potential environmental impacts is seen in the ACB system when PVC pipes are used instead of copper pipes. Recycling of materials can help lower the environmental impacts of each system. However, it did not reduce the environmental impacts of the manufacturing phase of the ACB system enough to be lower than those of the manufacturing phase of the CAV and VAV systems.

The shadow cost method provided a summary of the environmental impacts of each system and helped assess the systems from a cost perspective. The weighting method indicates that a VAV system might have lower environmental impacts than an ACB system, however, it should be noted that this method is more applicable in the Netherlands. Additionally, the results show that the main leading sources of potential impacts are the use of metals, the process of zinc coating used in galvanized steel, and energy use during the operational phase. It is also concluded that if the maintenance of the systems was taken into account, the VAV system might perform better than the ACB system due to less maintenance needed for the VAV system. Therefore, impacts due to the maintenance of the systems should be further researched. Moreover, the effect of different life spans of the systems on their environmental impacts should be explored more, as the systems are assumed to have the same life span in this study, for simplicity reasons, which is not admissible in real life.

Using a high amount of energy cannot be justified by the use of 100 % renewable energy source, as a slight reduction in total environmental impacts is observed when using electricity based on 100 % renewable energy. This, however, can be attributed to two main reasons. The first reason is that the reduction in environmental impacts when using 100 % renewable electricity source was compared to impacts when using Swedish electricity mix which is 50 % based on renewable sources. The second reason is that energy comes with some environmental burdens when using the LCA system modelling chosen in this study. Therefore, the next step should be performing a sensitivity analysis using a different LCA modelling system in which energy comes with less environmental impacts and/or comparing the reduction in impacts to a different electricity mix that uses even less renewable energy sources.

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Appendix I: Estimated material content in kg per system

Material Type	CAV	VAV	ACB
Galvanized Steel (kg)	7958.94	8126.69	4513.98
"Rubber" - EPDM (kg)	74.91	75.29	75.62
"Rubber" - Paraffin Oil (kg)	18.56	18.65	15.10
"Rubber" - acrylic dispersion (kg)	100.16	98.05	94.80
Steel (kg)	67.21	81.10	339.33
Mineral wool (kg)	146.70	271.50	144.04
Epoxy- Epoxy resin (kg)	2.21	2.19	5.21
Epoxy- Titanium Oxide (kg)	2.21	2.19	0.74
Polyetehlene (kg)	1.81	1.82	19.15
Stainless steel (kg)	128.31	128.06	145.82
Aluminum (kg)	201.94	232.87	494.15
PET (kg)	84.13	88.27	27.00
POM (kg)	11.53	10.90	2.11
PA66 (nylon) (kg)	11.64	15.38	8.68
ABS (kg)	11.53	10.90	2.10
PVC (kg)	4.07	3.87	3.40
Copper (kg)	501.47	501.47	1981.04
Iron (kg)	178.92	178.93	494.70
Zinc (kg)	-	-	0.28
Bakelite "Binder" (kg)	3.91	3.91	3.09
Electronics (kg)	1.37	5.05	24.87
Cardboard (kg)	1.44	1.44	1.44

Cast iron (kg)	8.10	8.10	8.10
Ceramics (kg)	0.18	0.18	0.18
Magnet (kg)	0.50	0.50	0.50
Paper (kg)	0.68	0.68	0.68
Plastic film (kg)	0.05	0.05	0.05
Plastics (kg)	3.51	3.51	3.51
Wood pallet (kg)	1.73	1.73	1.73
Plastic Diakon ST35G8 Acrylic "PMM" (kg)	-	-	0.23
Magnetit (Fe_3O_4) (kg)	-	-	0.05
Polypropylene (kg)	-	-	0.09
Polycarbonate (kg)	-	-	20.75
Chromium (kg)	-	-	0.14
Manganese (kg)	-	-	1.56
Titanium (kg)	-	-	0.28

Appendix II: Components per HVAC system

CAV SYSTEM				
Material	**Tillverkare**	**Typ**	**Produkt**	**Antal**
Galvanized	LINDAB	SR	SR 100-3000	8
Galvanized	LINDAB	SR	SR 125-3000	7
Galvanized	LINDAB	SR	SR 160-3000	14
Galvanized	LINDAB	SR	SR 200-3000	25
Galvanized	LINDAB	SR	SR 250-3000	43
Galvanized	LINDAB	SR	SR 315-3000	24
Galvanized	LINDAB	SR	SR 355-3000	11
Galvanized	LINDAB	SR	SR 400-3000	23
Galvanized	LINDAB	SR	SR 500-3000	16
Galvanized	LINDAB	BFU	BFU 250 15	11
Galvanized	LINDAB	BFU	BFU 250 45	6
Galvanized	LINDAB	BFU	BFU 250 90	29
Galvanized	LINDAB	BFU	BFU 315 15	5
Galvanized	LINDAB	BFU	BFU 315 90	2
Galvanized	LINDAB	BFU	BFU 355 15	2
Galvanized	LINDAB	BFU	BFU 355 90	4
Galvanized	LINDAB	BFU	BFU 400 45	2
Galvanized	LINDAB	BFU	BFU 400 90	5
Galvanized	LINDAB	BFU	BFU 500 90	5
Galvanized	LINDAB	BKFU	BKFU 200 90	1
Galvanized	LINDAB	BKFU	BKFU 250 90	3

Galvanized	LINDAB	BKFU	BKFU 315 90	2
Galvanized	LINDAB	BKFU	BKFU 400 90	4
Galvanized	LINDAB	BKFU	BKFU 500 90	3
Galvanized	LINDAB	BU	BU 100 30	1
Galvanized	LINDAB	BU	BU 100 90	24
Galvanized	LINDAB	BU	BU 125 15	4
Galvanized	LINDAB	BU	BU 125 90	5
Galvanized	LINDAB	BU	BU 160 15	2
Galvanized	LINDAB	BU	BU 160 45	1
Galvanized	LINDAB	BU	BU 160 60	2
Galvanized	LINDAB	BU	BU 160 90	18
Galvanized	LINDAB	BU	BU 200 15	2
Galvanized	LINDAB	BU	BU 200 30	4
Galvanized	LINDAB	BU	BU 200 45	5
Galvanized	LINDAB	BU	BU 200 90	29
Galvanized	LINDAB	EPF	EPF 500	1
Galvanized	LINDAB	ILU	ILU 160	2
Galvanized	LINDAB	ILU	ILU 200	6
Galvanized	LINDAB	ILU	ILU 250	2
Galvanized	LINDAB	ILU	ILU 315	1
Galvanized	LINDAB	ILU	ILU 400	1
Galvanized	LINDAB	ILU	ILU 500	4
Galvanized	LINDAB	NPU	NPU 125	5
Galvanized	LINDAB	NPU	NPU 160	4

Galvanized	LINDAB	NPU	NPU 200	4
Galvanized	LINDAB	NPU	NPU 250	19
Galvanized	LINDAB	NPU	NPU 315	9
Galvanized	LINDAB	NPU	NPU 400	11
Galvanized	LINDAB	NPU	NPU 500	3
Galvanized	LINDAB	PSU	PSU 500 160	1
Galvanized	LINDAB	RCFLU	RCFLU 125 100	3
Galvanized	LINDAB	RCFLU	RCFLU 200 100	1
Galvanized	LINDAB	RCFLU	RCFLU 200 125	3
Galvanized	LINDAB	RCFLU	RCFLU 250 100	1
Galvanized	LINDAB	RCFLU	RCFLU 250 125	1
Galvanized	LINDAB	RCFLU	RCFLU 250 160	8
Galvanized	LINDAB	RCFLU	RCFLU 250 200	9
Galvanized	LINDAB	RCFLU315250	RCFLU315250	20
Galvanized	LINDAB	RCFLU355315	RCFLU355315	12
Galvanized	LINDAB	RCFLU400250	RCFLU400250	1
Galvanized	LINDAB	RCFLU400315	RCFLU400315	3
Galvanized	LINDAB	RCFLU400355	RCFLU400355	11
Galvanized	LINDAB	RCFLU500315	RCFLU500315	1
Galvanized	LINDAB	RCFLU500400	RCFLU500400	7
Galvanized	LINDAB	RCLU	RCLU 500 355	1
Galvanized	LINDAB	RCU	RCU 250 200	1
Galvanized	LINDAB	TCPU	TCPU 100 100	9
Galvanized	LINDAB	TCPU	TCPU 125 100	1

Galvanized	LINDAB	TCPU	TCPU 125 125	1
Galvanized	LINDAB	TCPU	TCPU 200 125	2
Galvanized	LINDAB	TCPU	TCPU 200 200	2
Galvanized	LINDAB	TCPU	TCPU 250 160	4
Galvanized	LINDAB	TCPU	TCPU 250 200	8
Galvanized	LINDAB	TCPU	TCPU 250 250	7
Galvanized	LINDAB	TCPU	TCPU 315 125	1
Galvanized	LINDAB	TCPU	TCPU 315 160	8
Galvanized	LINDAB	TCPU	TCPU 315 200	12
Galvanized	LINDAB	TCPU	TCPU 315 250	6
Galvanized	LINDAB	TCPU	TCPU 315 315	1
Galvanized	LINDAB	TCPU	TCPU 355 160	3
Galvanized	LINDAB	TCPU	TCPU 355 200	4
Galvanized	LINDAB	TCPU	TCPU 355 250	6
Galvanized	LINDAB	TCPU	TCPU 400 160	2
Galvanized	LINDAB	TCPU	TCPU 400 200	4
Galvanized	LINDAB	TCPU	TCPU 400 250	9
Galvanized	LINDAB	TCPU	TCPU 400 400	1
Galvanized	LINDAB	TCPU	TCPU 500 125	1
Galvanized	LINDAB	TCPU	TCPU 500 160	4
Galvanized	LINDAB	TCPU	TCPU 500 200	10
Galvanized	LINDAB	TCPU	TCPU 500 250	5
Galvanized	LINDAB	TCPU	TCPU 500 315	1
Galvanized	LINDAB	TCPU	TCPU 500 400	3

Galvanized	LINDAB	TSTU	TSTU 500 315	1
Galvanized	LINDAB	XCPU315160	XCPU315160	1
Galvanized	LINDAB	LRBCB	LRBCB 315 1000	1
Galvanized	LINDAB	LRBCB	LRBCB 400 500	2
Galvanized	LINDAB	LRBCB	LRBCB 500 1200	1
Galvanized	LINDAB	LRBCB	LRBCB 500 600	3
Galvanized	LINDAB	LRCA	LRCA 200 500	2
Galvanized	LINDAB	LRCA	LRCA 250 1000	1
Galvanized	LINDAB	SLU	SLU 100 300 50	7
Galvanized	LINDAB	Airy	Airy-RECT-100	15
Galvanized	LINDAB	LKA	LKA-250	5
Galvanized	LINDAB	LKP	LKP-125	2
Galvanized	LINDAB	LKP	LKP-200	4
Galvanized	LINDAB	LKP	LKP-200	9
Galvanized	LINDAB	LKP	LKP-200	11
Galvanized	LINDAB	LKP	LKP-250	31
Galvanized	LINDAB	LKP	LKP-250	23
Galvanized	LINDAB	LKP	LKP-250	30
Galvanized	LINDAB	LKP	LKP-315	10
Galvanized	LINDAB	LKP	LKP-315	4
Galvanized	LINDAB	MBB	MBB-125-125-E	1
Galvanized	LINDAB	MBB	MBB-125-125-S	1
Galvanized	LINDAB	MBB	MBB-125-200-S	4
Galvanized	LINDAB	MBB	MBB-160-200-E	2

Galvanized	LINDAB	MBB	MBB-160-200-S	9
Galvanized	LINDAB	MBB	MBB-160-250-S	23
Galvanized	LINDAB	MBB	MBB-200-200-E	7
Galvanized	LINDAB	MBB	MBB-200-200-S	2
Galvanized	LINDAB	MBB	MBB-200-250-E	6
Galvanized	LINDAB	MBB	MBB-200-250-E	5
Galvanized	LINDAB	MBB	MBB-200-250-S	24
Galvanized	LINDAB	MBB	MBB-200-315-S	4
Galvanized	LINDAB	MBB	MBB-250-250-E	30
Galvanized	LINDAB	MBB	MBB-250-250-S	1
Galvanized	LINDAB	MBB	MBB-250-315-E	8
Galvanized	LINDAB	MBB	MBB-250-315-S	2
Galvanized	LINDAB	DRU	DRU 100	4
Galvanized	LINDAB CF 10000	LINDAB	LINDAB CF 10000	1

VAV system				
Material	**Tillverkare**	**Typ**	**Produkt**	**Antal**
Galvanized	LINDAB	SR	SR 100-3000	8
Galvanized	LINDAB	SR	SR 125-3000	7
Galvanized	LINDAB	SR	SR 160-3000	15
Galvanized	LINDAB	SR	SR 200-3000	30
Galvanized	LINDAB	SR	SR 250-3000	43
Galvanized	LINDAB	SR	SR 315-3000	22
Galvanized	LINDAB	SR	SR 355-3000	8
Galvanized	LINDAB	SR	SR 400-3000	20
Galvanized	LINDAB	SR	SR 500-3000	16
Galvanized	LINDAB	BFU	BFU 250 15	13
Galvanized	LINDAB	BFU	BFU 250 45	8
Galvanized	LINDAB	BFU	BFU 250 90	28
Galvanized	LINDAB	BFU	BFU 315 15	4
Galvanized	LINDAB	BFU	BFU 315 90	1
Galvanized	LINDAB	BFU	BFU 355 15	2
Galvanized	LINDAB	BFU	BFU 355 90	3
Galvanized	LINDAB	BFU	BFU 400 45	2
Galvanized	LINDAB	BFU	BFU 400 90	5
Galvanized	LINDAB	BFU	BFU 500 90	5
Galvanized	LINDAB	BKFU	BKFU 200 90	4
Galvanized	LINDAB	BKFU	BKFU 250 90	3
Galvanized	LINDAB	BKFU	BKFU 315 90	2

Galvanized	LINDAB	BKFU	BKFU 400 90	5
Galvanized	LINDAB	BKFU	BKFU 500 90	3
Galvanized	LINDAB	BU	BU 100 45	1
Galvanized	LINDAB	BU	BU 100 90	24
Galvanized	LINDAB	BU	BU 125 15	4
Galvanized	LINDAB	BU	BU 125 90	5
Galvanized	LINDAB	BU	BU 160 15	4
Galvanized	LINDAB	BU	BU 160 45	1
Galvanized	LINDAB	BU	BU 160 60	2
Galvanized	LINDAB	BU	BU 160 90	19
Galvanized	LINDAB	BU	BU 200 15	7
Galvanized	LINDAB	BU	BU 200 30	2
Galvanized	LINDAB	BU	BU 200 45	1
Galvanized	LINDAB	BU	BU 200 90	36
Galvanized	LINDAB	EPF	EPF 500	1
Galvanized	LINDAB	ILU	ILU 160	2
Galvanized	LINDAB	ILU	ILU 200	5
Galvanized	LINDAB	ILU	ILU 250	3
Galvanized	LINDAB	ILU	ILU 315	1
Galvanized	LINDAB	ILU	ILU 400	1
Galvanized	LINDAB	ILU	ILU 500	4
Galvanized	LINDAB	NPU	NPU 125	4
Galvanized	LINDAB	NPU	NPU 160	4
Galvanized	LINDAB	NPU	NPU 200	5

Galvanized	LINDAB	NPU	NPU 250	16
Galvanized	LINDAB	NPU	NPU 315	7
Galvanized	LINDAB	NPU	NPU 400	6
Galvanized	LINDAB	NPU	NPU 500	3
Galvanized	LINDAB	PSU	PSU 500 160	1
Galvanized	LINDAB	RCFLU	RCFLU 125 100	3
Galvanized	LINDAB	RCFLU	RCFLU 200 100	2
Galvanized	LINDAB	RCFLU	RCFLU 200 125	3
Galvanized	LINDAB	RCFLU	RCFLU 250 125	1
Galvanized	LINDAB	RCFLU	RCFLU 250 160	12
Galvanized	LINDAB	RCFLU	RCFLU 250 200	9
Galvanized	LINDAB	RCFLU315200	RCFLU315200	1
Galvanized	LINDAB	RCFLU315250	RCFLU315250	18
Galvanized	LINDAB	RCFLU355315	RCFLU355315	11
Galvanized	LINDAB	RCFLU400250	RCFLU400250	1
Galvanized	LINDAB	RCFLU400315	RCFLU400315	4
Galvanized	LINDAB	RCFLU400355	RCFLU400355	8
Galvanized	LINDAB	RCFLU500315	RCFLU500315	1
Galvanized	LINDAB	RCFLU500400	RCFLU500400	7
Galvanized	LINDAB	RCU	RCU 500 400	1
Galvanized	LINDAB	TCPU	TCPU 100 100	9
Galvanized	LINDAB	TCPU	TCPU 125 100	1
Galvanized	LINDAB	TCPU	TCPU 125 125	1
Galvanized	LINDAB	TCPU	TCPU 200 125	2

Galvanized	LINDAB	TCPU	TCPU 200 200	3
Galvanized	LINDAB	TCPU	TCPU 250 160	4
Galvanized	LINDAB	TCPU	TCPU 250 200	9
Galvanized	LINDAB	TCPU	TCPU 250 250	7
Galvanized	LINDAB	TCPU	TCPU 315 125	1
Galvanized	LINDAB	TCPU	TCPU 315 160	7
Galvanized	LINDAB	TCPU	TCPU 315 200	13
Galvanized	LINDAB	TCPU	TCPU 315 250	5
Galvanized	LINDAB	TCPU	TCPU 355 160	2
Galvanized	LINDAB	TCPU	TCPU 355 200	5
Galvanized	LINDAB	TCPU	TCPU 355 250	5
Galvanized	LINDAB	TCPU	TCPU 400 160	2
Galvanized	LINDAB	TCPU	TCPU 400 200	4
Galvanized	LINDAB	TCPU	TCPU 400 250	10
Galvanized	LINDAB	TCPU	TCPU 400 400	1
Galvanized	LINDAB	TCPU	TCPU 500 125	1
Galvanized	LINDAB	TCPU	TCPU 500 160	4
Galvanized	LINDAB	TCPU	TCPU 500 200	11
Galvanized	LINDAB	TCPU	TCPU 500 250	4
Galvanized	LINDAB	TCPU	TCPU 500 315	1
Galvanized	LINDAB	TCPU	TCPU 500 400	3
Galvanized	LINDAB	TSTU	TSTU 500 315	1
Galvanized	LINDAB	XCPU315160	XCPU315160	1
Galvanized	LINDAB	LRBCB	LRBCB 315 500	1

Galvanized	LINDAB	LRBCB	LRBCB 400 1000	2
Galvanized	LINDAB	LRBCB	LRBCB 400 500	4
Galvanized	LINDAB	LRBCB	LRBCB 500 1200	6
Galvanized	LINDAB	LRBCB	LRBCB 500 600	3
Galvanized	LINDAB	LRCA	LRCA 160 1000	1
Galvanized	LINDAB	LRCA	LRCA 160 500	1
Galvanized	LINDAB	LRCA	LRCA 200 1000	1
Galvanized	LINDAB	LRCA	LRCA 200 500	4
Galvanized	LINDAB	LRCA	LRCA 250 1000	1
Galvanized	LINDAB	LRCA	LRCA 250 500	3
Galvanized	LINDAB	LRCA	LRCA 315 1000	1
Galvanized	LINDAB	SLU	SLU 100 300 50	7
Galvanized	LINDAB	Airy	Airy-RECT-100	15
Galvanized	LINDAB	LKA	LKA-250	5
Galvanized	LINDAB	LKP	LKP-125	2
Galvanized	LINDAB	LKP	LKP-200	7
Galvanized	LINDAB	LKP	LKP-200	4
Galvanized	LINDAB	LKP	LKP-200	5
Galvanized	LINDAB	LKP	LKP-200	2
Galvanized	LINDAB	LKP	LKP-250	27
Galvanized	LINDAB	LKP	LKP-250	39
Galvanized	LINDAB	LKP	LKP-250	24
Galvanized	LINDAB	LKP	LKP-315	7
Galvanized	LINDAB	LKP	LKP-315	6

Galvanized	LINDAB	MBB	MBB-125-125-E	1
Galvanized	LINDAB	MBB	MBB-125-125-S	1
Galvanized	LINDAB	MBB	MBB-125-200-S	4
Galvanized	LINDAB	MBB	MBB-160-200-E	2
Galvanized	LINDAB	MBB	MBB-160-200-S	5
Galvanized	LINDAB	MBB	MBB-160-250-E	2
Galvanized	LINDAB	MBB	MBB-160-250-S	25
Galvanized	LINDAB	MBB	MBB-200-200-E	5
Galvanized	LINDAB	MBB	MBB-200-250-E	5
Galvanized	LINDAB	MBB	MBB-200-250-E	13
Galvanized	LINDAB	MBB	MBB-200-250-S	26
Galvanized	LINDAB	MBB	MBB-200-315-E	2
Galvanized	LINDAB	MBB	MBB-200-315-S	4
Galvanized	LINDAB	MBB	MBB-250-250-E	23
Galvanized	LINDAB	MBB	MBB-250-250-S	1
Galvanized	LINDAB	MBB	MBB-250-315-E	5
Galvanized	LINDAB	MBB	MBB-250-315-S	2
Galvanized	LINDAB	MBBV	MBBV-160-200-S	2
Galvanized	LINDAB	DRU	DRU 100	2
Galvanized	LINDAB CF 10000	LINDAB	LINDAB CF 10000	1
Galvanized	SPECIAL	VRU	VRU-2 160	1
Galvanized	SPECIAL	VRU	VRU-2 200	5
Galvanized	SPECIAL	VRU	VRU-2 250	4

Galvanized	SPECIAL	VRU	VRU-2 315	2
Galvanized	SPECIAL	VRU	VRU-2 400	6
Galvanized	SPECIAL	VRU	VRU-2 500	9

ACB system				
Material	**Tillverkare**	**Typ**	**Produkt**	**Antal**
Galvanized	LINDAB	SR	SR 100-3000	10
Galvanized	LINDAB	SR	SR 125-3000	45
Galvanized	LINDAB	SR	SR 160-3000	28
Galvanized	LINDAB	SR	SR 200-3000	20
Galvanized	LINDAB	SR	SR 250-3000	47
Galvanized	LINDAB	SR	SR 315-3000	17
Galvanized	LINDAB	SR	SR 355-3000	2
Galvanized	LINDAB	SR	SR 400-3000	3
Galvanized	LINDAB	SR	SR 710-3000	3
Galvanized	LINDAB	SR	SR 800-3000	9
Special	LINDAB	SRF	SRF-C 1000 61	1
Galvanized	LINDAB	BFU	BFU 250 15	13
Galvanized	LINDAB	BFU	BFU 250 30	4
Galvanized	LINDAB	BFU	BFU 250 45	2
Galvanized	LINDAB	BFU	BFU 250 90	18
Galvanized	LINDAB	BFU	BFU 315 30	4
Galvanized	LINDAB	BFU	BFU 315 45	2
Galvanized	LINDAB	BFU	BFU 315 90	6
Galvanized	LINDAB	BFU	BFU 355 90	1
Galvanized	LINDAB	BFU	BFU 400 90	1
Galvanized	LINDAB	BFU	BFU 800 90	8
Galvanized	LINDAB	BKFU	BKFU 200 90	1

Galvanized	LINDAB	BKFU	BKFU 250 90	3
Galvanized	LINDAB	BKU	BKU 125 90	1
Galvanized	LINDAB	BU	BU 100 15	2
Galvanized	LINDAB	BU	BU 100 90	25
Galvanized	LINDAB	BU	BU 125 15	20
Galvanized	LINDAB	BU	BU 125 30	12
Galvanized	LINDAB	BU	BU 125 45	14
Galvanized	LINDAB	BU	BU 125 90	50
Galvanized	LINDAB	BU	BU 160 15	2
Galvanized	LINDAB	BU	BU 160 45	3
Galvanized	LINDAB	BU	BU 160 90	15
Galvanized	LINDAB	BU	BU 200 15	3
Galvanized	LINDAB	BU	BU 200 30	4
Galvanized	LINDAB	BU	BU 200 90	11
Galvanized	LINDAB	ESU	ESU 400	1
Galvanized	LINDAB	ILU	ILU 160	1
Galvanized	LINDAB	NPU	NPU 100	1
Galvanized	LINDAB	NPU	NPU 125	7
Galvanized	LINDAB	NPU	NPU 160	14
Galvanized	LINDAB	NPU	NPU 200	10
Galvanized	LINDAB	NPU	NPU 250	24
Galvanized	LINDAB	NPU	NPU 315	4
Galvanized	LINDAB	NPU	NPU 400	1
Galvanized	LINDAB	NPU	NPU 800	4

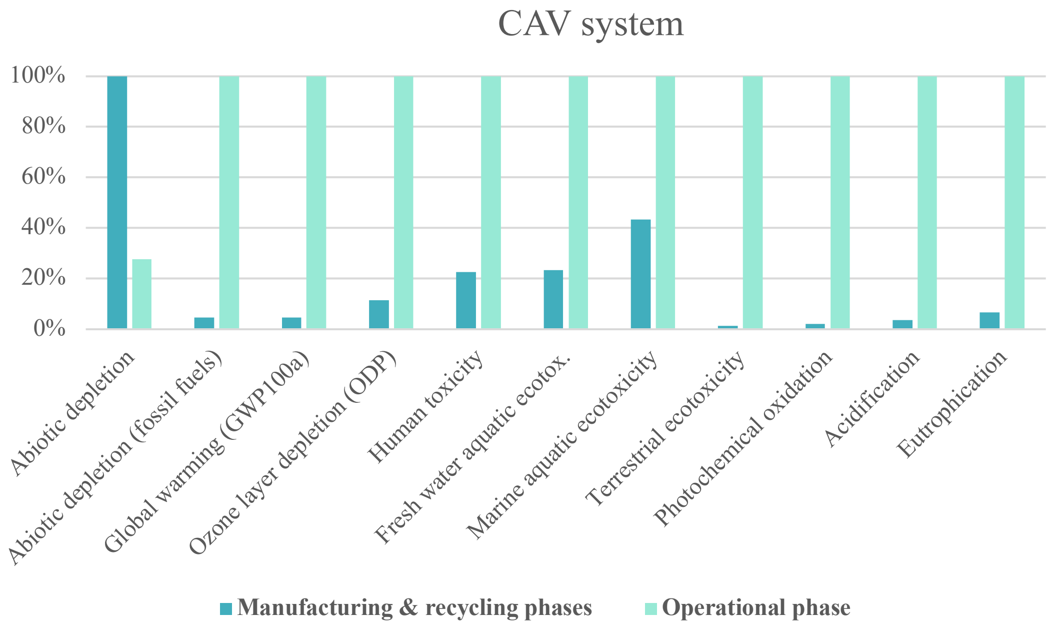
Galvanized	LINDAB	PSU	PSU 400 250	1
Galvanized	LINDAB	PSU	PSU 400 355	1
Galvanized	LINDAB	RCFLU	RCFLU 125 100	2
Galvanized	LINDAB	RCFLU	RCFLU 160 125	13
Galvanized	LINDAB	RCFLU	RCFLU 200 125	4
Galvanized	LINDAB	RCFLU	RCFLU 200 160	5
Galvanized	LINDAB	RCFLU	RCFLU 250 100	2
Galvanized	LINDAB	RCFLU	RCFLU 250 125	1
Galvanized	LINDAB	RCFLU	RCFLU 250 160	5
Galvanized	LINDAB	RCFLU	RCFLU 250 200	6
Galvanized	LINDAB	RCFLU315200	RCFLU315200	1
Galvanized	LINDAB	RCFLU315250	RCFLU315250	9
Galvanized	LINDAB	RCFLU355315	RCFLU355315	3
Galvanized	LINDAB	RCFLU400250	RCFLU400250	1
Galvanized	LINDAB	RCFLU400315	RCFLU400315	1
Galvanized	LINDAB	RCFLU710400	RCFLU710400	1
Galvanized	LINDAB	RCFLU800710	RCFLU800710	2
Galvanized	LINDAB	RCLU	RCLU 400 355	1
Galvanized	LINDAB	RCLU	RCLU 710 400	1
Galvanized	LINDAB	TCPU	TCPU 100 100	9
Galvanized	LINDAB	TCPU	TCPU 125 100	2
Galvanized	LINDAB	TCPU	TCPU 125 125	7
Galvanized	LINDAB	TCPU	TCPU 160 125	9
Galvanized	LINDAB	TCPU	TCPU 160 160	4

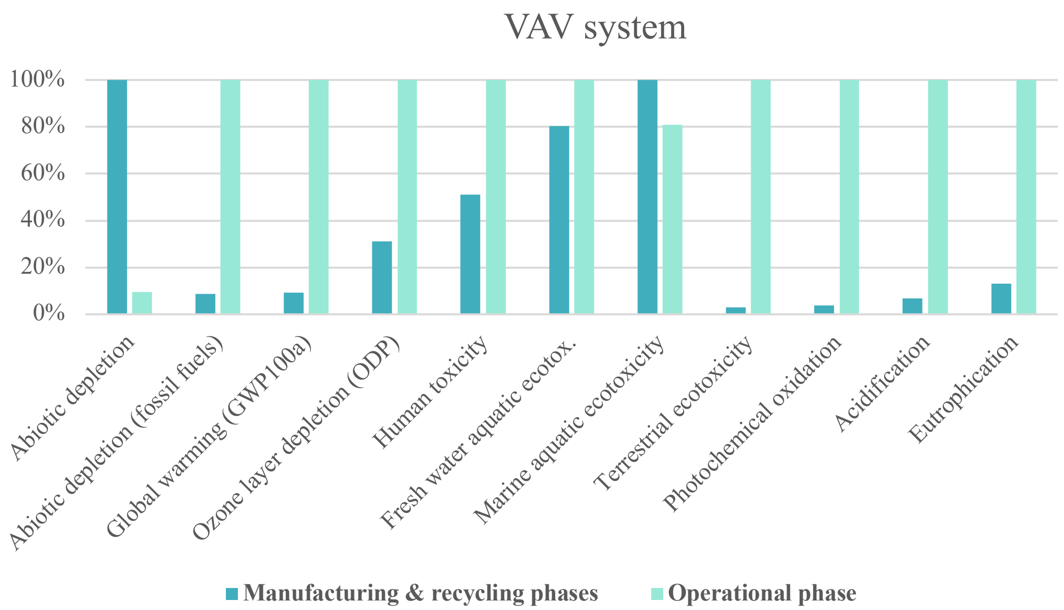
Galvanized	LINDAB	TCPU	TCPU 200 125	10
Galvanized	LINDAB	TCPU	TCPU 200 160	3
Galvanized	LINDAB	TCPU	TCPU 200 200	1
Galvanized	LINDAB	TCPU	TCPU 250 125	9
Galvanized	LINDAB	TCPU	TCPU 250 160	3
Galvanized	LINDAB	TCPU	TCPU 250 200	4
Galvanized	LINDAB	TCPU	TCPU 250 250	4
Galvanized	LINDAB	TCPU	TCPU 315 125	10
Galvanized	LINDAB	TCPU	TCPU 315 200	3
Galvanized	LINDAB	TCPU	TCPU 315 250	4
Galvanized	LINDAB	TCPU	TCPU 315 315	1
Galvanized	LINDAB	TCPU	TCPU 355 125	1
Galvanized	LINDAB	TCPU	TCPU 355 250	1
Galvanized	LINDAB	TCPU	TCPU 355 315	1
Galvanized	LINDAB	TCPU	TCPU 400 160	1
Galvanized	LINDAB	TCPU	TCPU 400 315	1
Galvanized	LINDAB	TCU	TCU 800 315	2
Galvanized	LINDAB	TSTCU	TSTCU 710 315	1
Galvanized	LINDAB	TSTCU	TSTCU 710 355	1
Galvanized	LINDAB	XCPU250160	XCPU250160	1
Galvanized	LINDAB	XCPU315125	XCPU315125	2
Galvanized	LINDAB	XCPU315250	XCPU315250	1
Galvanized	LINDAB	XCU	XCU 710 400	1
Galvanized	LINDAB	LRBCB	LRBCB 315 1000	1

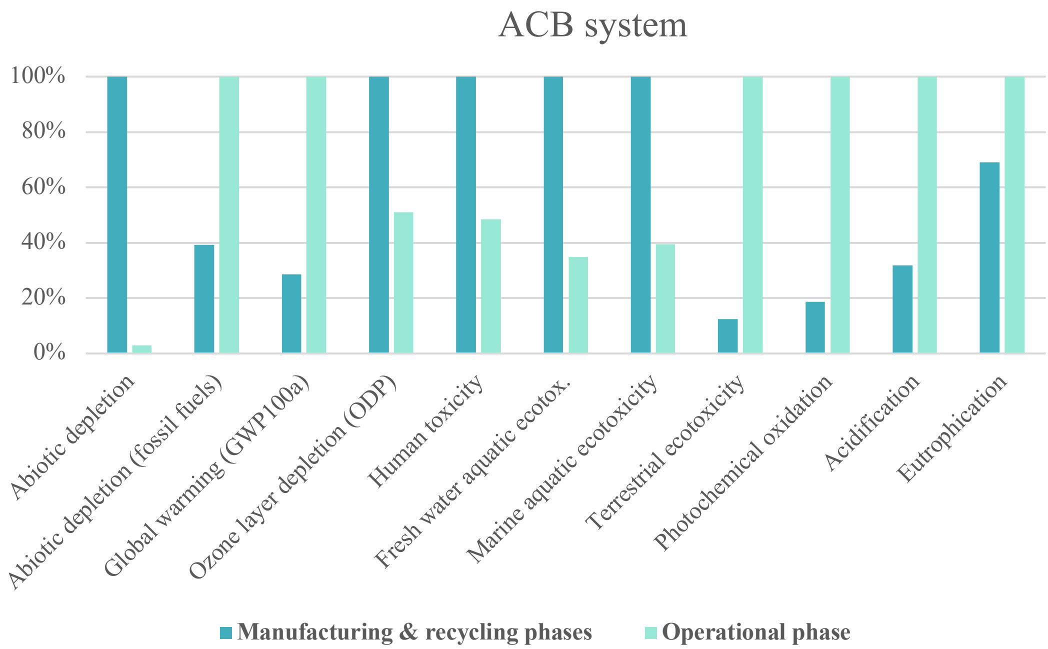
Galvanized	LINDAB	LRBCB	LRBCB 315 500	5
Galvanized	LINDAB	LRCA	LRCA 125 500	13
Galvanized	LINDAB	LRCA	LRCA 160 500	7
Galvanized	LINDAB	LRCA	LRCA 200 500	3
Galvanized	LINDAB	LRCA	LRCA 250 500	7
Galvanized	LINDAB	SLU	SLU 100 300 50	7
Galvanized	LINDAB	Airy	Airy-RECT-100	15
Galvanized	LINDAB	HF	HF 800	1
Galvanized	LINDAB	LKP	LKP-160	6
Galvanized	LINDAB	LKP	LKP-200	2
Galvanized	LINDAB	LKP	LKP-200	10
Galvanized	LINDAB	LKP	LKP-200	4
Galvanized	LINDAB	LKP	LKP-200	1
Galvanized	LINDAB	LKP	LKP-200	1
Galvanized	LINDAB	LKP	LKP-250	2
Galvanized	LINDAB	LKP	LKP-250	9
Galvanized	LINDAB	MBB	MBB-125-200-S	2
Galvanized	LINDAB	MBB	MBB-160-200-E	9
Galvanized	LINDAB	MBB	MBB-200-200-E	4
Galvanized	LINDAB	MBB	MBB-250-250-E	9
Galvanized	LINDAB	MBBV	MBBV-125-160-S	6
Galvanized	LINDAB	MBBV	MBBV-125-200-S	1
Galvanized	LINDAB	MBBV	MBBV-160-200-S	1
Galvanized	LINDAB	MBBV	MBBV-200-250-S	2

Galvanized	LINDAB	MBE	MBE-160-200	1
Galvanized	LINDAB	Plexus	Plexus IH60-12-125-A5-CoolingAndHeating	13
Galvanized	LINDAB	Plexus	Plexus IM60-12-125-A5-CoolingAndHeating	9
Galvanized	LINDAB	Plexus	Plexus IS120-12-125-A5-CoolingAndHeating	28
Galvanized	LINDAB	Plexus	Plexus IS60-12-125-A5-CoolingAndHeating	7
Galvanized	LINDAB	VHL	VHL 800	1
Galvanized	LINDAB	DRU	DRU 315	1
Galvanized	LINDAB	LPSR	LPSR-350-250-400-100	1
Galvanized	LINDAB	OLR	OLR-1000	1
Galvanized	LINDAB	OLR	OLR-1000	2
Galvanized	LINDAB	OLR	OLR-600	4
Galvanized	LINDAB	OLR	OLR-600	3
Galvanized	LINDAB	OLR	OLR-800	2
Galvanized	LINDAB CF 8000	LINDAB	LINDAB CF 8000	1
Galvanized	SPECIAL	FTCU	FTCU 125	13
Galvanized	SPECIAL	FTCU	FTCU 160	7
Galvanized	SPECIAL	FTCU	FTCU 200	3
Galvanized	SPECIAL	FTCU	FTCU 250	7
Galvanized	SPECIAL	FTCU	FTCU 315	6

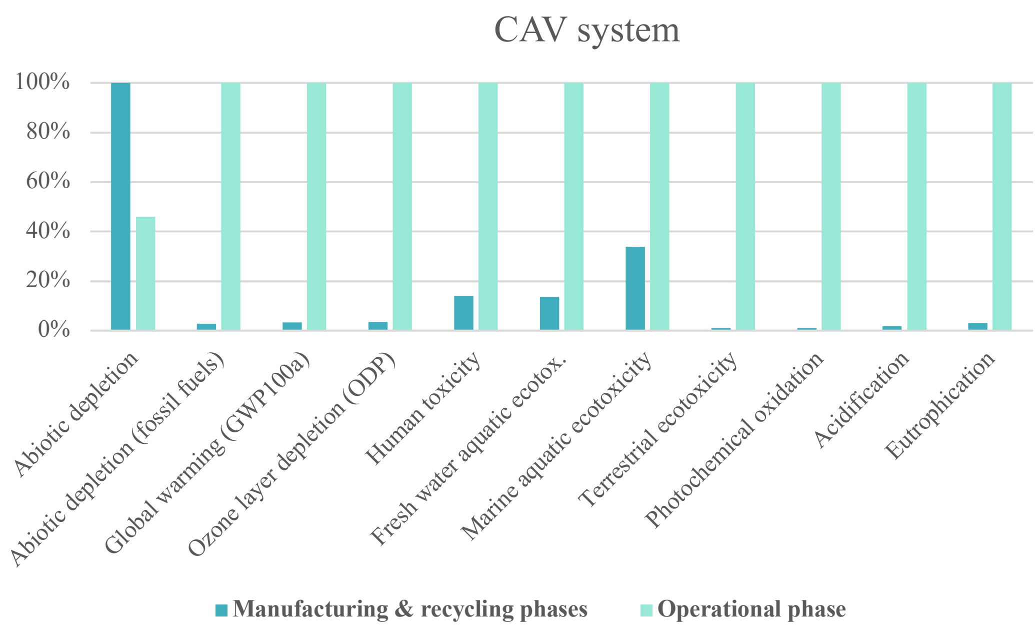
Appendix III: Relative difference of operational and manufacturing phase for the Base case

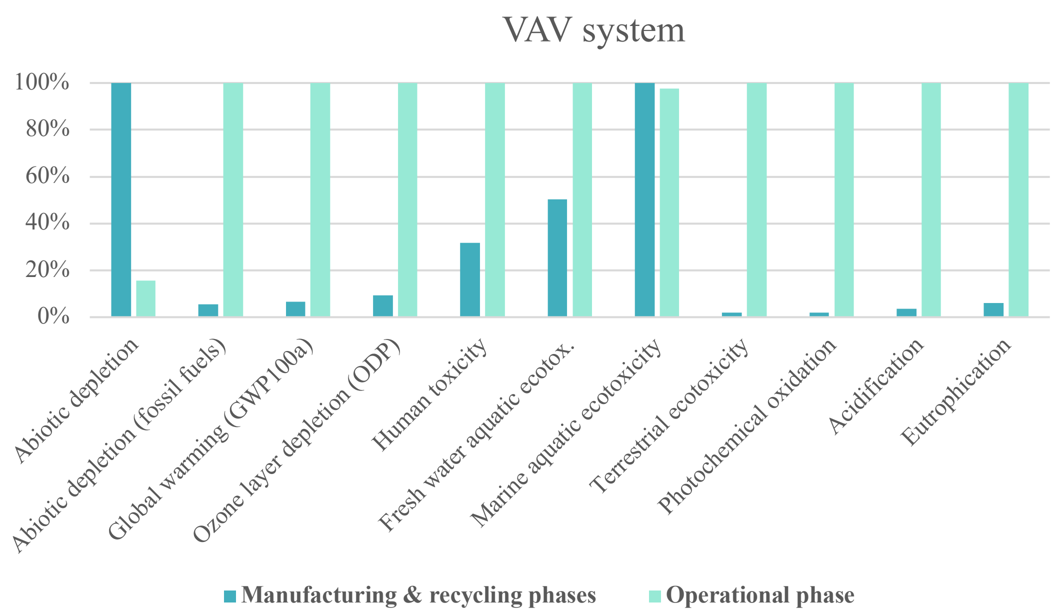


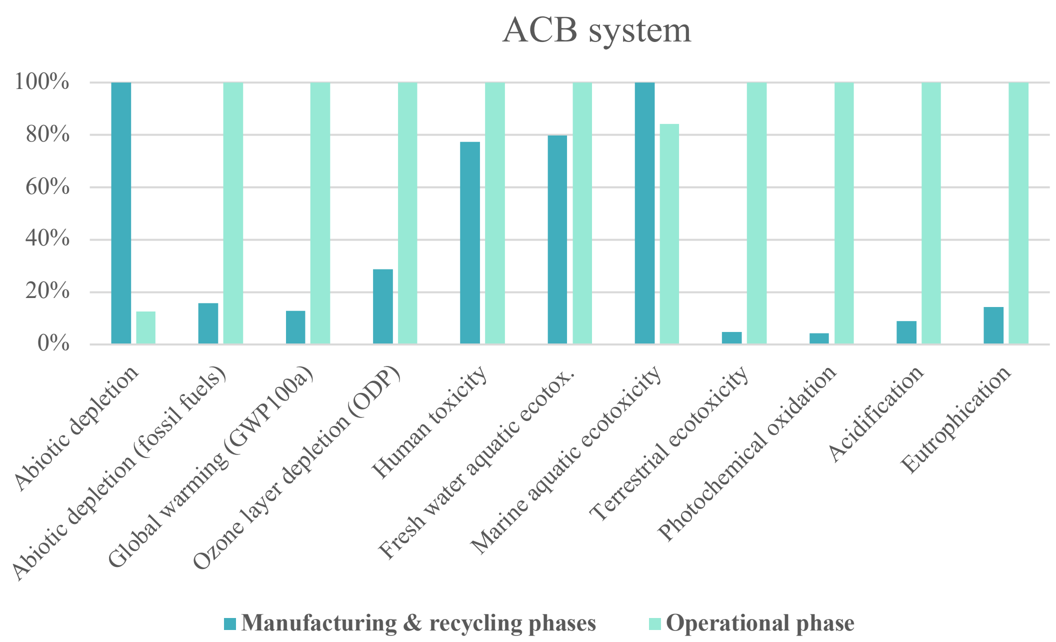



ACB system
100%
80%
60%
40%
20%
0%
Abiotic depletion
Abiotic depletion (fossil fuels)
Global warming (GWP100a)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
Manufacturing & recycling phases
Operational phase

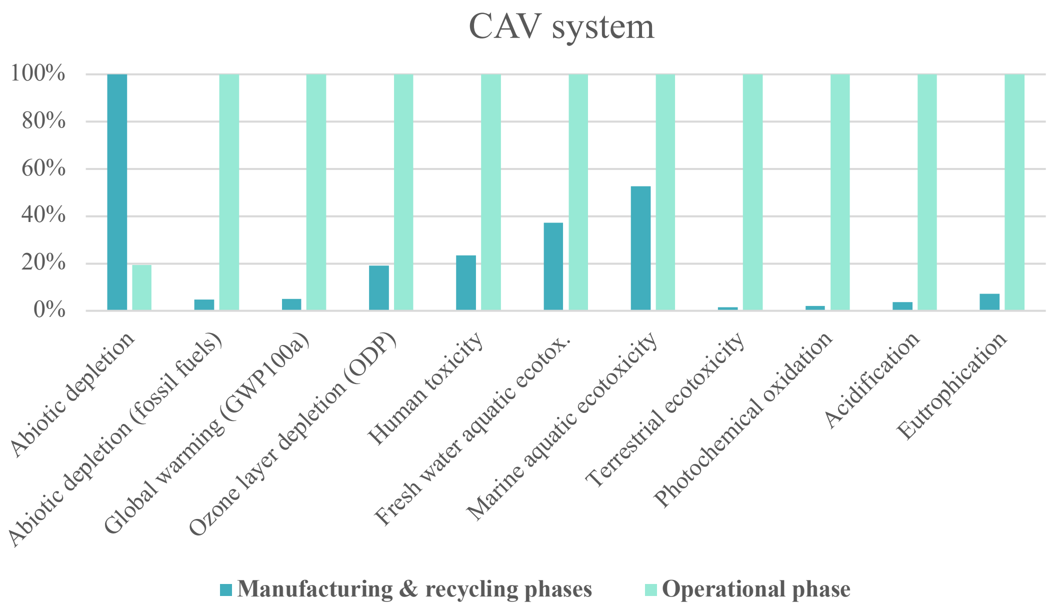
Appendix IV: Relative difference of operational and manufacturing phase of HVAC systems (Water connection: PVC pipes)

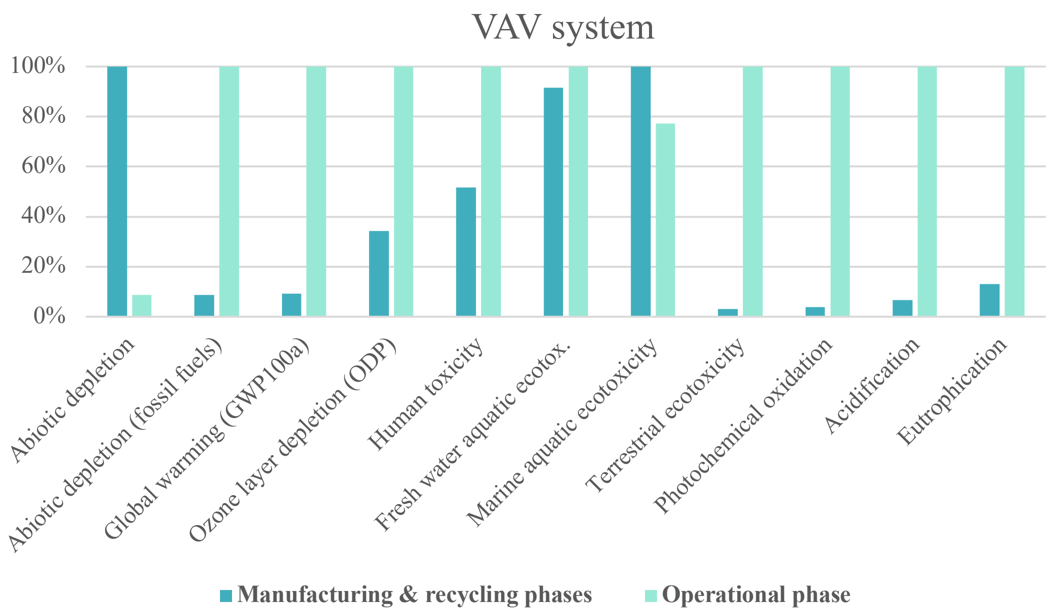


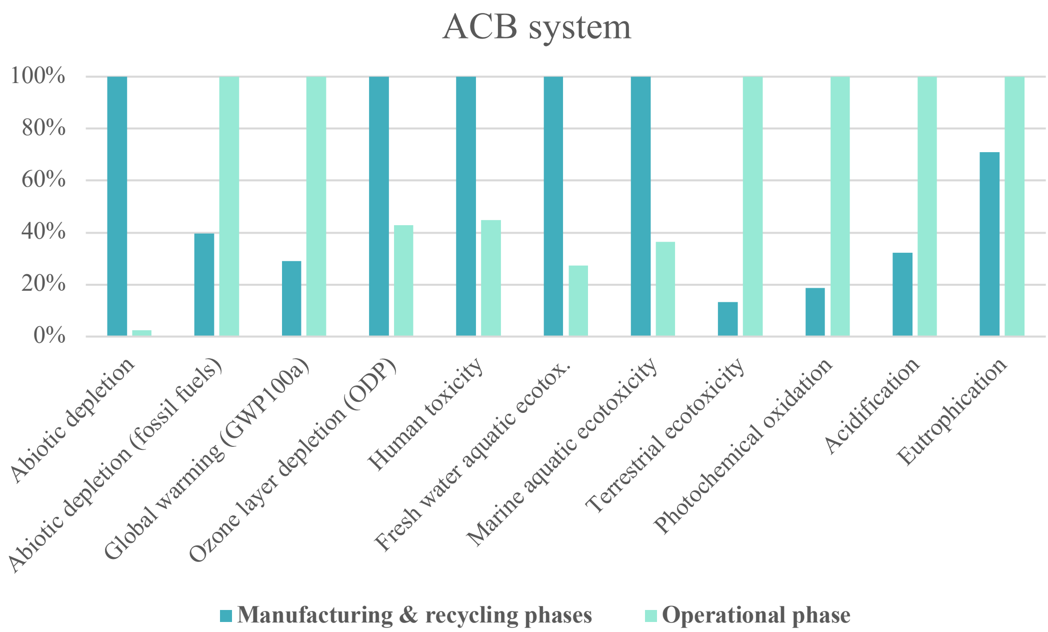



ACB system
100%
80%
60%
40%
20%
0%
Abiotic depletion
Abiotic depletion (fossil fuels)
Global warming (GWP100a)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
Manufacturing & recycling phases
Operational phase

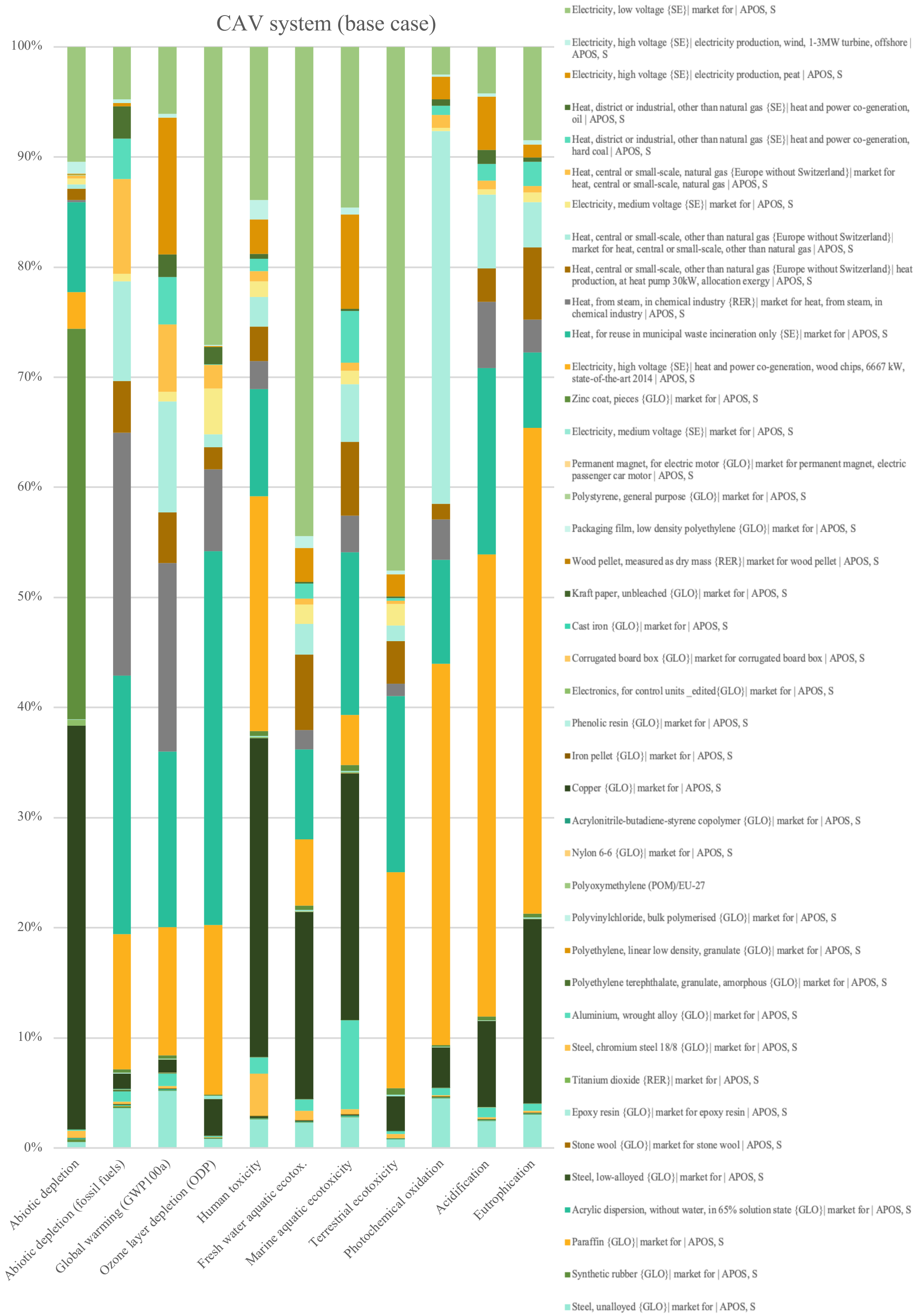
Appendix V: Relative difference of operational and manufacturing phase of HVAC systems (Electricity type: 100 % clean)

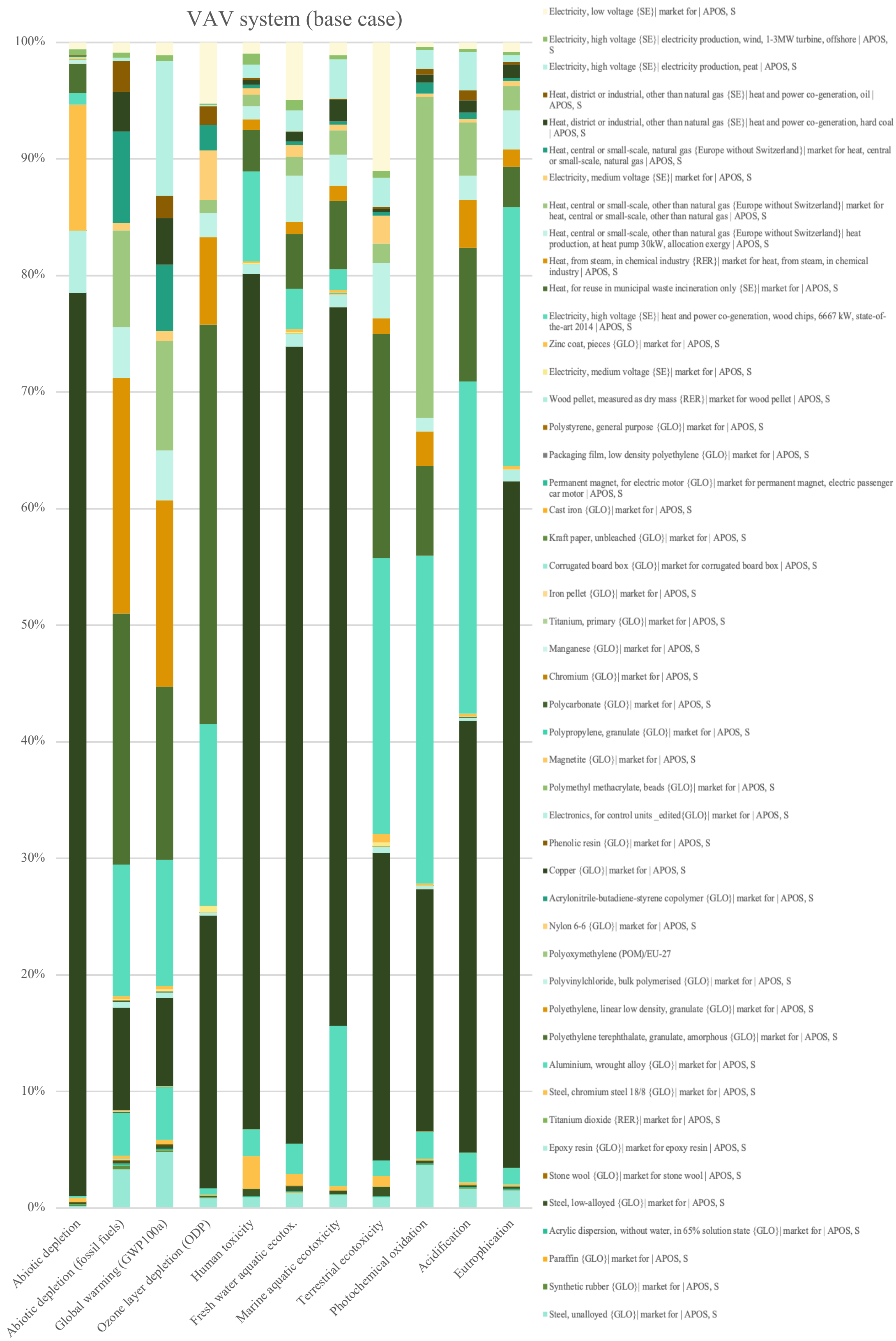


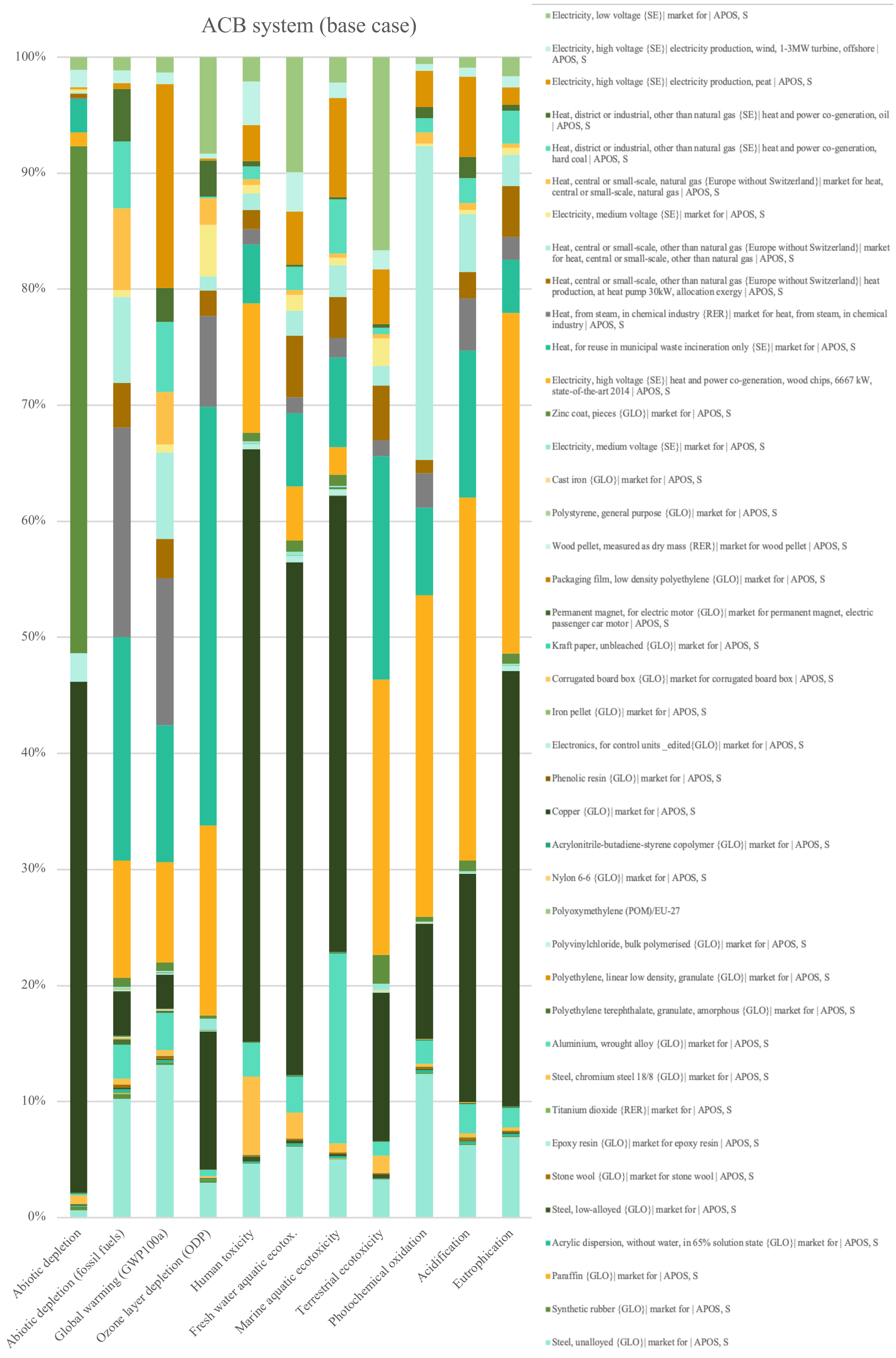



ACB system
100%
80%
60%
40%
20%
0%
Abiotic depletion
Abiotic depletion (fossil fuels)
Global warming (GWP100a)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
Manufacturing & recycling phases
Operational phase

Appendix VI: Impacts due to material/energy in percentage




VAV system (base case)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Abiotic depletion
Abiotic depletion (fossil fuels)
Global warming (GWP100a)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
Electricity, low voltage {SE}| market for | APOS, S
Electricity, high voltage {SE}| electricity production, wind, 1-3MW turbine, offshore | APOS, S
Electricity, high voltage {SE}| electricity production, peat | APOS, S
Heat, district or industrial, other than natural gas {SE}| heat and power co-generation, oil | APOS, S
Heat, district or industrial, other than natural gas {SE}| heat and power co-generation, hard coal | APOS, S
Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | APOS, S
Electricity, medium voltage {SE}| market for | APOS, S
Heat, central or small-scale, other than natural gas {Europe without Switzerland}| market for heat, central or small-scale, other than natural gas | APOS, S
Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, at heat pump 30kW, allocation exergy | APOS, S
Heat, from steam, in chemical industry {RER}| market for heat, from steam, in chemical industry | APOS, S
Heat, for reuse in municipal waste incineration only {SE}| market for | APOS, S
Electricity, high voltage {SE}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | APOS, S
Zinc coat, pieces {GLO}| market for | APOS, S
Electricity, medium voltage {SE}| market for | APOS, S
Wood pellet, measured as dry mass {RER}| market for wood pellet | APOS, S
Polystyrene, general purpose {GLO}| market for | APOS, S
Packaging film, low density polyethylene {GLO}| market for | APOS, S
Permanent magnet, for electric motor {GLO}| market for permanent magnet, electric passenger car motor | APOS, S
Cast iron {GLO}| market for | APOS, S
Kraft paper, unbleached {GLO}| market for | APOS, S
Corrugated board box {GLO}| market for corrugated board box | APOS, S
Iron pellet {GLO}| market for | APOS, S
Titanium, primary {GLO}| market for | APOS, S
Manganese {GLO}| market for | APOS, S
Chromium {GLO}| market for | APOS, S
Polycarbonate {GLO}| market for | APOS, S
Polypropylene, granulate {GLO}| market for | APOS, S
Magnetite {GLO}| market for | APOS, S
Polymethyl methacrylate, beads {GLO}| market for | APOS, S
Electronics, for control units _edited{GLO}| market for | APOS, S
Phenolic resin {GLO}| market for | APOS, S
Copper {GLO}| market for | APOS, S
Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | APOS, S
Nylon 6-6 {GLO}| market for | APOS, S
Polyoxymethylene (POM)/EU-27
Polyvinylchloride, bulk polymerised {GLO}| market for | APOS, S
Polyethylene, linear low density, granulate {GLO}| market for | APOS, S
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, S
Aluminium, wrought alloy {GLO}| market for | APOS, S
Steel, chromium steel 18/8 {GLO}| market for | APOS, S
Titanium dioxide {RER}| market for | APOS, S
Epoxy resin {GLO}| market for epoxy resin | APOS, S
Stone wool {GLO}| market for stone wool | APOS, S
Steel, low-alloyed {GLO}| market for | APOS, S
Acrylic dispersion, without water, in 65% solution state {GLO}| market for | APOS, S
Paraffin {GLO}| market for | APOS, S
Synthetic rubber {GLO}| market for | APOS, S
Steel, unalloyed {GLO}| market for | APOS, S


ACB system (base case)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Abiotic depletion
Abiotic depletion (fossil fuels)
Global warming (GWP100a)
Ozone layer depletion (ODP)
Human toxicity
Fresh water aquatic ecotox.
Marine aquatic ecotoxicity
Terrestrial ecotoxicity
Photochemical oxidation
Acidification
Eutrophication
Electricity, low voltage {SE}| market for | APOS, S
Electricity, high voltage {SE}| electricity production, wind, 1-3MW turbine, offshore | APOS, S
Electricity, high voltage {SE}| electricity production, peat | APOS, S
Heat, district or industrial, other than natural gas {SE}| heat and power co-generation, oil | APOS, S
Heat, district or industrial, other than natural gas {SE}| heat and power co-generation, hard coal | APOS, S
Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | APOS, S
Electricity, medium voltage {SE}| market for | APOS, S
Heat, central or small-scale, other than natural gas {Europe without Switzerland}| market for heat, central or small-scale, other than natural gas | APOS, S
Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, at heat pump 30kW, allocation exergy | APOS, S
Heat, from steam, in chemical industry {RER}| market for heat, from steam, in chemical industry | APOS, S
Heat, for reuse in municipal waste incineration only {SE}| market for | APOS, S
Electricity, high voltage {SE}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | APOS, S
Zinc coat, pieces {GLO}| market for | APOS, S
Electricity, medium voltage {SE}| market for | APOS, S
Cast iron {GLO}| market for | APOS, S
Polystyrene, general purpose {GLO}| market for | APOS, S
Wood pellet, measured as dry mass {RER}| market for wood pellet | APOS, S
Packaging film, low density polyethylene {GLO}| market for | APOS, S
Permanent magnet, for electric motor {GLO}| market for permanent magnet, electric passenger car motor | APOS, S
Kraft paper, unbleached {GLO}| market for | APOS, S
Corrugated board box {GLO}| market for corrugated board box | APOS, S
Iron pellet {GLO}| market for | APOS, S
Electronics, for control units _edited{GLO}| market for | APOS, S
Phenolic resin {GLO}| market for | APOS, S
Copper {GLO}| market for | APOS, S
Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | APOS, S
Nylon 6-6 {GLO}| market for | APOS, S
Polyoxymethylene (POM)/EU-27
Polyvinylchloride, bulk polymerised {GLO}| market for | APOS, S
Polyethylene, linear low density, granulate {GLO}| market for | APOS, S
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, S
Aluminium, wrought alloy {GLO}| market for | APOS, S
Steel, chromium steel 18/8 {GLO}| market for | APOS, S
Titanium dioxide {RER}| market for | APOS, S
Epoxy resin {GLO}| market for epoxy resin | APOS, S
Stone wool {GLO}| market for stone wool | APOS, S
Steel, low-alloyed {GLO}| market for | APOS, S
Acrylic dispersion, without water, in 65% solution state {GLO}| market for | APOS, S
Paraffin {GLO}| market for | APOS, S
Synthetic rubber {GLO}| market for | APOS, S
Steel, unalloyed {GLO}| market for | APOS, S

Lund University

Dept of Architecture and Built Environment: Division of Energy and Building Design
Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services