# Comparative life-cycle assessment of constant air volume, variable air volume and active climate beam systems for a Swedish office building

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## ABSTRACT

Energy use in buildings has a significant influence on the global energy demand and environmental impacts. Among all building systems, heating, ventilation, and air conditioning (HVAC) systems are the most energy-intensive in terms of their total energy requirements. The production and operation of HVAC systems have a significant impact on the environment. These systems are also among the largest consumers of natural resources and materials in the building sector. With an ever-increasing focus on energy and material use, the question remains, which HVAC system has a better environmental performance. This paper presents a comparison between the life cycle impacts of three different HVAC systems — Constant Air Volume (CAV), Variable Air Volume (VAV) and Active Climate Beams (ACB) — designed for a Swedish modern office building. The system boundary of the life cycle assessment is cradle-to-grave with options, over a 20-year period. The life cycle assessment (LCA) of the three systems has been performed using SimaPro software. The CML IA (baseline) method has been used for the impact assessment. The life cycle impacts have been weighted using the Dutch shadow cost method. The results show that from a life cycle perspective, the ACB and VAV systems have comparable environmental performance. The CAV system is shown to have the worst overall environmental performance. The manufacturing phase of the ACB system exhibits the highest environmental impacts among the three systems, reflecting its high use of copper. The operational phase is the main contributor to the environmental burden for all three systems.

## KEYWORDS

Life cycle assessment; Energy; HVAC system; Environmental impacts; Impact assessment

## 1 INTRODUCTION

The built environment is a major contributor to green-house gas emissions (Khasreen, Banfill, & Menzies, 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 (Zabalza, Aranda-Usón, & Scarpellini, 2009). In the European Union, the building sector is responsible 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 by at least 40 % by the year 2030, compared to the 1990 emission levels (European Commission, 2019).

Among all systems in buildings, Heating, Ventilation, and Air Conditioning (HVAC) systems are by far most energy-intensive, accounting for approximately 50 % of the total energy consumed by buildings (Pérez-Lombard, Ortiz, & Pout, 2008). Nonetheless, HVAC systems are one of the essential building service elements in modern buildings (Chen, 2011). The number of these systems being installed has increased dramatically over the last few years (BSRIA, 2018; Coletti & Fano, 2008). This is mainly due to increasing requirements on thermal comfort and climate change. With an aim of reducing energy consumption during the operational phase while providing good indoor air quality (IAQ), new HVAC systems, such as chilled beams, have been introduced (Chen, 2011). However, other life cycle phases of an HVAC system, including processing or manufacturing of materials, and installation and construction of components, among others, also consume large quantities of energy and generate significant environmental impacts. 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).

Overall, increased awareness toward environmental issues has led societies 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 Constant Air Volume (CAV) system, a Variable Air Volume (VAV) system, and an Active chilled beams (ACB) system have been evaluated and compared for a modern office building, in Sweden. Part of the aim of this work is to identify the major factors influencing the environmental impacts of each system, in addition to providing distinct evaluation and comparison of the three HVAC systems. The outcomes of this research would facilitate the future selection of the HVAC systems, and would also contribute to the development and improvement of the studied systems.

## 2 BUILDING DESCRIPTION

This study assesses three HVAC systems in a hypothetical modern office building assumed to be located in Malmö, Sweden. The building, shown in Figure 1, consists of three stories with a heated floor area of 1088 m$^2$. The building was previously used by Abugabbara et al. (2018) to compare the operational energy use of CAV, VAV, and ACB systems using the dynamic building energy simulation program TEKNOsim (Abugabbara and Javed, 2019; Javed et al., 2016). In the original work, the building was divided into six thermal zones and was assumed to have an occupancy pattern based on Halvarsson (2012). The U-value of the thermal envelope was set based on the Swedish building code (BBR) requirements (Boverkets byggregler, 2018). The indoor 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. The calculated energy consumption for the three HVAC systems is shown in Figure 2.

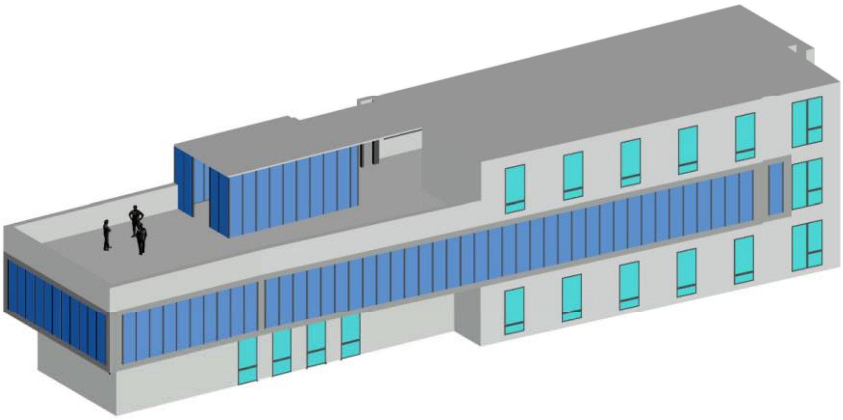

Figure 1: 3D building model (Abugabbara et al., 2018).

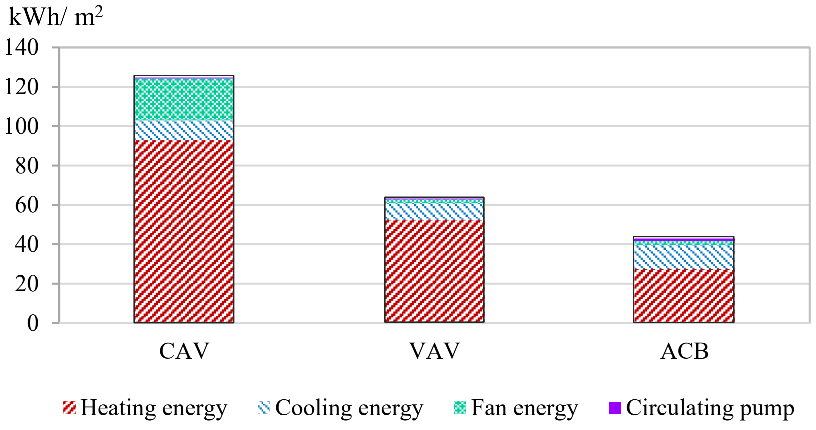

Figure 2: Annual energy consumption of three HVAC systems (Abugabbara et al., 2018).

# 3 LCA METHODOLOGY

## 3.1 Goal and scope

### 3.1.1 Functional unit

In this work, the function of the studied HVAC systems was to provide space heating and cooling for a modern office building in Sweden, while simultaneously maintaining the ventilation airflow requirements. 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.

### 3.1.2 System boundary

The LCA study included all components of HVAC systems inside the building envelope, as shown in Figure 3. All purchased energy, both electrical and thermal, were also taken into account.

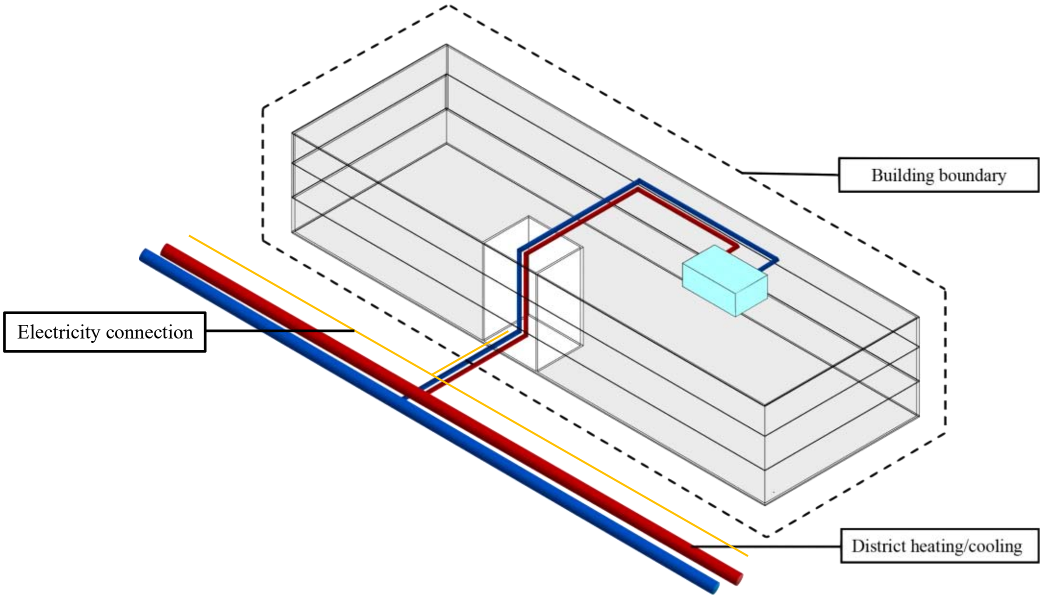

Figure 3: System boundary for material and energy flow.

The system boundary of the LCA study, shown in Figure 4, included extraction of raw materials, production of the materials, manufacturing of the components and usage during the operational phase. Available data form a commercial manufacturer (Lindab AB, 2019) was used for the evaluation of the manufacturing and operational phase of the HVAC components. The annual electricity of operation was also included.

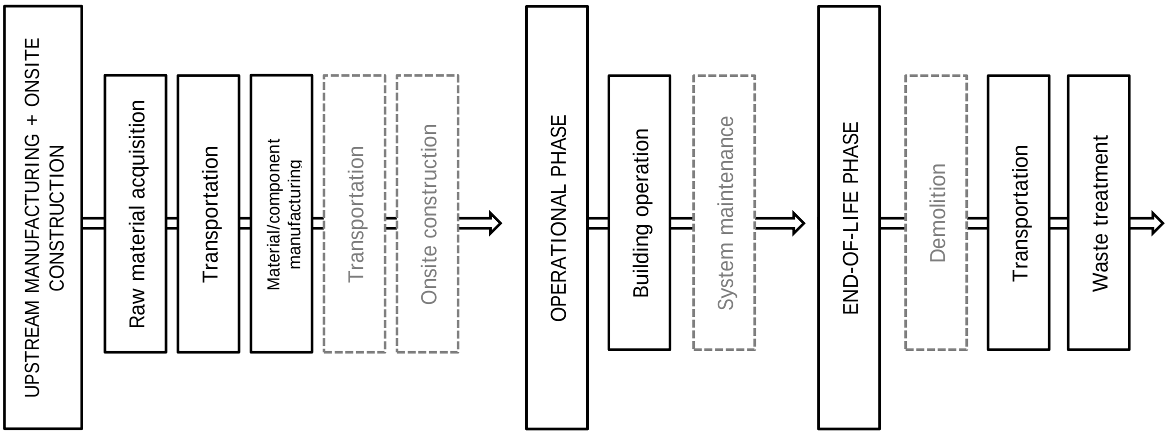

Figure 4: System boundary for LCA.

Energy needed for the waste treatment and recycling of materials was considered. Transportation to the waste treatment and recycling facilities was also taken into account. However, the phases shown in dashed boxes, including the demolition phase, maintenance phase and the transportation to the construction site were not included due to lack of data. Hence, the system boundary was set to be cradle to grave with options.

## 3.2 Inventory analysis

Ecoinvent v3 (2019) database, established by the Swiss Centre for Life Cycle Inventories, was used as the inventory data source (Martínez-Rocamora et al., 2016). Pre-defined materials and processes were used from the database. To provide a fair comparison between materials and to represent the worst-case scenario, market data from Ecoinvent 3 database was used for the processing of the materials. Market data includes averaged data from Europe, Asia, Africa, etc. The data accounts for the environmental impacts associated with extraction of raw materials, transport to production site, and energy used for production, among others (Lindvall, 2018).

### 3.2.1 Materials

Initially, a bill of quantity (BOQ) of all components of the three systems analyzed was obtained from the manufacturer of the HVAC systems. The material content for each component, along with the weight of each HVAC component, was obtained through the building product declarations (BPD) (Lindab AB, 2019). Materials that were stated to make up less than 1 % of a component and their percentages were not specified were not taken into account. Materials making up components that were not included in the BOQ such as pipes and pumps were obtained through Environmental Product Declarations (EPD) or were set according to pre-defined data found in the Ecoinvent database. Materials making up each system can be seen in Figure 5.

Recycling, incineration of waste and landfill rates were set based on estimated Swedish rates (FTI AB, 2018). Ninety-nine percent of the material scrap that could not be recycled was assumed to be incinerated while the remaining one percent was assumed to be landfilled.

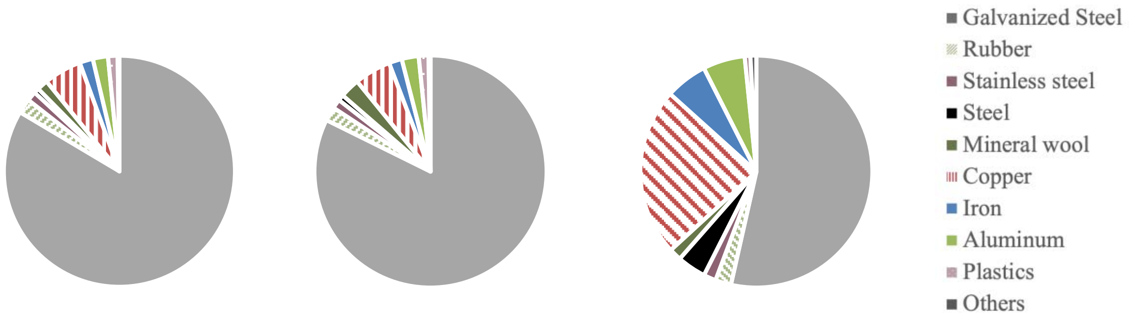

Figure 5: Materials making up the HVAC systems in the following order: CAV, VAV and ACB.

### 3.2.2 Energy

The electricity used by the HVAC components during the manufacturing and operational phase was set based on Swedish electricity mix from Ecoinvent database (Ecoinvent v3, 2019). Energy used for heating was set based on different energy types used in Sweden's district heating system, shown in Figure 6. Energy used for cooling was set based on district cooling produced by mechanical chillers at a seasonal COP of 3.

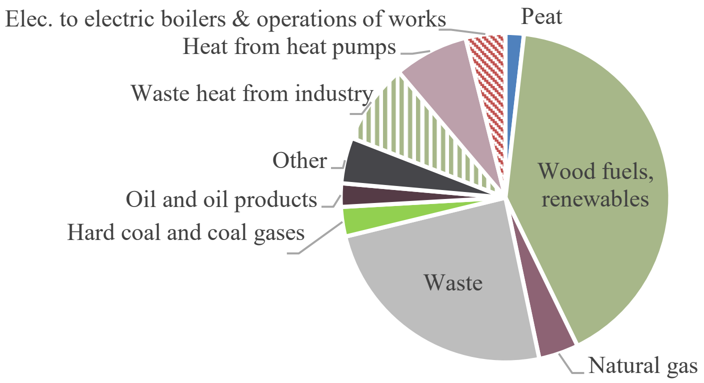

Figure 6: Total energy input for Sweden's district heating (SCB, 2017).

## 3.3 Life cycle impact assessment

The LCA study was conducted using SimaPRO, an LCA software developed and distributed by PRé Sustainability Consultants (Hollerud, Bowyer, Howe, Pepke, & Fernholz, 2017). Ecoinvent 3 database (Ecoinvent v3, 2019) was used as the inventory database in SimaPRO. The LCA system model chosen was Allocation at point of substitution (ASOP), which is based on the attributional approach. CML IA (baseline), an LCIA methodology developed at the University of Leiden in the Netherlands in 2001, was used to assess the potential environmental impacts of each system (Van Oers, 2012; Acero, Rodríguez, & Ciroth, 2014). The CML-IA (baseline) is a midpoint-oriented method that includes the characterization factors for all baseline characterization methods mentioned in the Handbook of LCA (ILCD, 2010). The results were normalized based on the EU 25+ 3 2000 reference values provided by CML IA (baseline) method and weighted based on the shadow cost method (Van Oers, 2012: De Bruyn et. al., 2010; de Klijn-Chevalerias and Javed, 2017). For this study, the environmental impacts of the three systems were first compared for each life cycle phase. Then, the total environmental impacts and shadow cost associated with the whole life cycle of the systems were compared.

### 3.4 Assumptions

The lifespan of the three HVAC systems was taken as 20 years. The generation of electricity, used for manufacturing and processing, operational phase of the building, and for all other activities, was based on Swedish electricity mix. The building was considered to be connected to district heating and cooling systems. The maintenance of the three HVAC system was assumed to be similar. It was assumed that the efficiency of the HVAC systems would remain the same throughout the life span of the systems. The annual energy use and emissions were assumed constant throughout the lifecycle of the systems. This means that the techno-sphere was assumed to have no changes throughout the period evaluated. Assumptions made for the waste treatment and transportation phases were based on Sweden's recycling rate and on the average data obtained from the Ecoinvent database, respectively.

## 4 RESULTS

The environmental impacts of the life cycle of the CAV, VAV and the ACB systems are presented in Figure 7. It can be observed that the operational phase is the dominant contributor to the total environmental impacts of the CAV and the VAV systems. However, for Abiotic depletion potential, it can be observed that the manufacturing phases of all three systems contribute more to the indicator than the operational phase. Furthermore, recycling and waste treatment phase are shown to reduce the environmental impacts of the systems.

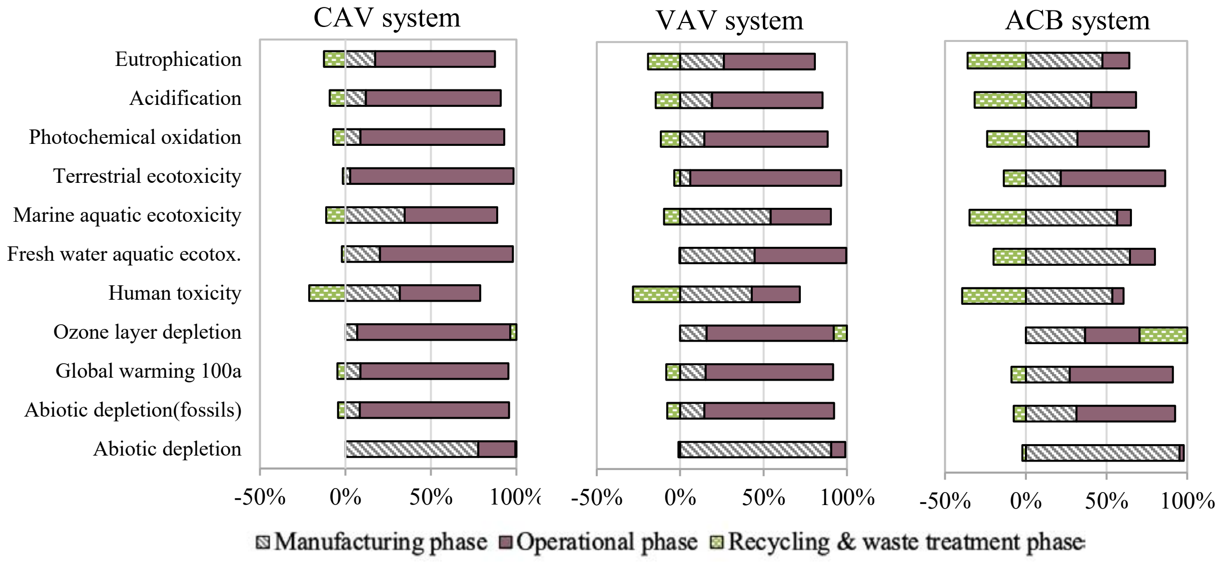

Figure 7: Environmental impacts of CAV, VAV and ACB system.

Unlike the CAV and the VAV systems, the manufacturing phase of the ACB system contributes to the majority of the environmental impacts. As earlier, the recycling and waste treatment phase mitigates the environmental impacts of the ACB system too.

The relative differences between the environmental impacts from the manufacturing and recycling phases of the CAV, VAV and ACB systems are presented in Figure 8. The manufacturing phase of the ACB system has the highest environmental impacts among all three systems, whereas the manufacturing phase of the CAV system has the lowest impacts. It can also be observed that relative difference between the environmental impacts of the CAV and the VAV systems for all indicators is quite small.

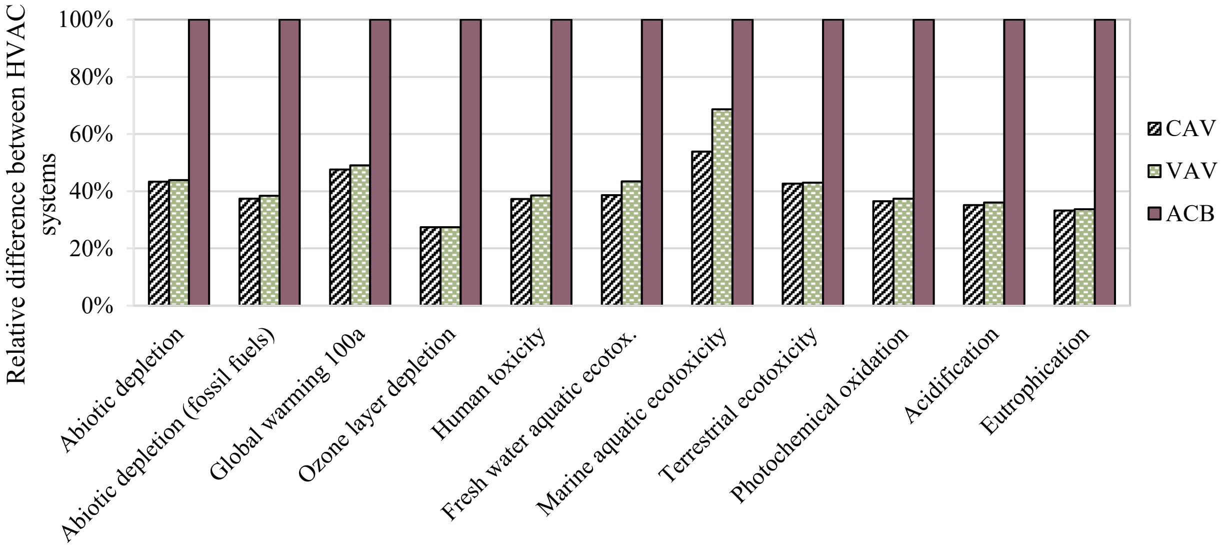

Figure 8: Relative difference between the environmental impacts of the manufacturing & recycling phases of CAV, VAV, and ACB systems.

Figure 9 presents the relative differences between the environmental impacts of the operational phase of CAV, VAV, and ACB systems over 20 years. The results shown in the figure indicate that the operational phase of the ACB system has the lowest environmental impacts among the three systems, whereas the CAV system has the highest impacts.

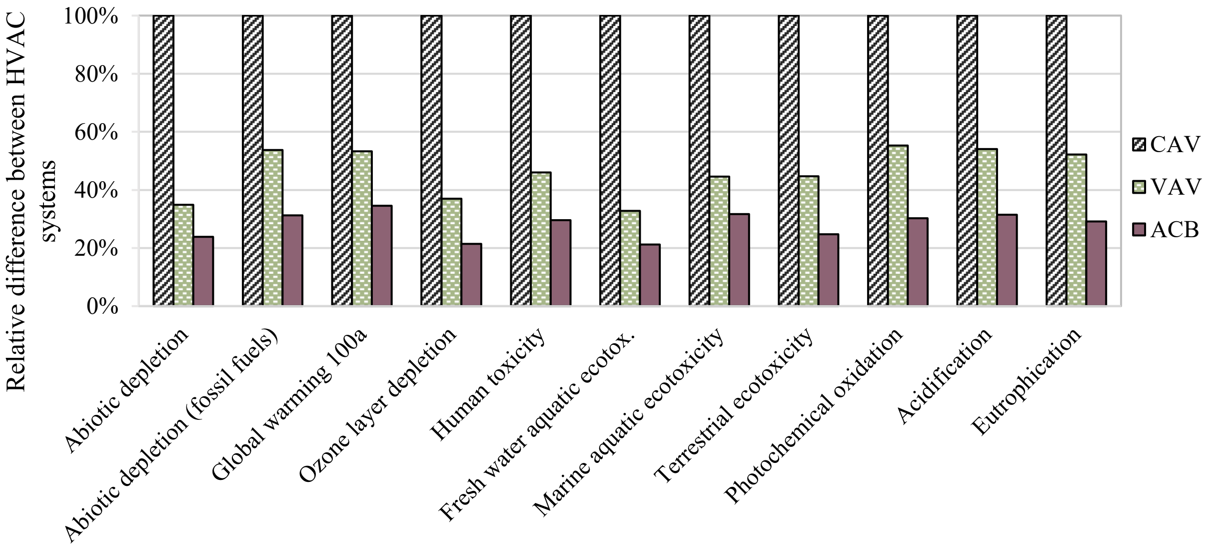

Figure 9: Relative difference between the environmental impacts of the operational phase of CAV, VAV, and ACB systems over 20 years.

Figure 10 presents the relative differences between the lifecycle impacts of CAV, VAV, and the ACB systems. It can be observed that the relative differences between the lifecycle impacts of the three systems vary depending on the environmental indicators. Nevertheless, the CAV system has the highest environmental impacts for all indicators except abiotic depletion of natural elements, for which the ACB system has the highest environmental impact.

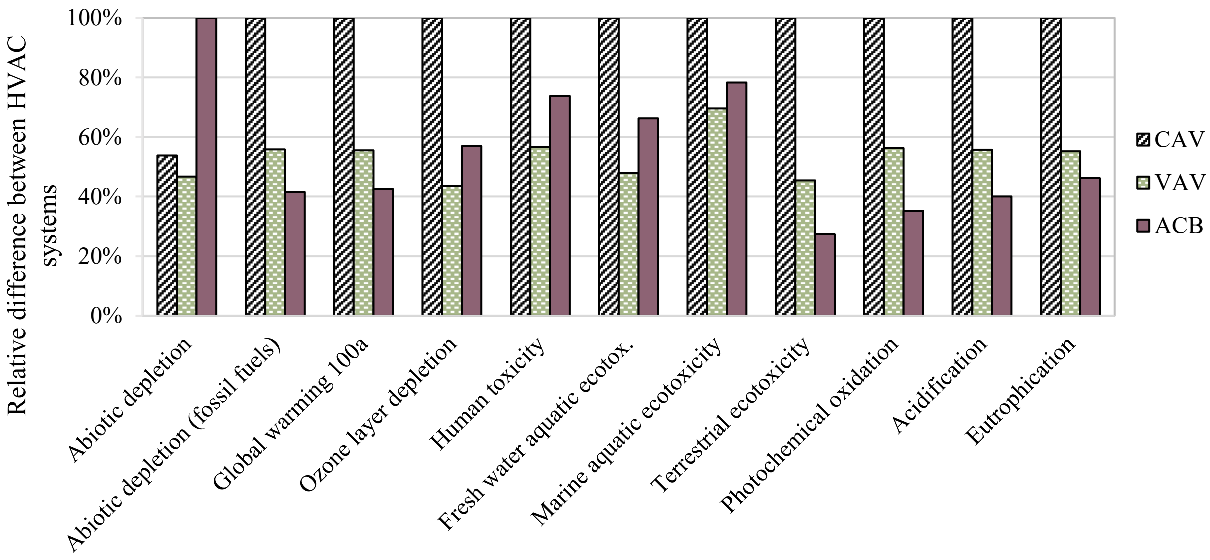

Figure 10: Relative difference between the environmental impacts of the life cycle of CAV, VAV, and ACB systems.

Figure 11 shows the total shadow cost for each of the three systems by aggregating scores of all individual environmental indicators into a single score. The shadow cost for each system has been calculated using a weighting factor, or more specifically, by assigning a unit cost to each environmental indicator. The Dutch weighting factors have been used for this study. It can be seen from the figure that the CAV system has the highest shadow cost among all three systems. Compared to the CAV system, the VAV and ACB systems have 38 and 33 % lower shadow costs, respectively.

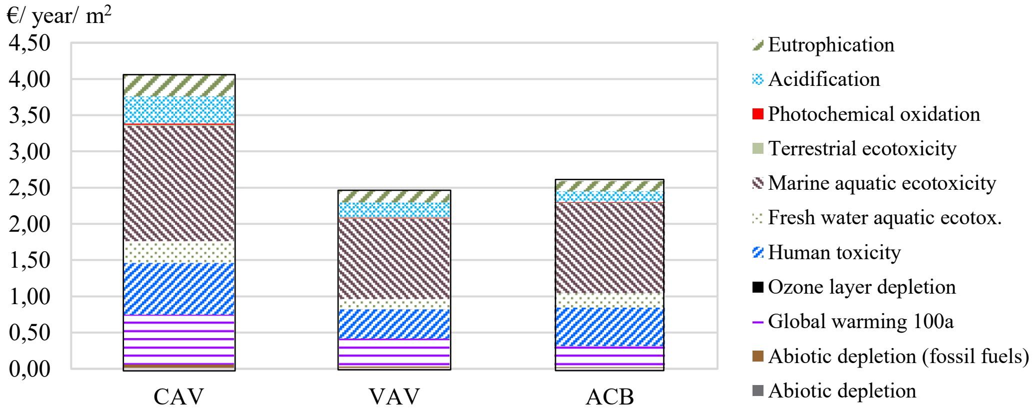

Figure 11: Total shadow cost of the CAV, VAV, and ACB systems.

## 5 DISCUSSION AND CONCLUSIONS

The LCA results clearly indicate that environmental impacts of the operational and the maunfacturing phases vary depending on the HVAC system. For CAV and VAV systems, the operational phase contributes most to the overall environmental impacts. Whereas, for ACB system, the maunfacturing phase has the highest environmental impacts compared to the other life cycle phases. The evironmental impacts from the operational phase of the ACB system are substantially lower than both the CAV and VAV systems. This is due to the high amount of energy used by the CAV and VAV systems during the operational phase. Overall, the CAV system has by far the highest environmental impacts over its life cycle. The life cycle environmental impacts of the ACB system are somewhat comparable to those of the VAV system. An exception to this is the Abiotic depletion, which takes into accounts the natural resources needed for the manufacturing process. Due to the high use of copper, the ACB system has the highest Abiotic depletion impact. The major sources of potential impacts include the use of metals, zinc coating for galvanized steel, and energy use during the operational phase.

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, have 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.

The shadow cost method provides an interesting perspective on the environmental performance of the three analyzed systems. It aggregates different impact indicators into a single score. The CAV system has the highest shadow cost, suggesting the worst overall environmental performance among the three analyzed systems. The VAV system has a slightly lower shadow cost than the ACB system. This indicates that the VAV system could have a marginally better environmental performance than the ACB system.

## 6 ACKNOWLEDGEMENTS

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