TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

CARBON FOOTPRINT OF HIGH-PERFORMANCE COMPUTING CENTERS: MEASUREMENT AND MITIGATION RECOMMENDATIONS

KÕRGJÕUDLUSEGA ANDMETÖÖTLUSKESKUSTE SÜSINIKU JALAJÄLG: MÕÕTMISE JA LEEVENDAMISE SOOVITUSED

MASTER THESIS

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Tallinn 2023

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No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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THESIS TASK

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(in English) *Carbon Footprint of High-Performance Computing Centers: Measurement and Mitigation Recommendations*

(in Estonian) *Kõrgjõudlusega andmetöötluskeskuste süsiniku jalajälg: mõõtmise ja leevendamise soovitused*

Thesis main objectives:

1. Investigate and explain the reasons behind the carbon footprint of HPC systems, including factors such as energy consumption of hardware, cooling and power distribution systems, and network infrastructure.
2. Utilize carbon footprint model to measure the environmental impact of high-performance computing (HPC) systems by analyzing energy consumption and emissions from data centers and other infrastructure.
3. Provide recommendations for reducing the carbon footprint of HPC systems and promoting sustainable computing practices.

Thesis tasks and time schedule:

No	**Task description**	**Deadline**
1.	Theoretical Literature review	15.02.2023
2.	Data Collection, Processing and Writing Methodology	20.03.2023
3.	Writing Results, Discussions, Conclusion and Recommendation	22.05.2023

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CONTENTS

List of Abbreviations and Symbols

HPC	High-Performance Computing
GHG	Green House Gases
CO_2	Carbon Dioxide
CH_4	Methane
N_2O	Nitrous Oxide
HFCs	Hydrofluorocarbons
PFCs	Perfluorocarbons
SF_6	Sulfur Hexafluoride
NF_3	Nitrogen Trifluoride
GWP	Global Warming Potential
ICT	Information and Communications Technology
GHGP	Greenhouse Gas Protocol
TWh	Terawatt-Hour
PAS	Publicly Available Specifications
LCA	Life Cycle Assessment
WRI	The World Resource Institute
WBCSD	World Business Council on Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
CDP	Customer Data Platform
BSI	British Standard Institution
PUE	Power Usage Effectiveness
EU	European Union
EP	European Parliament

ECA	European Court of Auditors
EC	European Commission
ATS	Automatic Transfer Switches
UPS	Uninterruptible Power Supply
GIME	Groupe Interinstitutioonel de Management Environnemental / Interinstitutional Group on Environmental Management
SLURM	Simple Linux Utility for Resource Management
Ton CO_2eq	Ton Carbon dioxide equivalent
PSF	Pragmatic Scaling Factor
GB	Giga Byte
gCO_2eq/kWh	Gram Carbon dioxide equivalent per kilo watt hour
cm^2	Square Centimeter
m^2	Square Meter
P_c	Power Consumption
P_{AC}	Cooling Power Consumption
CRAC	Computer Room Air Conditioner
HVAC	Heating Ventilation Air Conditioner
T	Temperature (°C)
SaaS	Software as a Service
PI	Performance Index
GPU	graphics processing unit
CPU	central processing unit

1 INTRODUCTION

High Performance Computing (HPC) has become an integral part of modern research and industry. Because of its capacity for processing enormous volumes of data and carrying out intricate computations, scientists and engineers have been able to work on issues that were previously seen as insurmountable. But the strength and sophistication of HPC systems have a price: a large carbon footprint.

The energy demand of data centers per square meter has significantly increased in recent years and can be up to 100 times higher than that of office accommodations. This can be attributed to the decrease in the size of processing servers and more efficient use of space and processing, which present challenges for facilities to provide adequate power and cooling capacity.[1]

The carbon footprint of HPC systems is primarily caused by the energy consumption of the supercomputers and data centers that run them. The energy consumption of HPC systems is driven by several factors such as the number and type of processors, the cooling systems used, and the power and cooling infrastructure of the data center. This high energy consumption leads to a large amount of greenhouse gas emissions, contributing to global warming and climate change.[2]

In recent years, there has been an increasing awareness of the environmental impact of HPC and efforts to reduce the carbon footprint of these systems. One of the most effective ways to reduce the carbon footprint of HPC systems is to increase their energy efficiency. This can be achieved through the development of more energy-efficient processors, the use of more efficient cooling systems, and the implementation of power management strategies.[3]

Another approach is to use renewable energy sources to power HPC data centers. This can be done by installing solar panels or wind turbines to generate electricity, or by purchasing renewable energy certificates. These certificates represent the environmental attributes of electricity generated from renewable sources and can be used to offset the carbon emissions associated with the HPC system.[4]

In addition to these efforts, HPC centers and research institutions can also participate in resource sharing and virtualization to increase the utilization of the available resources and make the system more efficient. By collaborating and pooling resources, HPC centers can reduce the number of systems required to meet the computational needs of the research community and reduce the associated energy consumption and carbon emissions.

The aim of this thesis is to assess and reduce the environmental impact of high-performance computing (HPC) systems, with a specific focus on the TalTech HPC center. The study uses the Greenhouse Gas Protocol, an international standard for calculating greenhouse gas emissions, to calculate the carbon footprint of the HPC center. By identifying the sources of emissions, the study can provide recommendations for mitigation strategies to reduce the environmental impact of the HPC center. The thesis also aims to increase awareness of the environmental impact of HPC systems and highlight the importance of developing more sustainable and energy-efficient solutions in the field of computing.

In addition to identifying and calculating the carbon footprint of TalTech HPC center, the thesis also includes comparative analyses. Using the Green Algorithm calculation method, the study compares the environmental impacts of TalTech HPC center with other HPC centers. Furthermore, the thesis compares the energy consumption and carbon footprint of TalTech HPC center with CRESCO4 HPC in Italy. This comparative analysis provides a broader understanding of the environmental impact of HPC centers and can inform the development of mitigation strategies to reduce their carbon footprint.

2 THEORETICAL BACKGROUND

2.1 Global Warming

Climate change is accompanied by a rise in global temperatures, which is commonly referred to as global warming. This phenomenon has been observed since the mid-19th century, as confirmed by numerous scholarly studies. Regional studies have also shown an increase in temperature in specific locations, affecting both natural and built environments on various scales.[5]

The Earth's temperature is predominantly influenced by the amount of solar energy it receives and the extent to which greenhouse gases in the atmosphere, such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone, trap that energy. Since the late 1700s, human activities related to agriculture and the burning of fossil fuels have caused an increase in the concentration of atmospheric greenhouse gases, particularly carbon dioxide, resulting in a rise in global temperatures. This warming has been significantly amplified since the 1950s, when a post-war surge in manufacturing, transportation, land use, population growth, and other socioeconomic activities led to a greater emission of greenhouse gases.[6]

The IPCC reported a concerning reality - global warming is actually accelerating. This acceleration can be attributed to three trends: an increase in emissions, a decrease in air pollution, and natural climate cycles. These factors will combine over the next two decades and result in climate change that is faster and more intense than originally predicted. Experts warn that we may even surpass the 1.5 °C level by 2030. Unfortunately, the climate-modeling community has yet to fully address the rapid changes that policymakers are most concerned about, as their focus tends to be on longer-term trends and equilibria.[7]

Greenhouse gases, such as carbon dioxide, are released into the atmosphere through various human activities, including burning fossil fuels, agriculture, and waste management. These emissions contribute to climate change by trapping heat in the atmosphere. Although natural processes, such as plant absorption, can remove some of these gases, the amount released by human activities far exceeds what can be naturally absorbed. The overwhelming scientific evidence supports the conclusion that greenhouse gas emissions are responsible for climate change and global warming.[8]

While some scientists may suspect that human activities could have contributed to recent changes in climate and global temperature, the IPCC has officially concluded that the warming observed over the past 50 years is primarily caused by human activities. Climate change poses significant threats to the natural resources, environments, and societies that rely on them. While the impact of climate change and global warming is already being felt by human life, it is also important to recognize that human activities are contributing to this phenomenon.[8]

There is a significant gap in addressing the impacts of global warming as less attention is given to the implementation and achievement of more challenging mitigation strategies.[9]

2.1.1 Effects of Global Warming

Greenhouse effect: The greenhouse effect is typically observed in colder and hilly regions where plants require more sunlight and warmer temperatures for their growth. To provide a suitable environment for the growth of fruits, vegetables, and flowers, a glass chamber is used to trap sunlight inside. The glass allows sunlight to enter but prevents it from escaping, resulting in a warmer temperature inside the chamber compared to the outside temperature. This phenomenon is referred to as the greenhouse effect.[10]

Climate change: refers to the rapid increase in the earth's temperature in recent years, which poses a threat to all living organisms. The impacts of global warming can be severe, and one of the most noticeable effects is the rise in sea levels due to the melting of ice and glaciers, resulting in a reduction in the supply of freshwater. In addition, global warming can lead to changes in natural and man-made weather patterns, affecting both land and sea, and causing acidification of the ocean.[11]

Sea levels rise is a consequence of global warming, as it leads to the melting of ice caps, glaciers, and the Atlantic zone. This phenomenon can cause disastrous outcomes.[12]

Global warming has an impact on agriculture as the increasing level of carbon dioxide in the atmosphere can result in crop growth that is twice as fast as normal. However, changes in climate conditions could also affect crop production, potentially leading to an increase in crop yield at a faster rate.[13]

2.2 GHG Emissions

Greenhouse gases are so called because of their ability to trap and retain heat within the Earth's atmosphere, much like the glass walls of a greenhouse retain heat inside. These gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases we will talk about each of them in the next paragraphs.[14]

2.2.1 Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is the primary greenhouse gas that is released into the atmosphere as a result of human activities. Although carbon dioxide is naturally present in the Earth's atmosphere as part of the carbon cycle, human activities are disrupting this cycle by adding more CO_2 to the atmosphere and altering the ability of natural "sinks" like forests and soils to absorb and store CO_2.[14]

While some CO_2 emissions occur naturally, such as from volcanic activity and the decay of organic matter, the increase in atmospheric CO_2 since the industrial revolution can be attributed to human activities such as burning fossil fuels, deforestation, and changes in land use. These activities release large amounts of CO_2 into the atmosphere, which accumulate over time and contribute to global warming and climate change.[14]

Efforts to mitigate CO2 emissions have become increasingly important in recent years, as the world faces the consequences of climate change. Initiatives such as the Paris Agreement aim to limit the increase in global temperatures to well below 2 degrees Celsius above pre-industrial levels. By reducing CO_2 emissions and supporting natural carbon sinks, it is possible to mitigate the impact of human activities on the carbon cycle and reduce the risks of climate change.[14]

2.2.2 Methane (CH_4)

The release of methane gas by human activities includes leaks from natural gas systems and the rearing of livestock. However, natural sources like wetlands also release methane gas. Additionally, natural processes occurring in soil and chemical reactions taking place in the atmosphere help eliminate methane gas from the atmosphere. Although methane's lifetime in the atmosphere is shorter than carbon dioxide (CO_2), it is much more potent in trapping radiation than CO_2. In fact, pound for pound, the impact of methane gas on the environment is 25 times greater than CO_2 over a period of 100 years.[14]

2.2.3 Nitrous Oxide (N_2O)

Human actions such as agriculture, fuel combustion, wastewater management, and industrial processes are responsible for augmenting the level of N_2O in the atmosphere. Nitrous oxide is naturally present in the atmosphere as a part of the Earth's nitrogen cycle and has various natural sources as well. The lifetime of nitrous oxide molecules in the atmosphere is around 114 years before they are eliminated through a sink or destroyed by chemical reactions. The effect of 1 pound of nitrous oxide on warming the environment is almost 300 times more than that of 1 pound of carbon dioxide.[14]

2.2.4 Fluorinated Gases

Fluorinated gases, unlike several other greenhouse gases, are primarily produced through human activities and do not have significant natural sources. They are released by using them as substitutes for ozone-depleting substances like refrigerants and via various industrial processes, such as aluminum and semiconductor manufacturing. These gases possess high global warming potentials (GWPs) in comparison to other greenhouse gases, which means that even minor atmospheric concentrations can cause a significant impact on global temperatures. Additionally, they can persist in the atmosphere for extended periods, often lasting thousands of years.[14]

There are four primary categories of fluorinated gases - hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). Due to their long atmospheric lifetimes and well-mixed nature in the atmosphere, they spread throughout the world after being released. Removal of many fluorinated gases can only occur through their destruction by sunlight in the upper atmosphere. Overall, fluorinated gases are the most potent and long-lasting greenhouse gases resulting from human activities.[14]

There has been a 60% increase in emissions of these gases since 1990. Furthermore, emissions of HFCs are projected to increase by nearly 140% between 2005 and 2020. As a result, reducing the emissions of these gases is crucial to mitigating the effects of global warming.[15]

2.3 Carbon Footprint

It is a methodology for calculating the total carbon-equivalent emission of greenhouse gases (GHG) of a product during its entire life cycle, from the initial production of raw materials used in its manufacturing to the disposal of the final product, while excluding emissions that occur during its use. Another method involves identifying and quantifying the specific greenhouse gas emissions from each activity within a particular process step in the supply chain, and a framework for assigning them to each output product.[16]

Climate change is having a widespread impact on life on Earth, including human societies, economies, and health. Greenhouse gas emissions, which are caused by human activities such as data centers and large-scale computation, are a significant contributor to this problem. Despite the important scientific advancements made possible by high-performance computing, the environmental impact of these technologies is often overlooked.[2]

Climate change will persist throughout this century and beyond, and the extent of climate changes will largely depend on worldwide greenhouse gas emissions and how the Earth's climate system responds to human-induced warming, particularly after mid-century. If greenhouse gas emissions are considerably reduced, global temperature increase may be limited to 2°C or less compared to preindustrial temperatures. However, without significant reductions, global average temperatures could potentially surge by 5°C or more by the end of this century, as compared to preindustrial temperatures.[17]

In the long term, the extent of climate change will predominantly rely on the quantity of greenhouse gases that are discharged into the atmosphere, the degree to which they are soaked up by the ocean, the biosphere, and other carbon sinks, and the sensitivity of Earth's climate to those emissions.[18]

In light of the severe consequences and global scale of climate change, there have been international discussions and policies aimed at reducing greenhouse gas (GHG) emissions. In 2015, the Paris Agreement was signed by governments of 195 countries, outlining objectives related to climate change mitigation and adaptation.[19]

Therefore, current human activities such as burning fossil fuels for energy, transportation, industrial processes, waste management, heating and cooling buildings, and existing land-use practices are not sustainable in the long term. This problem is further exacerbated by deforestation and the conversion of green spaces for other uses. To address this, it is important to find alternative methods of energy production, as well as implement policies and practices that focus on reducing emissions and preserving natural spaces. Additionally, reforestation and afforestation projects may also play a vital role in reducing the carbon footprint.[20]

2.3.1 Carbon Footprint Calculation

Calculating a carbon footprint involves estimating and adding up the amount of greenhouse gases (GHGs) emitted or removed during the entire life cycle of a product. This life cycle includes all stages of a product, from the sourcing of raw materials to manufacturing, packaging, distribution, use, and disposal. This is known as a "cradle to grave" analysis and is also known as a life cycle assessment (LCA). LCA provides a complete picture of inputs and outputs related to air pollutants, water usage, energy consumption, GHG emissions, and other environmental impacts, as well as cost-benefit initiatives.[21]

For carbon footprint calculation, LCA estimates the GHGs emitted or embodied at each stage of a product's life cycle, also known as GHG accounting. There are several standards and guidelines available for GHG accounting, including:

1. The GHG protocol of the World Resource Institute (WRI) and World Business Council on Sustainable Development (WBCSD), which provides sector-specific and general calculation tools and deals with quantifying GHG reductions due to mitigation methods in its Project protocol. It forms the basis for most GHG accounting guidelines, including ISO 14064 (parts 1 and 2)
2. ISO 14064 (parts 1 and 2), an international standard for determining boundaries, quantifying GHG emissions and removal, and designing GHG mitigation projects.
3. Publicly Available Specifications-2050 (PAS 2050) of the British Standard Institution (BSI), which specifies requirements for assessing the life cycle GHG emissions of goods and services.
4. 2006 IPCC guidelines for National Greenhouse Gas inventories, which classify all anthropogenic sources of GHG emissions into four sectors: energy, industrial process and product use, agriculture, forestry and other land use, and waste.
5. ISO 14040 and ISO 14044 are standards for carrying out LCA.
6. ISO 14067, a standard on carbon footprint calculation of products that is currently under development.[21]

2.4 Overview of GHG protocol for Corporates and Organizations

From the early 1990s to the mid-2000s, the global community made a concerted effort to address climate change by implementing measures to reduce greenhouse gas (GHG) emissions. This focuses on enhanced mitigation efforts aimed to limit the potential increase in global temperatures to between 3°C and 4°C above preindustrial levels by the end of this century, as scientific evidence had suggested by the mid-2000s.[22]

Carbon footprint calculation has become a widely used method of measuring greenhouse gas (GHG) emissions. Earlier studies focused solely on CO_2 emissions, but carbon footprint calculations now include all important GHGs. Carbon footprint reports are becoming more common in response to legal or business requirements and are typically calculated using the GHG protocol.[21]

Carbon footprint calculation has also been commercialized and is being used by organizations to measure their carbon emissions and adopt measures to reduce them. This has led to an increase in awareness of the impact of everyday activities on global warming. However, there is currently a lack of regulation and transparency in carbon footprint calculations, particularly in relation to online calculators. To effectively combat climate change, it is important for carbon footprint to be regulated and used as a tool to promote GHG emission reductions among businesses, events, and individuals. It should also be considered as an indicator of sustainable development.[21]

The Greenhouse Gas Protocol Initiative is a partnership between various stakeholders, including businesses, non-government organizations, governments, and others, brought together by the World Resources Institute, a US-based environmental NGO, and the World Business Council for Sustainable Development, a coalition of 170 international companies based in Geneva. Established in 1998, the goal of the initiative is to create internationally recognized standards for measuring and reporting greenhouse gas emissions in businesses and to promote their widespread use.[23]

The use of GHG Protocol standards is widespread, as 92% of Fortune 500 companies who responded to the CDP in 2016 used it directly or indirectly through a program based on it. It is the most widely used platform for corporate greenhouse gas reporting programs worldwide. The popularity of these standards is attributed to the extensive stakeholder engagement and consultation process undertaken by WRI and WBCSD during the development of each standard.[24]

The GHG Protocol Corporate Standard provides guidelines and standards for organizations to accurately account and report their greenhouse gas emissions, including carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. The objectives of the standard include ensuring accurate and fair emissions reporting, reducing the cost and complexity of compiling an emissions inventory, providing information for managing and reducing emissions, facilitating participation in voluntary and mandatory emissions programs, and promoting consistency and transparency in emissions reporting among organizations.[23]

To clearly distinguish between direct and indirect emission sources, increase transparency and accommodate the needs of various types of organizations and climate policies, three "scopes" (scope 1, scope 2, and scope 3) are established for greenhouse gas accounting and reporting. Scopes 1 and 2 are precisely defined in the standard to avoid duplication of emissions accounting by different companies. This makes the scopes suitable for use in greenhouse gas programs where avoiding double counting is important. Companies must separately account for and report on scopes 1 and 2 at a minimum. The Scopes are:[23]

1. Scope 1: Direct Greenhouse Gas Emissions

   Direct greenhouse gas emissions are a result of sources that are directly controlled by the company or organization. These sources include, but not limited to, combustion of fossil fuels in boilers, furnaces, vehicles and other equipment used by the company or organization. Emissions from chemical production, such as the use of certain chemicals in the production process, also falls under direct greenhouse gas emissions. The emissions produced by these sources are directly under the control of the company or organization and can be measured and reported accurately. These emissions are considered as the primary source of greenhouse gas emissions for the company or organization.[23]

2. Scope 2: Indirect Greenhouse Gas Emissions from Electricity

   Scope 2 covers greenhouse gas emissions that result from the generation of electricity purchased by the company or organization. This encompasses all electricity, whether it is purchased directly from the utility provider or brought into the organization's boundary through other means, like power purchase agreements (PPAs). These emissions occur at the facility where the electricity is generated, which could be a power plant or a renewable energy facility. The emissions from these facilities are not directly controlled by the company or organization but are still considered part of the organization's overall greenhouse gas emissions inventory. The company or organization can use the information of the emissions generated by the electricity purchased to make informed decisions to reduce its environmental impact and to set reduction targets.[23]

3. Scope 3: Other indirect GHG emissions

   Scope 3 is an optional reporting category that allows for the measurement and reporting of indirect emissions that are not covered by Scope 1 and Scope 2. These emissions occur as a result of the activities of the company or organization, but they are not directly owned or controlled by the company. Some examples of activities that fall under scope 3 are: emissions resulting from the extraction, production and transportation of materials purchased by the organization, emissions from the transportation of purchased fuels, emissions from waste disposal and treatment activities, emissions from the use of sold products and services and emissions from business travel. These emissions can be caused by activities that are not under the control of the company, but still, have an impact on the organization's overall greenhouse gas emissions inventory. It is important to note that, Scope 3 emissions are considered as an optional category for reporting, however, some mandatory reporting schemes or voluntary programs may require scope 3 reporting.[23]

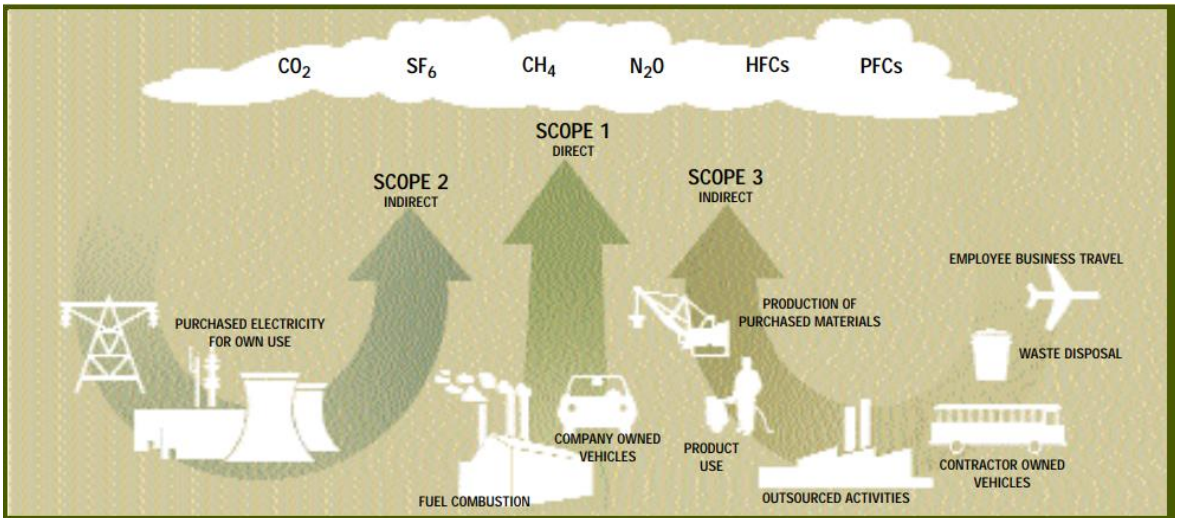

Figure 2.1 Scopes and Emissions Overview[23]

2.5 EU regulations and considerations related to carbon emissions.

Some governments require companies that emit greenhouse gases to report their emissions on an annual basis. These regulations usually focus on direct emissions from facilities under the control of the company within specific geographic areas. For example, in Europe, facilities that fall under the Integrated Pollution Prevention and Control Directive must report emissions that exceed a certain threshold for each of the six greenhouse gases and the emissions are reported in a publicly available database called European Pollutant Emissions Register, allowing for comparison of emissions from different facilities and sectors across countries. [23]

The European Parliament (EP) declared a climate emergency in Europe on November 28th, 2019 and called on all EU countries to achieve net-zero greenhouse gas emissions by 2050. The EP also acknowledged its own responsibility to reduce its carbon footprint and proposed measures to do so. Similarly, the European Commission (EC) announced its intention to reduce its environmental impact and become climate neutral by 2030 through a comprehensive action plan in 2020. The European Council also adopted a 2050 carbon neutrality target for the EU, with the exception of Poland, which supported the goal but was unable to commit to implementing it.[25]

The European Climate Law legislates the objective outlined in the European Green Deal for Europe to become climate-neutral by 2050. The law also establishes an intermediate goal of reducing net greenhouse gas emissions by at least 55% by 2030, as compared to 1990 levels. Climate neutrality by 2050 implies achieving net zero greenhouse gas emissions for all EU countries, mainly through reducing emissions, investing in green technologies, and preserving the natural environment. The law aims to ensure that all EU policies support this goal and that all sectors of the economy and society contribute to it. To reach this goal, the law calls for a reduction in emissions from all sectors, including energy, transport, buildings, agriculture, and waste, as well as the promotion of renewable energy sources and the use of energy-efficient technologies. It also requires the monitoring and reporting of emissions, the development of strategies for adaptation to the impacts of climate change, and the creation of a just transition fund to support those most affected by the transition to a low-carbon economy.[26]

The Commission has evaluated that the current commitments will result in a net reduction of 225 million tons of CO_2 equivalent by 2030. To ensure adequate mitigation efforts are in place by 2030, it is deemed appropriate to limit the contribution of net removals towards the Union's 2030 climate target to that level. This decision is subject to review of relevant Union legislation to ensure achievement of the target. This is done to ensure that the current commitments are sufficient to meet the Union's 2030 climate target, and to ensure that additional mitigation efforts are taken if required. The review of relevant Union legislation will help to assess whether the current commitments are adequate, and if not, what additional measures should be taken.[27]

Given the paramount importance of achieving climate neutrality by 2050, which is a crucial step in addressing the global climate crisis, and the commitments made by the European Union as part of the Paris Agreement, it is imperative to take action to eliminate energy subsidies that are not aligned with this objective. These subsidies, particularly those for fossil fuels, are a significant contributor to greenhouse gas emissions, which drive climate change. It is important to note that phasing out these subsidies should be done in a way that does not negatively impact the efforts to reduce energy poverty, which is a major concern for many communities, particularly in developing countries. Therefore, it's important to identify and implement alternative solutions that can support low-income households and ensure that the phasing out process is done in a fair and equitable manner.[27]

As for the F-gases, the current Regulation represents a significant improvement over previous measures, implementing comprehensive changes including limiting the total amount of HFCs sold in the EU from 2015 onward, with a gradual phasing down to one-fifth of 2014 sales by 2030. This reduction is the primary catalyst for transitioning toward more eco-friendly technologies. In addition, the Regulation prohibits the use of F-gases in many newly developed types of equipment where less harmful alternatives are readily available, including home and supermarket refrigerators, air conditioning systems, foams, and asthma sprays. The Regulation also mandates the prevention of F-gas emissions from existing equipment by requiring appropriate checks, servicing, and gas recovery at the end of the equipment's lifecycle.[28]

The Union budget and the European Union Recovery Instrument, as established by Council Regulation (EU) 2020/2094, play a significant role in promoting climate objectives. These institutions have committed to dedicating a significant portion of their total expenditure, at least 30%, towards supporting these objectives. This allocation is done through an effective methodology which follows sector-specific legislation.[27]

Despite efforts by EU institutions and bodies to share best practices for reducing their carbon footprint through inter-institutional environmental management groups such as the GIME, more work is needed to standardize the way they calculate and report their greenhouse gas emissions. Additionally, not all institutions and bodies include their indirect emissions in their calculations and the use of green public procurement is not mandatory. Furthermore, there is currently no unified approach for offsetting emissions. This has been an issue that has been raised in the past, as an ECA special report from 2014 called for the need to harmonize methods and metrics for measuring carbon footprint of EU institutions and bodies. Even today, it remains difficult to compare their carbon footprint directly[25]

2.6 HPC Environmental impact

Addressing global warming, managing resources, and improving environmental performance are critical challenges that must be addressed with urgency. The information and communications technology (ICT) industry, which is responsible for around 2-3% of the world's carbon footprint, must take steps to improve its environmental performance. However, ICT applications have the potential to greatly enhance performance in other sectors of the economy and society, which account for the remaining 97-98% of the carbon footprint. To address these environmental challenges, governments and business organizations have implemented a variety of programs and initiatives related to ICT and the environment.[29]

These programs and initiatives include investing in renewable energy sources, increasing energy efficiency, reducing waste, implementing green building standards, and encouraging the use of sustainable practices. Additionally, ICT can be used to develop solutions that reduce energy consumption and improve the efficiency of production processes.[29]

The data center and high-performance computing sector contributes significantly to climate change, with an estimated 100 megatons of CO_2 emissions per year, which is similar to that of American commercial aviation. Despite the rapid growth in demand, energy efficiency has also improved, resulting in stable overall electricity consumption for data centers. However, this trend is expected to change in the future with predictions of a significant increase in energy needs for the sector, possibly reaching three times the current levels.[2]

This is due to the increasing demand for cloud services, which require more data centers and more powerful computing resources. With the continued development of technology, the demand for more computing power is only expected to increase, leading to a corresponding increase in electricity consumption. This, in turn, means that the electricity consumption associated with data centers is likely to continue to grow, unless new approaches are adopted to reduce their energy needs.[2]

Deep learning, with its well-known power-intensive and costly training algorithms, has begun to address its carbon footprint. The size of machine learning (ML) models has grown exponentially in recent years, with some algorithms requiring thousands of core-hours of training, resulting in a significant increase in energy consumption and cost. In the field of natural language processing (NLP), research has shown that the design and training of translation engines can emit between 0.6 and 280 tons of CO_2. Some NLP algorithms require frequent retraining, amplifying their energy consumption. Other fields, such as astronomy, also rely heavily on supercomputers for data analysis, prompting investigations into the carbon footprint of the field. For example, it has been estimated that the usage of supercomputers by Australian astronomers results in the emission of 15 kilotons of CO_2 per year, equivalent to 22 tons per researcher. Cryptocurrencies and their associated "mining farms" have also seen a significant increase in their environmental impact in recent years, raising questions about their sustainability. A 2018 study estimated that Bitcoin alone consumed 46 TWh of energy annually, resulting in the release of 22 Mt of CO_2 into the atmosphere. As of March 2021, Bitcoin's energy usage was estimated to be 130 TWh, which would place it ahead of Argentina and Ukraine in terms of energy consumption if it were a country. While cryptocurrency mining relies on dedicated hardware rather than regular processors, and therefore does not compete directly with scientific computing, the magnitude of its carbon footprint needs to be addressed urgently.[2]

The energy used for Bitcoin mining comes from a variety of sources, ranging from renewable to non-renewable sources, and is largely produced from burning fossil fuels. As the demand for cryptocurrency increases, so does the energy consumption and associated emissions, making it a growing contributor to global GHG emissions. As more and more people use cryptocurrency, the need for more energy to fuel the mining process increases, creating a cycle of demand and supply. As more energy is consumed, more GHG emissions are released into the atmosphere, contributing to climate change. This cycle of demand and supply exacerbates the environmental impact of cryptocurrency, as more energy is consumed and emissions released into the atmosphere, further exacerbating the effects of climate change.

2.7 HPC Data Centers and Related Energy Consumption

2.7.1 HPC Data Centers

A data center refers to a collection of structures dedicated to centralized accommodation, interconnection, and operation of IT and network telecommunications equipment. These centers provide services such as data storage, processing, and transport, while also offering support facilities for power supply and environmental control. To ensure the desired service availability, data centers must also maintain the necessary levels of resilience and security.[1]

The unique infrastructure of a data center consists of three distinct areas: the IT room, the data center support area, and the ancillary spaces. The IT room is a controlled environment where computer and telecommunications equipment, which generates significant amounts of heat, is housed along with associated cabling. The IT equipment is highly sensitive to fluctuations in temperature and humidity, making it necessary for data centers to maintain strict environmental conditions to ensure the integrity and functionality of the hosted equipment. The data center support areas are where systems such as Uninterruptible Power Supplies (UPS), cooling control systems, and switchboards are located. The ancillary spaces, such as offices, lobbies, and restrooms, are separate areas from the IT and data center support areas.[30]

To provide high-quality services, an HPC data center must have the necessary infrastructure to accommodate the equipment required for delivering those services. However, such data centers are known for their high and constant energy consumption due to the need to energize the equipment 24/7 and support high-priority services with high availability. Therefore, uninterrupted energy support with the same service characteristics is essential to take advantage of hosted services. According to research, HPC data centers worldwide consume between 1 to 5% of the total global electricity usage.[31]

HPC data centers typically comprise multiple computing nodes, each consisting of multiple processing cores. These systems continue to grow in size and performance, raising concerns about their increased energy requirements. It is crucial to take measures to reduce this energy consumption.[32]

2.7.2 Current State of HPC Centers

In recent years, the matter of energy consumption in information technology equipment has garnered more attention, with a rising acknowledgment of the importance of managing energy usage throughout the entire information and communications technology (ICT) industry.[33]

Modern data centers are made up of three main components: data storage, servers, and a local area network (LAN). These centers connect to the rest of the network through a gateway router. Efficiency improvements in cloud computing data centers, such as sleep scheduling and virtualization of computing resources, have led to significant energy savings in these centers.[34]

In countries where broadband access is prevalent, the transmission and switching networks associated with the internet require a considerable amount of energy to operate. These networks are responsible for the distribution and switching of data packets between servers and endpoints, thereby facilitating communication between users. It has been estimated that these networks consume an additional 0.4% of the total electricity consumption in these countries.[35]

In a data center, long-term storage is provided by hard disk arrays and associated equipment, such as cache memories, disk array controllers, disk enclosures, and redundant power supplies. In a cloud computing data center, storage space is consolidated, and hard disk usage is centrally managed, which reduces the number of hard disks used, increasing energy efficiency. Additionally, infrequently accessed files are stored in capacity optimized hard disks that enter a low-power mode when not in use, consuming minimal energy. Therefore, in the analysis, power consumption for storage is attributed only to the files that are actively being accessed.[34]

As the number of servers and power consumption increases, along with the rising cost of electricity, the proportion of IT budget spent on data center expenses is expected to grow. Currently, large corporations are spending between 4-8% of their IT budget on electricity, and this percentage is projected to increase significantly in the near future. Without significant improvements in efficiency, companies with large data centers may face a decrease in profitability.[36]

The management of data centers is often divided between the IT department and the corporate real estate department within an organization. As a result, data center managers are often not held accountable for energy costs and their performance is typically measured based on their ability to maintain data center stability and meet the increasing demand of the organization, rather than energy efficiency.[36]

This is due to the fact that the IT department is focused on managing the technology side of the data center while the real estate department is focused on the day-to-day operations and maintenance of the physical space, such as cooling and power. As a result, the costs of energy consumption can be overlooked, leading to inefficiencies and higher energy costs. As a result, it is essential that the IT and corporate real estate departments collaborate to ensure optimal energy consumption and cost savings.

2.7.3 Cloud Computing

The IT industry has not yet arrived at a single, definitive definition of cloud computing, and ongoing debates persist regarding the potential range of services that may become available in the future.[37]

Cloud computing can be defined as a model that facilitates on-demand network access to a shared pool of configurable computing resources, which can be quickly provisioned and released with minimal management effort or service provider interaction. The concept allows for the efficient use of computing resources, reducing costs and increasing productivity for businesses and organizations. This technology has a broad scope of applications, making it a popular solution for various industries.[38]

Cloud computing provides a potential financial advantage by enabling end-users to share a centralized pool of storage and computing resources. Rather than owning and managing their own systems, they can access these resources on-demand, resulting in cost savings and improved resource utilization.[39]

End-users can also benefit from the convenience of accessing their data and services from any location, centralized management of data backups, access to additional capacity as needed, and usage-based charging models.[40]

Cloud service providers typically leverage existing data centers as a foundation and invest in the required infrastructure and management systems. In exchange, they receive a fee from end-users based on usage or time-based metrics.[41]

Cloud computing encompasses both the delivery of applications as services over the internet, and the hardware and systems software present in data centers that provide those services. The services themselves are commonly referred to as Software as a Service (SaaS). The data center hardware and software constitute what we refer to as a "cloud". When a cloud is available for public use on a pay-as-you-go basis, it is classified as a Public Cloud, with the service being sold termed as Utility Computing. Private Clouds, on the other hand, refer to internal data centers of businesses or organizations that are not available to the public.[42]

Although the potential energy savings associated with cloud computing have received some attention, the shift in energy usage has been largely overlooked. Cloud computing can reduce energy consumption in the delivery of computing and storage services by utilizing large, shared servers and storage units. This is particularly evident when end-users migrate to devices with lower capabilities and energy consumption. However, cloud computing also leads to increased network traffic and associated energy consumption, which must be taken into consideration.[43]

As technology advances, there has been a steady increase in the energy efficiency of equipment. With each new generation of technology, there have been significant improvements in the energy efficiency of servers, resulting in exponential gains over time.[44]

2.8 What is a green data center?

A green data center is a repository for storage, management, and dissemination of data in which mechanical, lighting, electrical and computing systems are designed for maximum energy efficiency and minimum environmental impact. Data centers are one of the organizations where the Greening process should begin. Green data center operations strategically align IT organization with sustainable organizational objectives to achieve greater corporate social responsibility. Some of the benefits of green data center include Lower server and Storage temperature and costs, increased system and storage reliability, density, and uptime, maximizes software and hardware utilization thus lowers energy use, increased environmental and business sustainability solutions, lower carbon emissions and limiting the effects of global warming and extending the life of data center.[45]

The green data center concept has become a reality, as IT leaders are tasked with building environmentally efficient data centers, either through new construction or retrofitting existing ones. A green data center is a highly dense, energy-saving computing environment, where software technologies regulate data growth and manage capacity requirements, managers implement Service Level Agreements to monitor energy consumption, computing infrastructure is optimized for energy efficiency and performance, and the physical structure is designed for maximum energy efficiency.[45]

Green IT, also known as Green Computing, is a method for making the use of power and production technology more environmentally friendly and cost-effective. It encompasses various concepts such as virtualization, cloud computing, outsourcing, recycling, and power management. The goal of Green IT is to increase energy efficiency in the use of IT devices and maximize the utilization of existing data center equipment. At the same time, organizations must meet the high reliability, performance, and availability requirements for delivering new IT services quickly to support business processes. To achieve these objectives, IT must have a well-defined Green IT strategy or framework that is aligned with the overall business strategy and goals. This strategy must be quickly and effectively translated into IT operational processes to ensure seamless alignment between business and IT in the most efficient manner.[45]

Recent advancements in hardware and software technologies, such as low-power processors, solid-state drives, and energy-efficient monitors, have helped to mitigate the issue of high energy consumption. Additionally, several software approaches have also significantly contributed to improving energy efficiency. Historically, power and energy-efficient resource management techniques were applied primarily to mobile devices due to their battery-powered nature and the need to extend their battery life. However, with the growing power and energy consumption of servers and data centers, the focus of power and energy management techniques has shifted to these systems.[45]

2.8.1 Green Computing

Green computing is a method of designing and operating computer systems with the goal of reducing their energy consumption and environmental impact. This can be achieved through various techniques, such as using energy-efficient components, implementing virtualization technology, and recycling waste materials. For example, utilizing power management techniques to reduce the overall power consumption of computer systems, or using renewable energy sources to power data centers. Additionally, implementing virtualization technology can help reduce the number of physical servers needed, which in turn reduces energy consumption and waste. And recycling waste materials from data centers can prevent pollutants from entering the environment.[46]

Virtualization can also offer several advantages for development tasks, including operating system development. By running the new system as a guest in a virtual environment, developers can avoid the need to frequently reboot the physical computer every time a bug or issue arises, which can save valuable time and resources. Additionally, virtualization provides a safe and isolated environment for testing and experimentation, allowing developers to test new software and configurations without affecting the underlying physical system. This can lead to faster and more efficient development processes, as well as improved system stability and reliability.[47]

To effectively measure the progress and performance of these efforts in data centers, specific metrics, or evaluation criteria, are used. These green performance metrics for data centers can be either qualitative or quantitative measures of the environmental effects of data center operations. For example, measuring the power usage effectiveness (PUE) of a data center, which compares the total amount of power used by the data center to the amount of power used by the IT equipment, can provide a quantitative assessment of the data center's energy efficiency. Additionally, measuring the carbon footprint of a data center, which calculates the total amount of carbon emissions produced by the data center's operations, can provide a qualitative assessment of the data center's environmental impact. These metrics can help data center operators to track their progress towards more energy-efficient and sustainable operations.[46]

Green computing helps to minimize the environmental impact of IT systems by ensuring that the data centers use energy-efficient hardware and software, as well as by encouraging the adoption of renewable energy sources for powering the data centers. It also helps to reduce the amount of waste generated by IT systems, such as electronic waste from old hardware. Green computing also encourages the use of virtualization technologies, which reduces the amount of hardware needed to run applications. It also encourages the use of cloud computing services, which reduces the energy and other resources used to store and process data. Additionally, green computing encourages the use of recyclable materials for new hardware and the reuse of old hardware whenever possible.[4]

2.9 Thermal Management Systems

Due to the growing need for ICT services and the correlation between data center expenses and floor space, manufacturers have developed and manufactured smaller, high-powered modules. Compared to traditional data centers, which typically dissipate an energy flux ranging from 430-861 W/m^2, the latest generation of data centers are capable of dissipating energy fluxes that are at least 10 times higher, ranging from 6458-10,764 W/m^2.[48]

Data centers have a much higher energy dissipation range compared to the capacity of conventional HVAC systems for similarly sized rooms (40–86 W/m^2), which poses a significant challenge in designing and manufacturing thermal management systems. These systems must be capable of handling increasing thermal loads and maintaining safe operating temperatures for electronic components. Accurate and reliable information about maximum thermal loads and temperature limits for each component in a data center is crucial to designing an effective thermal management system and for waste heat recovery purposes.[49]

Proper cooling of a data center is essential to ensure the availability and reliability of IT equipment. With the continuous advancements in the microprocessor industry, the number of transistors and clock rates are increasing, resulting in a significant rise in heat dissipation density. This high heat density can lead to elevated junction temperatures, which can adversely impact the reliability of IT components. In fact, high temperatures are the primary cause of component failure.[50]

With the continued expansion of the data center market and the advent of server components with higher power density, it is anticipated that the proportion of electricity consumed by data centers will continue to rise in the foreseeable future. Estimates suggest that annual increases in data center power demand could reach as high as 15 to 20 percent. Therefore, there is a growing need to explore sustainable practices and energy-efficient solutions that can help minimize the environmental impact of data centers while also ensuring their continued growth and functionality.[51]

Not only has the number of data centers grown, but so has their size, floor area, and computing density. The data center industry operates on a diverse range of scales, with the creation of massive data centers that can have floor areas of approximately 9000 square meters and house thousands of server racks, consuming several megawatts of power. At the same time, there has been an increasing trend towards the development of compact data centers, which can house more computing power in smaller spaces.

The construction costs and annual operating costs for a typical data center are estimated to be around \$15,000 and \$1500 per square meter, respectively.[52]

The high-power consumption of servers results in a significant amount of heat generation, which can cause severe problems if not appropriately managed. Therefore, data centers need to use cooling systems to regulate the temperatures of the server racks to avoid damage to the IT equipment. However, cooling also consumes a considerable amount of energy, leading to high operational costs and an increased carbon footprint. To address these concerns, researchers are exploring various techniques to reduce energy consumption in data centers. One approach is dynamic need-based resource allocation, which involves allocating resources based on the current workload demands of the system. By dynamically adjusting the resources, it is possible to optimize energy usage while maintaining performance and reliability. This approach has the potential to significantly reduce energy waste and associated costs in data centers, making them more environmentally sustainable and financially viable.[53]

Data centers today often utilize servers with extremely high power densities, exceeding 100 W/cm^2, and in some cases reaching as high as 200 W/cm^2. Consequently, the heat dissipation requirements for a rack with a 0.65 m^2 footprint can reach up to 30 kW, which is around 30 times higher than what was required by a typical rack of the same size back in 1990. This dramatic increase in heat generation poses a significant challenge for data center operators, as it necessitates the use of sophisticated cooling systems to maintain safe operating temperatures for the IT equipment. It also highlights the need for continuous innovation and improvement in energy efficiency to reduce operational costs and minimize the carbon footprint of data centers.[54]

A common layout for data centers involves organizing the racks and perforated floor tiles in a raised floor setup, with a hot-aisle/cold-aisle arrangement. The cooling system, which can be a Computer Room Air Conditioner (CRAC) or Heating Ventilation Air Conditioner (HVAC), releases cold air underneath the elevated floor, which flows through the racks from the front side. As it passes through the racks, the cool air absorbs heat and exits from the back of the racks. The hot air forms hot aisles behind the racks and is removed back to the air conditioner intakes, which are often located above the hot aisles. Each rack contains multiple chassis, with each chassis hosting several computational devices such as servers or networking equipment.[55]

In the context of High-Performance Computing (HPC), servers are often engaged in long-term tasks that can last for hours or even days. For instance, some simulation of a new design may involve running the simulation on hundreds of servers in parallel for multiple days. If a data center has 2000 processors, a task that requires 10% of the data center's capacity would involve a task size of 200, and 200 processors would be needed to execute the task at hand.

When power consumption distribution changes in closed environments like data centers, it takes approximately 10 to 20 minutes for the temperature distribution to reach a new steady state.[56]

To understand the cooling effect on the energy consumption of data centers, we can divide the power consumption into two main components: the computing energy cost, which includes energy usage by computing and networking devices, and the cooling energy cost. The computing power consumption, represented as P_c.[55]

$$P_c = \sum_{i=1}^{n} P_i. \qquad (2.1)$$

Where P_c - computing power consumption, W

n - number of computing nodes

P_i – power consumption of node i

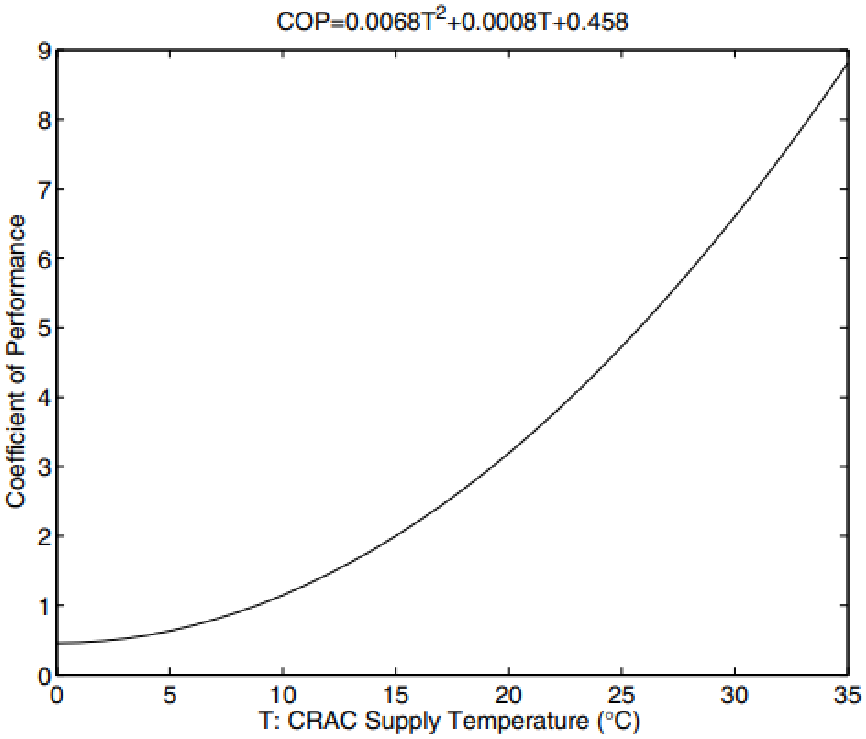

Figure 2-2 Coefficient of performance curve for the chilled-water CRAC units at the HP Labs Utility Data Center.[55]

The cooling energy cost or consumption where T is CRAC Supply Temperature (°C) can be described as: [57]

$$P_{AC} = \frac{P_c}{CoP(T)}, \quad (2.2)$$

Where P_{AC} – Cooling Power Consumption, W

P_c – Computing Power Consumption, W

CoP - Coefficient of performance

T – CRAC Supply Temperature °C

The CoP is a measure of the efficiency of the air conditioning system and is defined as the ratio of the amount of heat removed by the cooling device to the energy consumed by the device. The Coefficient of Performance (CoP) model is represented in Figure 2-2. The data for this model was gathered from a water-chilled Computer Room Air Conditioner (CRAC) unit located in the HP Utility Data center. The equation for the CoP model is given as:[57]

$$CoP(T)= (0.0068T^2 +0.0008T +0.458) \quad (2.3)$$

The CoP(T) function depends on the temperature T of the supplied cold air. It is important to note that the CoP does not vary linearly, and generally increases as the temperature of the supplied air increases. Therefore, running the cooling system at a higher temperature can save energy. This is because providing colder air requires the cooling device to work harder, consume more energy, and remove more heat from the supplied cold air.[55]

Therefore, to minimize P_{AC}. we need to maximize the temperature of the supplied cold air (T). The total energy consumption of operating a data center can be defined as:[55]

$$P_{Total} = P_{AC} + P_c \quad (2.4)$$

It is crucial to recognize that cooling significantly contributes to the overall power consumption of the HPC center. Hence, it is imperative to consider the impact of cooling when analyzing and managing the power demands of the center.

3 METHODOLOGY

3.1 TalTech High-Performance Computing Center

TalTech HPC Centre is located at TTÜ Infotehnoloogia Maja (ICT), Akadeemia tee 15a, basement floor and is responsible for creating and overseeing the computing resources that are utilized for scientific purposes. In addition to managing a pair of computing clusters as well as a cloud infrastructure.[58]

The resources of the HPC center are comprised of four essential components that offer diverse solutions to meet the varying needs of its users. These components are continuously evolving and expanding to enhance their capabilities:[58]

1. The HPC2 cluster is the newest computing cluster which was installed in 2019. The SLURM cluster manager is used to manage computer jobs on this cluster. Each node on the HPC2 cluster is equipped with 2 x Intel Xeon Gold 6148 2.40 GHz processors, providing a total of 40 cores and 80 threads per node, along with 96GB of RAM, 25 Gb/s Ethernet, and 800GB of local scratch space. Nodes hpc2node1 through hpc2node18 are connected to the FDR InfiniBand interconnect. Additionally, there is 20TB of shared storage available.[58]

2. The GPU server has two AMD EPYC 7742 processors per server, providing a total of 128 cores and 256 threads per server. Additionally, the server is equipped with 8 Nvidia A100 GPUs, 1TB of memory, and 100Gb/s Ethernet connectivity.[58]

3. The HPC1 cluster was initially installed in 2013 with 232 nodes, of which approximately 100 nodes are still in operation. Each node on the HPC1 cluster features 2 x Intel Xeon E5-2630L processors, providing reliable performance. In addition, each node comes equipped with 48GB of RAM and 800GB of local scratch space available. The cluster also has 146TB of shared storage. Forty-eight nodes are connected to high-speed connection, which ensures fast data transfer speeds. The HPC1 cluster also features a large memory node with 1TB of RAM, which can be accessed via the SLURM mem1tb partition. Additionally, there is a GPU server available on this cluster with 2 Nvidia Tesla K20Xm GPUs. This server can be utilized as a Visualization node.[58]

4. The OpenStack Cloud is a cloud computing service that is available to users. The cloud service consists of four compute nodes that allow users to create and

manage virtual machines and other cloud-based resources. In addition, the cloud service offers 65TB storage.[58]

3.2 Utilizing Estonian GHG model to evaluate organization's emissions.

The GHG calculation model is a useful tool for organizations looking to assess and understand their greenhouse gas emissions. It is based on the most commonly used international methodological guidelines and standards established by the Greenhouse Gas Protocol. These guidelines and standards provide a standardized approach for organizations to measure and track their emissions, allowing for consistent and comparable results.[59]

At the same time, the model takes into account the specific conditions and assumptions that are specific to Estonia. This helps to create a harmonized methodological basis and data for Estonian organizations to calculate their carbon footprint. This approach makes it easier for Estonian organizations to understand and compare their emissions to other organizations within the country. The model can be used by any organization, including both public, private and non-profit entities, who want to assess their GHG emissions at the organizational level. However, it should be noted that the model is intended to be universal and includes the most commonly used categories of activities and emissions sources. Therefore, organizations may need to adapt the model to include additional activities or emissions sources that are specific to their operations.[59]

The guidance provided by the Ministry of the Environment includes an Excel-based calculation model, which organizations can use to assess their greenhouse gas emissions. The model comes with emission factors and detailed instructions on how to input activity data into the automated spreadsheets. Organizations can use the model as is, or they can tailor it to meet their specific needs. This model allows organizations to accurately measure their GHG emissions. It also provides them with the data they need to set reduction targets, develop a reduction plan, and track the progress they have made over time. It is also a cost-effective way to manage GHG emissions. The calculation model is available on the Ministry of the Environment website.[59]

3.3 Defining organizational and operational boundaries.

3.3.1 Organizational boundaries

Companies have the option of using two different methods, the equity share and control approaches, when consolidating their greenhouse gas emissions for corporate reporting. The company is expected to report their consolidated GHG data according to one of the two approaches.[23]

If the reporting company fully owns all its operations, the organizational boundary will remain the same regardless of the approach selected. For companies with shared operations, the organizational boundary and resulting emissions may vary depending on the chosen approach. Both wholly owned and joint operations may see a change in how emissions are categorized when operational boundaries are set, depending on the approach selected.[23]

The operational control is when a company has operational control over an operation if the company or one of its subsidiaries has full authority to introduce and implement its operating policies at the operation. This criterion aligns with the current accounting and reporting practices of many companies that report emissions from facilities they operate, such as holding the operating license. It is expected that in most cases, if the company or one of its subsidiaries is the operator of a facility, it will have operational control.[23]

The control approach to consolidating GHG emissions requires companies to account for 100% of the emissions from operations over which they have control. Emissions from operations in which the company has an interest, but no control are not included. Control can be defined in terms of financial or operational terms, and companies must choose between the operational control or financial control criteria.[23]

Given that the HPC center is a part of Tallinn Technical University, it would be appropriate to use the operational control approach. This is because as a self-managed organization, the HPC center has complete autonomy and control over its usage policy, energy consumption, working hours, and the ability to add or remove new machines in the data center. This means that the HPC center has the full authority to introduce and implement its operating policies, making it a perfect fit for the operational control approach. Furthermore, this approach aligns well with the current accounting and reporting practices of many companies that report emissions from facilities they operate, such as holding the operating license. This approach captures the HPC center's operational control over the data center and its emissions, giving a more accurate and comprehensive picture of the greenhouse gas emissions.

3.3.2 Operational Boundaries

The determination of the operational boundary, including scope 1, scope 2, and scope 3 emissions, is established at the corporate level after the organizational boundary is defined. This chosen boundary is then consistently implemented across the organization to identify and classify direct and indirect emissions at every operational level. In this particular case study, the main focus of the calculation is on the server room emissions.[23]

Companies report their greenhouse gas (GHG) emissions from sources they own or control as "scope 1" emissions. These emissions primarily come from activities such as generating electricity, heat, or steam through the combustion of fuels in stationary sources, physical or chemical processing of materials, transportation of materials, products, waste and employees using company-owned/controlled mobile combustion sources, and fugitive emissions from equipment leaks, methane emissions from coal mines and venting, HFC emissions from refrigeration and air conditioning equipment, and methane leaks from gas transportation.[23]

Since High-Performance Computing (HPC) operations do not involve activities mentioned above we can exclude "scope 1" emissions from the calculation of the HPC's greenhouse gas (GHG) footprint. This means that we will not consider emissions from these sources when determining the overall environmental impact of our HPC operations.

Companies report the emissions from purchased electricity that is used in their operations as "scope 2" emissions. These emissions are a type of indirect emissions, which can represent a significant proportion of a company's total greenhouse gas (GHG) emissions. By accounting for scope 2 emissions, companies can evaluate the risks and opportunities associated with changes in electricity and GHG emissions costs also companies can also use this information to inform their business decisions, such as investing in renewable energy sources or switching to a more energy efficient manufacturing process. Additionally, accounting for scope 2 emissions allows companies to understand their overall environmental impact and identify areas for improvement.[23]

In our study, we will focus on the energy consumption of the server room in the HPC center, as it is the most power-consuming aspect of the HPC structure. We will be disregarding the energy consumption of the office space where the HPC administration team works, as it is significantly lower compared to the server room. We will be tracking the energy consumption of the server room, which houses the machines that are used on a daily basis, as it holds the majority of the HPC's energy consumption.

Scope 3 emissions, also known as other indirect greenhouse gas (GHG) emissions, are optional for companies to report. Companies may choose to focus on accounting and reporting those activities that are relevant to their business and goals, and for which they have reliable information.[23]

In this study, we will be focusing on the power consumption of the machines in the HPC center from a computing consumption perspective. Therefore, we will be disregarding scope 3 emissions, in order to have a more direct and clear understanding of the energy consumption of the machines in the HPC. This will enable us to make comparisons with other HPCs in case the need arises, by taking into account the number of machines they have and the amount of energy they consume as depicted in Figure 3.1 below.

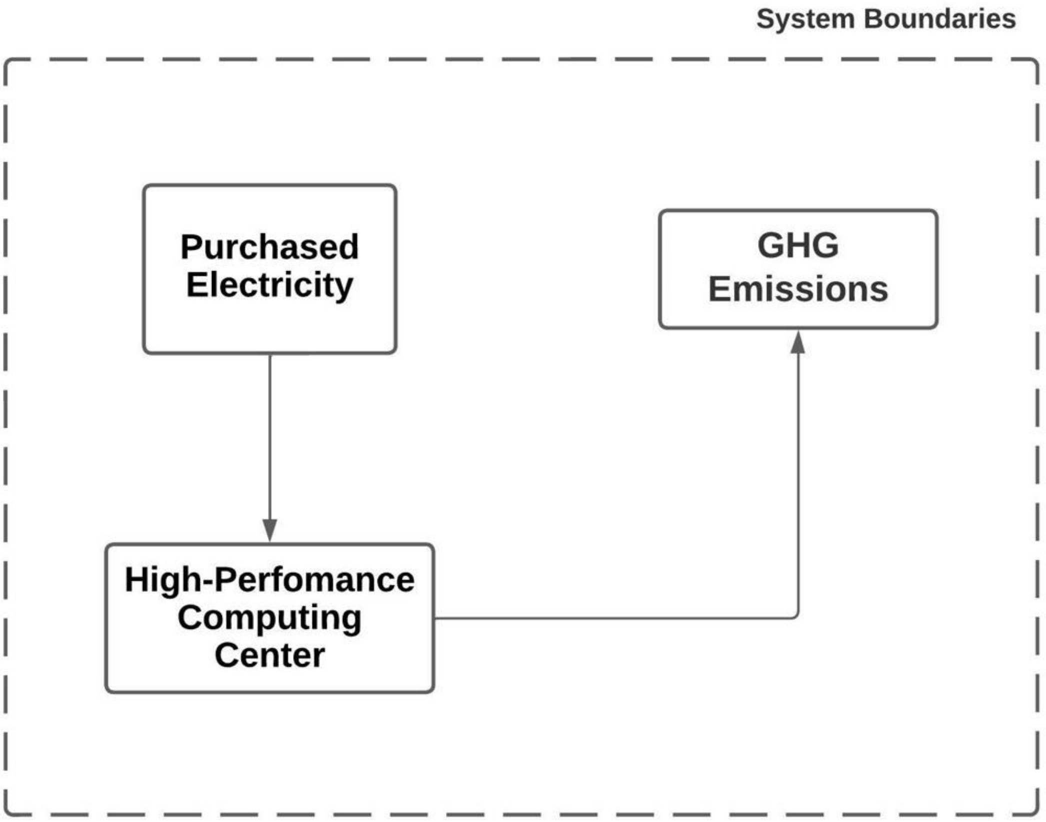

Figure 3.1 System Boundaries

3.4 Data Collection

The data for greenhouse gas (GHG) emissions can be collected through different methods such as direct on-site measurements or estimations based on emission factors and models. The choice of method depends on factors such as the objective (mandatory, voluntary, or for internal management), credibility, feasibility, cost, and capacity.[21]

As the energy consumption in data centers continues to increase, efforts to improve their operational efficiency have become more widespread. This has led to the development of many common metrics and methods for assessing performance in data centers. Currently, most metrics focus on the efficient use of individual resources during the operation of a data center, which can be useful for interpreting and reducing the operational energy consumption expenditure.[60]

Data centers that provide web services or cloud computing often consist of thousands of nodes. Every watt saved on each machine can make a significant impact on energy consumption. In 2008, the global consumption for data centers was estimated to be 29 GW and it has been growing at a rate of 12% annually. It is projected that by 2020, the global consumption of data centers will reach 113 GW.[61]

3.4.1 List of Equipment in the High-Performance Computing Center

In order to meet the demanding computing requirements of its users, the High-Performance Computing (HPC) center houses a range of state-of-the-art computing equipment. These machines are designed to deliver the high levels of performance, reliability, and scalability that are essential for cutting-edge research and analysis. The following is a list of the computing equipment currently in use at the HPC center:

1. Cluster Supercomputers: These high-performance systems are designed for parallel computing and can handle large amounts of data and complex computations.

2. Servers: The HPC center operates a fleet of servers that are optimized for high performance and reliability. These servers are used to manage the network, store and process data, and run applications.

3. Storage Systems: To support the large amounts of data generated by the HPC center, a range of high-capacity storage systems are used to store and manage the data. These systems are designed for high performance, scalability, and reliability.

4. Networking Equipment: The HPC center is equipped with advanced networking equipment, including switches, routers, and other devices that are essential for maintaining high-speed and reliable network connections.

By investing in the latest computing equipment, the HPC center is able to provide its users with the tools they need to conduct cutting-edge research and analysis. This, in turn, helps to drive advances in science, technology, and other areas of study, while supporting the critical work of the HPC center.

Below Table 3.1 detailing the equipment used in a High-Performance Computing (HPC) center:

Table 3.1 HPC Center Equipment.

No.	**Machine Type**	**Quantity**	**Specification**
1	Gray Nodes	48	2 x Intel Xeon E5-2630L 6C with 64 GB RAM and 1 TB local drive, 1 Gbit Ethernet, QDR infiniband
2	Green Nodes	32	2 x Intel Xeon Gold 6148 20C 2.40 ghz, 96 GB DDR4-2666 R ECC RAM, 25 Gbit Ethernet, 18 of these FDR infiniband
3	AMP1	1	CPU: 2x AMD EPYC 64core, RAM: 1 TB ,gpus: 8x A100 Nvidia 40GB with 128 cores 256 threads
4	AMP2	1	CPU: 2x AMD EPYC 7713 64core (3rd gen EPYC, Zen3), RAM: 2 TB, gpus: 8x A100 Nvidia 80GB and 128 cores 256 threads
5	Nova Nodes	5	768GB of RAM and 80 threads each
6	CephFS Storage	1	65 TB net capacity storage
7	Visualization Node	1	2x nvidia Tesla K20Xm grapic cards
8	IBM GPFS Machine	1	1.5 PB net capacity storage

9	Air conditioner	1	Used to cool down the server room.
10	Liquid cooling	1	Liquid Cooling as the main Cooling Device for the computing machines.
11	Uninterruptible power supply (UPS)	1	Emergency power to a load when the input power source or mains power fails
12	Networking switches	8	Used to connect all the machines with each other.

In our study, we will use ZABBIX to monitor and store statistical data on power consumption for the entire server room in the HPC center, including energy consumption of the machines and cooling systems. ZABBIX readings are taken on daily basis with constant intervals and then stored in a database with a timestamp for each reading. We will present data recorded in 2022 as our base year for tracking and estimation over time, by displaying a graph for each month of the year.

The data collected from Zabbix over a 12-month period was analysed. This representation of the data allowed for an effective comparison of the values across the entire period and provided an understanding of the trends and patterns in the data. The presentation of the data added valuable insights into the study.

3.4.2 Monthly Power Consumption Data

The data displayed in the figures provide valuable insights into the power consumption trends over the year and allows for identifying any fluctuations or deviations from the average. The figures are available in Appendix 1. Table 3.2 summarizing the readings from the graphs:

Table 3.2 Power Consumption Readings

Month	**Average Power Consumption Reading (KW)**
1-2-2022 to 28-2-2022	35.06
1-3-2022 to 31-3-2022	36.76
1-4-2022 to 30-4-2022	33.84
1-5-2022 to 31-5-2022	37.56
1-6-2022 to 30-6-2022	39.95
1-7-2022 to 31-7-2022	36.11
1-8-2022 to 31-8-2022	29.88
1-9-2022 to 30-9-2022	28.65
1-10-2022 to 31-10-2022	34.9
1-11-2022 to 30-11-2022	34.87
1-12-2022 to 31-12-2022	32.43
1-1-2023 to 1-2-2023	30.51
Total	**410.52**

3.4.3 Aggregated Annual Power Consumption Data

The following graphs represent the readings of the minimum, maximum, and average values of power consumption over a one-year period, starting from February 1, 2022, to February 1, 2023.

The X-axis represents time (Month), and the Y-axis represents the power consumption values in units of energy (KW). The green line represents the average power consumption over the year, blue the red and red lines represent the minimum and maximum power consumption, respectively.

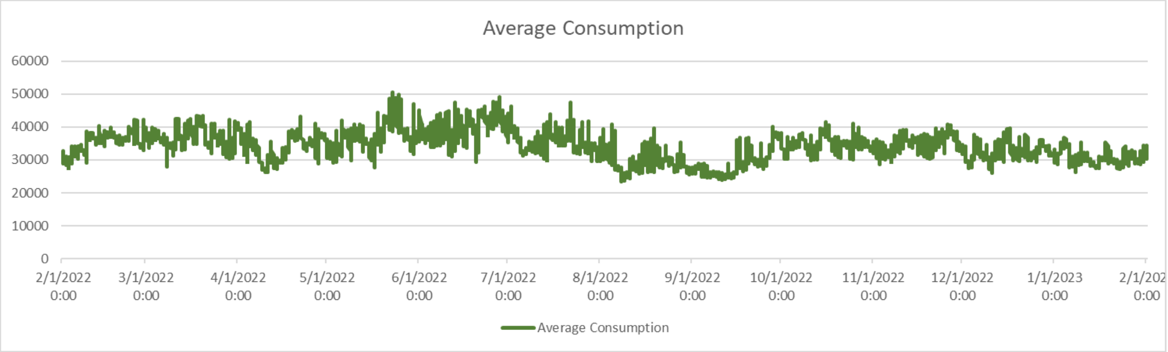

Figure 3.14 Average Power Consumption 1-2-2022 to 1-2-2023

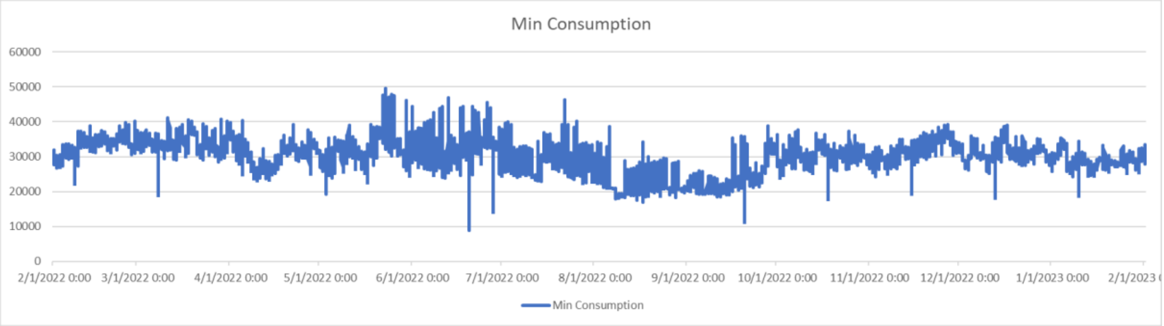

Figure 3.15 Minimum Power Consumption 1-2-2022 to 1-2-2023

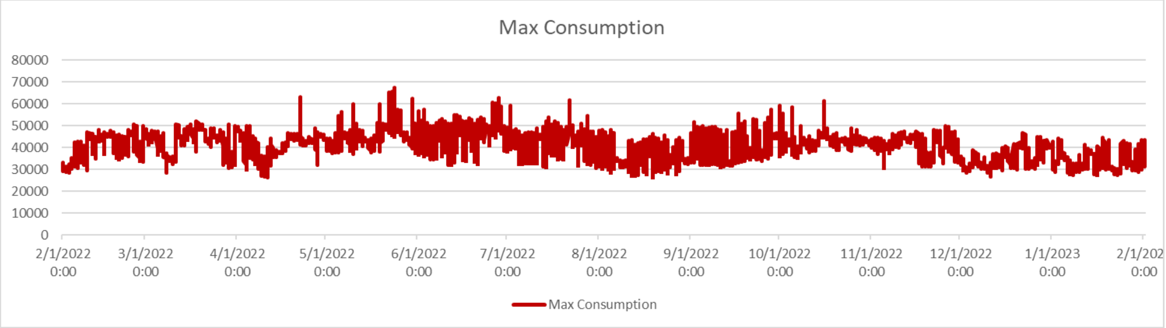

Figure 3.16 Maximum Power Consumption 1-2-2022 to 1-2-2023

3.5 Identifying and Quantifying Uncertainties in Data Collection and Calculation Process

3.5.1 Current Challenges in Data Collection

Measuring the carbon footprint of data center operations can be challenging for several reasons:

1. Data centers often have shared infrastructure and support, making it difficult to accurately calculate the CO_2 emissions produced by a specific application, user, or computing server.

2. The CO_2 emissions produced by a data center are affected by multiple factors, such as the data center's energy efficiency and the sources of energy used. These factors make it difficult to measure the carbon footprint of data center computing with a high degree of accuracy.

As the data for the GHG calculations at the HPC center is sourced exclusively from the Zabbix database, it is crucial to thoroughly examine the uncertainties involved in data collection. This includes a deep exploration of the potential sources of error or inaccuracies. By taking this approach, the HPC center can proactively address any issues with the data collection process, ensuring the accuracy and reliability of the GHG calculations:[62]

> Measurement errors: These can occur due to factors such as the precision of the monitoring equipment, the environment in which the measurements are taken, or the accuracy of the sensors used. For example, if the monitoring equipment is not properly calibrated, readings may be skewed, leading to inaccurate results. Additionally, if the environment is not stable, such as if there are temperature or humidity fluctuations, the readings may be affected.
>
> Data quality issues: Data quality can be affected by factors such as missing data, incorrect data, or corrupted data. For example, if the data transmission process is interrupted, some data may be lost, leading to gaps in the data set. Additionally, incorrect data can be entered during the data collection process, leading to inaccurate results.
>
> Calibration issues: Monitoring equipment may need to be calibrated regularly to ensure accurate readings. If the equipment is not calibrated properly, readings may be inaccurate. Calibration should be performed by trained personnel and should be done according to established protocols.

Data processing errors: Data processing errors can occur during data entry, data cleaning, data aggregation, or data analysis. For example, incorrect formulas or calculations can lead to incorrect results. Additionally, errors can occur during data entry, such as incorrect data values or incorrect data type assignments.

Human errors: Human errors can occur at any stage of the data collection and calculation process, such as incorrect data entry, misinterpretation of results, or incorrect calculation formulas. To minimize human errors, it is important to have clear procedures and guidelines in place and to regularly review and validate the data and results.

3.5.2 Enhancing Current Data Collection Methods.

To ensure the accuracy and quality of the Greenhouse Gas (GHG) calculations for the High-Performance Computing (HPC) center, it is imperative to establish a series of processes and procedures for data collection. This will involve a thorough review of current methods to identify areas for improvement, as well as the implementation of new techniques and technologies to increase the reliability and accuracy of the data. In order to achieve this goal, the following steps should be taken:

1. Develop a comprehensive data collection plan, including clear guidelines and protocols for data collection and management.

2. Evaluate and assess the current methods of data collection and identify areas where they can be improved or enhanced.

3. Implement new tools and technologies to automate and streamline data collection, reducing the risk of human error and improving accuracy.

4. Train staff and stakeholders on the proper use of these new tools and technologies to ensure that data collection is conducted in a consistent and standardized manner.

5. Regularly monitor and assess the effectiveness of these processes, making adjustments as necessary to maintain the quality of the data collected.

By taking these steps, the HPC center can be confident that its GHG calculations are based on high-quality, reliable data, and that they will be well-positioned to accurately assess and report on their GHG emissions in the coming years.

3.6 Power Usage Effectiveness (PUE)

The original concept of PUE was centered on the power consumed by IT equipment and the power utilized by facility systems/components that support the IT equipment and the computer room. Power is generally measured in kilowatts (kW) and is used during design stages, offering an instantaneous measurement of power drawn at a specific point in time. Energy, on the other hand, is the product of power (kW) consumed over time by any equipment, and it is measured in kilowatt-hours (kWh).[63]

To comprehend PUE, it is crucial to distinguish between the different types of equipment in a data center based on their function or purpose. These can be classified into two primary categories:[63]

- IT Equipment and Site Infrastructure systems. IT Equipment comprises all the Information Technology and Communication Equipment that the data center serves.[63]
- Site Infrastructure encompasses all the facility systems/components that provide support to IT Equipment.[63]

Power Usage Effectiveness (PUE) is a metric that represents the energy efficiency of a data center, focusing primarily on the energy consumption of computing equipment, excluding cooling and other overheads. It has gained international recognition as a standard for assessing the power efficiency of data centers and is defined as follows:[64]

$$PUE=\frac{Engergy_{DC}}{Engergy_{IT}} \qquad (4.2)$$

Where $Energy_{IT}$ – Power Consumption of IT Equipment, W

$Energy_{DC}$, Total Power Consumption, W

$Energy_{IT}$ represents the power consumption of IT equipment in a data center, including servers, network equipment, storage units, peripherals, and all devices responsible for managing, processing, storing, or routing data. $Energy_{DC}$ refers to the total power consumption of a data center, encompassing both the power consumed by IT equipment and the infrastructure, which includes power supply systems, lighting systems, and air conditioning and cooling systems. The lower the PUE value for a data center, the greater its energy efficiency. An ideal PUE of 1.0 indicates that all energy consumption is allocated solely to IT equipment.[64]

A higher PUE value indicates lower efficiency for the facility, as it consumes more "overhead" energy to power the electrical load. The ideal PUE value of 1 signifies maximum achievable efficiency with no overhead energy consumption. However, this is currently unattainable due to the electricity used by UPS, fans, pumps, transformers, lighting, and other auxiliary equipment, in addition to the IT load consumption.[65]

According to [66] research paper which evaluated, analyzed, and presented the current trends in energy consumption and efficiency in data centers in the European Union using data submitted by companies participating in the European Data Center Energy Efficiency Code of Conduct program. They collected detailed information from 289 out of 325 data centers. Their method incorporated various types of data, including building information, operational data, IT measurements, and power data. Building information included data center type, building type, building area, construction date, and location, while operational data consisted of rated IT load, temperature, and relative humidity set points, and mechanical system type.[64]

Based on the research findings, the average PUE can be determined to be 1.80. This value can be applied to the TalTech High-Performance Computing (HPC) center, as demonstrated in the result section below.[64]

By utilizing the PUE concept, we can estimate the carbon footprint of each category of equipment, which can guide us in reducing the total carbon footprint of the HPC center. This can be achieved by implementing reduction measures tailored to each type of equipment, whether it falls under IT equipment or site infrastructure.

PUE provides an estimate of the energy consumption of a data center facility by comparing it to the energy consumption of IT equipment. It indicates the data center facility's energy usage in terms of multiples of IT equipment energy consumption. This enables a fair comparison by contrasting the energy consumption of IT equipment against that of the site infrastructure, which is designed to offer various services (cooling, power, lighting, security, etc.) to the IT equipment and support the data center's mission. Consequently, the data center industry has been striving to benchmark every data center, showcasing technologies and design approaches that improve data centers with PUE in focus. However, PUE is primarily intended for measuring performance improvements within a data center rather than comparing different data centers.[63]

As a metric for data center site infrastructure, PUE takes into account the energy consumption of:[63]

- Mechanical/cooling systems (chillers, condensing units, humidifiers/dehumidifiers, etc.)
- Electrical systems (UPS technology, power distribution, generators, transformers, etc.)
- Security systems (fire protection, EAC, intruder detection systems, etc.)
- Lighting systems
- Ancillary systems (monitoring technologies, SCADA, etc.)

It can be confidently stated that PUE is a metric associated with data center site infrastructure. The more emphasis placed on optimizing site infrastructure for energy efficiency, the greater the impact will be reflected in the PUE value. PUE can be considered the most effective method for obtaining an initial impression or preliminary understanding of a data center's energy efficiency.[63]

4 RESULTS AND DISCUSSIONS

4.1 Overview of the model results

4.1.1 Applying Collected Data to The Estonian GHG Model for Calculation of Emissions

Table 4.1 presents the results of the application of the Greenhouse Gas (GHG) Protocol model to monthly CO_2 emissions data. The GHG Protocol is a widely recognized tool for quantifying and managing an organization's greenhouse gas emissions. It also provides a comprehensive overview of the monthly CO_2 emissions and the corresponding environmental impact. By comparing the results of different months, one can identify trends and patterns in the CO_2 emissions and identify opportunities for improvement.[67]

Table 4.1 GHG Model Results

Month	**Power Consumption Reading (KW)**	**Total Power Consumption (KWh) = KW*24 Hours*No. of Days**	**Emission Factor*** **(kg CO_2 eq/kwh)**	**Carbon Footprint (Ton CO_2eq) =Total Power Consump.*Emission Factor/1000**
1-2-2022 to 28-2-2022	35.06	23560.32	0.637	15.00
1-3-2022 to 31-3-2022	36.76	27349.44	0.637	17.41
1-4-2022 to 30-4-2022	33.84	24364.8	0.637	15.51
1-5-2022 to 31-5-2022	37.56	27944.64	0.637	17.79
1-6-2022 to 30-6-2022	39.95	28764	0.637	18.31

1-7-2022 to 31-7-2022	36.11	26865.84	0.637	17.10
1-8-2022 to 31-8-2022	29.88	22230.72	0.637	14.15
1-9-2022 to 30-9-2022	28.65	20628	0.637	13.13
1-10-2022 to 31-10-2022	34.9	25965.6	0.637	16.53
1-11-2022 to 30-11-2022	34.87	25106.4	0.637	15.98
1-12-2022 to 31-12-2022	32.43	24127.92	0.637	15.36
1-1-2023 to 1-2-2023	30.51	22699.44	0.637	14.45
Total	**410.52**	**299607.12**		**190.72**

*Please note that the emission factor was calculated by the Estonian GHG model which is based on the system used by Elering company to determine the source of electricity consumed in Estonia.[67]

The following graphs depict the carbon footprint of each month, showing the amount of carbon emissions produced during the year of study. The graphs represent the data in a visual format, making it easy to understand and compare the carbon footprint of each month. The y-axis shows the carbon emissions in metric tons, while the x-axis displays the months of the year. The height of each bar corresponds to the carbon footprint for that particular month.

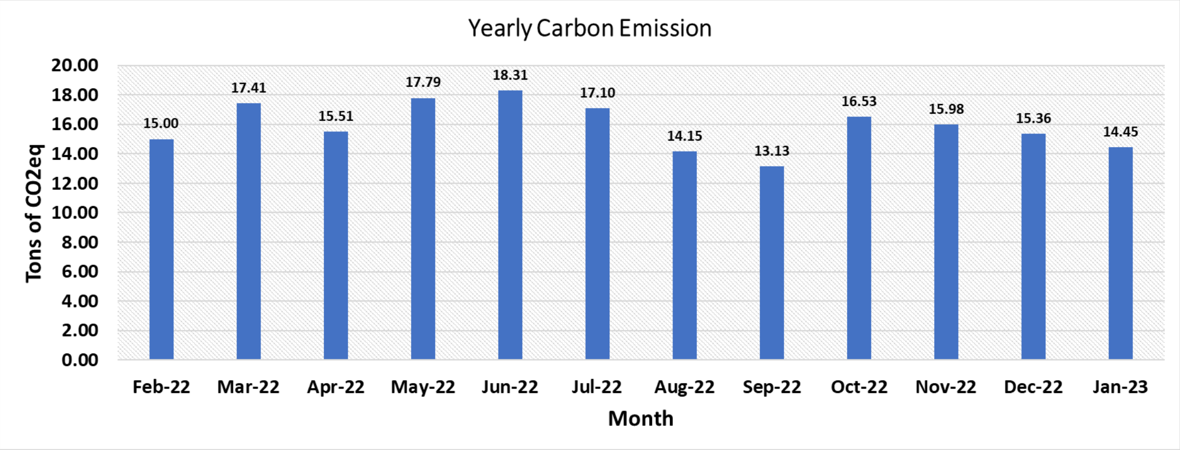

Figure 4.1 Yearly Carbon Emissions

The observed graph depicts variations in emissions over the course of a year, which can be attributed to two primary factors. Firstly, fluctuations in temperature necessitate changes in cooling power consumption, which can impact emissions. Secondly, the volume of computing jobs submitted by users varies throughout the year, leading to changes in the number of active machines’ power consumption and therefore emissions. These factors contribute to the observed fluctuations in emissions over time.

4.1.2 Differentiating between IT Equipment and Other Equipment Using PUE under the Estonian GHG model

Using PUE (Power Usage Effectiveness) to analyze the power consumption data of TalTech HPC center, we can distinguish between the energy consumed by IT equipment or machines and the energy used by the rest of the site's infrastructure such as cooling.

The approach used in “Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency”[66] research involves comparing the PUE to different factors like facility size, construction year, and rated IT electrical load. The calculation of the PUE value relies on accurate data regarding the energy consumption of 289 of 325 data centers all over Europe. According to research findings the Average PUE is 1.8 and that is the value we are using in our calculation.[64]

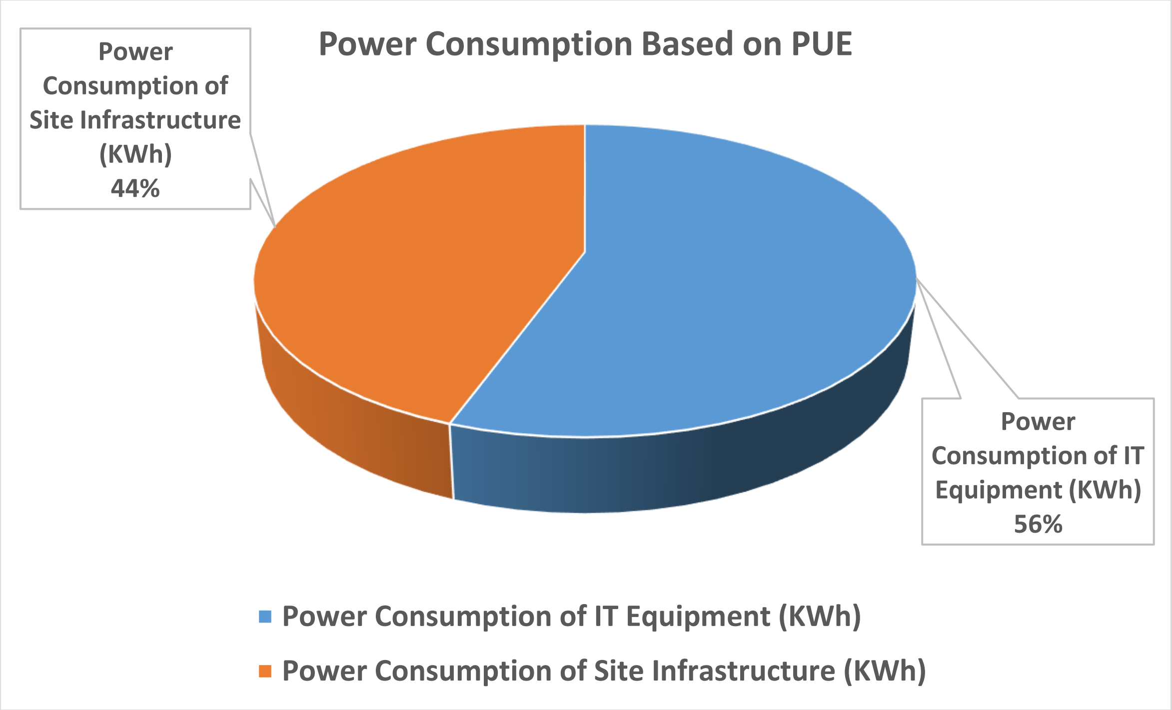

Figure 4.2 Power Consumption based on PUE under the Estonian GHG model.

By identifying the sources of energy consumption, PUE can be utilized to enhance data center energy consumption by not only assessing the current energy consumption situation but also setting future goals and tracking progress easily.[72]

In light of the new values above, we can now determine the carbon footprint of each component within the two primary categories of equipment at the TalTech High-Performance Computing (HPC) center. Shown in figure 4.3.

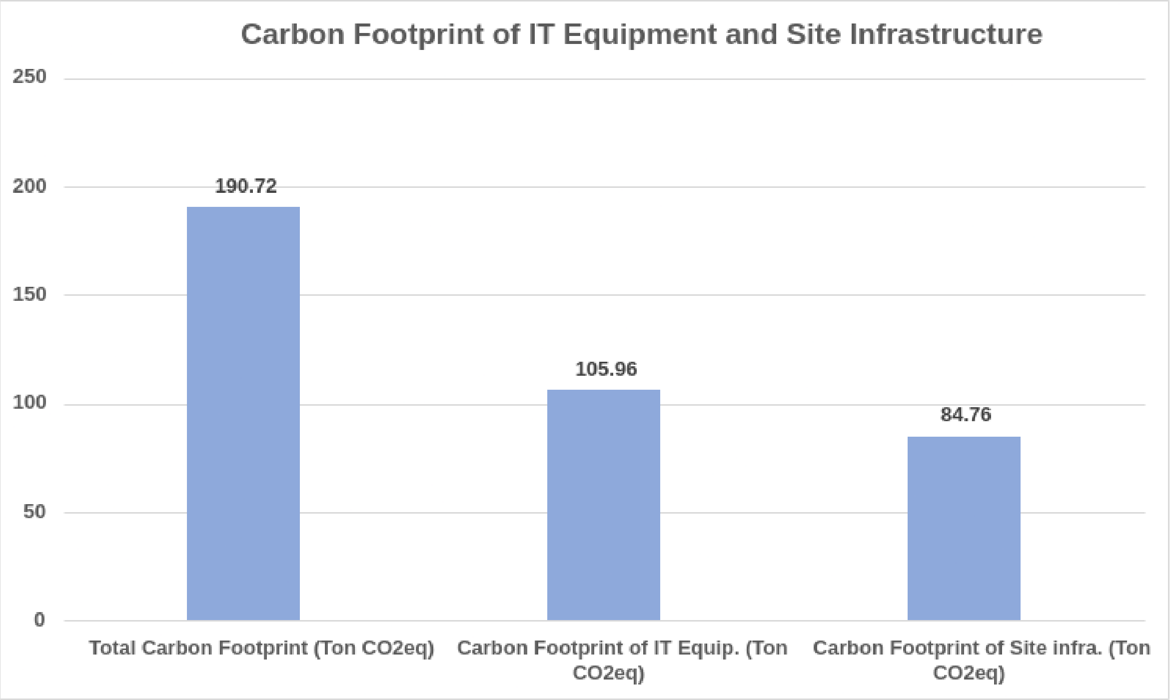

Figure 4.3 Carbon Footprint of IT Equipment and Site Infrastructure under the Estonian GHG model

4.2 Comparative Analysis

4.2.1 Using the green algorithm model

The Green algorithm study provides a methodology to measure the carbon footprint of any computational task in a standardized and reliable manner. It also defines metrics to provide context to greenhouse gas emissions. To make the process easy, the authors developed an online tool called Green Algorithms. This tool requires minimal information and does not interfere with existing code. It can accommodate different hardware configurations. The study also quantifies the GHG emissions generated by algorithms used in particle physics simulations, weather forecasts, and natural language processing. In addition, the tool accounts for the geographical location of the data center.[2]

To understand more about the process of calculating we must understand the formula used to calculate the GHG emissions. To determine the carbon footprint, the methodology estimates the energy consumption of the algorithm and the carbon intensity associated with generating this energy at a particular location. The Carbon Intensity metric is influenced by the location and the technologies employed for electricity generation.[2]

Carbon Footprint = Energy Consumption * Carbon Intensity

(4.3)

Where Carbon Footprint , Ton CO_2eq

Energy Consumption: Total Power Consumption, kWh

Carbon Intensity- $gCO_2eq\ kWh^{-1}$

The power consumption of the computing cores is determined by their model, number, and usage factor, while the memory power consumption is determined solely by its size. Additionally, the Power Usage Effectiveness (PUE) factor accounts for the energy consumed by auxiliary operations such as cooling and lighting in the data center. A Pragmatic Scaling Factor (PSF) is also included to account for multiple identical runs, such as those used for testing or optimization.[2]

Energy Consumption = Runtime * (Power Draw for Cores * Usage + Power Draw for Memory) * PUE * PSF

(4.4)

Where Runtime – Total Number of hours

Power Draw for Cores - Power Consumption of the CPU cores, kW

Usage – Core usage factor

Power Draw for Memory - Power Consumption of the memory, kW

PUE - Power Usage Effectiveness factor

PSF - Pragmatic Scaling Factor

In addition, the green algorithm project provides a monitoring application that can be installed within the HPC cluster, providing real-time metrics and automatically gathering algorithms details to estimate the corresponding energy usage and carbon footprint.[68]

Table 4.3 illustrates the model's implementation, which accounts for the total runtime of one year or 8766 Hours, location to be Estonia and provides separate estimates for each machine type available in the HPC center where we used the exact type of the machine CPU otherwise if not found the average value was used or looked for the manufacturer’s datasheet to acquire the power usage per core. The used CPU model and other equation values are as follow in table 4.2 and PUE will be 1.8 [64] and PSF will be considered one. And since the processing time is difficult to calculate for each individual type of our nodes, it was assumed that core usage accounted for 100% of the run time.[2]

Table 4.2 Values used in the calculations.

No.	**Machine Type**	**Runtime**	**PUE**[64]	**Usage**[2]	**PSF**	**CPU Model**
1	Gray Nodes	8766	1.8	1	1	Intel Xeon E5-2630L
2	Green Nodes	8766	1.8	1	1	Intel Xeon Gold 6148
3	AMP1	8766	1.8	1	1	Any (Average)
4	AMP2	8766	1.8	1	1	Any (Average)
5	Nova Nodes	8766	1.8	1	1	Any (Average)
6	Big-Mem	8766	1.8	1	1	Any (Average)

In the following table we will use the model to calculate the energy consumption from equation 4.4 and calculate the carbon footprint as well.

Table 4.3 Carbon Footprint Based on the green algorithm model.

No.	**Machine Type**	**Quantity**	**No. Cores (CPUs)**	**Total RAM (GB)**	**Energy Consumption (KWh)**	**Carbon Footprint (Ton CO_2eq)**
1	Gray Nodes	48	576	3072	108940	65.22
2	Green Nodes	32	1280	3072	169530	101.50
3	AMP1	1	128	1000	30110	18.03
4	AMP2	1	128	2000	35990	21.55
5	Nova Nodes	5	200	768	42380	25.37
6	Big-Mem	1	32	1000	11940	7.15
	Total	**88**	**2344**	**10912**	**398890**	**238.82**

As shown in the table above the total carbon footprint for the HPC center to operate for one year will be 238.82 Ton CO_2eq which is not that far from the carbon emissions we got from the Estonian GHG model which was 190.72 Ton CO_2eq.

However, The Green Algorithm approach has certain limitations that must be acknowledged.one of them the model can only estimate the carbon footprint of the greenhouse gases (GHGs) that are emitted during the operation of computers for specific tasks. The project did not conduct a life cycle assessment of the hardware used, nor have considered the broader environmental and social impact of its production, maintenance, and disposal, or the energy sources used in power plants. While incorporating such factors is desirable, it is not feasible on a large scale, and would significantly restrict the applicability of our method. Furthermore, our method converts the impact of different GHGs into CO_2eq, assuming a 100-year timescale. However, this approach has been challenged as it may not accurately reflect the impact of short-lived climate pollutants like methane.[69]

4.2.2 CRESCO4 HPC Case Study

The CRESCO4 HPC system which is considered one of the top HPC facilities in Italy, was created to provide a versatile platform using state-of-the-art multi-core technology. As of June 2008, the system was ranked 125 on the top 500 list in terms of performance. To ensure optimal performance for a range of applications, the system has been divided into two primary sections. The first section is geared towards applications that require high memory and moderate parallel scalability. The second section is designed for applications that have limited memory requirements, but high scalability needs.[70]

The case study was conducted on the CRESCO4 HPC system over a one-year period from February 2016 to February 2017. The study aimed to assess the overall energy consumption of the system, which comprises 38 Supermicro F617R3-FT chassis. Each chassis accommodates 8 dual CPU nodes, with each CPU containing 8 cores (Intel E5-2670) operating at a frequency of 2.6 GHz. In total, the system boasts 4864 cores, with a RAM memory of 4 GB per core.[71]

To gain a comprehensive understanding of the energy efficiency of the system, the study mapped the number of running jobs, along with their core counts, to each Zabbix interval (timestamp = 1 hour). Figure 4.2 presents the aggregated data collected over the course of a year using Zabbix. The data reveals an average consumption of 45KW, indicating that the system's yearly power consumption would be approximately 3094200 KWh. This value is calculated by multiplying the power consumption reading by 24 hours by 365 days. However, this analysis didn’t consider the external cooling consumption or other supporting IT equipment and only considers the power consumption of the computing nodes.[71]

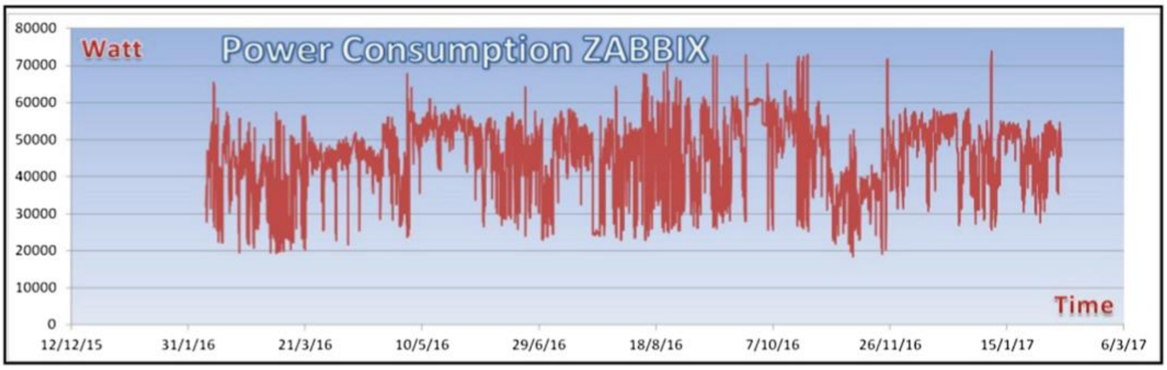

Figure 4.4 Yearly Carbon Emissions [71]

In order to calculate the total power consumption of the data center and have proper comparison with TalTech Data center we must know the total power consumption of CRESCO4 which is estimated to be 150KW that increases the total yearly consumption to 1314000 KWh. This value is calculated by multiplying the power consumption reading by 24 hours by 365 days. The difference is staggering but justified since the external cooling system and other supporting IT equipment draw a considerable amount of power as well.[70]

In 2020 the emission intensity or carbon intensity of electricity generated in the Italy to be 371 g CO_2eq/kWh. It is possible to estimate the amount of carbon emissions produced by supercomputer based on its energy consumption. The carbon intensity of electricity is a measure of how much CO_2 is emitted into the atmosphere per unit of electricity generated, and this value can vary based on factors such as the source of fuel used for electricity generation and the efficiency of the power plant.[72]

The total carbon footprint will be the result of multiplying the carbon intensity = 371 g CO_2eq/kWh and the total yearly power consumption = 1314000 KWh which equals 487.5 Ton CO_2eq.

In order to understand the contrast between TalTech HPC and CRESCO4 HPC performance over the year, we can analyze the carbon footprint per node. TalTech HPC comprises approximately 88 nodes while CRESCO4 HPC consists of 304 nodes. To determine TalTech's performance, we can calculate the total emissions and divide it by the number of nodes.

$$PI = E / n \tag{4.1}$$

Where PI – Performance Index, Ton CO_2eq/node

E – Total Emission, Ton CO_2eq

n – Number of Nodes

the PI for TalTech HPC is 2.2 Ton CO_2eq/node and for CRESCO4 HPC is 1.6 Ton CO_2eq/node. A lower PI indicates better performance as it signifies less emission released by the HPC. The difference in total carbon emissions and the PI between the TalTech HPC and CRESCO4 HPC could be attributed to several factors, such as how many cores in each data center and how big is the cooling systems, the electricity sources available in each country and the integration of green energy into the grid. Additionally, differences in job scheduling techniques across HPC systems may also contribute to differences in energy consumption. This paper will further explore additional methods for increasing energy efficiency and reducing energy consumption in HPC centers.

4.3 Identification of Major Sources of Emissions and Potential for Reduction

4.3.1 Energy Supply and Consumption

Maintaining a highly reliable power supply for critical services is essential to ensuring the smooth operation of the HPC center and avoiding downtime. At the same time, individual systems in the HPC center consume a significant amount of energy, which must be carefully managed and monitored to ensure efficient use of resources.

Furthermore, the energy distribution network itself must be maintained and developed to keep pace with the changing demands of the IT environment. This requires ongoing investment in hardware and software, as well as a dedicated team of experts to manage the network.[73]

Ensuring a continuous and uninterrupted power supply is essential for certain receivers in a center to prevent damage to delicate components and maintain the operation of critical services. These services include network and storage devices, important data processing systems such as email and websites, and a group of computing machines. To guarantee the quality of services provided, it is necessary to have a reliable and uninterrupted power supply, which is typically achieved through redundancy in the power supply and the installation of resilient devices to ensure that at least one power source remains operational.[73]

4.3.2 Data Center Under-utilization

The resources utilization of a data center is often not efficient. This is because the traditional method of overprovisioning resources to meet peak demand results in underutilization of resources for the majority of the time, leading to an energy-inefficient data center that can significantly increase costs for the provider. Inefficient resource utilization can also lead to performance issues for users of the data center, as they may not have access to the necessary resources when they need them. As a result, there is a need for more efficient resource management techniques that can optimize the use of resources in data centers and improve their overall performance and energy efficiency.[74]

4.3.3 Cooling of Data Centers

Cooling electronics remains a major challenge for the computer, network, and telecom industries as it affects equipment performance and customer acceptance for new products. While cooling at the device level, such as for high-performance microprocessors, has been a focus of innovation for some time, cooling at the data center level has become a critical concern from technical, economic, and policy perspectives.[75]

HPC relies heavily on cooling to ensure their equipment performs well and meets performance expectations. Despite advancements in device-level performance and integration, cooling remains a challenge and can limit the equipment overall performance achievable with racked servers and communications gear. The high electric power demands of these systems, along with the significant portion of energy used for cooling (35-50%), create a growing operating expense burden.[75]

Efficient cooling operation in a data center can be affected by thermal imbalances. These imbalances can create hot spots, which can exceed the maximum inlet air temperature specified for servers, leading to damage of electronic components and causing them to fail prematurely. Additionally, non-uniform equipment loads in the data center can cause certain areas to heat up more than others, while irregular air flows can cause some areas to be cooler than others. Complex airflow patterns in high heat density data centers can also contribute to the creation of hot spots. Therefore, it is important to prioritize thermal-aware workload scheduling with the goal of reducing both the maximum temperature for all compute nodes and the imbalance of the thermal distribution in the data center. In order to achieve this, ambient temperature sensors and onboard sensors can be deployed to obtain thermal distribution and computer node temperatures in the data center.[55]

4.3.4 Environmental Impact and Potential for Reduction

High-performance computing (HPC) has significant environmental impacts, mainly due to its high energy consumption and associated carbon emissions. Some of the key environmental concerns related to HPC include:

Energy consumption: HPC systems consume vast amounts of energy to perform complex calculations, which can lead to increased greenhouse gas emissions and strain on power grids.[76]

E-waste: HPC equipment has a limited lifespan[77], and the rapid development of new technologies leads to a shorter replacement cycle, resulting in electronic waste that can be harmful to the environment if not disposed of properly. E-waste is one of the most rapidly expanding waste categories globally and poses a significant risk to the planet. Out of the total solid waste found in landfills, 70% of hazardous waste is attributed to e-waste. This vast quantity of e-waste releases numerous toxic substances, volatile organic compounds, and heavy metals that not only deplete resources but also contribute to environmental pollution and global climate change.[78]

Natural Resource depletion: The production of ICT products contributes to the depletion of Earth's natural resources, thereby disrupting the balance of natural diversity. For instance, the manufacture of a single desktop computer with a 17-inch monitor requires at least 240 kg of fossil fuels, 22 kg of chemicals, and 1,500 kg of water. This amounts to a total material input of 1.8 tons.[78]

Hardware Production: Computer hardware production leads to severe pollution. Various components of a computer and its peripherals contain numerous harmful heavy metals that are not only dangerous to the environment but also pose significant risks to human and animal health. The metals, chemicals, and toxic materials used in computer manufacturing result in health hazards, water contamination, and air pollution, ultimately harming the global environment.[78]

To address the several issues discussed above and promote sustainable HPC practices, various strategies can be employed to reduce their environmental footprint. These strategies include the following key aspects:

1. Energy-efficient hardware: Implementing energy-efficient processors with more clock frequency, memory, and storage can reduce the energy consumption of HPC systems.[78]

2. Efficient cooling systems: Using advanced cooling techniques, such as liquid cooling and free cooling, can minimize energy consumption by reducing the reliance on traditional air conditioning.[55]

3. Renewable energy: Powering HPC facilities with renewable energy sources, such as solar, wind, or hydropower, can help reduce the carbon footprint associated with their operation.[79]

4. Software optimization: Developing algorithms and software that optimize the use of hardware resources can result in more energy efficient HPC systems. Which can be achieved using modern compilers[78]

5. Facility design: Designing HPC data centers to minimize energy consumption, such as using natural ventilation and optimizing airflow, can contribute to a lower environmental impact.[80]

6. Recycling and proper e-waste management: Apart from the energy consumption and emissions during operation, data centers contribute to "embodied" life cycle emissions. These emissions stem from raw material extraction, manufacturing, transportation, and end-of-life disposal or recycling. Companies should intensify their efforts to minimize embodied emissions throughout their supply chains, including devices and infrastructure.[81]

By considering these factors and implementing the suggested strategies, the environmental impact of high-performance computing can be significantly reduced, promoting a more sustainable future for the industry.

5 CONCLUSION AND RECOMMENDATIONS

5.1 CONCULSION

High-Performance Computing (HPC) refers to systems capable of processing vast amounts of data and performing complex calculations much faster than other computers. By combining their computing power, HPC solutions allow various scientific, business, and engineering organizations to tackle problems. High-Performance Computing (HPC) has become a crucial component in numerous research projects that were previously considered unfeasible.

This advanced technology has revolutionized the way researchers approach complex problems and has opened up new avenues for exploration and discovery. A prime example of HPC in action can be found at the HPC center of Tallinn University of Technology. This center serves as a hub for various research, showcasing the potential of HPC to push the boundaries of what is possible in fields such as science and engineering. The HPC center at Tallinn University of Technology highlights the important role that HPC plays in driving progress and innovation in a variety of disciplines.

Investigating the environmental impact of High-Performance Computing (HPC) has become increasingly important in light of the rapid growth of computing power. To gain a deeper understanding of the role of HPC in carbon emissions, further studies are necessary. The examination of this issue is of paramount importance as the continued growth of HPC could have significant implications for energy consumption and CO_2 emissions. A comprehensive analysis of the energy efficiency of HPC systems, including data centers, can help to minimize the environmental impact and promote sustainability in the industry.

In this study, we conducted an analysis of the power consumption in a High-Performance Computing (HPC) system over the course of one year. The majority of the power consumption is generated by the computing machines and their accompanying cooling systems. By understanding the power usage of the HPC system over a long period of time, we can identify potential areas for improvement and optimize the design of the cooling systems to reduce the amount of power consumed. This can lead to significant cost savings for the system.

We investigated the fluctuations in power consumption, which are driven by two main factors: changes in cooling system operation in response to elevated temperatures and fluctuations in computing load caused by researchers utilizing varying amounts of computing resources. Specifically, increased computing demand leads to the activation of additional computing machines, which in turn results in an increase in power consumption. Our findings contribute to a deeper understanding of the complex interplay between cooling systems, computing load, and energy consumption in HPC environments.

By pooling resources among several High-Performance Computing (HPC) centers, we can help to reduce the overall energy consumption and decrease the strain on individual systems. Sharing resources among HPC centers allows for the reduction of total power consumption and eliminates the need for multiple smaller machines, instead promoting the use of a larger, centralized computing machine that can be used by multiple organizations. This resource sharing strategy can not only reduce energy consumption but also provide a more cost-effective and efficient computing solution for all parties involved.

Further research is necessary to find additional ways to implement "green computing" in order to decrease the environmental impact of High-Performance Computing (HPC) caused by carbon emissions as a direct result from power consumption. It is essential to investigate new and more environmentally friendly computing solutions. Further studies are necessary to identify and explore methods for making HPC more sustainable, such as through energy-efficient hardware, power management techniques, or alternative energy sources. This research will play a crucial role in reducing the environmental impact of HPC and building a greener future.

5.2 RECOMMENADTIONS

5.2.1 High-Performance Computing Center Design

HPC center Design involves incorporating environmentally friendly elements into the design process. The design should consider all aspects of energy usage in a data center, from the IT equipment to the HVAC system, to the location, configuration, and construction of the building. There are five key areas that energy-efficient design practices can be applied to: IT systems, environmental conditions, air management, cooling systems, and electrical systems. Implementing green design decisions during the design phase helps to reduce environmental impact and costs, as opposed to ignoring environmental factors and having to use cleanup strategies later on. Examples of green design decisions include substituting toxic solvents with benign alternatives or incorporating more energy-efficient technologies like semiconductors.[4]

5.2.2 Data Centers Co-location

Colocation data centers are gaining popularity due to their unique management approach. In a colocation, the operator offers essential infrastructure services like space, power supply, cooling, and networks to tenants. The tenants, on the other hand, bring their own servers to the colocation and concentrate on running their business operations, without having to worry about maintaining the infrastructure. As a result, numerous internet companies, including Facebook and Apple, are choosing to rent infrastructure services from colocation providers, allowing them to outsource the burden of managing their servers.[82]

5.2.3 Eco-Friendly Power Sources Utilization

High-performance computing centers consume a significant amount of electricity, and one approach to reduce their environmental impact is by using eco-friendly power sources. Adopting such power sources could greatly affect the performance of the data center, though this may be challenging for some centers due to geographical barriers. Nevertheless, they could obtain green energy certificates as an alternative means to achieve this goal.

The variable nature of renewable energy sources poses a challenge to their efficient utilization in data centers. To ensure a reliable energy supply, redundant energy sources and transition systems must be utilized. These systems should be capable of making automatic transitions between energy sources without causing interruptions to the equipment. This requires the use of advanced battery technologies and power management strategies.[79]

5.2.4 Thermal Management:

In terms of layout, racks should be arranged in rows on a raised floor over a shared plenum, with modular computer room air conditioning units along the walls to circulate warm air from the machine room over cooling coils and direct the cooled air into the shared plenum. This design will ensure that cool air is distributed evenly throughout the machine room, and that equipment in the racks can draw in cool air from the cool aisles.[80]

Heat waste utilization, taking inspiration from the LUMI supercomputer in Finland, data centers can adopt waste heat utilization practices to decrease their environmental impact. By redirecting the waste heat back into the district heating network, LUMI was able to contribute up to 20% of the district heating needs of a neighboring city. This recycling of waste heat resulted in a significant reduction of the city's carbon footprint by 12,400 tons. By implementing similar strategies in other data centers, we can make use of the waste heat to reduce the carbon footprint of both the data center and the surrounding community.[83]

Using tools like The Thermal Aware Scheduling Algorithm which is a scheduling algorithm that is specifically designed to consider thermal factors in data center scheduling. The algorithm consists of two main stages, namely job sorting and resource allocation. During the job sorting stage, incoming jobs are sorted in decreasing order of predicted temperature increase. Then, during the resource allocation stage, the algorithm allocates jobs to resources with lower temperatures in order to reduce the overall temperatures of the compute nodes. The algorithm is an online scheduling tool that periodically updates the thermal information of the data center via temperature sensors, allowing it to make real-time adjustments to improve thermal efficiency.[80]

5.2.5 Guidelines for Selecting Equipment from Manufacturers

The growing concern to safeguard the environment from industrial pollution means that sustainable manufacturing practices and technologies are no longer just an option, but a necessary choice. While various environmentally friendly production techniques have been developed and others are being researched, this alone is not enough to solve the issue. Manufacturers also need to invest in better equipment, more efficient processes, and innovative technologies to reduce their environmental impact and help protect the planet.[84]

Implementing more environmentally conscious purchasing practices in High Performance Computing (HPC) centers would involve procuring HPC equipment that is certified as environmentally friendly and uses less energy during its operation.

Additionally, it is important to consider purchasing from manufacturers who have established end-of-life solutions for their machines, such as responsible recycling programs or trade-in options. This type of procurement would likely come at a higher cost, but it is a crucial step towards reducing the environmental impact of HPC centers and promoting sustainability in the industry. By making more eco-friendly equipment choices, HPC centers can not only help to reduce their carbon footprint but also demonstrate their commitment to sustainability and corporate social responsibility.[84]

5.2.6 Guidelines for Selecting Efficient Equipment

One way to reduce energy losses and running costs in the distribution network is by utilizing Distributed Uninterruptible Power Supply (UPS) devices. This solution involves installing a battery or large capacitor within the power supply of the computer device to store electrical energy. The power-up time for this internal UPS can range from 300 milliseconds for capacitors to 10 minutes for standard 12V gel batteries. This enables the elimination of large Static UPS units from the computing center infrastructure while minimizing energy losses in the network. The switchover time is rapid, taking less than 300 milliseconds through an ATS switch. However, the maintenance of these distributed backup power systems is costly, particularly for units with standard lead-acid batteries, and not all computer systems have sufficient space to install them.[73]

In recent years, energy efficiency has become a crucial aspect in the design of modern computing systems, particularly in data centers, due to their high consumption of electrical power. This not only leads to expensive operating costs but also contributes significantly to carbon dioxide emissions, with IT infrastructures currently responsible for about 2% of total CO_2 footprints. If energy-efficient methods and algorithms to manage computing resources are not developed, it is expected that IT's impact on energy consumption and CO_2 emissions will continue to increase. The power management challenge becomes more complex when viewed from the data center level, where multiple interconnected computing nodes must be managed as a single resource to minimize energy consumption. [45]

6 SUMMARY

High-Performance Computing (HPC) is a technology that utilizes powerful computer systems to process large amounts of data and perform complex calculations at high speeds. This technology allows organizations in various fields, such as science, business, and engineering, to solve challenging problems that would otherwise be unapproachable. HPC has become an essential tool for cutting-edge research and innovation. As HPC technology continues to grow and consume more energy, it is crucial to study its energy efficiency and minimize its environmental impact. This will require an analysis of HPC systems, including data centers, to promote sustainability in the industry.

The idea of a "green data center" is now a practical solution for IT leaders who are looking to create energy-efficient computing environments. This can be achieved through constructing new data centers that are environmentally friendly or retrofitting existing ones. The defining features of a green data center include using software technologies to control data growth and capacity requirements, implementing Service Level Agreements to track energy consumption, optimizing computing infrastructure for both energy efficiency and performance, and designing the physical structure to maximize energy efficiency.

This thesis tried to analyze the power consumption of TalTech University's High-Performance Computing (HPC) Center over a one-year period. ZABBIX software was used to collect data and track trends in energy consumption. The collected data was then used to calculate the carbon footprint of the HPC using the GHG calculation model. The model is based on Estonian-specific assumptions and conditions, providing a standardized approach and data for Estonian organizations.

Most of the power consumption was found to come from the computing machines and cooling systems. The fluctuations in power consumption were investigated and found to be driven by changes in cooling system operation and computing load. The study's findings provide insights into the relationship between cooling systems, computing load, and energy consumption in HPC environments, which can be used to optimize the design of HPC systems and reduce power consumption.

Energy efficiency has become a critical factor in the design of contemporary computing systems, particularly data centers, due to their substantial electrical power consumption. This results in not only high operating costs but also a significant contribution to carbon dioxide emissions. Energy efficiency is a key factor in reducing HPC environmental impact and costs. Five areas that can be improved through green design decisions include IT systems, environmental conditions, air management, cooling systems, and electrical systems. By implementing sustainable manufacturing practices and technologies, HPC centers can choose equipment that is certified as environmentally friendly, uses less energy, and has established end-of-life solutions.

It is important to purchase HPC equipment that is energy efficient and certified as environmentally friendly. This includes considering the manufacturer's end-of-life solutions, such as responsible recycling programs or trade-in options. Although this may come at a higher cost, it is a necessary step towards reducing the environmental impact of HPC centers and promoting sustainability in the industry. By making eco-friendly equipment choices, HPC centers can reduce their carbon footprint and show their commitment to sustainability and corporate social responsibility.

Pooling resources among multiple HPC centers can be an effective way to reduce energy consumption and provide a more efficient and cost-effective computing solution. By sharing computing resources, the total power consumption can be reduced and the need for multiple small machines can be eliminated. Instead, a larger centralized computing machine can be used by multiple organizations, reducing energy consumption and promoting sustainability in the industry.

To reduce the impact of High-Performance Computing (HPC) on the environment, further research is needed to explore and implement "green computing" solutions. This includes investigating energy-efficient hardware, power management techniques, and renewable energy sources.

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8 Appendices

8.1 Appendix 1

The following figures depict the graphical representation of monthly readings recorded by Zabbix over a one-year period, commencing on February 1, 2022, and concluding on February 1, 2023:

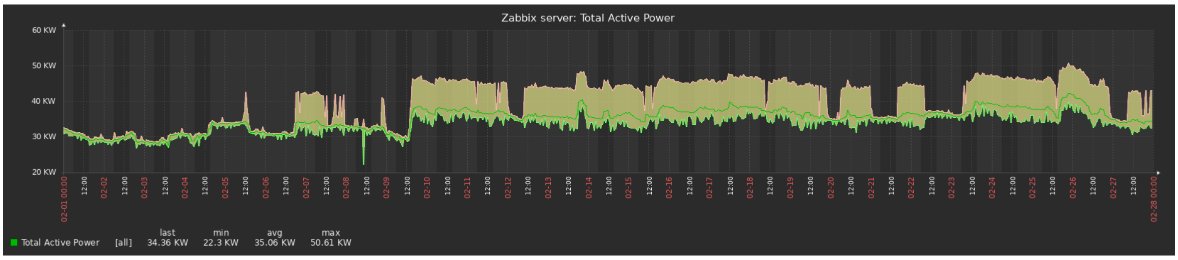

Figure 3.2 Power Consumption 1-2-2022 to 28-2-2022

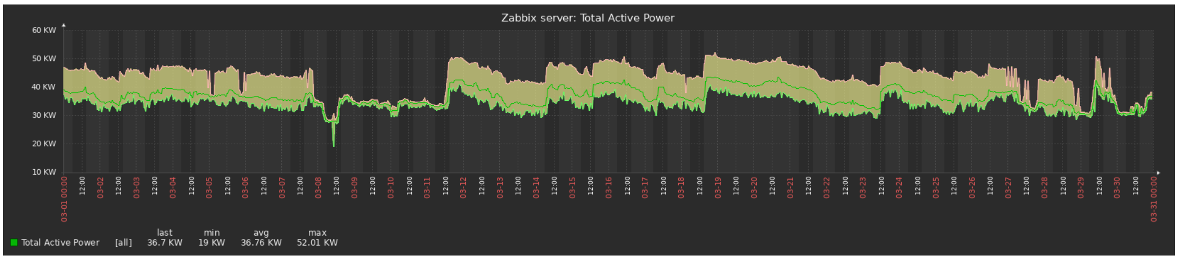

Figure 3.3 Power Consumption 1-3-2022 to 31-3-2022

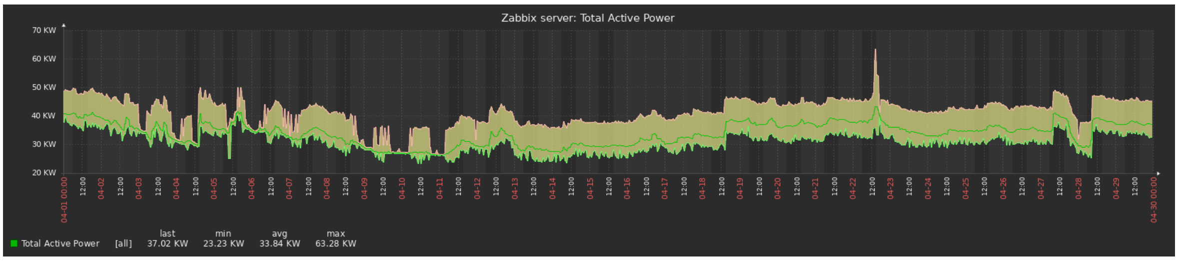

Figure 3.4 Power Consumption 1-4-2022 to 30-4-2022

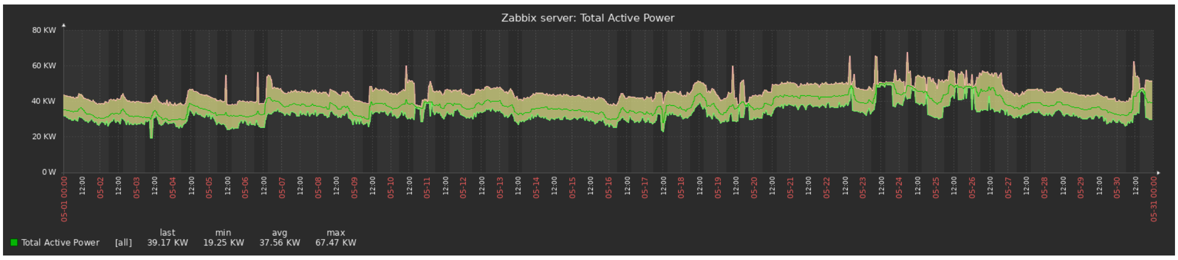

Figure 3.5 Power Consumption 1-5-2022 to 31-5-2022

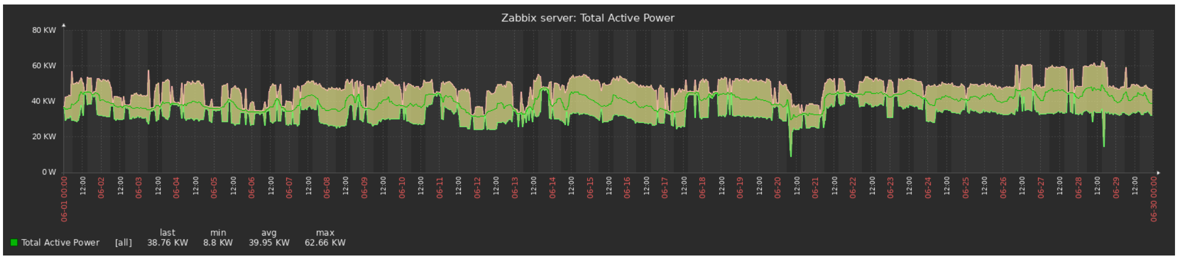

Figure 3.6 Power Consumption 1-6-2022 to 30-6-2022

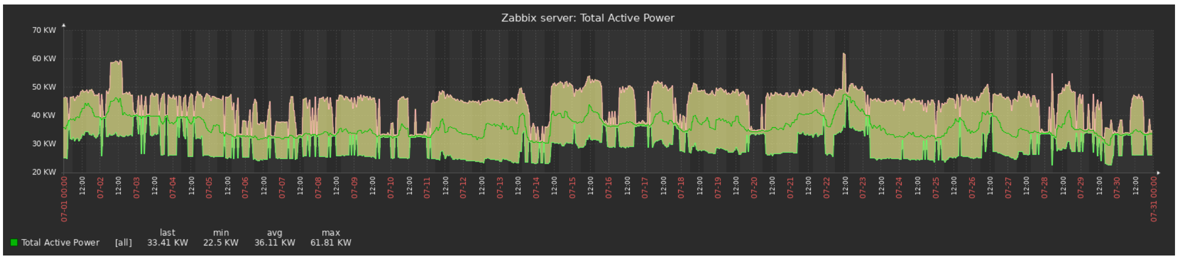

Figure 3.7 Power Consumption 1-7-2022 to 31-7-2022

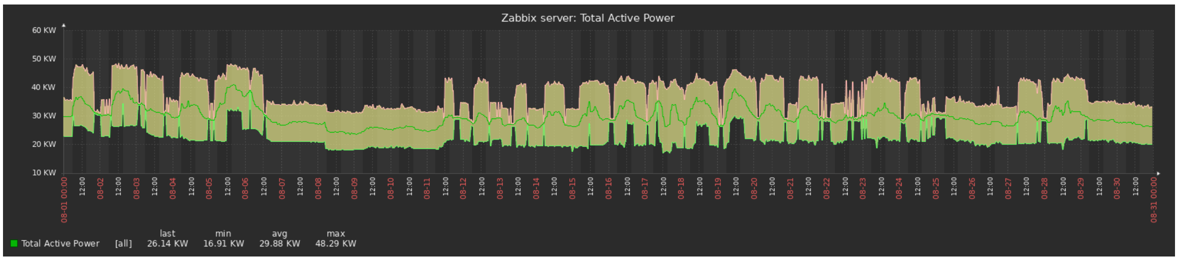

Figure 3.8 Power Consumption 1-8-2022 to 31-8-2022

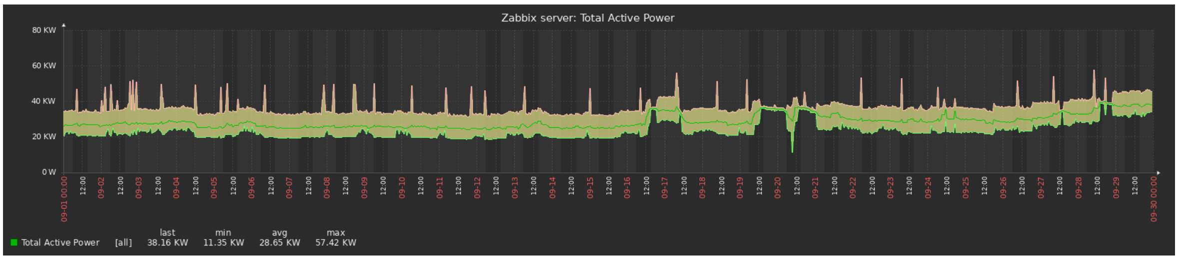

Figure 3.9 Power Consumption 1-9-2022 to 30-9-2022

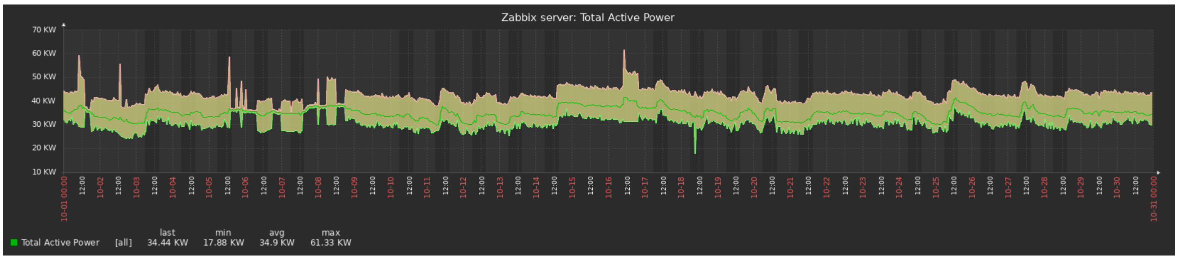

Figure 3.10 Power Consumption 1-10-2022 to 31-10-2022

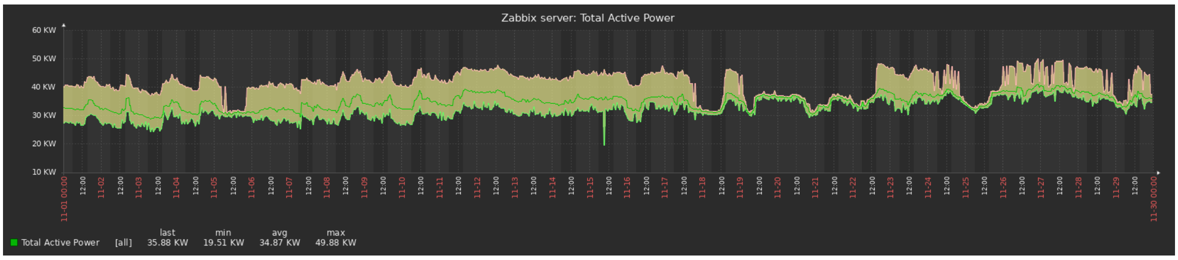

Figure 3.11 Power Consumption 1-11-2022 to 30-11-2022

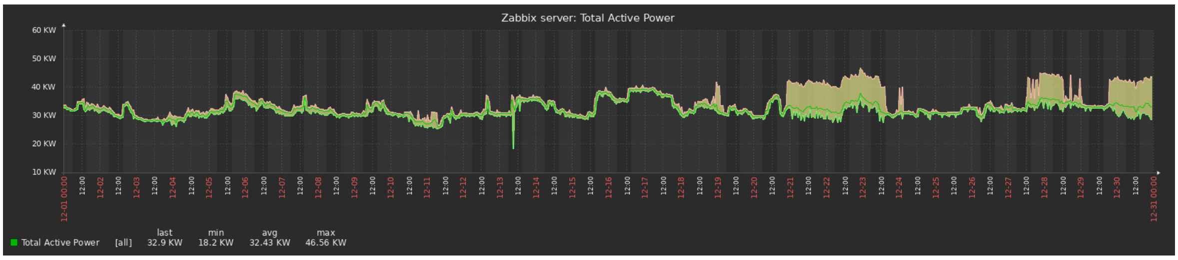

Figure 3.12 Power Consumption 1-12-2022 to 31-12-2022

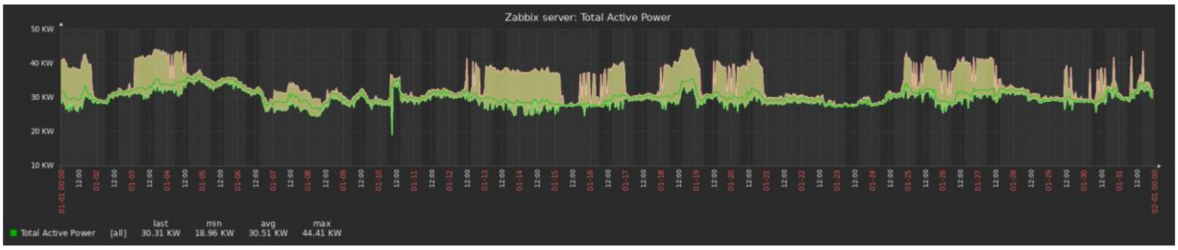

Figure 3.13 Power Consumption 1-1-2023 to 1-2-2023