The Hidden Footprint of Truck Connectivity

A Life Cycle Assessment of Vehicle-to-Cloud Connectivity

Master's Thesis in Industrial Ecology

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Illustration of truck-to-cloud connectivity, generated using Google Gemini (2026).

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Abstract

As the transport sector undergoes a rapid digital transformation, the environmental trade-offs between the benefits of vehicle connectivity and the burdens of the supporting digital infrastructure remain poorly understood. This study performs a Life Cycle Assessment (LCA) to quantify the environmental impact of cloud-based data center services required for truck connectivity and balances these against the enabled fuel savings. The assessment covers the life cycle of a data center, including building construction, hardware manufacturing, and operations.

The results indicate that the environmental burden of data centers is heavily dominated by the operational phase and the manufacturing of servers, where printed circuit boards (PCBs) constitute the primary impact driver. In contrast, building construction has a minor influence on the total life cycle impact. The magnitude of the impacts from the operational phase is primarily a result of the high electricity use and varies significantly with the electricity mix.

Regarding truck operations, the study finds that connectivity services enable fuel consumption reductions that significantly outweigh the data center infrastructure's burdens. The results show a resilient net-positive outcome, where the scale of climate benefits remains much larger than the impact of the required digital infrastructure, even under scenarios of significantly increased data demand. The study concludes that while vehicle connectivity introduces new material and energy demands, it can serve as a powerful tool for reducing the overall environmental footprint of the transport sector.

Keywords: *Truck Connectivity, Vehicle-to-Cloud Connectivity, Information and Communication Technology, Cloud, Data Center, Server, Life Cycle Assessment, Environmental Impact.*

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List of Acronyms

Below is the list of acronyms that have been used throughout this thesis:

ADP	Abiotic Resource Depletion Potential
AP	Acidification Potential
BEV	Battery Electric Vehicle
BTDC	Boden Type Data Center
CAV	Connected and Autonomous Vehicle
CPU	Central Processing Unit
CV	Connected Vehicle
DC	Data Center
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDD	Hard Disk Drive
ICEV	Internal Combustion Engine Vehicle
ICT	Information and Communication Technology
ITS	Intelligent Transportation Systems
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ODD	Optical Disk Drive
OTA	Over-the-Air
PCB	Printed Circuit Board
PCC	Predictive Cruise Control
PSU	Power Supply Unit
PUE	Power Usage Effectiveness
RAM	Random Access Memory
V2C	Vehicle to Cloud communication
V2I	Vehicle to Infrastructure communication
V2N	Vehicle to Network communication
V2P	Vehicle to Pedestrian communication
V2V	Vehicle to Vehicle communication
V2X	Vehicle to Everything communication
WTW	Well-To-Wheel

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Introduction

This chapter introduces the research area by exploring the technical and environmental context of vehicle connectivity alongside its potential sustainability benefits. It then provides a comprehensive review of previous research regarding the environmental assessment of data centers. Building on this background, the chapter concludes by presenting the specific aim and research questions of the study.

1.1 Background

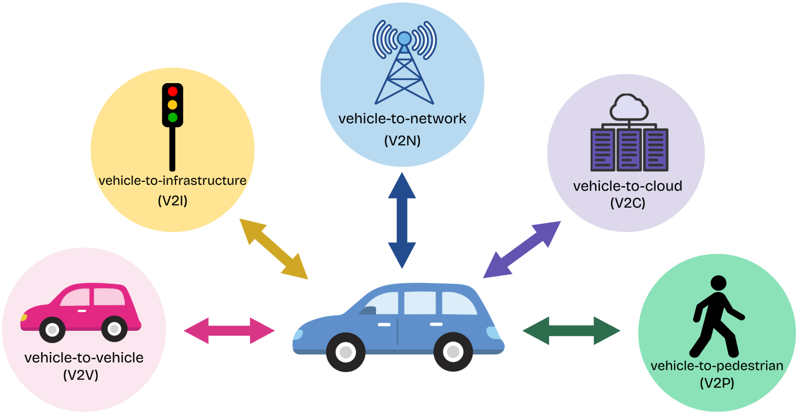
Road transport accounts for approximately one fifth of the total Greenhouse Gas (GHG) emissions within the European Union (European Parliament, 2019). Of these emissions, heavy-duty trucks account for 27.1%. Therefore, significant efforts have been made to reduce emissions from the transportation sector, primarily by improving fuel efficiency and transitioning from conventional combustion engines to electric vehicles. In parallel with these developments, major advancements in digital technologies, including Artificial Intelligence (AI), cloud and edge computing, and 5G networks, are accelerating the digital transformation of the mobility sector. These technologies enable smarter and more connected transportation systems, creating new opportunities to further enhance vehicle efficiency, optimize traffic management, and reduce environmental impacts through digital solutions. (European Commission, n.d.-a)

Intelligent Transportation Systems (ITS) are rapidly expanding to meet the growing demand for safer, more efficient, and sustainable transportation solutions. A central component of modern ITS is the Connected Vehicle (CV), which uses Information and Communication Technology (ICT) for real-time data exchange, allowing the driver to make more informed driving decisions (Elassy et al., 2024). The ability of connected vehicles to communicate with each other and their surroundings enables a variety of digital services, ranging from advanced safety systems and infotainment (such as music streaming) to environmental optimization. Environmental optimization functions are increasingly critical for large automotive companies such as Volvo Trucks. Specific connected services, such as Predictive Cruise Control (PCC) and advanced route planning, enable highly efficient fleet management by eliminating unnecessary driving, ultimately reducing both operational fuel costs and the overall environmental impact of the fleet. This highlights the potential of vehicle connectivity to contribute to a more sustainable and resource-efficient transportation sector.

Vehicle connectivity is closely linked to vehicle automation, the use of technology to assist or entirely replace human operators in navigating and controlling vehicles. Automation is typically categorized into six distinct levels, as defined by SAE International (n.d.), and connectivity is a prerequisite for reaching the higher automation levels. The automation levels range from 0, no automation, to 5, full automation, which represents an unconditional self-driving vehicle. Levels 1-2 provide driver support such as adaptive cruise control or lane keeping assist, but the driver is still the one making the driving decisions. Levels 3-5 represent different levels of automated driving, where the vehicle makes some or all driving decisions.

Additionally, there are different types of vehicle connectivity (RGBSI, 2020), as seen in Figure 1.1. Vehicle-to-Vehicle (V2V) communication has significant safety and efficiency benefits by enabling the driver to get a better understanding of the surrounding traffic. Vehicle-to-Infrastructure (V2I) connectivity includes e.g. connection with nearby traffic lights or cameras, and can result in improvements such as efficient speed adjustments. Vehicle-to-Pedestrian (V2P) connection uses smart phones or other devices to enable data exchange between drivers and vulnerable road users such as pedestrians and bicyclists. Vehicle-to-Network (V2N) communication can connect the vehicle to cellular networks, while the Vehicle-to-Cloud (V2C) communication utilizes these networks to transmit vehicle data to cloud data centers. The automation level and type of connectivity will determine the impact of the connectivity.

Figure 1.1: Different types of vehicle connectivity.



There is a wide range of connectivity services that have the potential to increase fuel efficiency and reduce environmental impacts of connected and automated vehicles (CAVs). Kopelias et al. (2020) mention the following services and their potential environmental benefits:

- **Eco-driving**, which refers to optimizing the acceleration and braking of the vehicle with the aim of reducing emissions.
- **Platooning**, meaning to use connectivity to coordinate a line of trucks driving

with minimal gaps, has the potential to reduce fuel consumption by decreasing air resistance. The effect varies depending on the specific vehicle's position, where higher reductions are reached for the vehicles in the middle of a platooning line-up, while the first and last vehicles achieve a lower effect.

- **Lightweight designs** in highly automated vehicles are enabled due to a reduced need for safety equipment, and can lead to lowered fuel consumption.
- **Route optimization** aimed at reducing emissions has the potential to reduce fuel consumption by avoiding congestion and recommending or choosing the most environmentally efficient routes.
- **Congestion avoidance** can in itself reduce fuel consumption significantly during peak congestion hours. This greatly depends on the penetration level of CAVs, since a higher share of CAVs in traffic leads to a better possibility of optimizing the driving situation and thus avoiding congestion.

While these vehicle connectivity services support efficiency in areas such as safety, time management, and sustainability, they also impose environmental burdens through intensive data transmission, edge computing, as well as Data Center (DC) operations (Jerléus et al., 2024). DCs are vital components of the modern ICT infrastructure, offering a wide range of services for data storage and processing. There are several types of DC facilities, including cloud DCs which provide shared IT infrastructure to multiple users, offering leased and managed resources through third-party providers and enabling access via the internet (Smalley, 2024). Cloud DCs are a central part of vehicle connectivity, enabling high computational loads and data storage external to the vehicle (Resolute Dynamics, 2025).

The core components of a DC consist of IT equipment such as servers that support data processing, storage, and transmission (McKinsey, 2025). In addition, supporting infrastructure such as cooling systems, power supply units, and high-speed network connectivity are required to ensure reliable and continuous operation (Smalley, 2024). As DCs operate uninterrupted to provide constant access to information, they are highly energy-intensive facilities, requiring significant amounts of electricity for both IT equipment and cooling systems, as well as water for cooling and electricity production. Maintaining appropriate temperature and humidity levels is essential for ensuring safe operation and optimal equipment performance (Palo Alto Networks, n.d.). Moreover, the manufacturing of server hardware involves substantial use of scarce minerals and metals, adding to the resource intensity of DCs (European Commission, Joint Research Centre, 2015). Collectively, these factors demonstrate that DCs impose considerable environmental burdens, both during operation and throughout the lifecycle of their infrastructure and equipment.

Although DCs are becoming more energy efficient through technological advancement, the continued expansion of digital services is increasing their overall energy demand, with the sector's share of global energy consumption projected to reach

3–13% by 2030 and its contribution to global GHG emissions projected to reach 14% by 2040 (Jerléus et al., 2024). Consequently, the net environmental benefit of vehicle connectivity services depends on whether its operational efficiencies, such as optimized routing and smoother driving, are sufficient to outweigh the negative impacts of its own digital ecosystem (Gawron et al., 2018).

1.2 Previous Research on Data Centers

The holistic environmental footprint of the digital ecosystem required for vehicle connectivity, specifically in relation to data centers, remains a subject of academic debate and uncertainty. To assess these environmental impacts, Life Cycle Assessment (LCA) is a highly valuable tool. However, it can be very challenging to apply due to its intensive need for detailed and recent data. This is particularly evident in the ICT industry, where products are complex and evolve rapidly. ICT products consist of thousands of individual components sourced from multiple suppliers, each of which is continuously improved, replaced, or redesigned to meet the growing demand for higher performance (Okrasinski et al., 2012). This complexity makes the collection of reliable environmental data for LCAs especially difficult.

A literature review of existing LCA studies on data centers reveals that many open-source analyses rely on the same outdated datasets (e.g. Whitehead et al. (2015)), despite the clear need for up-to-date, industry-specific primary data. One reason for this is that Life Cycle Inventory (LCI) data are frequently not publicly accessible. This lack of transparency hinders external peer review, limits improvement, and makes further research more difficult. The reason for this limited accessibility is that primary data often is proprietary or confidential information to companies, making the collection of LCI data very difficult and making many studies dependent on secondary data (CarbonBright, n.d.).

The results of LCA studies are often inconsistent due to differences in the underlying data and assumptions, as well as subjective methodological choices. The limited number of LCA studies on data centers are highly heterogeneous, with large variations in scope and system boundaries. Many studies focus solely on the operational phase, ignoring other life cycle stages. This may be explained by the long-standing assumption that embodied carbon has a relatively minor environmental impact compared to the operational phase. However, recent studies show that this assumption is misleading, as embodied carbon can account for a substantial share of total data center emissions. This is largely due to improvements in energy efficiency and the transition to renewable energy, which significantly reduce operational emissions. Therefore, upstream emissions are important both today and in the near future, highlighting the need for LCA studies to adopt a cradle-to-grave perspective. (Chien, 2023)

Furthermore, many LCA studies focus on high-impact components of data centers in isolation, such as IT equipment or cooling systems (e.g. Isler-Kaya and Karaosmanoglu (2023)), thus missing the broader system impacts. The impact assessment itself can also vary significantly, with some studies focusing only on Greenhouse Gas (GHG) emissions and water use, potentially overlooking other important impact categories. The differing compositions, sizes and locations of DCs also create major differences in material usage and operational energy and water usage. Factors such as choice of cooling system or surrounding climate has significant impacts on the resulting environmental impact of a DC. These differences result in the LCA results being highly varying, thus making it difficult to draw general conclusions. Taken together, these challenges highlight the need for more robust and context-specific LCA approaches when assessing the environmental impact of connectivity. In particular, there is a need for studies that integrate both vehicle and ICT systems within a transparent framework that accounts for the inherent variability in data centers.

1.3 Aim & Research Questions

Previous research has often looked at vehicles and ICT impacts separately, usually treating vehicle connectivity as a small supporting detail rather than the main focus. Because of this, the actual environmental impact of the connected services is not fully understood. Specifically, there is very little research that quantifies the impacts from the digital infrastructure, like cloud computing, and weighs them against the fuel and energy savings these services actually provide. Life Cycle Assessment (LCA) has a growing importance within the ICT sector, however, studies assessing the environmental impacts of cloud services remain limited, fragmented, and often lack transparency.

Based on the identified research gap, this thesis aims to evaluate the net environmental impacts associated with vehicle connectivity by performing an LCA of a data center. The analysis then compares the environmental burdens from utilizing a data center with the environmental benefits enabled by connectivity services, such as energy and fuel reductions through route optimization.

To address this aim, the following research questions are formulated:

1. What is the life cycle environmental burden of the cloud-based data center services required to support truck connectivity?
2. What is the environmental benefit that can be achieved in truck operations through cloud connectivity services?
3. What is the net environmental impact when the burdens of the digital infrastructure are balanced against the enabled benefits from cloud connectivity?

2

Methodology

The methodology of this thesis follows a structured approach that integrates a literature review, a Life Cycle Assessment (LCA), and expert consultations. The literature review provides a foundation by mapping the current state of the art in vehicle connectivity and data center assessments. The LCA serves as the primary quantitative method to evaluate the environmental burden of data center operations. Additionally, consultations with industry experts were used to validate assumptions and address data gaps. Furthermore, this chapter incorporates a description of boundaries and limitations of the study.

2.1 Literature Review

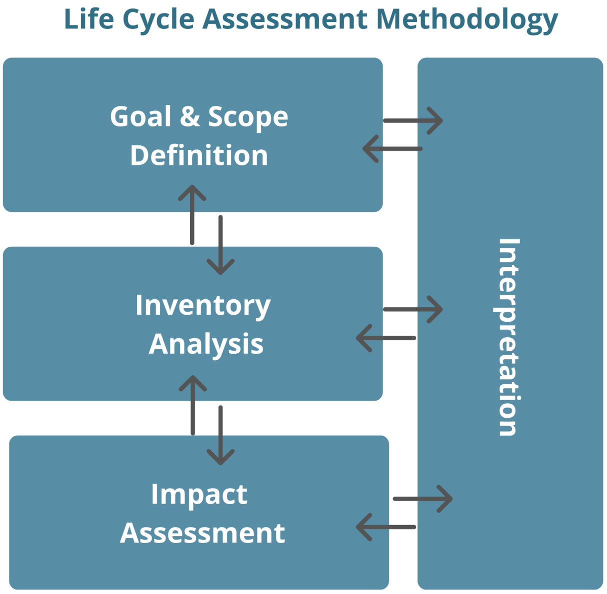
A systematic literature review has been conducted to establish a comprehensive theoretical foundation and to identify the current state of the art within the study area. Relevant publications are primarily identified through searches in ScienceDirect and Scopus. The initial search terms include *vehicle connectivity, connected vehicles,* and *Life Cycle Assessment of data centers,* To get a full picture of what studies exist regarding LCAs of data centers, the following ScienceDirect search was performed: (*'life cycle assessment' OR 'environment') AND 'data center'.* For the vehicle part, the search was: *(vehicle connectivity OR connected vehicles) AND (environmental impact OR life cycle assessment).* Only peer reviewed scientific articles in English were utilized for the state of the art section.

As the field has developed rapidly in recent years, the literature review focuses mainly on recent studies. However, a select few older publications were also included, as many recent studies rely heavily on their data. In addition to the specific searches, the snowball method was also applied, using primary sources as starting points and reviewing their reference lists (backward) and tracking more recent citations (forward). By this method it was possible to identify additional relevant studies that were not captured in the initial keyword search. To complement the academic research, gray literature was consulted, including EU reports and documentation from key industry actors. These sources provided essential data on data center operations and environmental benchmarks, as well as specific Bill of Materials (BOM) data used to model server life cycle inventories.

2.2 Life Cycle Assessment

In order to assess the environmental impacts associated with connectivity services in trucks, and the underlying infrastructure such as data centers, a Life Cycle Assessment (LCA) was employed. LCA is a standardized and widely recognized method for evaluating the environmental performance of products and systems across their entire life cycle (Baumann & Tillman, 2004). It provides a quantitative, science-based framework for assessing environmental impacts, thereby supporting informed decision-making in the design and development of these products and systems. This study follows the methodological framework defined by ISO 14040 and 14044, as illustrated in Figure 2.2, consisting of Goal & Scope Definition, Inventory Analysis, Impact Assessment and Interpretation. The following sections describe the methodological choices regarding the LCA.

Figure 2.1: The methodological steps of a LCA according to ISO standard.



2.2.1 Goal & Scope Definition

2.2.1.1 Goal

The goal of this thesis is to provide a bridge between the vehicle and cloud data center worlds, by evaluating the environmental impacts associated with vehicle connectivity. This includes comparing the environmental benefits enabled by connected services, with the environmental burdens arising from the supporting digital infrastructure. By applying a Life Cycle Assessment (LCA) approach, the results can help IVL advance the current state of knowledge on how vehicles and data centers interact. These insights will strengthen IVL's ability to advise both the industry and policy-makers, ensuring that the shift toward intelligent mobility is done sustainably. Additionally, the results will provide direct value to Volvo Group and the wider automotive industry. It can act as a guide for the difficult trade-off of where to process data: should it be handled internally inside the truck (Edge), or externally via cloud data centers (V2C)? Ultimately, this study can help companies make much more informed choices in their future LCAs by showing whether or not the environmental footprint of cloud connectivity is significant enough to change the total impact of the vehicle's life cycle.

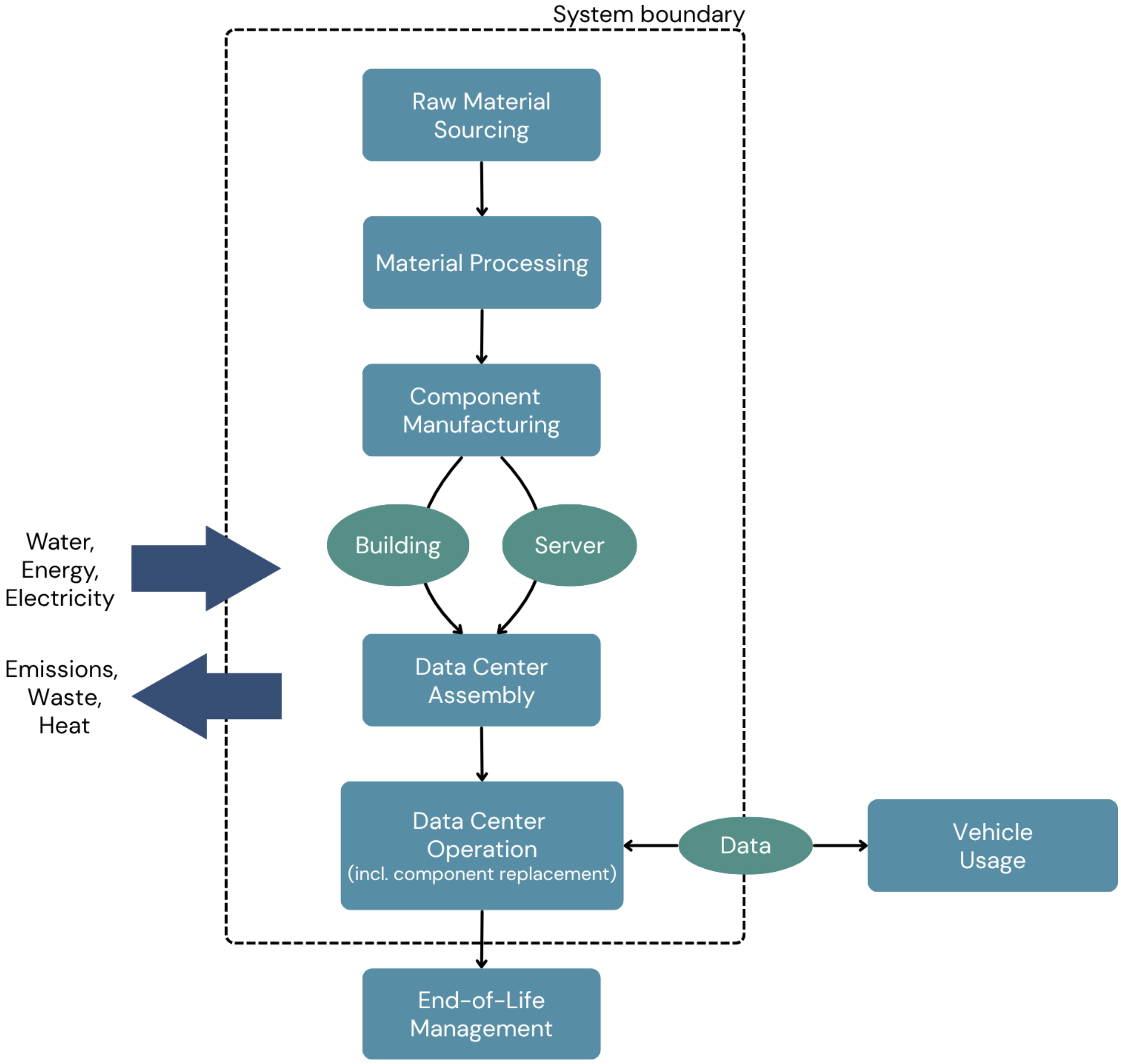
2.2.1.2 Scope

In order to assess the environmental impact of vehicle connectivity services, the scope of this study specifically includes the digital infrastructure required for these services. Consequently, a cradle-to-grave LCA, excluding end-of-life management, is conducted on a European cloud data center, over a lifetime of 30 years. A European scope was chosen since it is unknown to which data center or data centers the vehicles transmit their data. The vehicles may send data to cloud data centers located in different European countries rather than only within the country where the vehicle is used. The system boundaries encompass the life cycle stages: raw material sourcing, material processing, component manufacturing and operation, but exclude end-of-life management. An attributional LCA is chosen for this study, as the objective is to assess the environmental impacts of an existing system. In contrast, a consequential LCA would instead evaluate the environmental implications of changes between an existing and a potential future system (Baumann, 2010). The environmental assessment is conducted in OpenLCA 2.6.1, using ecoinvent 3.12 as the background database.

Functional Unit
The functional unit of the study is defined as the usage of cloud connectivity services in one truck over the course of one year. To determine the impact attributable to truck connectivity, the total environmental burden of the data center is subsequently allocated to a single vehicle. By anchoring the assessment to a single truck on an annual basis, the results become transparent and can easily be scaled to represent larger fleet operations or differing time frames.

Product System & Boundaries
Figure 2.2 illustrates the system boundary applied in the LCA of the Data Center (DC). The DCs life cycle consists of everything from raw material sourcing, material processing, component manufacturing, DC assembly, and DC operation including continuous component replacements. Due to using the cut-off method for allocation, the end-of-life management is not included in the system boundary, since the environmental benefits as well as the energy use for recycling is then allocated to the next product (Ekvall et al., 2020). All building and server components are assumed to be reused or recycled. This modeling choice was made to maintain consistency with the primary data source utilized for the life cycle inventory, and thus to avoid uncertainties through arbitrary assumptions.

Figure 2.2: System map covering the life cycle of a data center.



The modeled system distinguishes between building-related and server-related components, which are subsequently assembled into the final data center system. By utilizing ecoinvent as the background database, all upstream environmental burdens from the value chain, including raw material sourcing, material processing, and component manufacturing, were systematically included in the assessment. However, emissions arising during the construction of the building, the assembly of the servers, and the final assembly of the data center were not included, due to lack of reliable and suitable data. The same applies for transportation between life cycle stages, which is included through the use of ecoinvent market processes, up until the server and building assembly.

Allocation

This study focuses on two key areas where allocation is particularly important. Firstly, an allocation method needs to be chosen to determine how to handle possible reuse and recycling at end-of-life of the system components. Ecoinvent recommends using the cut-off method, which follows the "polluter pays" principle and allocates the environmental impact of material production to the first user of the material (ecoinvent, 2024). The cut-off method is applied to all material flows coming from or sent to another product system. This methodological choice aligns with the approach taken by Borisová and Vesterlund (2025), whose study serves as the primary source for the life cycle inventory. Their research included a sensitivity analysis comparing the cut-off method with Allocation at the Point of Substitution (APOS), but the resulting variance was found to be minor. Consequently, a separate APOS analysis was deemed unnecessary for this study.

The second allocation step regards how to determine which share of the modeled DC's environmental impact that can be assigned to Volvo Trucks' cloud connectivity services. Due to the multi-tenant nature of cloud computing, where multiple users share both physical and virtual resources, it becomes difficult to accurately measure and attribute impacts to individual users. This process is complex and adds uncertainty, making it harder to assess the environmental impact of ICT systems (Westerhof et al., 2023). Data center services includes three main parts: data processing, short term data storage, and long term data storage (as classified e.g. in the model Cloud Carbon Footprint (n.d.)). To find the share of DC services utilized by one Volvo truck, all three aspects should ideally be taken into account. However, only numbers regarding long-term data storage were available and thus used as a basis for allocation. This was then assumed to be applicable to all DC services. This also assumes that the full storage capacity is utilized during the assessed period. The allocation procedure is further explained in section 4.2.

2.2.2 Impact Assessment

For the Life Cycle Impact Assessment (LCIA), the EF v3.1 methodology was used. This LCIA method was selected based on its broad applicability, comprehensive coverage of environmental impact categories, and widespread use in European LCA studies. The following impact categories were selected because they reflect key environmental concerns associated with data center operation and manufacturing, all of which are defined and described by European Commission (n.d.-b):

- **Material resources: metals/minerals** reflects the depletion of material resources, based on the premise that current extraction of high-quality resources leads to future reliance on lower-quality reserves. This impact is assessed using the Abiotic Depletion Potential (ADP) indicator for minerals and metals and is expressed in kilograms of antimony equivalents (kg Sb-Eq).

- **Acidification** refers to the accumulation of acidifying substances in air, water, and soil, which can lead to environmental damage such as forest decline and increased fish mortality. Major sources include combustion processes in electricity generation, heat production, and transport. This impact is quantified using the Accumulated Exceedance (AE) indicator and expressed in moles of hydron equivalents (mol H+-Eq).

- **Energy resources: non-renewable** captures the consumption and depletion of fossil energy resources over time. It is assessed using the Abiotic Depletion Potential (ADP) indicator for fossil fuels and is expressed in megajoules (MJ), based on net calorific value.

- **Climate change (total)** represents the increase in global average temperatures resulting from greenhouse gas (GHG) emissions, primarily from the combustion of fossil fuels such as coal, oil, and natural gas. These impacts are quantified using the Global Warming Potential over a 100-year time horizon (GWP100) and expressed in kilograms of carbon dioxide equivalents (kg CO_2-Eq).

- **Water use** considers the extraction of water from natural sources such as lakes, rivers, and groundwater, while accounting for regional water scarcity by assigning greater impact to water use in water-stressed areas. This impact is assessed using the User Deprivation Potential (deprivation-weighted water consumption) indicator and is expressed in cubic meters (m^3) of water use, adjusted to local availability.

2.2.3 Sensitivity Analysis

For parameters deemed as uncertain or based on assumptions, a sensitivity analysis is conducted. This process is essential to evaluate the robustness of the life cycle results and to determine how variations in key inputs might shift the overall results. By testing these variables, the study can identify which factors have the most significant influence on the outcome. The following parameters are included: Data Center lifetime, Server lifetime, Electricity mix, Data center energy efficiency (measured in Power Usage Effectiveness (PUE)). See chapter 3 for further explanations of these parameters.

2.3 Expert Consultations

To complement the literature review and LCA methodology, a series of informal consultations were conducted with experts from various departments at Volvo Trucks and external specialists, including researchers and experts within the areas of vehicles and data centers. These consultations, carried out through a combination of scheduled meetings and ongoing electronic correspondence, were essential for developing a comprehensive understanding of the complex architecture of vehicle-to-cloud connectivity. Beyond providing a deeper insight into the studied systems, the expert dialogue served as a crucial tool for data acquisition and validation. It enabled the collection of primary data and the refinement of technical assumptions in cases where public documentation was unavailable.

2.4 Assessment of Net Climate Impacts

Finally, the potential climate benefits of truck connectivity were quantified by integrating operational data from Volvo on fuel consumption reduction potentials with existing literature regarding how these can be translated into greenhouse gas (GHG) emissions. This stage of the study focused exclusively on climate impact, as it was identified as the most critical environmental category and due to time constraints. To capture a broad spectrum of potential savings, two distinct powertrain technologies were compared: Internal Combustion Engine Vehicles (ICEV) and Battery Electric Vehicles (BEV). For the BEV, the analysis further accounted for regional variations by evaluating the impact of different local electricity mixes. The net climate impact was determined by weighing the life cycle burdens of the data center services (quantified in the LCA) against the operational benefits enabled by connectivity. To ensure the robustness of these findings, two break-even analyses were conducted to identify the equilibrium points where the environmental costs of the required data center infrastructure would offset the operational climate benefits.

2.5 Boundaries & Limitations

General boundaries of the study includes focusing on vehicle-to-cloud (V2C) connectivity, and thus excluding other connectivity pathways, such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). The focus of the study lies on trucks due to the cooperation with Volvo Trucks, determining data availability. This means that passenger cars, busses and construction equipment, that also can operate with these kinds of connectivity, are excluded from the scope. Additionally, the analysis is delimited to the *environmental* impacts associated with vehicle connectivity. Connected vehicle technologies can also provide additional benefits, such as improved traffic safety and enhanced user comfort or entertainment (e.g., internet access and infotainment services), as well as introduce non-environmental risks, including cybersecurity and privacy concerns. However, these social, safety, and ethical aspects fall outside the scope of this study and are therefore not considered.

While the data center is functionally connected to vehicle usage through data transmission, this study focuses specifically on the environmental impact associated with transmitting and processing vehicle-generated data in data centers, as this has been identified as a key research gap in the current literature. In contrast, the energy use and hardware required within the vehicle to enable connectivity have already been studied and are therefore excluded from this assessment. In the literature review the potential environmental benefits of connectivity services, such as emissions saving from eco-driving, are further examined. Furthermore, the energy use and infrastructure associated with intermediate data transmission networks, including mobile networks, base stations, and core network infrastructure, are excluded from the system boundaries, as these are considered outside the primary focus of the study and are assumed to contribute less significantly to the overall environmental impact compared to data center operation.

Moreover, several limitations and delimitations regarding the scope of the Life Cycle Assessment were established. The study is delimited to the analysis of a specific, relatively small data center facility, based on the Boden Type Data Center (BTDC) as the primary source for the inventory data. This choice implies that the study does not account for the vast heterogeneity within the data center industry regarding different hardware configurations, energy efficiencies, or facility scales.

Regarding the life cycle inventory, certain stages and flows were excluded due to data scarcity and to maintain dataset consistency. For instance, while the impacts of raw materials and components such as PCBs and aluminum include their respective production and transport processes naturally from ecoinvent, the final assembly stages of servers and building infrastructure, as well as the final transport to the site, are excluded. Finally, the allocation of environmental burdens is based on storage capacity measured in TBh, an approach that assumes a constant ratio between storage and processing power in the DC. Due to the high heterogeneity and rapid development within the DC industry, the assessment represents a temporal snapshot in time. While it reflects current technological standards, it does not incorporate future shifts toward more AI-intensive workloads or advanced liquid cooling technologies.

3

Life Cycle Inventory

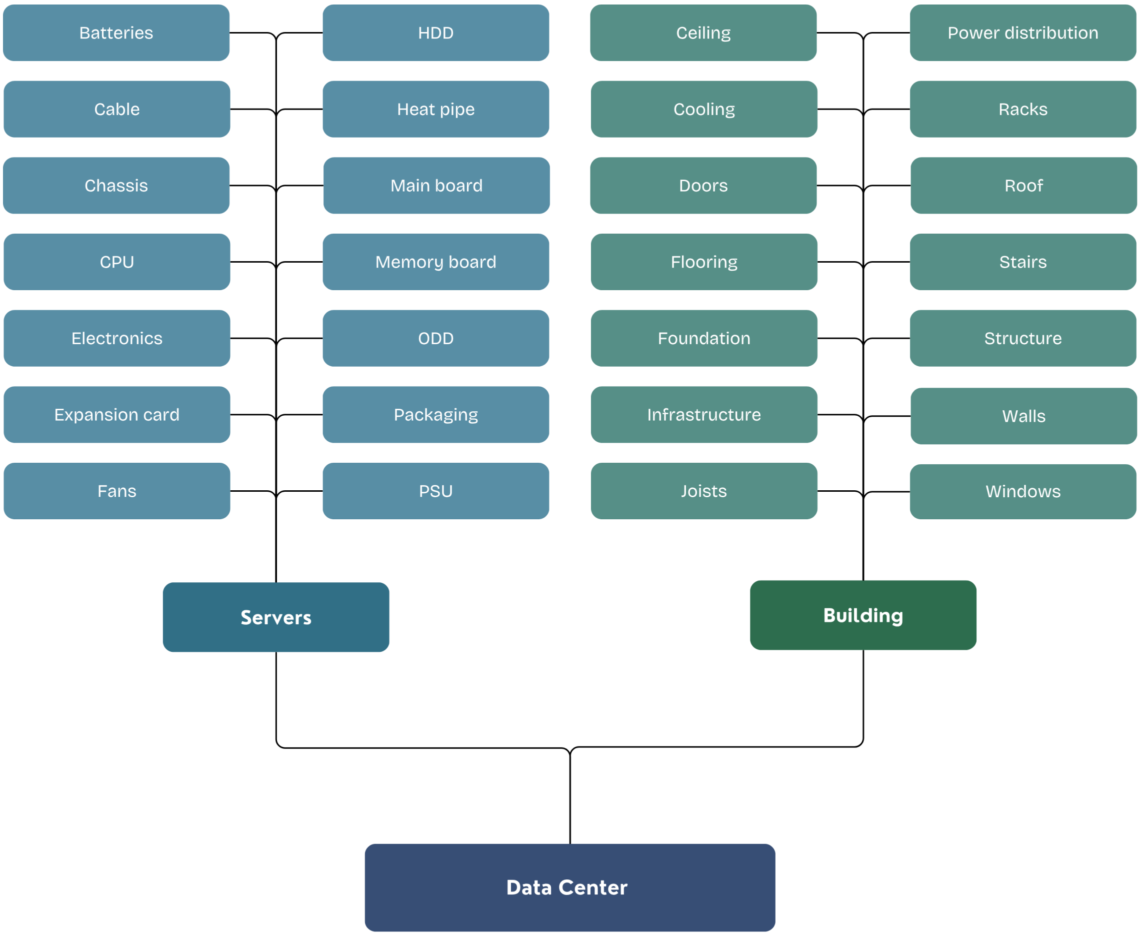
This chapter presents the Life Cycle Inventory (LCI) data compiled for the assessment. The data is systematically divided into two main domains. First, the digital infrastructure is detailed, encompassing the complete technical specifications of the data center. Second, the transport system parameters are established, detailing the specific vehicle data. Together, these datasets form the complete system model used for the environmental evaluation.

3.1 The Modeled Data Center

The main source used for this Life Cycle Inventory (LCI) is an article by Borisová and Vesterlund (2025), who conducted an LCA of a specific type of data center called Boden Type Data Center (BTDC). This is an EU initiative to create as efficient as possible data centers with the possibility of reducing the associated energy use and environmental burdens significantly. The main differences between a BTDC and a 'standard' data center regards the location and high degree of cooling efficiency. The DC is located in northern Sweden, leading to high availability of renewable electricity, as well as lower need for cooling due to the cold climate.

As illustrated in Figure 3.1, the modeled data center system was structured into two primary subsystems: Servers and Building, which were later divided into smaller assemblies. These assemblies were further broken down into specific hardware and infrastructural components. The complete inventory data for the system is detailed in Appendix A. The hardware of a server is a complex system consisting of many critical components made for data processing, storage, communications, backups, and other functions. These include Central Processing Units (CPUs), which act as the "brain" of the system, the memory board for temporary data storage, and Hard Disk Drives (HDDs) for long-term storage. These components are connected through the main board (Hertvik, 2026) and supported by additional elements such as Power Supply Units (PSU), Optical Disk Drive (ODD), expansion card, fans, heat pipes, batteries, cables, other electronics and packaging (European Commission, Joint Research Centre, 2015). The servers internal components are then enclosed by a chassis, a case designed to fit into a server rack (Tozzi, 2025).

Figure 3.1: The structure and components of the modelled data center.



A key component present in several parts of the server is a Printed Circuit Board (PCB), which serves to physically support and electrically connect electronic components (PCBINQ, 2025). PCBs are present in the main board, expansion cards, chassis, and several other components, and has a significant influence on the overall environmental impact, mainly due to the high energy demand during manufacturing (Wang et al., 2025). Therefore, a more detailed representation of PCBs was considered important. In the study of the BTDC (Borisová & Vesterlund, 2025), only specific metals used in PCBs were included, whereas this study instead used a more aggregated PCB component from ecoinvent to better capture the full material composition and environmental impacts of PCBs.

The inventory data for the building components was also based on Borisová and Vesterlund (2025), which in turn was modeled using Bouley (2010). The building shell consisted of structural components such as the foundation, flooring, walls, and roof, as well as specific supporting systems related to data center operations, such as server racks, power distribution, and cooling systems.

The modeled DC facility hosts a total of 2160 servers, with an assumed lifespan of 5 years each. The DC lifetime is 30 years, and thus a total of 12 960 servers are required in the full DC lifetime. Each server has a total long-term (HDD) storage capacity of 160 GB as the BTDC, described in Herzog et al. (2020). This means the maximum HDD storage capacity of the DC is 2160 * 160 = 345 600 GB (345.6 TB). Since the DC has a lifetime of 30 years, the maximum total lifetime storage capacity is calculated to be approximately 90 million TBh.

3.2 Modifications & Sensitivity Parameters

Since the BTDC represents a very specific type of DC, some alterations were necessary in the inventory data for this study to be representative of a ’standard’ European DC. These modifications were made based on a mix of literature and discussions with industry experts. The BTDC software facilitates a holistic cooling approach, which enables higher Power Usage Effectiveness (PUE) for the DC operation. PUE measures the ratio between the total facility energy demand and the IT equipment energy usage, and highlights the efficiency of the facility. An efficient DC would thus have a PUE close to 1.0 as this means all energy used by the facility is directly used by the IT equipment. The BTDC has been measured to have a PUE below 1.02, showing a very high energy efficiency (Herzog et al., 2020). However, in 2025, the global average PUE of DCs was 1.54 according to Donnellan et al. (2025), and the EU average is also above 1.5 (European Commission, 2022). Therefore, a PUE of 1.54 was chosen for this study.

Emissions occurring during the operational phase of the data center, such as metals and organic compounds, were also included based on the inventory data from Borisová and Vesterlund (2025). Water use during the operational phase was not included in their assessment of the BTDC since the cold climate led to the possibility of free air cooling (which does not require water). Since the modeled DC in this thesis is an average European one, water use is deemed to be relevant. This can be estimated based on the IT electricity demand, together with the average European Water Usage Effectiveness (WUE) of 0.58 L/kWh (European Commission & Borderstep, 2025). WUE measures the amount of water (L) needed per kWh electricity demand for the IT equipment, and thus the operational water demand was calculated by multiplying these two factors.

A few of the parameters were based on assumptions and found to vary highly between data centers and different studies. These were therefore examined through a sensitivity analysis, to determine the effects of these uncertainties. The following parameters were studied:

- **Data center lifetime:** While some research suggests a technical lifespan of 15-30 years (Stojkovic et al., 2025), other studies indicate that the physical facilities may remain viable for 30-50 years (Eloke, 2025). In the examined literature conducting LCAs of data centers, a reference period ranging from 25 to 60 years is applied (Borisová & Vesterlund, 2025; Whitehead et al., 2015; Zhang et al., 2025). A lifespan of 30 years was chosen as a baseline in this study, with the sensitivity analysis covering 15 and 50 years to be in the mentioned reasonable range according to the literature.

- **Server lifetime:** While general literature suggests typical server lifespans of 3-8 years (WeLOOP, 2020) or 4-6 years (Stojkovic et al., 2025), life cycle assessments often prioritize a shorter replacement cycle. A value of 3 years is commonly utilized in LCAs (Borisová & Vesterlund, 2025; Zhang et al., 2025). However, recent research suggests that the average server refresh cycles are slowing down to a more common usage of 5 years, which is thus what has been used as the baseline in this study. To analyze the effect of this choice, a lifespan of 3 years has additionally been studied in the sensitivity analysis.

- **Electricity mix:** During the operational phase, the electricity mix has a huge impact on the environmental impact of data centers. A European average electricity mix has been used as the baseline, and the sensitivity analysis includes the Swedish and Polish electricity mixes as examples of best and worst cases, respectively, due to highly varying shares of renewable energy in these countries.

- **Power Usage Effectiveness (PUE):** To represent a European data center, an average PUE of 1.54 was chosen as the baseline. The BTDC, on the other hand, has been measured to have a PUE below 1.02, due to utilization of the cold climate as well as a holistic cooling approach streamlining the cooling systems (European Commission, 2022). Therefore, this value has been included in the sensitivity analysis to represent a possible best case scenario.

3.3 Truck Connectivity

The data long-term stored by Volvo's trucks is found to be 220 TB (Volvo Trucks, personal communication, April 24, 2026), which can be translated to 1 927 200 TBh per year. This is assumed to be data collected from a total of 700 000 vehicles, which have connectivity services (Volvo Trucks, personal communication, April 24, 2026), meaning each vehicle stores on average 2.75 TBh per year. This is used as a base for allocating the environmental impacts of the DC to one truck's annual usage.

The truck connectivity additionally comes with benefits in terms of enabling a reduced fuel consumption. Utilizing fuel reduction services such as Predictive Cruise Control (PCC), is assumed to lead to a reduction of 5%, based on a combination of literature and expert consultations. This number is considered conservative with regards to fuel saving potentials found in literature and chosen in order not to overestimate the connectivity benefits. This number was used as a basis for calculating the truck's annual potential emission reduction resulting from cloud connectivity. The study analyzes two trucks, one Internal Combustion Engine Vehicle (ICEV) and one Battery Electric Vehicle (BEV). The studied ICEV has a fuel consumption of 0.23 L/km and the BEV has an electricity consumption of 1.1 kWh/km (Volvo Trucks, personal communication, May 18, 2026). The estimated annual mileage is 116 000 km, representative for both of the studied trucks.

4

Life Cycle Impact Assessment

This section shows the Life Cycle Impact Assessment (LCIA) results, firstly over the whole data center lifespan, and secondly the share of which can be allocated to the functional unit (usage of connectivity services in one vehicle over the course of one year). Additionally, the results of the sensitivity analysis are presented and visualized, covering uncertain and potentially significant parameters.

4.1 Data Center Life Cycle Results

This section presents the results of the LCA of providing a data center service for the entire lifespan of a Data Center (DC). Table 4.1 shows the results of five different impact categories divided into three subsystems: operations, server manufacturing, and building manufacturing, as well as total impacts. The operational phase includes the usage of electricity (European average mix) and water to run the DC and additional operational emissions of metals and organic compounds. The server and building subsystems include material sourcing and manufacturing of all hardware and facility components that the DC consists of.

Table 4.1: Results of the impact categories by the life cycle stages *operation, server manufacturing and building manufacturing.*

	Material resources: metals/ minerals [kg Sb-Eq]	**Acidification** [mol H^+-Eq]	**Energy resources: non-renewable** [MJ, net cal. value]	**Climate change** [kg CO_2-Eq]	**Water use** [m^3 world Eq deprived]
Total	4550	381 000	1 400 000 000	70 000 000	36 500 000
Operation	58.1	274 000	1 240 000 000	57 400 000	31 900 000
Server	4480	106 000	158 000 000	12 300 000	4 480 000
Building	15.3	1960	3 240 000	304 000	95 000

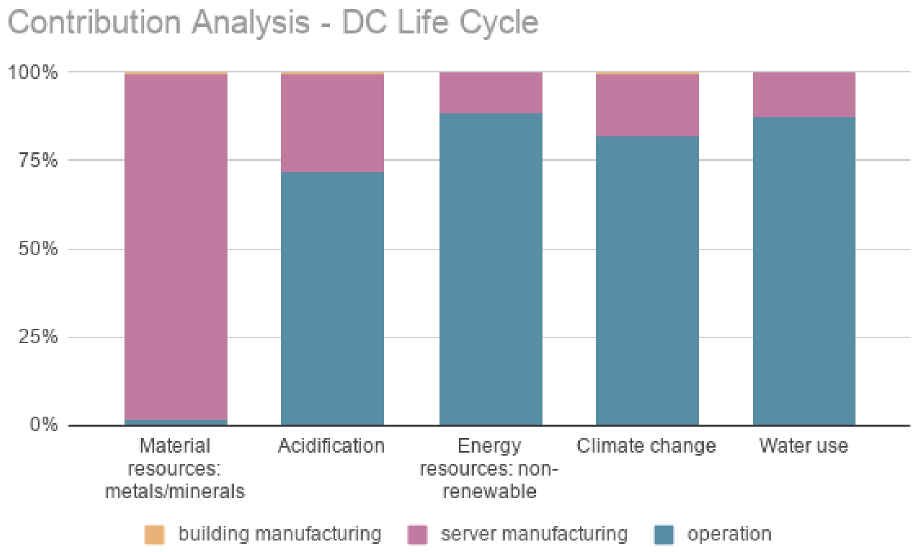
Taking into account the maximum cumulative lifetime storage capacity of approximately 90 million TBh for the modeled DC, the environmental impacts were normalized per TBh of stored data to enable scalability, comparability, and applicability of the results in other studies and use cases, see Table 4.2.

Table 4.2: Results of the impact categories by the life cycle stages *operation, server manufacturing and building manufacturing*, per TBh data stored.

	Material resources: metals/ minerals [kg Sb-Eq]	**Acidification** [mol H^+-Eq]	**Energy resources: non-renewable** [MJ, net cal. value]	**Climate change** [kg CO_2-Eq]	**Water use** [m^3 world Eq deprived]
Total	$5.01 \cdot 10^{-5}$	$4.20 \cdot 10^{-3}$	15.5	0.770	0.401
Operation	$6.39 \cdot 10^{-7}$	$3.01 \cdot 10^{-3}$	13.7	0.630	0.351
Server	$4.93 \cdot 10^{-5}$	$1.16 \cdot 10^{-3}$	1.74	0.135	0.0493
Building	$1.69 \cdot 10^{-7}$	$2.16 \cdot 10^{-5}$	$3.57 \cdot 10^{-2}$	$3.35 \cdot 10^{-3}$	$1.05 \cdot 10^{-3}$

Figure 4.1 further illustrates the contribution of each subsystem to the total impact. From this contribution analysis, it is clear that the operational phase causes the majority of impacts across all categories except Material Resources (metals & minerals), where server manufacturing accounts for the largest majority of impacts. The manufacturing of the building and included building components, such as power distribution and fans, account for a minor impact (<1%) across all impact categories. Below, each of these subsystems will be further described.

Figure 4.1: Share of impacts by the life cycle stages *operation, server manufacturing and building manufacturing.*



4.1.1 Operation

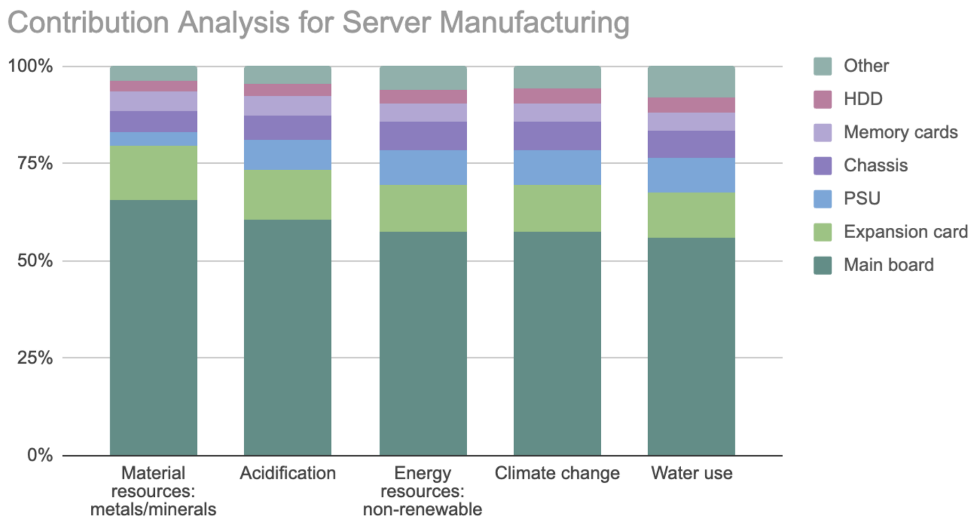
The operational phase accounts for a significantly larger share of the environmental impact than hardware manufacturing across all categories, with the exception of Material Resources (metals & minerals). Notably, operations contribute to 72-89% of all other impact categories. The operational impact is primarily driven by electricity consumption and associated indirect emissions from electricity production, rather than direct emissions from the facility. The operational water use is also seen to be minor in this category, accounting for less than 0.2% of operational impacts within every category, even the water use category. This is likely due to high water use for electricity production. For instance, electricity production from oil uses around 3 L/kWh (Cleveland, 2025), while the operational water use in the DC is 0.58 L/kWh.

Since the data center relies on an average European electricity mix, a large portion of the power is generated from fossil-based sources, leading to substantial greenhouse gas (GHG) emissions. Furthermore, this footprint is affected by the Power Usage Effectiveness (PUE) being 1.54, meaning that approximately a third of the operational electricity is used for cooling and other demands within the DC facility on top of the IT load, further increasing the overall indirect emissions from electricity production.

4.1.2 Server

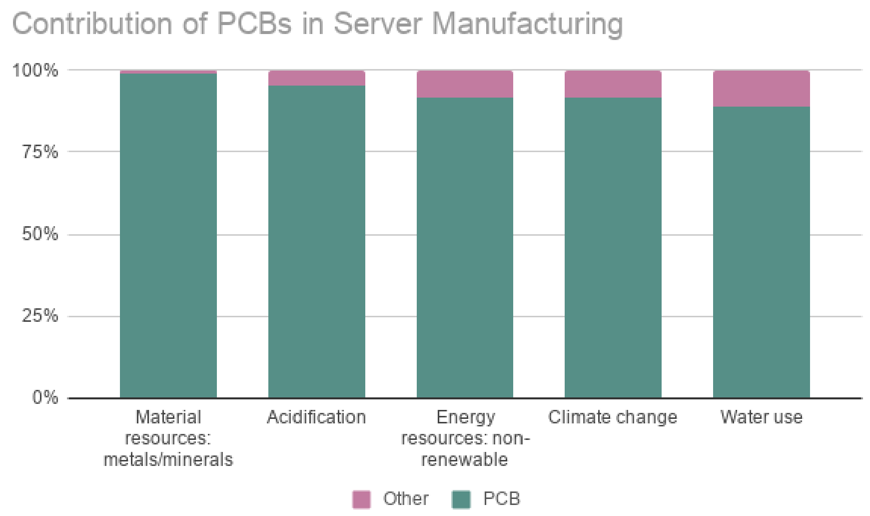
Server manufacturing accounts for the second-largest share of the environmental impact across all categories after the operational phase, with the exception of Material Resources (metals & minerals), where the server hardware accounts for 98% of the impact. For the remaining categories, server manufacturing accounts for 11-28% of the impacts. Figure 4.2 presents a contribution analysis of the server's hardware components across the five impact categories.

Figure 4.2: Share of impacts by server components.



The results reveal that the main board is the primary contributor to the environmental burden of server manufacturing across all examined impact categories. The main board is in this study composed entirely of Printed Circuit Boards (PCBs), which are inherently high-impact components due to the complex and energy-intensive manufacturing processes. A significant portion of this impact stems from indirect emissions associated with the electricity consumption during these fabrication stages. PCBs are not only present in the main board, but in fact integral elements in 8 out of the 14 included server components. Collectively, the PCBs account for between 89-99% of the total environmental impact of server manufacturing across all categories, as illustrated in Figure 4.3.

Figure 4.3: Share of impacts of PCBs in server manufacturing.

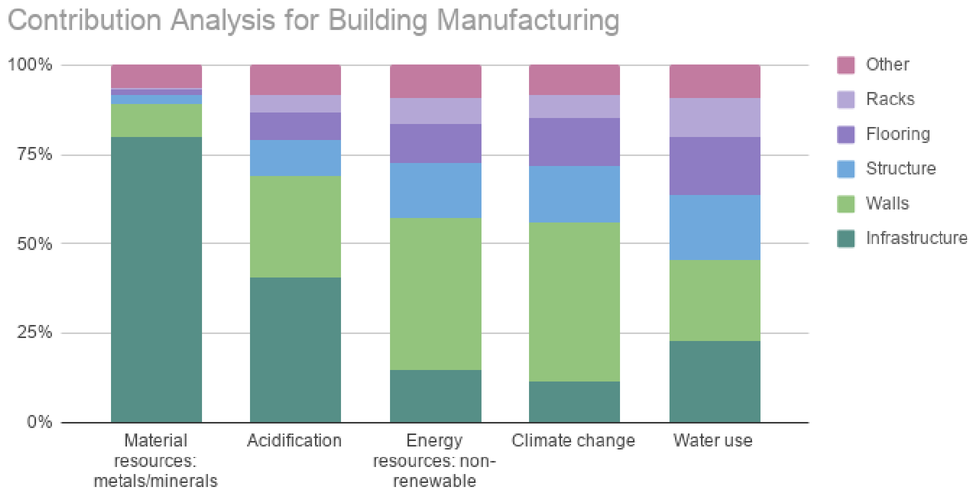


Moreover, the server manufacturing phase accounts for a substantial water footprint, driven by both the direct water use required during manufacturing processes and the indirect water use associated with electricity generation. Conversely, the high impact in the material resources category is directly linked to the extraction of raw materials. PCBs require a large variety and significant share of metals, including precious and rare earth metals. This intensive consumption of non-renewable natural resources leads to a substantial depletion of abiotic resources, directly reflecting the growing scarcity of these critical materials. Specifically, PCBs account for 97.3% of the total life cycle impact in the category.

4.1.3 Building

The building manufacturing accounts for the smallest share of the overall environmental impact, representing less than 1% of the total footprint across all categories. As illustrated in Figure 4.4, the contribution analysis of the building components reveals varying primary drivers depending on the impact category. The infrastructure is the dominant contributor to mineral and metal use, acidification, and water use. Conversely, the construction of the walls is the main contributor to both energy resource depletion and climate change.

Figure 4.4: Share of impacts by building components.



4.2 Results Allocated to a Truck

A data center is typically shared between many users and devices due to its multi-tenant nature. Therefore, the environmental impact of the DC must be allocated to estimate the share associated with one specific end user, in this case a cloud-connected truck. In addition, data centers provide different types of services, including short-term storage, long-term storage, and data processing. Ideally, the allocation factor should be based on all of these services. However, since long-term storage was the only available and quantifiable data identified in the inventory analysis, it was assumed to be representative and applicable to the overall DC services utilized by the vehicle. Each truck stores 2.75 TBh/year, as found in section 3. Using this together with the normalized environmental impacts per TBh seen in Table 4.2, the environmental impact per functional unit could be calculated. The results are shown in Table 4.3.

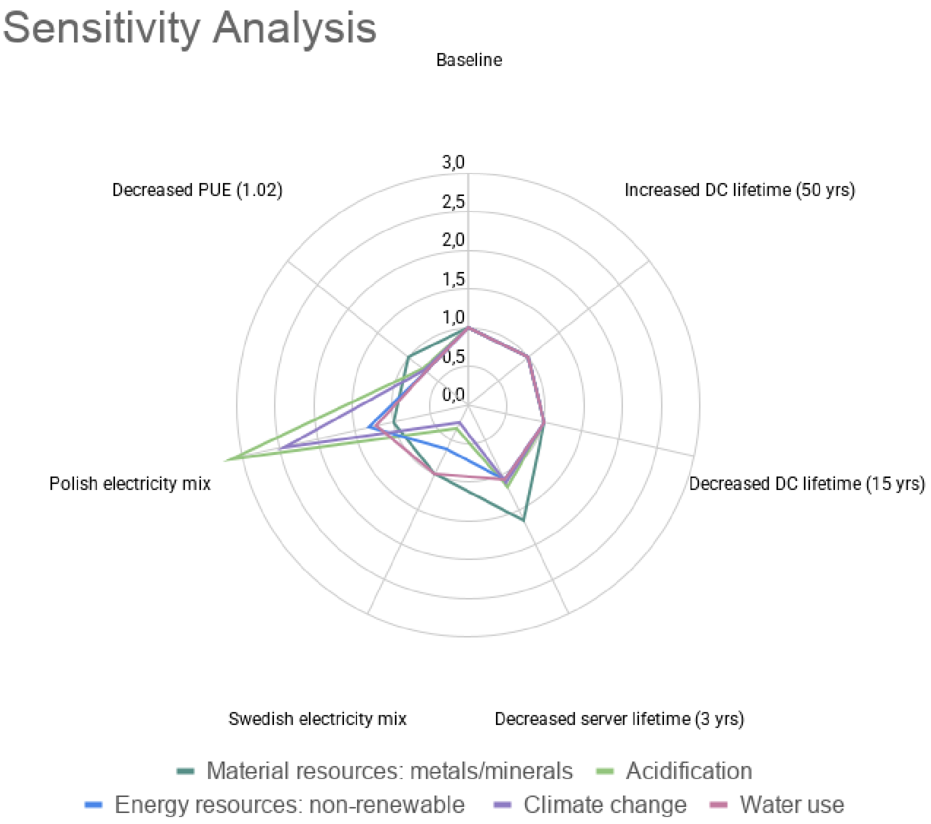
Table 4.3: Total results of the impact categories per functional unit.

	Material resources: metals/ minerals [kg Sb-Eq]	**Acidification** [mol H^+-Eq]	**Energy resources: non-renewable** [MJ, net cal. value]	**Climate change** [kg CO_2-Eq]	**Water use** [m^3 world Eq deprived]
Total	$1.38 \cdot 10^{-4}$	$1.16 \cdot 10^{-2}$	42.5	2.12	1.11

4.3 Sensitivity Analysis

The sensitivity analysis covers parameters which have been identified to differ significantly in the literature and have potential significant impacts on the results, and thus need to be studied further. Sensitivity analyses was performed individually for the following parameters: Data Center (DC) facility lifetime (baseline 30 years), server lifetime (baseline 5 years), operational electricity mix (baseline European average mix), Power Usage Effectiveness (PUE) (baseline 1.54). Figure 4.5 presents the results of the sensitivity analysis, where the relative impact of each parameter is illustrated in a radar chart. The results are presented per functional unit. It is important to note that by altering DC lifetime, the total lifetime storage capacity (in terms of TBh) is also altered linearly, and the allocation factor thus changes accordingly.

Figure 4.5: Results of the sensitivity analysis as share of baseline results.



It is evident that the largest change, and thus the most sensitive parameter, is the electricity mix. With the Swedish electricity mix, the climate change impact drops by 76%, while the Polish mix causes an increase by 144%. The acidification potential is also highly influenced by this alteration. Since the operational phase has a major impact across most categories, and is made up mainly by electricity usage, a change in electricity mix is consequently of high importance for the results. Altering the electricity mix from an average European one to a Swedish energy mix significantly decreased the impact, as the Swedish grid relies heavily on renewable and nuclear sources, which require minimal non-renewable energy inputs. In contrast, the Polish electricity mix increased the impacts substantially due to its high share of fossil fuels. This variation is also reflected in the energy resources category, since the analysis focuses on non-renewable energy resources, hydropower and wind appear highly favorable as they bypass the extensive fossil fuel extraction and combustion losses associated with traditional thermal power plants.

Varying the DC lifetime results in virtually no change to the final environmental impact categories per functional unit. This independence occurs due to a simultaneous linear scaling of both the absolute environmental burdens and the total storage capacity of the data center. While a longer DC lifetime increases the cumulative electricity consumed, water used, and the total number of servers required over its life cycle, it proportionally increases the total DC capacity (expressed in TBh) over that same extended period. Because the allocation to a single truck is based on its share of the total TBh, the truck's relative allocation factor decreases at the exact same rate as the DC's total footprint grows. Since building manufacturing remains constant, and represents the subsystem with the least impact across all categories, this linear relationship holds almost perfectly. Consequently, the normalized impact per vehicle remains constant over increased and decreased lifetimes, regardless of whether a category is driven by operational energy (e.g., climate change) or server manufacturing (e.g., use of minerals and metals).

In contrast, variations in server lifetime produce an uneven response across the impact categories. Reducing the server lifetime from 5 to 3 years, while remaining a constant building lifetime, significantly increases the total amount of servers required over the DC's lifetime. While this shorter lifespan does not influence operational impacts, it amplifies the burdens associated with manufacturing. Consequently, the results vary between categories: mineral and metal depletion is the most sensitive parameter, showing a 66% increase due to the material-intensive nature of IT hardware and its use of scarce metals. The other categories, less dependent on hardware manufacturing, show more moderate increases ranging between 7% and 18%.

Finally, by decreasing the PUE, the mineral and metal depletion is practically unchanged while the other impact categories decrease by 24-30%. This factor only alters the operational phase, creating a lower need for electricity to support the hardware of the DC, and thus does not affect the use of minerals and metals. Therefore, this change primarily causes indirect effects due to increased electricity production.

5

Climate Benefits & Net Impact

This section evaluates the existing literature on the environmental benefits enabled by vehicle connectivity. In addition, it assesses the net climate impact of truck connectivity by calculating the climate savings enabled in trucks and weighing them against the environmental burdens associated with the underlying data center infrastructure, as identified in the LCA.

5.1 Previous Research on Connected Vehicles

The environmental implications of vehicle connectivity identified in the literature are highly varying, both in terms of definitions and system boundaries, as well as in the subsequent results. The majority of studies focus only on high automation levels and examine only passenger vehicles. For the system boundaries, a common variation lies in the definition of the connectivity and automation level. Moreover, the computational load of connectivity is distributed between the internal edge computing and the external computing in the clouds. However, most studies report impacts per vehicle or per service, and thus do not make the direct distinction of which of these utilize clouds. Since many of these factors are not always explicitly defined in existing studies, a degree of uncertainty persists regarding the generalizability of the reported impacts.

Kopelias et al. (2020) conducted a literature review synthesizing the existing literature on the environmental impacts of connected and autonomous vehicles (CAVs). They identified factors which directly or indirectly influence the environmental impact of CAVs. The study notes that the expected reduction in greenhouse gas (GHG) emissions varies highly between studies, ranging from 5% to 60%. However, fuel consumption appears to be the most significantly influenced metric, with reported reduction rates ranging between 30% and 90%. Furthermore, Gawron et al. (2018) conducted a life cycle assessment on CAV subsystems, focusing on both hardware burdens and operational benefits. The researchers found that while the added weight, power demand, and data transmission of CAV hardware could increase energy use and emissions, these impacts are often offset by operational efficiencies. Specifically, when integrating effects such as eco-driving, platooning, and intersection connectivity, the study reports a potential net reduction in energy use and GHG emissions of up to 9%.

Liu et al. (2024) demonstrate that the environmental benefits of vehicle connectivity depend heavily on the driving environment and powertrain technology. They found that intelligent vehicles can reduce life cycle carbon emissions by 3.5-22.4%, depending on these factors. Their findings show that connectivity and automation are most effective at mitigating emissions in complex urban traffic compared to long-haul highway transport. However, the overall outcome is also influenced by systemic risks. Kopelias et al. (2020) highlight a potential 'rebound effect,' where the increased accessibility of automated transport can lead to higher road usage and a growing vehicle fleet, ultimately offsetting the initial emission reductions.

While the environmental benefits of connectivity in passenger vehicles are relatively well-documented, a significant gap remains in peer-reviewed literature focusing explicitly on heavy-duty trucks. Most existing research operates on a theoretical level, leaving a distinct shortage of empirical data that reflects real-world operations. However, available truck-specific data indicates a clear variance. Commercial marketing and controlled field tests under ideal, hilly conditions demonstrate peak fuel savings of up to 17% (Skrúcaný et al., 2025). This is a result of implementing Predictive Cruise Control (PCC), an advanced cruise control system that uses topographic map data to anticipate upcoming road terrain and automatically optimize the vehicle's speed and gear shifts to save fuel. In contrast, a deployment of an autonomous driving paradigm known as Fuel-Efficient Autonomous Driving (FEAD), demonstrated a more conservative fleet-wide average fuel saving of 5.71% compared to manual driving (Yang et al., 2026). Traditional features like PCC depend heavily on the terrains and how the driver chooses to behave. In contrast, the FEAD results highlight that shifting to data-driven automation offers an automated approach to decarbonization that operates independently of human factors.

In summary, the literature suggests that vehicle-to-cloud connectivity serves as a critical enabler for significant environmental improvements in the transport sector. By facilitating strategies such as platooning, eco-driving, and congestion avoidance, vehicle connectivity can achieve substantial fuel savings and emission reductions. However, there is a high variability in the literature regarding the actual magnitude of these savings and the outcome is highly dependent on the specific situation.

5.2 Quantifying Operational Truck Benefits

To determine the net climate impact, the climate benefits of truck connectivity are calculated using a combination of literature findings and consultations with experts at Volvo Trucks. Because the relationship between energy consumption and emissions is highly dependent on powertrain technology, two vehicle types are examined: one Internal Combustion Engine Vehicle (ICEV) and one Battery Electric Vehicle (BEV). While connectivity may yield similar relative energy reductions for both platforms, the resulting climate impacts are not equivalent. For the ICEV, reduced consumption directly translates into lower tailpipe GHG emissions. In contrast, the environmental performance of the BEV, which produces zero tailpipe emissions, is determined by its electricity consumption and the carbon intensity of the grid mix used for charging. Consequently, evaluating the environmental benefits of connectivity requires an approach that accounts for both energy efficiency improvements and the emission factors of the underlying energy sources. The specifications and energy consumption profiles for both studied vehicles are presented in Table 5.1.

Table 5.1: Vehicle specifications and energy consumption (Volvo Trucks, personal communication, May 18, 2026).

Vehicle Type	Energy Source	Consumption
ICEV	Diesel	0.23 L/km
BEV	Electricity	1.1 kWh/km

Connectivity services such as Predictive Cruise Control (PCC) were assumed to enable fuel savings of approximately 5%, based on literature research and discussions with experts at Volvo. The uncertainty associated with this assumption and its subsequent results is further discussed in the break-even analysis. The estimated annual mileage is 116 000 km, representative for both of the studied trucks (Volvo Trucks, personal communication, May 18, 2026). By applying this mileage and a fuel consumption reduction factor of 5%, the following fuel reductions are achieved for one vehicle operating over a year:

$$\textbf{ICEV: } 0.23\text{ L/km} \cdot 116\,000\text{ km/year} \cdot 5\%\text{ saved} \approx 1334\text{ L saved/year}$$

$$\textbf{BEV: } 1.1\text{ kWh/km} \cdot 116\,000\text{ km/year} \cdot 5\%\text{ saved} = 6380\text{ kWh saved/year}$$

According to the Global Logistics Emissions Council (GLEC) Framework (Lewis et al., 2025), B7 diesel (standard commercial diesel) has an energy density of 35.3 MJ/L, and an emission factor of 85.9 g CO_2-eq/MJ well-to-wheel (WTW), meaning that it includes everything from the production to the consumption of the fuel. This means that each liter of fuel results in ca 3 kg CO_2-eq emitted for an ICEV. By multiplying the emission factor per liter of diesel by the annual amount of diesel saved, the total annual reduction in CO_2-eq emissions for the ICEV are calculated.

$$3\,\mathrm{kg\,CO_2e/L} \cdot 1334\,\mathrm{L/year} \approx 4002\,\mathrm{kg\,CO_2eq/year}$$

For the BEV, the GHG reductions per year were calculated using ecoinvent data in openLCA, based on the annual electricity savings. To find a fully representative result, these are evaluated over different driving locations and thus different electricity mixes: average European, Swedish, and Polish (representing the baseline, best case and worst case, respectively, as used in the sensitivity analysis for the precedent LCA). The results show an annual emission reduction of 2182 (Europe), 251 (Sweden) and 5985 (Poland) kg CO_2-eq, respectively.

5.3 Weighing & Net Impact

By weighing the calculated benefits from the connectivity fuel reductions against the burdens associated with a trucks' data center usage, the net climate impact is found.

Only the climate change impact category was analyzed due to time constraints and since it was deemed most relevant. A constant burden of 2 kg CO_2-Eq, as in the baseline scenario, was assumed. Since ICEVs are entirely dependent on fossil fuels, the reduction in fuel consumption directly translates into a significant decrease in GHG emissions. Although regional variations in fuel production exist, the primary driver of the impact is the combustion process itself, which remains constant across different geographies. For the BEV on the other hand, The results are presented for BEV vehicles using European, Swedish, and Polish electricity mixes, respectively. The net climate impacts derived from connectivity services is shown in Table 5.2.

Table 5.2: Combined net climate impact per functional unit, comparing digital burdens, vehicle operational benefits, and net impact (burden − benefit) across vehicle types and regions.

Vehicle (location)	**Burden** [kg CO_2-Eq]	**Benefit** [kg CO_2-Eq]	**Net Impact** [kg CO_2-Eq]
ICEV	2	4002	-4000
BEV (Europe)	2	2182	-2180
BEV (Sweden)	2	251	-249
BEV (Poland)	2	5985	-5983

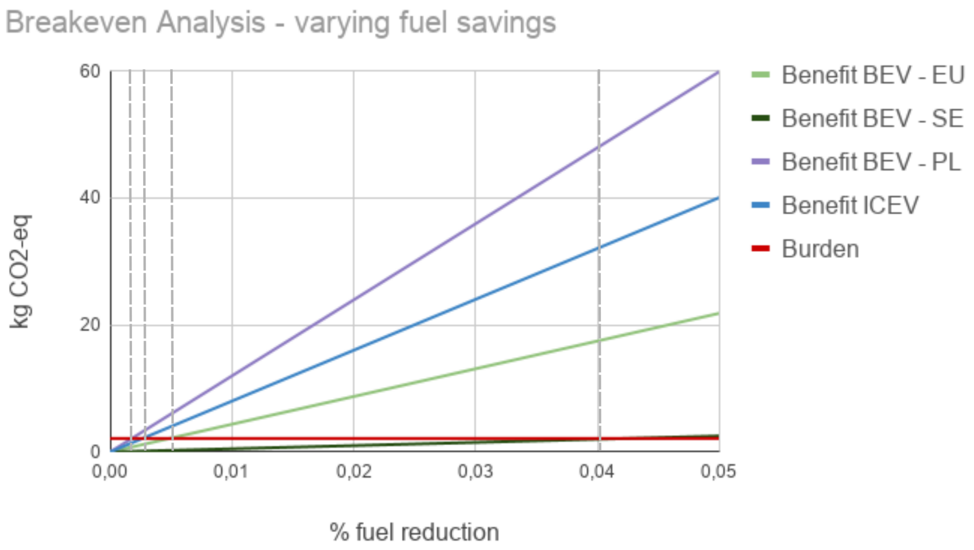
A significant climate benefit can be seen for all vehicles and locations. For the BEV, it can be seen that both the benefits and the resulting net environmental impact vary significantly across regions. This variation is primarily driven by differences in electricity production and the composition of the electricity mix in each region. As a result, regions with more carbon-intensive electricity mixes, such as Poland, show substantially higher benefits from connectivity services compared to regions with low-carbon electricity, such as Sweden. The absolute reduction in GHG emissions for ICEVs is higher than for BEVs in all cases except the Polish one, making connectivity a potent tool for immediate emission reductions in internal combustion vehicles.

These results demonstrate that the implementation of connectivity services consistently yields a net climate benefit across all analyzed vehicle types and geographic regions. While the magnitude of these benefits fluctuates depending on regional energy mixes and specific vehicle configurations, the overarching trend confirms that the operational efficiency gains enabled by connectivity outweigh the environmental burdens associated with the required data center infrastructure. In regions with carbon-intensive electricity grids, the relative benefit of connectivity in BEVs is particularly pronounced, as even marginal efficiency improvements lead to significant reductions in total GHG emissions. Ultimately, the results indicate that connectivity is a robust instrument for improving the environmental performance of heavy-duty transport.

5.4 Break-even Analysis

Two break-even analyses were conducted to evaluate the robustness of the results and identify the equilibrium points where the environmental cost of connectivity would offset its benefits. The first analysis examined the minimum fuel saving required to justify a fixed climate burden of 2 kg CO_2-eq. The results can be seen in Figure 5.4, and show that a remarkably small reduction in fuel consumption is sufficient to achieve a net benefit; the required saving ranges from only 0.002% for a BEV in Poland to 0.04% for a BEV in Sweden. When comparing these thresholds to the previously identified reduction potential of 5%, it can be concluded that there is a significant margin of benefit, reinforcing the conclusion that connectivity services are a highly robust tool for emission reduction.

Figure 5.1: Results of the break-even analysis.



There is an inherent sensitivity in the data center climate burden due to the assumptions and modeling choices embedded in the LCA. While the baseline model indicates an impact of approximately 2 kg CO_2-eq per functional unit, the sensitivity analysis (Section 4.3) shows that altering key parameters can cause the climate impact to vary from a 76% decrease to a 144% increase. This translates to a potential infrastructure burden range between 0.5 and 4.9 kg CO_2-eq. However, when contrasted against vehicle operational savings, this variance does not alter the study's core conclusion. Even under the worst-case scenario of 4.9 kg CO_2-eq, the vehicle efficiency improvement required to offset these digital emissions remains exceptionally low; a marginal fuel reduction of merely 0.1% is sufficient for the connectivity services to remain net-beneficial in all examined cases, demonstrating that the climate pay-back of the system is robust against data uncertainties.

The second analysis instead fixed the climate benefits for each vehicle and varied the amount of data storage required. According to Volvo, the total required data storage is increasing rapidly, currently by ca 3% per month (Volvo Trucks, personal communication, May 8, 2026), and thus there is a high importance of understanding the effects of an increased amount of data stored. This analysis found that a net climate burden would only occur if the data requirements reached extreme levels, ranging from 330 TBh per vehicle for a BEV in Sweden to 8000 TBh for a BEV in Poland. Given that the current data requirement is estimated at only 2.75 TBh per vehicle, the storage would need to increase majorly before the infrastructure's climate burden would outweigh its operational benefits. This further strengthens the conclusion that connectivity provides a net environmental gain, even under scenarios of extreme data intensity.

6

Discussion

This chapter provides a comprehensive analysis of the study's findings. The results are interpreted in relation to the environmental burdens associated with connectivity services and their underlying infrastructure, as well as the potential environmental benefits. Second, the credibility and reliability of these results are evaluated through a critical analysis of the data quality, methodological assumptions, and the outcomes of the sensitivity analysis.

6.1 Interpretation of Results

By applying a Life Cycle Assessment (LCA), this study found the environmental footprint associated with cloud Data Center (DC) infrastructure, necessary to provide connectivity services to a truck in operation over the course of a year. Results were found for five relevant impact categories, and found that the operational phase dominates all categories except Material Resources: minerals & metals, which was dominated by server manufacturing, and specifically the high-impact PCBs, present in many of the hardware components. Given that building manufacturing accounts for a minor share of the total DC life cycle impact, the discourse on DC sustainability should primarily focus on hardware manufacturing and increasing operational efficiencies.

Electricity consumption is a dominant factor across several impact categories, accounting for nearly the entire environmental footprint of the operational phase. The magnitude of these impacts is inherently tied to the energy source and the specific composition of the electricity mix used, and thus closely related to the location of the DC. Another critical aspect often highlighted in the discussion about DC sustainability is water consumption. However, the results indicate that direct water usage for cooling systems constitutes only a minor fraction of the total water use, compared to the indirect water consumption associated with electricity production.

Moreover, a sensitivity analysis was conducted, showing that the electricity mix is the most influential parameter to the results. This highlights that a substantial share of the impact associated with DC operations can be reduced by increasing energy efficiency and the use of renewable energy sources. Consequently, the geographical location of the DC becomes an important consideration, as establishing facilities in regions with a high share of renewable energy, such as Sweden, can significantly lower operational emissions. This is further illustrated by the sensitivity analysis of the Power Usage Effectiveness (PUE) parameter. A lower PUE reflects higher energy efficiency in data centers, primarily through reduced energy demand for cooling and other supporting systems. The results show that improvements in PUE can significantly decrease the overall environmental impact. Consequently, strategies such as optimizing cooling technologies, improving energy efficiency, and locating data centers in colder climates can play a crucial role in reducing emissions.

As the electricity mix shifts towards renewable sources and PUE decreases, the environmental burden of the operational phase is reduced. This creates a shift where the relative importance of hardware manufacturing increases, making embodied impacts a critical focal point. While DC lifetime shows practically no change of environmental impacts across the categories, server lifetime specifically affects material-intensive categories. Shorter server lifespan amplify the burden of manufacturing, particularly for depletion of minerals and metals, without affecting operational impacts. As the manufacturing phase becomes more dominant, extending server lifetimes and implementing strategies for the reuse, recycling, and substitution of scarce minerals becomes essential for long-term sustainability.

The LCA results showing the climate burden of DC services were then weighed against the potential emission savings enabled by truck connectivity. The net climate impact of vehicle connectivity services is found to be positive across all analyzed scenarios, as the operational fuel efficiency gains significantly outweigh the life cycle burdens of the supporting DC infrastructure. However, the magnitude of this net climate impact is highly dependent on both the fuel type and the geographical location of vehicle operation. For the Battery Electric Vehicles (BEVs), the net environmental benefit varies significantly across regions, driven by the carbon intensity of the local electricity production. In regions with a high share of fossil fuels, such as Poland, each kilowatt-hour of energy saved through connectivity services results in a substantially higher reduction in greenhouse gas (GHG) emissions compared to low-carbon regions like Sweden. This suggests that while connectivity is beneficial in all scenarios, its strategic importance as a carbon-reduction tool is most pronounced in carbon-intensive markets.

The calculated net impact is subject to uncertainty, with a risk of underestimation of the environmental burdens and overestimation of the associated benefits. This may be related to underestimated impacts from DC services or assumptions regarding the amount of data storage required per vehicle, as well as the potential overestimation of the fuel and energy savings enabled by connectivity services. A break-even analysis was performed to test the sensitivity of this factor, revealing that the climate benefits of connectivity are robust. Based on the calculated climate burden of DC services, a fuel saving of only 0.04% is required to achieve a net climate benefit across all studied vehicles. Crucially, this threshold is significantly lower than the reduction of 5% assumed in this study, suggesting a climate-positive outcome even under conservative assumptions. Even when factoring in data uncertainties due to LCA modeling choices and assumptions, based on the sensitivity analysis, a marginal reduction of just 0.1% is sufficient to outweigh the burdens. Furthermore, projected increases in future data storage are unlikely to offset the environmental advantages of connectivity.

6.2 Comparison with Previous Research

The comparability of the results with other LCA studies on DCs is limited due to differences in scope and the inherent variability between different DC facilities. DCs have major differences in both material composition and operational practices. As found from the literature review (see 1.2), studies of DCs include highly varying inventory lists as well as life cycle stages, making comparisons very difficult. For instance, while some studies focus exclusively on operational energy use, others incorporate complex hardware manufacturing chains or end-of-life processing. These methodological and physical variations make direct comparisons especially difficult, as the environmental profile of one facility may not be representative of another.

However, when comparing the results with Borisová and Vesterlund (2025) study on the Boden Type Data Center (BTDC), it becomes evident that their study reports a lower total environmental impact for both operational activities and hardware manufacturing. The lower operational impact can be largely attributed to a lower PUE and the use of hydropower electricity. As a result, the relative contribution from operational impacts is less prominent in their study. The differences in hardware related impacts can be explained by methodological choices, as this study includes PCB manufacturing, which accounts for a substantial share of the total server impact, whereas Borisová and Vesterlund (2025) only considered individual metals. This leads to further differences in the contribution analysis of the server itself. In this study, the main board, expansion cards, and power supply unit dominate the environmental impacts, while BTDC identifies the hard disk drive and chassis as the primary contributors.

Regarding the environmental benefits of vehicle connectivity, significant discrepancies exist between studies, as detailed in Section 5.1. The literature review reveals potential fuel consumption reductions ranging from around 5% to 90%, a span that highlights the extreme variability in current research. These differences can likely be attributed to variations in vehicle specifications, as well as the specific levels of automation and connectivity employed in each study. Furthermore, the environmental efficiency of connectivity appears to be highly dependent on the operational context. Impacts are generally more enhanced in urban settings, which may explain why long-haul heavy-duty vehicles might report lower reduction rates compared to passenger transport in more congested environments. The assumed 5% used in this thesis sits at the lower end of the found spectrum in literature, but is shown to be sufficient to outweigh the climate burdens with high margin. No previous studies were identified that assessed the full life cycle of the data center while solely comparing its impacts to the fuel savings enabled by connectivity. As a result, the final results of this study could not be directly compared with existing literature.

The inherent difficulty in comparing the results across different studies underscores the need for more contemporary LCA studies focused on modern DC architectures and the emerging field of vehicle connectivity. The reliance on detailed life cycle inventories and the inclusion of all life cycle stages, from raw material extraction to end-of-life, is important in order to not under- or overestimating the environmental burden of DCs. Furthermore, more generalizable studies on vehicle connectivity, including more application-specific fuel reduction estimates, should be prioritized. In line with this, there is a notable scarcity of research exploring the connection between DCs and specific end-use applications, such as vehicle connectivity. Addressing this research gap is essential to develop a more holistic understanding of how digital infrastructures support or offset the environmental goals of the transport sector.

6.3 Limitations

A primary limitation of this study lies in the significant heterogeneity of the data center industry, where vast variability in hardware configuration, energy efficiency, and operational practices leads to high sensitivity in environmental impact results. Consequently, these findings represent a 'snapshot' in time, tied to a specific technological profile that may vary significantly across different facilities. This temporal limitation is further intensified by the rapid evolution of the ICT sector. As the industry shifts toward AI-intensive workloads and advanced liquid cooling, current results may become less representative of future infrastructures. The increasing demands for data processing and AI-related services mean that environmental profiles are in constant change, highlighting the critical importance of continuously updated LCA studies to capture future technological shifts and changing system conditions.

This study assesses a relatively small DC that may not be fully representative of a typical European facility, which oftentimes operates on a significantly larger scale. While upscaling the results to reflect a larger facility was considered, it was determined that the lack of a standardized and robust methodology for such scaling introduced unacceptable levels of uncertainty. To preserve the integrity of the data and avoid potential modeling errors, it was decided to maintain the original scale of the facility as specified in the primary data source. While an increase in DC size could potentially lead to economies of scale and thereby reducing the environmental impact per TBh stored, any such estimation would be speculative without a verified scaling framework. Additionally, while the raw materials and components sourced from ecoinvent (e.g., PCBs and aluminum) include their respective production and transportation impacts, the assembly stages for the servers and the building components do not include the manufacturing processes or transport to the site. This was excluded due to being deemed negligible in relation to the total impact. The network infrastructure required for data to be transmitted between vehicles and clouds are also excluded from this study and might result in an underestimation of the results. However, as the break-even analysis showed, there is a significant margin of benefit and so this is unlikely to alter the conclusion that connectivity is climate-beneficial.

Another limitation exists regarding allocating the impacts based on storage capacity (TBh). While usage is defined by both processing (vCPUh) and storage, the study assumes a constant ratio between the two. In reality, user requirements vary, some may process large amounts of data with minimal storage, and vise versa. Without specific data on these patterns, this approach may over- or underestimate the environmental burden depending on the actual computational intensity of the user. Additionally, the allocation is based on the storage at a specific on-premise data center. However, it is possible that these vehicles also utilize other data centers simultaneously for different services. Since the study only accounts for the resources within the specific facility provided, this may result in an underestimation of the total data center impact associated with each vehicle.

Finally, it is important to recognize that this study is strictly delimited to environmental impacts. In a broader context, vehicle connectivity offers a range of advantages that must be weighed against its ecological footprint. Enhanced connectivity is a key enabler for improved traffic safety through real-time communication, as well as increased user comfort and entertainment services. Conversely, the centralization of vehicle data in public data centers introduces complex challenges regarding data privacy and cybersecurity. Therefore, when making strategic decisions about the implementation of connected vehicle technologies, stakeholders should not rely solely on environmental metrics. A holistic evaluation is essential to fully understand the net value of these technologies, balancing environmental sustainability with social benefits, safety improvements, and ethical considerations such as data management.

6.4 Future Research

The results in this study creates opportunities for future research in several areas. For Volvo, it is possible to combine the results with different types of internal data, to make further connections between the environmental impacts of DC services and the vehicles. This includes the possibility of adding the impacts of the internal material truck components which enable the cloud connectivity. Thus, the manufacturing and operational impacts from these components could be included in the weighing of benefits and burdens.

The results can also be used to guide decision making for Volvo regarding some crucial trade-offs. Firstly, it can be compared to the environmental impact found in standard vehicle LCAs, in order to determine whether or not the impact from cloud connectivity is significant and thus should be included in future vehicle LCAs.
Secondly, this study's findings can be used to guide the choice between centralized cloud computing and localized 'edge' processing. In addition to evaluating which approach is environmentally preferable, such decisions must also account for latency requirements, as cloud computing can introduce response delays for safety related functions, especially in situations where real-time responses are required.

The results of this study, specifically the DC impact expressed per TBh of data stored, provide a modular framework that can be utilized by other actors across various industries. By applying these baseline figures to their specific data storage requirements, researchers and organizations can estimate the environmental footprint of other end-use applications beyond vehicle connectivity.

Furthermore, there is a critical need for more comprehensive studies conducted with high levels of transparency and methodological precision. As evidenced in the literature, there is a notable scarcity of thorough environmental assessments regarding DCs, primarily due to the lack of accessible primary data from industry facilities. Future research would therefore benefit significantly from closer collaboration with DC operators to obtain primary site-specific data and improve the accuracy of environmental assessments related to connectivity services.

With the rapid advancement of technology, particularly the increasing integration of AI, DCs must evolve to accommodate increasingly intensive computational loads. This evolution necessitates significant infrastructural shifts, such as the implementation of advanced liquid cooling systems and higher server densities. Future research should account for this trajectory, as the 'standard' data center of today differs substantially from those of the past and will continue to transform. Furthermore, investigating hyperscale data centers, which have become increasingly more popular, would be of particular interest. Given the potential for economies of scale to reduce the environmental burden per TBh in larger facilities, a comparative analysis of these results would provide valuable insights into the net impact of large-scale connectivity.

7

Conclusion

The aim of this study was to quantify the environmental trade-offs of digitalizing the transport sector by balancing the infrastructure burdens of data centers against the operational savings enabled by truck connectivity. By addressing the formulated research questions, the following conclusions can be drawn:

Regarding the environmental burden of DC services (RQ1), the results demonstrate that the footprint of the cloud-based services required for truck connectivity is dominated by the operational phase and hardware manufacturing. Within the manufacturing stage, the production of printed circuit boards (PCBs) is identified as the primary contributor to environmental impacts, particularly in categories related to resource depletion and toxicity. Furthermore, electricity consumption and its associated upstream resource requirements constitute the primary driver during the operational phase. This emphasizes that sustainability efforts should prioritize both the material efficiency of high-impact components like PCBs and the transition to low-carbon energy grids and higher operational efficiency in DCs. Locating DCs in cold climates with high availability of fossil-free electricity is a key enabler for greening the DC sector.

In terms of the environmental benefits in truck operations (RQ2), the analysis confirms that cloud connectivity acts as a significant lever for emission reductions. These benefits are realized through services such as route planning and predictive cruise control, which optimize fuel efficiency and thereby reduce energy demand and emissions. Even when using conservative estimates, the savings enabled by connectivity services represent a substantial decrease in the overall climate impact of truck operation.

Finally, regarding the net environmental impact (RQ3), the study provides a robust argument for the net-positive climate effect of connectivity. The break-even analysis reveals that the environmental burdens of the digital infrastructure are small in comparison to the enabled emission savings. For all studied vehicles the margin is remarkably high, showing that data storage requirements would need to increase by several thousand percent before reaching an equilibrium where the infrastructure burdens offset the climate advantages provided by improved fuel efficiency.

In summary, while the digitization of the transport sector introduces new infrastructure-related burdens, these are a necessary and relatively low cost for achieving significant net climate gains. To maximize these benefits, strategic focus must remain on high-efficiency hardware manufacturing and the siting of data centers in regions with sustainable energy profiles.

References

Baumann, H., & Tillman, A.-M. (2004). *The hitch hiker's guide to LCA: An orientation in life cycle assessment methodology and application*. Studentlitteratur.

Borisová, S., & Vesterlund, M. (2025). Assessing the environmental impact of operating a Swedish data centre in subarctic climate. *Journal of Cleaner Production*, *536*, 146819. https://doi.org/10.1016/j.jclepro.2025.146819

Bouley, D. (2010). Estimating a Data Center's Electrical Carbon Footprint.

CarbonBright. (n.d.). Life Cycle Assessment: The 4 Stages. Retrieved May 5, 2026, from https://www.carbonbright.co/insight/lca-life-cycle-assessment-the-4-stages?utm.com

Chien, A. A. (2023). *Proceedings of the 2nd Workshop on Sustainable Computer Systems*. Association for Computing Machinery. https://doi.org/10.1145/3604930

Cleveland, C. (2025, July). What methods of electricity generation use the most water? Retrieved May 5, 2026, from https://visualizingenergy.org/what-methods-of-electricity-generation-use-the-most-water/

Cloud Carbon Footprint. (n.d.). Cloud Carbon Footprint - An open source tool to measure and analyze cloud carbon emissions. Retrieved May 4, 2026, from https://www.cloudcarbonfootprint.org/

Donnellan, D., Lawrence, A., Bizo, D., Rogers, D. O., Judge, P., Davis, J., Smolaks, M., & Weinschenk, R. (2025). Uptime Institute Global Data Center Survey 2025.

ecoinvent. (2024, February). System Models. Retrieved April 29, 2026, from https://support.ecoinvent.org/system-models

Ekvall, T., Björklund, A., Sandin, G., Lagergren, J., & Rydberg, M. (2020). Modeling recycling in life cycle assessment.

Elassy, M., Al-Hattab, M., Takruri, M., & Badawi, S. (2024). Intelligent transportation systems for sustainable smart cities. *Transportation Engineering*, *16*, 100252. https://doi.org/10.1016/j.treng.2024.100252

Eloke, P. (2025). Embodied Carbon and Life Cycle Assessment of Data Centre Structures: A Review of Sustainable Construction Materials (United Kingdom Focus). *European Modern Studies Journal*, *9*(6), 213–230. https://doi.org/10.59573/emsj.9(6).2025.15

European Commission. (n.d.-a). Digitalising transport - towards smart and sustainable mobility.

European Commission. (n.d.-b). Life Cycle Assessment & the EF methods - Green Forum. Retrieved May 11, 2026, from https://green-forum.ec.europa.eu/

green-business/environmental-footprint-methods/life-cycle-assessment-ef-methods_en

European Commission. (2022, August). On the path to green, clean and economical data centres throughout Europe. Retrieved April 30, 2026, from https://cordis.europa.eu/article/id/436271-on-the-path-to-green-clean-and-economical-data-centres-throughout-europe

European Commission & Borderstep. (2025). *Assessment of the energy performance and sustainability of data centres in EU*. Publications Office of the European Union. Retrieved May 15, 2026, from https://data.europa.eu/doi/10.2833/3168794

European Commission, Joint Research Centre. (2015). *Environmental footprint and material efficiency support for product policy: Analysis of material efficiency requirements of enterprise servers*. Publications Office. https://doi.org/10.2788/409022

European Parliament. (2019, March). CO2 emissions from cars: Facts and figures (infographics). Retrieved April 27, 2026, from https://www.europarl.europa.eu/topics/en/article/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics

Gawron, J. H., Keoleian, G. A., De Kleine, R. D., Wallington, T. J., & Kim, H. C. (2018). Life Cycle Assessment of Connected and Automated Vehicles: Sensing and Computing Subsystem and Vehicle Level Effects. *Environmental Science & Technology*, *52*(5), 3249–3256. https://doi.org/10.1021/acs.est.7b04576

Hertvik, J. (2026, January). What Are Servers? A Practical Guide for Modern IT & AI. Retrieved April 30, 2026, from https://www.splunk.com/en_us/blog/learn/computer-servers.html

Herzog, R., Summers, J., Batz, T., Beresford, A., Blylod, F., Fredricksson, S., Gustafsson, J., Olsson, D., Sarkinen, J., Kozma, L., & Lindh, N. (2020). Open Research Data Pilot - BTDC [Accepted: 2020-10-16T13:32:35Z]. https://doi.org/10.24406/fordatis/87

Isler-Kaya, A., & Karaosmanoglu, F. (2023). Life cycle assessment of a climate-friendly data center cooling device. *Energy and Buildings*, *288*, 113006. https://doi.org/10.1016/j.enbuild.2023.113006

Jerléus, K., Ibrahim, M. A., & Augustsson, A. (2024). Environmental footprints of the data center service sector in Sweden. *Heliyon*, *10*(11), e31290. https://doi.org/10.1016/j.heliyon.2024.e31290

Kopelias, P., Demiridi, E., Vogiatzis, K., Skabardonis, A., & Zafiropoulou, V. (2020). Connected & autonomous vehicles – Environmental impacts – A review. *Science of The Total Environment*, *712*, 135237. https://doi.org/10.1016/j.scitotenv.2019.135237

Lewis, A., Ehrler, V., & Schön, A. (2025, October). *Global Logistics Emissions Council Framework v3.2* (tech. rep.). Global Logistics Emissions Council.

Liu, Y., Liu, Q., Gao, L., Xing, Y., Chen, Y., & Zhang, S. (2024). The life cycle assessment and scenario simulation prediction of intelligent electric vehicles. *Energy Reports*, *12*, 6046–6071. https://doi.org/10.1016/j.egyr.2024.11.056

McKinsey. (2025, July). What is a data center? | McKinsey. Retrieved April 29, 2026, from https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-a-data-center

Okrasinski, T., Malian, J., & Arnold, J. (2012). Data Assessment and Collection for a Simplified LCA Tool. *Carbon Management Technology Conference*, CMTC–151108–MS. https://doi.org/10.7122/151108-MS

Palo Alto Networks. (n.d.). What is a Data Center? Retrieved April 29, 2026, from https://www.paloaltonetworks.com/cyberpedia/what-is-a-data-center

PCBINQ. (2025, June). What is a Printed Circuit Board (PCB)? Meaning and Types. Retrieved April 30, 2026, from https://www.pcbinq.com/what-is-pcb/

Resolute Dynamics. (2025, August). Vehicle-to-Cloud Connectivity: Architecture, Benefits & Risks Resolute Dynamics – Capture Connect Control [Section: Award]. Retrieved May 8, 2026, from https://resolute-dynamics.com/vehicle-to-cloud-connectivity-architecture-benefits-risks/

RGBSI. (2020). Driving Change: The Future of Mobility.

SAE International. (n.d.). Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. https://doi.org/10.4271/J3016_202104

Skrúcaný, T., Vrábel, J., Rakyta, A., Kassai, F., & Caban, J. (2025). Impact of the Use of Predictive Cruise Control in Freight Transport on Energy Consumption. *Energies*, *18*(23), 6171. https://doi.org/10.3390/en18236171

Smalley, S. S., Ian. (2024, September). What Is a Data Center? | IBM. Retrieved April 29, 2026, from https://www.ibm.com/think/topics/data-centers

Stojkovic, J., Zhang, C., Goiri, Í., & Bianchini, R. (2025, September). Rearchitecting Datacenter Lifecycle for AI: A TCO-Driven Framework [arXiv:2509.26534 [cs]]. https://doi.org/10.48550/arXiv.2509.26534

Tozzi, C. (2025, July). Server Rack vs. Chassis: What's the Difference, and Why Does It Matter? Retrieved April 30, 2026, from https://www.datacenterknowledge.com/servers/server-rack-vs-chassis-what-s-the-difference-and-why-does-it-matter-

Wang, Z., Huang, G., & An, C. (2025). Recyclability and recovery of carbon from waste printed circuit boards within a circular economy perspective: A review. *Journal of Environmental Management*, *375*, 124266. https://doi.org/10.1016/j.jenvman.2025.124266

WeLOOP. (2020). A SITUATIONAL ANALYSIS OF A CIRCULAR ECONOMY IN THE DATA CENTRE INDUSTRY.

Westerhof, R., Atherton, R., & Andrikopoulos, V. (2023, May). An Allocation Model for Attributing Emissions in Multi-tenant Cloud Data Centers [arXiv:2305.10439 [cs]]. https://doi.org/10.48550/arXiv.2305.10439

Whitehead, B., Andrews, D., & Shah, A. (2015). The life cycle assessment of a UK data centre. *The International Journal of Life Cycle Assessment*, *20*(3), 332–349. https://doi.org/10.1007/s11367-014-0838-7

Yang, R., Li, W., Ren, J., Xiang, J., Wu, Y., Lai, Z., Zhang, J., Ge, X., Chen, S., Zhang, S., Cao, X., & Jia, P. (2026, January). Nationwide Fleet-Scale Neural

Autonomous Heavy-Duty Trucking that Rivals Champion Human Drivers in Fuel Efficiency. https://doi.org/10.21203/rs.3.rs-8734823/v1

Zhang, M., Carbajales-Dale, M., Ma, X., Guo, L., & Fan, C. (2025). Cleaner grid or smarter cooling? Environmental impact trade-offs of a data center using the life cycle assessment method. *Cleaner Energy Systems*, *12*, 100223. https://doi.org/10.1016/j.cles.2025.100223

A

Appendix - Life Cycle Inventory

All life cycle inventory elements used in the LCA modeling, starting from the sub-assemblies for the servers and building, to data center assembly and operational phase. Finally, parameters used in the inventory are showed.

Table A.1: Life Cycle Inventory (LCI) data for the Server assembly.

Sub-assembly	Ecoinvent Term	Amount	Unit
Server assembly		**30706.5189**	**g**
Batteries sub-assembly		44.6	g
	battery cell production, Li-ion, LFP	1.6	g
	battery production, Li-ion, LFP, rechargeable	43	g
Cables sub-assembly		470	g
	market for brass	7	g
	market for zinc	96	g
	market for synthetic rubber	35	g
	market for polyvinylchloride, unspecified polymerisation, weighted average	145	g
	market for polyurethane, rigid foam	2	g
	market for polyethylene, high density, granulate	104	g
	market for Wire drawing, copper	81	g
Chassis sub-assembly		13454	g
	market for aluminium, primary, ingot	249	g
	market for Steel, unalloyed	12265	g
	market for Acrylonitrile-butadiene-styrene copolymer	348	g
	market for Polycarbonate	282	g
	market for printed wiring board, surface mounted, unspecified, Pb free	131	g
	market for Copper concentrate, sulfide ore	179	g

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Table A.1 – Continued from previous page

Sub-assembly	**Ecoinvent Term**	**Amount**	**Unit**
CPU sub-assembly		54	g
	market for printed wiring board, surface mounted, unspecified, Pb free	54	g
Electronics sub-assembly		2909.4089	g
	market for epoxy resins, liquid	1176.97	g
	market for Glass fibre	1722.01	g
	market for Silicon, single crystal, Czochralski process, electronics	6.56	g
	market for Magnesium	0.0039	g
	market for Titanium	3.62	g
	market for Neodymium oxide	0.245	g
Expansion card sub-assembly		349	g
	market for printed wiring board, surface mounted, unspecified, Pb free	349	g
Fans sub-assembly		945.18	g
	market for Steel, unalloyed	386	g
	market for Polyethylene terephthalate, granulate, bottle grade	206	g
	market for Polycarbonate	195.32	g
	market for Acrylonitrile-butadiene-styrene copolymer	24.86	g
	market for Copper concentrate, sulfide ore	78	g
	market for Reinforcing steel	55	g
HDD sub-assembly		1749.33	g
	market for Aluminium, primary, ingot	786.6	g
	market for Steel, unalloyed	547.12	g
	market for Reinforcing steel	152	g
	market for Polycarbonate	60.47	g
	market for Acrylonitrile-butadiene-styrene copolymer	7.7	g
	market for Polycarbonate	36.708	g
	market for Glass fibre	15.732	g
	market for printed wiring board, surface mounted, unspecified, Pb free	68	g
	market for Copper concentrate, sulfide ore	7	g
	market for permanent magnet, for electric motor	68	g

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Table A.1 – Continued from previous page

Sub-assembly	**Ecoinvent Term**	**Amount**	**Unit**
Heat pipe sub-assembly		582	g
	market for Steel, unalloyed	140	g
	market for Copper concentrate, sulfide ore	442	g
Main board sub-assembly		1667	g
	market for printed wiring board, surface mounted, unspecified, Pb free	1667	g
Memory cards sub-assembly		135	g
	market for printed wiring board, surface mounted, unspecified, Pb free	135	g
ODD sub-assembly		189	g
	market for Aluminium, primary, ingot	1	g
	market for Steel, unalloyed	115	g
	market for Acrylonitrile-butadiene-styrene copolymer	12	g
	market for Polyethylene, high density, granulate	28	g
	market for Polycarbonate	7	g
	market for printed wiring board, surface mounted, unspecified, Pb free	19	g
	market for Copper concentrate, sulfide ore	7	g
Packaging sub-assembly		4733	g
	market for Polyethylene, high density, granulate	78	g
	market for Polystyrene, extruded	1026	g
	market for Kraft paper	3629	g
PSU sub-assembly		3425	g
	market for aluminium, primary, ingot	226	g
	market for steel, unalloyed	1346	g
	market for ethylene vinyl acetate copolymer	75	g
	market for polycarbonate	51	g
	market for cable, unspecified	31	g
	market for fan, for power supply unit, desktop computer	154	g

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Table A.1 – Continued from previous page

Sub-assembly	Ecoinvent Term	Amount	Unit
	market for printed wiring board, for power supply unit, desktop computer, Pb free	1542	g

Table A.2: Life Cycle Inventory (LCI) data for the Building Assembly.

Sub-assembly	Ecoinvent Term	Amount	Unit
Building assembly		**712127.842**	**kg**
Ceiling sub-assembly		4224	kg
	market for Gypsum plasterboard	4224	kg
Cooling sub-assembly		375	kg
	market for Electronics, for control units	20	kg
	market for Cellulose fibre	27.5	kg
	market for Weaving, synthetic fibre	47.15	kg
	market for steel, low-alloyed, hot rolled	280.35	kg
Doors sub-assembly		940	kg
	market for polyvinyl chloride, suspension polymerised	300	kg
	market for calendering, rigid sheets	300	kg
	market for Fibreboard, hard	0.314	m^3
	market for Door, inner, wood	12.73	m^2
Flooring sub-assembly		329810.9	kg
	market for Polystyrene foam slab, 10% recycled	200	kg
	market for Polystyrene foam slab for perimeter insulation	500	kg
	market for Gravel, crushed	56600	kg
	market for Concrete, normal strength	109.3	m^3
	market for Glued laminated timber, average glue mix	14.222	m^3
	market for Wood chips, dry, measured as dry mass	7070	kg
Foundation sub-assembly		26117.4	kg

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Table A.2 – Continued from previous page

Sub-assembly	**Ecoinvent Process Term**	**Amount**	**Unit**
	market for Concrete, normal strength	11.02	m^3
Infrastructure sub-assembly		40 + (server_amount× 0.1612)	kg
	market for Light emitting diode	20	kg
	market for Plug, inlet and outlet, for network cable	2 × servers_amount	items
	market for Electric connector, peripheral type buss	20	kg
	market for Cable, network cable, category 5, without plugs	4 × server_amount	m
Joists sub-assembly		2640	kg
	market for Joist, engineered wood	974.29	m
Power distribution sub-assembly		1846.11	kg
	market for Wire drawing, copper	1611.72	kg
	market for polyvinylchloride, unspecified polymerisation, weighted average	234.39	kg
Racks sub-assembly		6278.904	kg
	market for steel, low-alloyed, hot rolled	5595.48	kg
	market for Aluminium, primary, ingot	683.424	kg
Roof sub-assembly		184447	kg
	market for stone wool, packed	551.424	kg
	market for clay Roof tile	12335	kg
	market for Sawnwood, beam, hardwood, dried (u=20%), planed	10.492	m^3
Stairs sub-assembly		6162	kg
	market for Concrete, normal strength	2.6	m^3
Structure sub-assembly		23500	kg
	market for Steel, low alloyed	23500	kg
Walls sub-assembly		289998	kg

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Table A.2 – Continued from previous page

Sub-assembly	Ecoinvent Process Term	Amount	Unit
	market for Laminated timber element, transversally prestressed, for outdoor use	9.177	m^3
	market for Cellulose fibre	2820	kg
	market for Gypsum plasterboard	11417.63	kg
	market for Clay brick	230748	kg
	market for Autoclaved aerated concrete block	23700	kg
	market for Fibreboard, hard	4.22	m^3
	market for Plywood	4.22	m^3
	market for Glass wool mat, uncoated, Saint-Gobain ISOVER SA	2810	kg
	market for Glued laminated timber, average glue mix	12.67	m^3
	market for Gypsum plasterboard	8288	kg
	market for Glued laminated timber, average glue mix	13.95	m^3
	market for Autoclaved aerated concrete block	52000	kg
Windows sub-assembly		2123.528	kg
	market for polyvinylchloride, unspecified polymerisation, weighted average	200	kg
	market for injection moulding	200	kg
	market for Glazing, double, U<1.1 W/m2K, laminated safety glass	61.52	m^2
	market for Window frame, wood, U=1.5 W/m2K	4.04	m^2

Table A.3: Life Cycle Inventory (LCI) data for the Data Centre Assembly.

Assembly	Amount	Unit
Data centre assembly		
Server assembly	30.7065189 × server_amount	kg
Building assembly	712127.842 + (server_amount × 0.1612) + (cooling_amount × 375)	kg

Table A.4: Life Cycle Inventory (LCI) data for the Data Center Operation.

Flow	Amount	Unit
Inputs to the process		
Market group for electricity, high voltage	3587743.59 × DC_lifetime × PUE	kWh
market group for tap water	62426738.47	kg
Emissions and waste to air		
Mercury II	0.00002 × air	μg
Aluminium III	0.10416 × air	μg
Arsenic ion	0.0052083 × air	μg
Barium II	0.010416 × air	μg
Beryllium II	0.00052083 × air	μg
Cadmium II	0.00052083 × air	μg
Chromium III	0.10416 × air	μg
Molybdenum VI	0.0010416 × air	μg
Nickel II	0.0052083 × air	μg
Vanadium V	0.0010416 × air	μg
Zinc II	0.52083 × air	μg
Manganese II	0.0052083 × air	μg
Lead II	0.001156 × air	μg
m-Xylene	0.35 × air	μg
Xylenes, unspecified	0.35 × air	μg
Toluene	0.6 × air	μg
Ethanol	1.7 × air	μg
Aldehydes, unspecified	3.5 × air	μg
Acetone	1.2 × air	μg
NMVOC	1.1 × air	μg

Table A.5: Parameters used in the Life Cycle Inventory.

Parameter	Description	Value	Unit
DC_lifetime	Data center operational lifetime	30	years
Server_lifetime	Server operational lifetime	5	years
Servrar_samtidigt	Active concurrent servers (30×24×3 constant)	2160	items
Server_amount	Total servers over DC lifetime	12960	items
Cooling_amount	Total cooling infrastructure systems (DC_lifetime/Cooling_lifetime)	6	items
Cooling_lifetime	Lifespan of cooling systems	5	years
PUE	Power Usage Effectiveness factor	1.54	–
air	629788493 × DC_lifetime	18893654790	m3

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