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Liquid versus Air: Life Cycle Carbon of Cooling Down AI Data Centers

William J. Hassel

A Thesis in the Field of Sustainability

for the Degree of Master of Liberal Arts in Extension Studies

Harvard University

February 2025

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Abstract

The rise of AI and cryptocurrency technologies has led to exponential growth in data centers globally. As these facilities consume substantial energy and contribute to significant greenhouse gas emissions, implementing sustainable cooling technologies in data center facilities is increasingly crucial. Preliminary findings suggested that applying liquid cooling systems within these data centers holds significant potential to markedly decrease energy consumption, greenhouse gas emissions, and water usage (Manganelli et al., 2021). Initial estimations indicate that data center facilities incorporating liquid cooling mechanisms could reduce both embodied and operational carbon emissions by up to 50% throughout their life cycle compared to those employing conventional air cooling methods. This adaptation could result in near-zero water usage and decrease the physical size of data center buildings, further reducing carbon emissions and capital expenditure, potentially achieving cost neutrality over the facility's life cycle.

I primarily sought to answer three questions: How do liquid and conventional air cooling methods compare in terms of carbon emissions when evaluated through a comprehensive LCA? How does adopting liquid cooling influence data center facility design and resource utilization? Considering both upfront and operational costs, what are the cost implications of transitioning from traditional air cooling to liquid cooling? I hypothesized that data centers with liquid cooling systems will demonstrate substantial reductions in embodied and operational carbon emissions and water use, and despite higher upfront costs, liquid cooling systems will prove cost-neutral over their life cycle.

To test these hypotheses, I analyzed the environmental and cost implications of data center cooling technologies through a comparative life cycle assessment (LCA) of liquid and traditional air cooling systems. The LCA adhered to the ISO standards (14040, 14044, 14067, and 15686), encompassing all stages of the data center's life cycle, reporting Global Warming Potential in kgCO2e. Material inventory data from equipment manufacturers and data center operators were aggregated and anonymized to create representative models of data centers using both cooling methods. The liquid cooling LCA models achieved up to 50% reductions in embodied and operational carbon emissions compared to conventional air cooling systems. Liquid cooling also enabled near zero water usage and a 50% smaller data center building size, which resulted in embodied carbon reductions and less resource use throughout the life cycle.

My research findings present a compelling case for approaching data center cooling solutions with a holistic life cycle perspective, identifying the most environmentally sustainable and cost-effective cooling method, and providing recommendations for reducing data centers' environmental impact. The outcomes should be significant for data center operators, designers, and construction managers, enabling more sustainable and cost-effective design strategies for future data centers.

Dedication

This work is dedicated to my Mom and Dad, Vicky and Bill, and my partner, Lisa. This thesis, the culmination of four years of effort toward earning a master's degree, stands as a testament to the values my parents instilled in me and the unwavering support my family has provided throughout my life.

To my Mom, who spent countless hours reading with me, fostering my love for learning, and encouraging a relentless curiosity. Your unwavering support shaped the foundation of who I am.

To my Dad, who valued education, instilled in me a tireless work ethic, and supported me unconditionally. You were always the first to read my drafts, offering invaluable insights, and your belief in me made all the difference.

To Lisa, my partner in life, who stood by me through late nights, moments of doubt, and the chaos of impossible deadlines. Your endless patience, thoughtful discussions, and countless acts of support—both big and small—carried me through this four-year journey.

This work exists because of your love, encouragement, and sacrifices. I am eternally grateful.

Acknowledgments

I extend my deepest gratitude to my thesis director, Dr. Tom Gloria, whose mentorship and inspiration made this year-long thesis journey transformative. Our discussions have provided insights and knowledge far beyond the scope of this thesis, and I am profoundly grateful for his guidance.

Heartfelt thanks also go to my research advisor, Dr. Mark Leighton, who sharpened my research skills and elevated my academic writing. He created opportunities that made the Harvard experience both tangible and meaningful. His generosity in hosting events and fostering camaraderie among students provided a sense of belonging that made this journey unforgettable.

Special thanks to Jeff North, whose steadfast support and candid advice kept me on the academic track during moments of uncertainty. His encouragement, especially during the challenges of the first pandemic semester, and his willingness to host the "Usual Suspects" provided invaluable guidance and a much-needed sense of community. I also thank my colleagues Cor van Egmond and Hashem Izadi Moud for their thought-provoking discussions and challenging ideas that helped shape this thesis. I would like to extend my gratitude to Dan Harmon for providing me with a fulfilling role in sustainability at Turner Construction and the autonomy to pursue my master’s degree. Finally, I thank all my peers for fostering an environment of collaboration and inspiration, which enriched my understanding of sustainability and supported both personal and professional growth.

Table of Contents

Dedication v

Acknowledgments vi

List of Tables x

List of Figures xi

Definition of Terms xii

Chapter I. Introduction 1

Research Significance and Objectives 3

Background 5

Air Cooling and Liquid Cooling 7

Model Overviews: Air Cooling and Liquid Cooling 12

Energy Source Carbon Emissions for Data Center Operations 16

Life Cycle Assessment (LCA) 17

Data Center Facility Size 19

Life Cycle Cost (LCC) 20

The Need for a Deeper Environmental and Cost-Effective Analysis 22

Research Questions, Hypotheses, and Specific Aims 23

Specific Aims 24

Chapter II. Methods 26

Life Cycle Assessment (LCA) 26

Life Cycle Inventory (LCI) 27

Life Cycle Cost (LCC) Analysis....28
One Click LCA and the Life Cycle Carbon Tool....29
Data Sources and Methodologies....30
CIBSE TM65 Methodology....32
Interpretation, Comparison, and Sensitivity Analysis....33
Research Limitations....35
Current State of PCRs for MEP Equipment....36
Uncertainty....37
Functional Unit....38
Traditional Space Conditioning Functional Unit....39
Computing Capacity in MW for AI Workloads....41
Limitations of MW of Compute as a Proxy for Computing Power....42
System Boundary....43
Assumptions....47
Cooling Requirement for the Evaporative System....49
Cooling Requirements for the Immersion System....51
Life Cycle Inventories....53
Chapter III. Results....56
Air: Evaporative Cooling on Grid Power....58
Liquid: Immersion Cooling on Grid Power....60
Sensitivity Analysis – Change to Renewable Power....62
Air: Evaporative Cooling on Renewable Power....63
Liquid: Immersion Cooling on Renewable Power....65

Sensitivity Analysis – Zero Out B6 Energy Consumption 67
Air: Evaporative Cooling With No B6 Energy Consumption 68
Liquid: Immersion Cooling With No B6 Energy Consumption 70
Carbon Footprint Comparison 72
Intensity vs Absolute Metrics 76
Scaled Results 77
Life Cycle Cost 78
Capital Expenditure (CapEx) 78
Operational Expenditure (OpEx) 80
Cost of Carbon 82
Chapter IV. Discussion 83
Energy Consumption and Cooling Efficiency 83
Embodied Carbon and Data Center Design 84
Water Usage and Sustainability Impacts 85
Jevons Paradox and the Future of Data Center Cooling 85
Limitations and Future Research 86
Conclusions 86
Appendix 1 Air Cooled Data Sources 87
Appendix 2 Liquid Cooled Data Sources 103
References 118

List of Tables

Table 1. Life cycle system boundary. 45

Table 2. Description of life cycle stages and analysis scope. 46

Table 3. Assessed impact categories.....47

Table 4. Model assumptions. 48

Table 5. Foreground data and bill of materials for the air cooled model.....54

Table 6. Foreground data and bill of materials for the liquid cooled model.....55

Table 7. Building life cycle carbon footprint utilizing grid power. 57

Table 8. Evaporative cooling global warming (kg CO2e) life cycle stages. 58

Table 9. Immersion cooling global warming (kg CO2e) life cycle stages. 60

Table 10. Building life cycle carbon footprint with renewable energy proxy. 62

Table 11. Evaporative cooling global warming (kg CO2e) life cycle stages. 63

Table 12. Immersion cooling global warming (kg CO2e) life cycle stages. 65

Table 13. Building life cycle carbon footprint, zero out B6 stage. 67

Table 14. Evaporative cooling global warming (kg CO2e) life cycle stages. 68

Table 15. Immersion cooling global warming (kg CO2e) life cycle stages. 70

Table 16. Air cooled bill of materials. 87

Table 17. Air cooled data sources. 95

Table 18. Liquid cooled bill of materials. 103

Table 19. Liquid cooled data sources.....110

List of Figures

Figure 1. Degree of processor cooling difficulty. 9

Figure 2. Evaporative cooling model. 13

Figure 3. Immersion cooling model and GRC product. 15

Figure 4. The EN 15978 Building Life Cycle Framework.....17

Figure 5. Uncertainty at every step. 38

Figure 6. LCA scope and boundaries. 44

Figure 7. Total life cycle impact by resource type, evaporative cooling. 59

Figure 8. Total life cycle impact by resource type, immersion cooling. 61

Figure 9. Total life cycle impact by resource type, evaporative cooling. 64

Figure 10. Total life cycle impact by resource type, immersion cooling. 66

Figure 11. Total life cycle impact by resource type, evaporative cooling. 69

Figure 12. Total life cycle impact by resource type, immersion cooling. 71

Figure 13. Carbon footprint comparison of life cycle stages (kg CO2e). 72

Figure 14. Life cycle carbon comparing elements. 73

Figure 15. Life cycle carbon by life cycle stage (without B6). 74

Figure 16. Life cycle carbon by element (without B6). 75

Figure 17. Life cycle carbon comparing elements (without B6). 75

Definition of Terms

Air cooling: A method of dissipating heat that uses air as a medium. It works by moving cooler air across the surface of a device or system to reduce its temperature.

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

Carbon dioxide equivalent (CO2e): the universal unit of measurement used to indicate the global warming potential (GWP) of each of the six greenhouse gases, expressed in terms of the GWP of one unit of carbon dioxide. It is used to evaluate the release (or avoidance of release) of different greenhouse gases on a common basis.

Embodied carbon emissions: The total greenhouse gas emissions generated during the entire life cycle of a product, including production, transportation, use, and disposal (*Construction LCA Glossary*, n.d.).

EPD (Environmental Product Declaration): A standardized document that quantifies environmental impacts associated with a product's life cycle, typically governed by ISO 14025. EPDs provide transparent, third-party verified information to evaluate environmental impacts, supporting sustainable decision-making.

Functional unit: represents the measurable function of a system, providing a consistent basis for comparison across scenarios evaluated in an LCA (Jolliet et al., 2016).

HVAC: Heating, ventilating, and air-conditioning systems.

Immersion cooling: A cooling method used in data centers where IT components and servers are directly immersed into a thermally conductive dielectric liquid or coolant.

LCA: Life cycle assessment (LCA): In regards to buildings, a comprehensive methodology used to evaluate the environmental impact of a building from cradle to grave, considering all stages of its life cycle, including materials, construction, operation, maintenance, and disposal (*Construction LCA Glossary*, n.d.).

LCC: Life cycle costing. An analysis method that calculates the total cost of ownership, considering all costs of acquiring, owning, and disposing of a building or system.

LCI: Life cycle inventory. A data collection phase in LCA where the inputs and outputs for a product throughout its life cycle are identified and quantified.

Liquid cooling systems: Cooling methods that use liquid or fluid as a medium to absorb and transfer heat away from the system, aiding in the prevention of overheating.

ISO 14040: An international standard specifying principles and framework for conducting Life Cycle Assessment (LCA), including the definition of goal and scope, inventory analysis, impact assessment, and interpretation. It supports transparent, comprehensive assessments of the environmental aspects of a product's life cycle.

ISO 14044: This standard provides guidelines and requirements for carrying out a Life Cycle Assessment (LCA), focusing on methods for data collection, impact assessment, and result interpretation. It complements ISO 14040 by detailing the methodological requirements.

ISO 14067: This standard specifies principles, requirements, and guidelines for quantifying and reporting the carbon footprint of products (CFP). It includes considerations for greenhouse gas emissions throughout a product's life cycle, ensuring that carbon footprint assessments are transparent, consistent, and comparable. This standard aligns with Life Cycle Assessment (LCA) methodologies and supports efforts to reduce the carbon impact of products by identifying significant emission sources.

MJ (Megajoule [of heat removed]): A unit of energy representing the amount of heat energy extracted from a system. In data centers, it can be used to measure the energy efficiency of cooling systems by indicating the total heat removed from IT equipment per unit of energy used by the cooling system.

MW (Megawatt [of computing capacity]): A unit of measurement representing the power capacity used to support computing workloads in data centers. For data centers, it includes not only power consumed by IT equipment but also cooling and auxiliary systems, used as a proxy for computational power.

Operational carbon emissions: The emissions produced as a direct result of a building's energy consumption during operation.

PCR (product category rules): Specific guidelines and requirements for developing EPDs, ensuring that assessments of environmental impacts follow consistent criteria. PCRs provide structure for comparing products within the same category by standardizing life cycle stages, data quality, and impact metrics.

PUE: Power usage effectiveness: a metric used to evaluate the energy efficiency of a data center. It is defined as the ratio of the total energy consumed by the data center (including cooling, lighting, and other infrastructure) to the energy consumed by the IT equipment (servers, storage, and networking devices).

Chapter I

Introduction

Data centers, spaces dedicated to holding servers to store and process data, are the nerve centers of the digital age, underpinning everything from businesses to social networks to financial institutions. As the digital information repositories of our era, they have proliferated with the exponential rise in data demand. By 2025, newly created data will be 175 zettabytes, equating to a 146-fold increase in the 15 years between 2010 and 2025 (Daigle, 2021). The US International Trade Commission noted that more data was created between 2018 and 2020 than in all human history preceding 2018. This growth and increasing workload of data centers has resulted in unprecedented energy consumption and carbon emissions, posing a significant sustainability challenge (Daigle, 2021; Masanet et al., 2020; Siddik et al., 2021).

Data centers are being planned, ordered and commissioned in record numbers. This is shown in statistics such as a 50% increase being forecast for the power footprint of data centers by 2025, as well as 500% growth in global data generated between 2019 and 2025, according to the Uptime Institute. Data centers are being built in unprecedented numbers and at far higher computing densities than ever before. Data centers need to pack more punch per rack or per square foot to keep up with demand (Robb, 2023).

In January 2024, the International Energy Agency (IEA) issued its energy outlook, highlighting electricity demand from emerging technologies such as data

centers, cryptocurrency, and artificial intelligence for the first time in its projections. “The IEA estimates that, added together, this usage represented almost 2 percent of global energy demand in 2022 — and that demand for these uses could double by 2026, which would make it roughly equal to the amount of electricity used by the entire country of Japan” (Calvert, 2024, p. 1).

Data centers are planned and engineered facilities designed to house an extensive array of information technology (IT) equipment, including servers, data storage systems, and networking infrastructure. The physical design of data center facilities is a complex task that considers several factors, including spatial layout for optimal equipment arrangement, structural robustness to withstand external and internal loads, and provisions for scalability to accommodate future growth (*How to Design and Build a Data Center*, n.d.). Although almost any building has the potential to operate some IT equipment, large scale enterprise data centers, called hyperscale data centers, consist of a facility dedicated to the housing and operation of IT equipment. A vital element of these hyperscale facilities, and a significant contributor to their overall energy consumption, is the cooling system, representing up to 40% of a data center's total energy consumption. (Zhang et al., 2017)

Conventional air cooling approaches necessitate larger buildings and more extensive heating, ventilating, and air-conditioning (HVAC) equipment, leading to escalated levels of energy use and water consumption. Additionally, air, as an insulator, is less suitable for efficiently dissipating the concentrated heat generated by server racks in data centers. Conversely, liquid cooling, utilizing mediums like water or non-conductive dielectric fluids, is far more adept and efficient at transferring heat than air,

more than 3,500 times more efficient (ASHRAE, 2021). The ability of liquid to carry significantly larger amounts of heat per volume offers tremendous advantages. Several promising and emerging direct liquid cooling techniques have shown potential in recent studies (Manganelli et al., 2021).

However, the environmental implications of transitioning from traditional air cooling to liquid cooling in data center facilities remain understudied. Framing the impacts of these cooling technologies in the context of a life cycle approach on data center facilities is crucial to achieving sustainability. The large-scale data center industry requires significant amounts of natural resources and contributes to environmental degradation while emitting large amounts of embodied and operational carbon dioxide emissions. The life cycle approach considers not only the operational impacts but also the material, energy, and water consumption during the manufacturing, construction & installation, and end-of-life phases (Hoosain et al., 2023; Kass & Ravagni, n.d.). Previous studies have focused on operational energy savings, water conservation, and cost savings; however, a comparative LCA will offer a more thorough understanding of the environmental impacts throughout the life cycle of these facilities.

Research Significance and Objectives

This thesis filled the existing research gap by conducting a comparative life cycle assessment (LCA) of data center facilities, explicitly comparing the environmental implications of adopting liquid cooling versus traditional air cooling. The significance of this research was its analysis and comparison of the environmental and cost impacts of adopting advanced liquid cooling technologies in data center facility design over their life cycle, thereby demonstrating the lowest carbon and cost effective design. The

implications of such research are vast, given the increasing prevalence of data centers and their significant contributions to energy consumption and greenhouse gas emissions.

This research is timely, considering the Open Compute Project's recognition of the importance of liquid cooling and data center LCAs, and the UN Environment Program - Copenhagen Center on Energy Efficiency calls for a multi-impact life cycle approach to determine data center sustainability (*Copenhagen Centre on Energy Efficiency*, n.d.; *Open Compute Project*, n.d.). The LCA results offer a holistic view of the environmental impacts and sustainability implications. In this context, the proposed research provided valuable insights and guidance for data center operators, designers, construction managers, and sustainability professionals, informing design and operation strategies for future data centers.

Therefore, the objectives of this research were:

- To perform a comparative LCA of a data center facility with liquid cooling systems and a data center with traditional air cooling systems, analyzing the carbon footprint of each
- To identify the most environmentally sustainable cooling method, provide recommendations for reducing the environmental impact of data centers, thereby facilitating more informed decision-making in the design and operation of these facilities
- To analyze the effects of liquid cooling on data center facility design, including implications for structural considerations and spatial requirements. This analysis clarified the broader implications of adopting advanced cooling technologies beyond energy and water conservation

- To conduct a total cost of ownership (TCO) analysis comparing liquid and traditional air cooling systems in data centers, factoring in upfront, operational, and life cycle costs (LCC)

Background

According to the Global Alliance of Buildings and Construction, “in 2021, the building and construction sector accounted for around 37% of energy and process-related global emissions, reaching an all-time high of approximately 10 GtCO2” (Huang et al., 2018; *Tracking Progress | Globalabc*, n.d.). Due to their nature of operation, “data centers are energy-intensive enterprises, estimated to account for around 1% of worldwide electricity use” (Masanet et al., 2020, p. 984). In addition, the servers housed within data centers generate significant heat, necessitating robust cooling systems. Two primary types of cooling systems are traditionally employed in data centers: air cooling and liquid cooling, each having distinct features and operational dynamics.

The study emphasizes that while decarbonization in early construction stages (A1-A3) is well-documented, there is a research gap in addressing emissions during transportation, operations, and end-of-life phases. Additionally, the lack of real-time carbon assessments during operational stages (B6-B7) hinders precise emissions tracking, highlighting the need for continuous carbon-tracking methodologies and standardization in LCAs. These findings are particularly relevant for understanding the comprehensive carbon impacts of advanced cooling technologies in data centers, suggesting that improvements in real-time carbon tracking and life cycle integration could be essential for reducing the environmental footprint in this sector.

The rapid evolution of data centers and escalating concerns about their environmental impact underscores the need for comprehensive and comparative studies. While the potential benefits of advanced cooling technologies such as liquid cooling are increasingly recognized, research that holistically examines these benefits within a life cycle context remains sparse. Case studies are beginning to emerge comparing liquid cooling with air cooling from a perspective of operational energy savings, water conservation, and cost savings, yet none have approached this topic with a life cycle view of environmental impacts (Major et al., 2022; Pambudi et al., 2022; Shah et al., 2011; Thornock et al., 2023). Concurrently, LCAs are becoming more common in the general built environment to benchmark and determine lower carbon materials, but few LCAs are being done on energy-intensive and mechanical, electrical, and plumbing (MEP) heavy projects such as data centers (Fnais et al., 2022; Röck et al., 2020). Limited data is available for LCAs being performed on data center projects, possibly due to the resource-intensive heavy workload of performing whole building LCAs (Flucker et al., 2018). The author has found almost no research that performs a comparative LCA to determine the overall effects of advanced cooling on data center design. This gap may exist due to the workload required for LCAs and the fact that liquid cooling historically has been a niche market, only recently being explored in hyperscale data centers due to the convergence of AI computing requirements and the spotlight on energy and water consumption of data centers.

While decarbonization in early construction stages (A1-A3) is well-documented, there is a research gap in addressing emissions during transportation, operations, and end-of-life phases. The lack of carbon assessments during operational stages (B6-B7) hinders

emissions reporting, highlighting the need for carbon-tracking methodologies and standardization (Paneru et al., 2024). Understanding the comprehensive carbon impacts of advanced cooling technologies in data centers will potentially highlight that improvements in carbon tracking and life cycle integration could be essential for reducing the environmental footprint of data centers.

Air Cooling and Liquid Cooling

Traditional air cooling is a widely adopted technique for heat management in data centers. It employs large volumes of air to dissipate heat from the equipment, a process that can be energy-intensive, especially for large-scale facilities. In this system, cooler ambient air is drawn across the equipment, absorbing heat, and then expelled outside the data center. Its efficiency largely depends on the ambient temperature, which can pose challenges in warmer climates without additional cooling mechanisms. This method primarily utilizes fans, heat sinks, and in certain instances, Computer Room Air Conditioners (CRAC) or Computer Room Air Handlers (CRAH) for heat dissipation. (*Data Center Cooling 101*, 2023). A variant of this method, evaporative air cooling, leverages the process of water evaporation to lower the air temperature. However, this method can be water-intensive, and its efficiency can be affected by the ambient air's humidity level. The energy consumption in air cooling is primarily associated with the fan operation for air movement and additional cooling equipment if employed (Moazamigoodarzi et al., 2019).

Emerging as a promising alternative, liquid cooling uses a specialized non-conductive coolant to absorb and transport heat away from the data center components. Liquids offer significantly higher heat transfer efficiency than air, rendering liquid

cooling potentially more efficient. In direct-to-chip liquid cooling, coolant is circulated through a cold plate attached directly to the heat-generating components. Immersion cooling, another variant, involves submerging the entire hardware in a dielectric liquid coolant. Both methods offer superior heat transfer efficiency, facilitating higher cooling densities and allowing for more compact data center designs.

Driving the need for higher heat dissipation is the increasing performance demands and greater power for central processing units (CPUs) and graphic processing units (GPUs). Initially (2000-2010), performance was enhanced by increasing device power, nearing the threshold of requiring liquid cooling. This was circumvented by a shift to multicore processing (post-2010), spreading the power among more cores. However, since 2018, multicore benefits have waned, and power must be increased for further performance gains, resulting in higher heat loads (Figure 1). This current period, characterized by competing vendors increasing power to outperform their rivals, is called the “power wars” (ASHRAE, 2021).

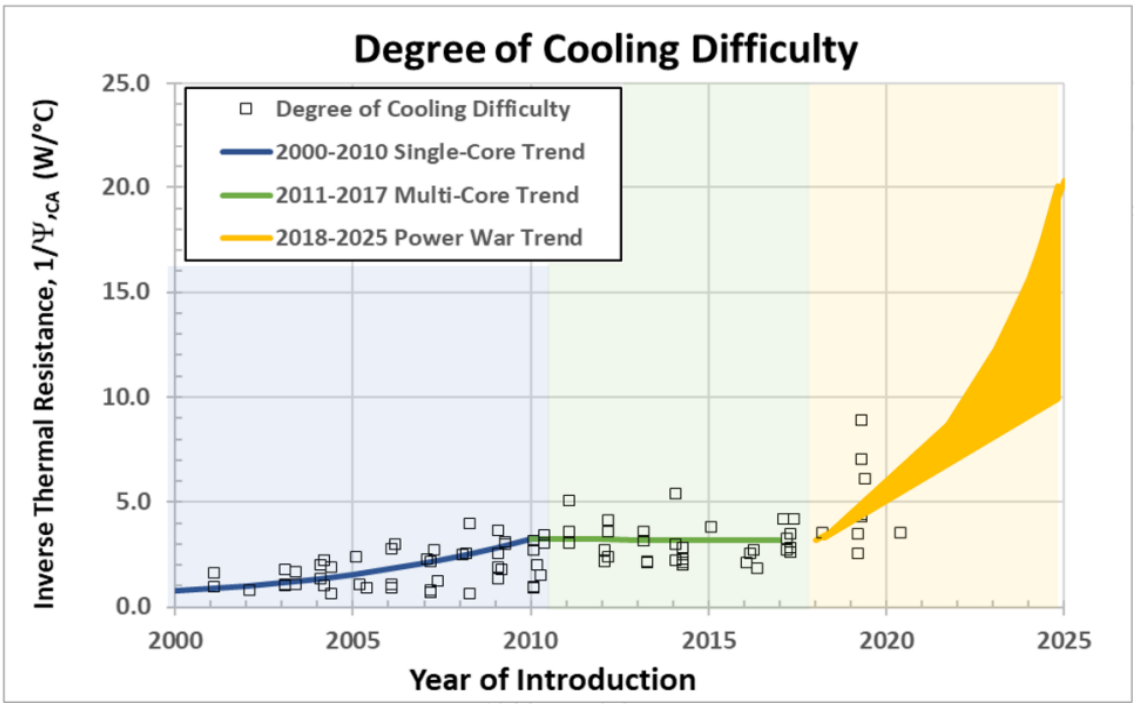


Figure 1. Degree of processor cooling difficulty.

(ASHRAE, 2021).

Liquid systems use pumps and heat exchangers instead of fans and HVAC equipment to cool the increased heat loads generated from the power wars. Pumps circulate the coolant, and heat exchangers extract the heat before the coolant is recirculated. This can result in significant energy savings, as pumps consume less energy than fans and HVAC systems in air-cooled data centers (*Liquid Cooling vs. Air Cooling in the Data Center*, n.d.; Major et al., 2022). However, these components require regular maintenance and can present risks such as potential leaks. In addition to these considerations, liquid cooling systems can offer other advantages, like reducing the need for bulky air-handling units, enabling higher server density, and shrinking the physical footprint of the data center, thereby contributing to cost savings.

Comparing the two, air cooling, while effective, often requires large volumes of air for heat dissipation, leading to significant energy consumption and larger data center facilities. In contrast, liquid cooling, given the higher heat transfer capacity of liquids, can cool effectively with lesser energy, leading to potentially lower operational energy costs and smaller data center buildings.

A pattern emerges from a review of studies on cooling methods in data centers: liquid cooling systems tend to offer greater energy efficiency than air cooling systems, primarily due to their superior heat transfer capacity. This shift in cooling models can significantly decrease a data center's cooling energy consumption. These studies encompass a broad range of variables, such as server density, varied climatic conditions, and the characteristics of regional electricity grids.

In high-density server environments, a prevalent characteristic of hyperscale data centers and cryptocurrency mining facilities engaged in the power wars, liquid immersion cooling has been found to exhibit exceptional efficiency. Pambudi et al. (2022) noted that this cooling methodology demonstrates the capacity to regulate thermal conditions across substantial server arrays while achieving a 22% reduction in energy consumption compared to conventional air cooling systems. However, liquid cooling may not be warranted when there is less demand for processor performance.

The universal application of liquid cooling across all climatic conditions remains an open question. The study conducted by Pambudi et al. (2022), for instance, took place in the hot and humid climate of Singapore, while IBM tested a liquid cooling system during a hot summer day in Poughkeepsie, New York (Iyengar et al., 2012). In this test, the energy required for cooling represented less than 3.5% of the total IT power

consumption, a considerable contrast to the 40% typically observed in traditional data centers (X. Zhang et al., 2017). This constitutes an impressive 90% decrease in cooling energy consumption. Given these parameters, a standard 1 Megawatt data center could potentially realize annual savings of $240,000, assuming an energy cost of $0.11 per kWh (Iyengar et al., 2012).

Chi et al. (2014) compared the efficiencies of an air-cooled system and a fully immersed liquid cooled system operating under identical IT hardware conditions, in the temperate climate of Leeds, UK. The results favored the liquid-cooled system, which yielded around 96 kW of power savings and an 88% reduction in cooling energy consumption (Chi et al., 2014). Furthermore, in colder climates, the feasibility of free cooling for data centers presents an attractive option. “Free cooling of data centers utilizes a natural cold source, making it possible to save the energy consumption of data centers” and achieve the purpose of cooling in a renewable and sustainable way (Zhang et al., 2014, p. 172). For instance, a free cooling study conducted in China demonstrated the considerable potential of this method (Dong et al., 2017). The study found that the available utilization time of outside cold air in Beijing and Kunming exceeded 6,000 hours; in Harbin, it was over 7,000 hours. These figures translated to a substantial decrease in cooling costs, ranging from 68%-80%, thereby highlighting the significant benefits of free cooling in suitable climates.

Even though successful implementation of liquid cooling technology has been documented in hotter climates, such as the tropical environment of Singapore, the hot New York summer, and the temperate climate of Leeds, the need for evaluating further climate variables is evident. Specifically, comparing liquid cooling’s efficacy in colder

and drier climates, where evaporative air cooling and free cooling are known to perform well, requires investigation.

Lastly, the carbon reductions of liquid cooling systems are tightly linked to regional electrical grid characteristics. For instance, in regions heavily reliant on fossil fuels for electricity generation, the energy savings from liquid cooling could significantly reduce carbon emissions (Pambudi et al., 2022). Conversely, data centers that source their energy primarily from inexpensive clean grids or renewable sources, driving their operational emissions to near-zero levels, may exhibit lesser sensitivity to the energy savings realized by the adoption of liquid cooling technologies.

While the findings from these studies present a compelling case for liquid cooling systems, the path to wide-scale adoption requires continued research to understand the full breadth of benefits and situational dependencies associated with this promising technology. Variables such as the specifics of regional electricity grids, server power and density, and diverse climates, particularly colder and dryer climates, necessitate further exploration.

Model Overviews: Air Cooling and Liquid Cooling

The conventional evaporative air cooled data center model is a widely used cooling system, designed to manage the heat generated by servers and IT equipment. This system works by drawing ambient air over cooling coils, where water is evaporated to lower the air temperature before circulating it through the data center (Figure 2). It relies heavily on air movement and the evaporative cooling process to dissipate heat, making it energy and water intensive, especially in warm climates. Evaporative air cooling is cost-effective and easier to implement compared to advanced cooling technologies like liquid

cooling. However, even under standard operating conditions, evaporative cooling typically results in higher energy consumption and water use. An evaporative system's efficiency is dependent on external environmental conditions such as temperature and humidity, which can limit its performance in certain climates. Despite these limitations, it remains the conventional choice for data centers due to its relatively low upfront costs and established infrastructure.

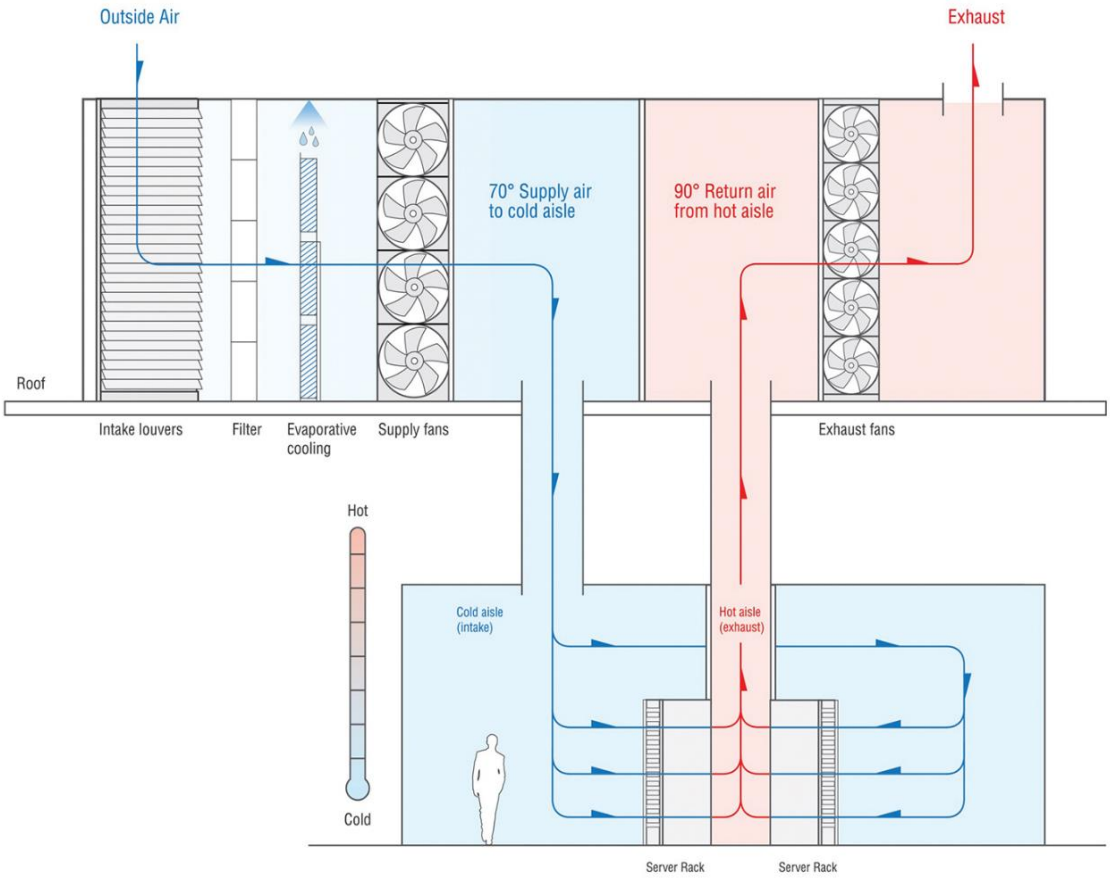


Figure 2. Evaporative cooling model.

(Heslin, 2015)

Liquid immersion cooling is an innovative and highly efficient method of thermal management for data centers (Figure 3). In this system servers and IT components are

fully submerged in a thermally conductive, dielectric liquid (Gloukhovtsev, 2024). Liquid immersion cooling offers superior heat dissipation compared to air or even direct liquid cooling (DLC), making it effective for high-performance, high-density computing environments such as those used in AI, machine learning, and cryptocurrency mining. By eliminating the reliance on air movement, immersion cooling significantly reduces energy consumption and can allow for more compact and efficient data center designs. This method reduces the need for water and minimizes noise and maintenance requirements. While it requires a higher initial investment, immersion cooling provides substantial long-term operational savings and environmental benefits, positioning it as the cutting-edge solution for sustainable data center operations.

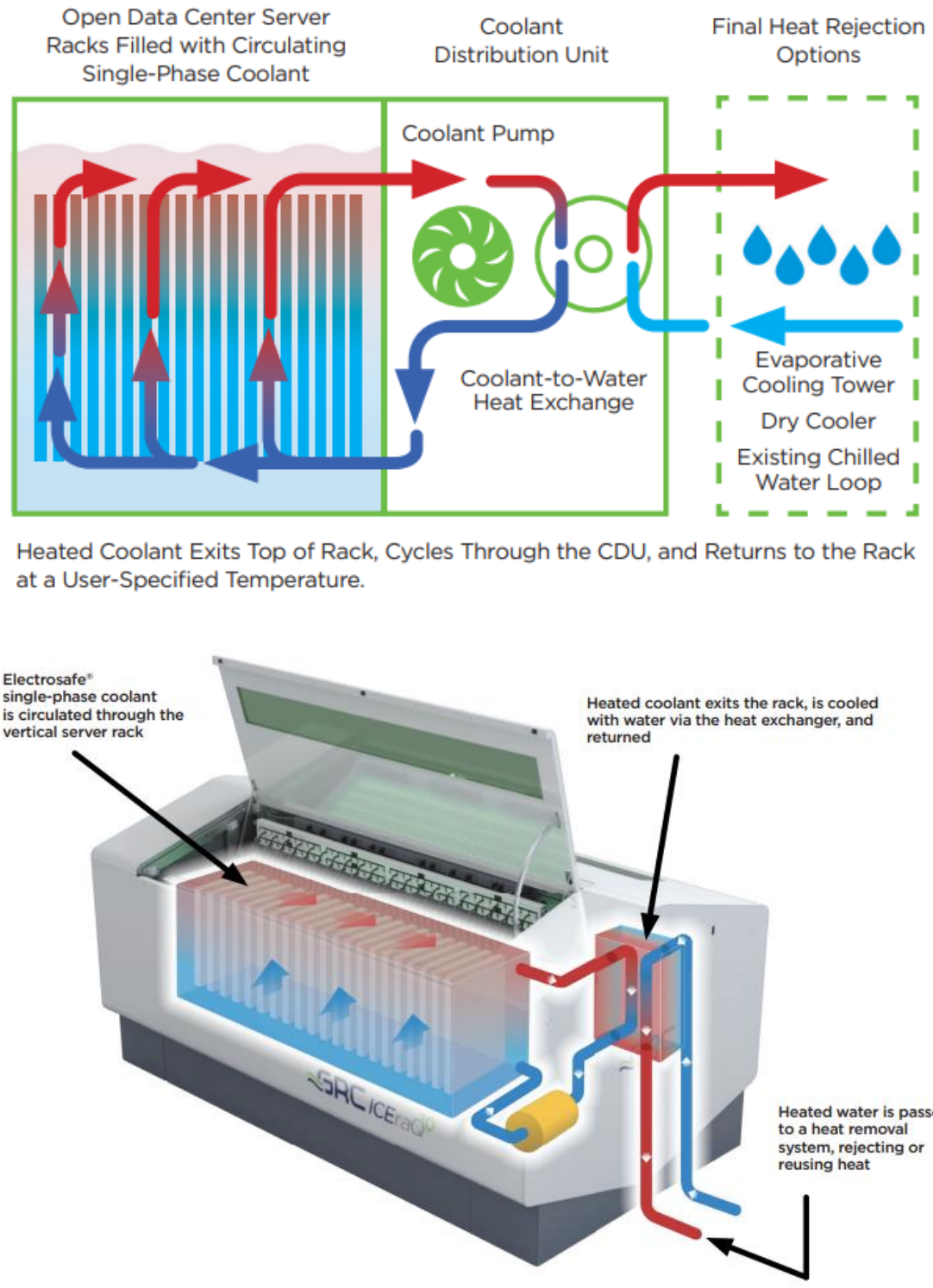


Figure 3. Immersion cooling model and GRC product.

*(*Comparing Data Center Cooling Technologies, *n.d.; GRC - Green Revolution Cooling, 2018)*

Energy Source Carbon Emissions for Data Center Operations

The energy source powering a data center is a critical factor in determining its carbon emissions, as operational energy consumption typically accounts for the majority of a data center's total life cycle emissions. Modern data centers, especially those using advanced cooling technologies, can consume energy equivalent to small towns, placing immense pressure on energy grids. The carbon intensity of these operations is directly linked to the composition of the energy grid—whether it relies on fossil fuels or renewables.

Data centers that procure renewable energy, via Power Purchase Agreements (PPAs) or on-site generation, significantly reduce their carbon footprint by offsetting emissions from operational power consumption. This shift is essential for data centers operating in regions with carbon-heavy grids, where relying solely on energy efficiency measures may be insufficient to meet sustainability targets. The operational phase emissions, categorized under Scope 2 (indirect emissions from purchased electricity), can be drastically reduced when renewable energy is prioritized.

Decarbonizing the energy source shifts attention toward embodied carbon, the emissions from the materials and construction of data centers. As grids decarbonize and data centers increasingly adopt renewable energy, embodied emissions will become a more significant portion of total life cycle emissions. Reducing embodied carbon and optimizing overall facility design must become a parallel focus to fully address the environmental impact of data center operations.

Life Cycle Assessment (LCA)

Buildings are significant contributors to greenhouse gas (GHG) emissions and thus are a critical area of focus in addressing the climate crisis. To effectively mitigate the climate-change impacts associated with buildings, it is crucial to consider not just their operational energy consumption and related GHG emissions but also their complete life cycle. In this respect, life cycle assessment (LCA) offers a comprehensive approach to assessing the environmental impacts of a product or service throughout its life cycle. When applied to evaluate the environmental impacts of materials and systems in a building, this method is often called Whole Building Life Cycle Assessment (WBLCA).

The WBLCA framework provides a standardized method for assessing the environmental impacts of buildings, breaking their life cycle into several distinct stages (*Embodied Carbon Primer*, n.d.). The majority of emissions from building and construction come from the use stage (B1-B7) and the product stage (A1-A3), as outlined in the EN 15978 Building Life Cycle Framework (Figure 4).

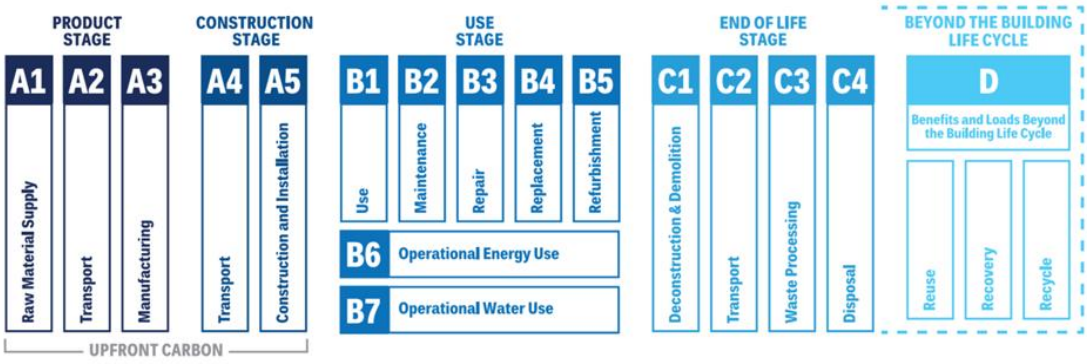


Figure 4. The EN 15978 Building Life Cycle Framework.

(Adopted from BS EN 15978: Sustainability of Construction Work, 2011)

The comprehensive approach provided by the EN 15978 Building Life Cycle Framework is a crucial tool for understanding the environmental implications of any structure, from raw materials to construction to end of life. While not yet commonplace, applying this same framework and methodology to data centers is necessary. Studies have begun to venture into LCAs for data centers, including the early analysis of Shah et al. (2011) on the life cycle impact of a hypothetical data center in the USA. Using a combination of economic input-output models, which examine inter-industry relationships, and process-based analyses, which focus on individual system operations, their findings underscored the need to broaden evaluation metrics beyond merely operational energy use for data centers to become more sustainable (Shah et al., 2011). Similarly, a recent study by Gorkem and Unver (2023) used LCA to investigate the environmental impacts of a data center using the Ecoinvent database, an internationally recognized Life Cycle Inventory (LCI) database (Görkem Üçtuğ & Can Ünver, 2023). The models introduced in their research provide a framework that allows data center designers and managers to gauge the relative environmental impacts of varying design or operational choices.

These traditional research approaches, such as economic input-output models and secondary data from LCI databases, are utilized when specific inventory data are unavailable. Once Environmental Product Declarations (EPDs) are available for the specific products involved in the analyzed system, “the data derived from these sources should be utilized instead of traditional input and output information due to their higher quality level” (Strazza et al., 2016, p. 334). This approach ensures that the research utilizes the most precise and relevant data possible. Primary, product-specific data is

favored due to its direct relevance and specificity. However, in its absence, the use of secondary data from credible sources fills the gap, preserving the integrity of the research analysis (Strazza et al., 2016).

Whitehead et al. (2015) noted that most data center environmental impact assessments primarily focus on energy consumption and often fail to consider the interconnectedness of various issues. They argued for a more comprehensive, holistic approach, reinforcing the emphasis Shah et al. (2011) placed on moving beyond simple energy consumption metrics to understand data center sustainability fully. While the studies mentioned provide important insights, they also highlight the complexity of evaluating the environmental impact of data centers. The results of LCA studies depend heavily on the methodological approaches employed, the quality of primary and secondary data, and the specific data center characteristics examined.

Data Center Facility Size

The energy savings and improved heat dissipation efficiency of liquid cooling systems can also lead to potentially smaller data center building sizes. This is particularly relevant for hyperscale data centers, where cooling constitutes a significant portion of the total facility size.

On the environmental impact front, liquid cooling reduces water consumption, energy use, and overall data center footprint compared to air-cooled data centers (Major et al., 2022). Their case study analyzed two 36 MW hypothetical data center concepts: a traditional evaporative air-cooled data center and a liquid immersion cooling data center, and examined several components of design: mechanical systems (cooling), electrical systems, and physical space. The authors concluded that liquid cooling reduced the total

campus lot area by 31% and reduced the data center building size by 60% compared to air-cooled data centers (Major et al., 2022).

Spatial requirements for immersion cooling are one-third smaller than CRAC infrastructure resulting in higher energy efficiency, less GHG emissions, and less building construction (Pambudi et al., 2022). One-third less infrastructure results in less concrete and steel structural elements, and less mechanical, electrical, and plumbing (MEP) for each data hall, thereby reducing the embodied carbon of the facility.

As hyperscale data center operators begin to incorporate renewable energy sources into their operations, the emissions associated with the B stage operational energy use are significantly reduced, often nearing zero. This shift makes the embodied carbon in the facility a more prominent aspect of the total life cycle emissions. In this context, liquid cooling technologies offer even more significant advantages. The reduction in infrastructure size translates into less use of concrete and steel, the two materials with the highest embodied carbon footprints (Pambudi et al., 2022). The adoption of liquid cooling can help to further reduce the life cycle emissions of data centers, particularly as these facilities transition towards renewable energy use and the balance of emissions shifts from operational energy use to embodied carbon.

Life Cycle Cost (LCC)

The life cycle cost analysis of data center cooling methods, specifically air and liquid cooling, involves upfront and operational costs. While the examined studies (Jalili et al., 2021; Kanbur et al., 2021; Pambudi et al., 2022) generally concur that liquid cooling systems have a higher initial investment, they also underscore the potential for significant operational cost savings due to enhanced energy and water efficiency.

Jalili et al. (2021) conducted a cost-benefit analysis of a liquid immersion cooling system compared to a traditional air-cooled system in a data center. The authors found that while the initial investment for the liquid cooling system was higher due to the need for specialized equipment and potential retrofitting of the data center, the operational costs were significantly lower. The reduction in operational costs was attributed to a decrease in energy use for cooling and less maintenance required, outweighing the initial investment over time. The authors also noted that the overhead cost of air cooling increases with higher server power, whereas costs remain relatively stable with liquid cooling. To test this theory, they built three immersion tanks and boosted the processor speed, discovering immersion cooling provides power savings offsets, compensates for the chip degradation, and provides thermal benefits, resulting in a 7% decrease in the total cost of ownership (TCO) (Jalili et al., 2021).

Kanbur et al. (2021) examined the economic feasibility of a direct-to-chip liquid cooling system in a high-performance computing data center. Similar to Jalili et al., the authors observed that liquid immersion becomes more affordable for higher server power rates, which are required by advanced computing such as AI, and have a lower future life cycle cost. The study also highlighted the reduction in cooling infrastructure, such as CRAC units, contributing to space savings and additional cost benefits. Kanbur et al. (2021) concluded that despite the higher upfront cost, the liquid cooling system offered substantial energy savings, especially in high-density server configurations.

Pambudi et al. (2022) evaluated the total cost of ownership of data centers using air and liquid cooling systems. In addition, their findings suggested that liquid cooling systems may be lower cost and less capital investment while leading to a decrease in the

TCO due to lower energy consumption and less dependency on external cooling infrastructure (Pambudi et al., 2022). In line with the Pambudi findings, Iceotope, a manufacturer of cold plate liquid cooling technology, states that their system has a 20-year TCO savings of 11% compared to traditional air cooled solutions (*Precision Liquid Cooling from the Cloud to the Edge*, n.d.).

The Need for a Deeper Environmental and Cost-Effective Analysis

While liquid cooling has been shown to surpass traditional air cooling in terms of energy efficiency, translating into reduced energy consumption and smaller building footprints, a more in-depth exploration of its specific environmental consequences is needed. The existing literature consistently suggests that liquid cooling can mitigate the environmental impact of data centers due to their lower carbon footprint, reduced water use, and efficient land use.

Several forward-looking industry stakeholders are now beginning to share remarkable metrics related to their liquid cooling systems. For instance, Iceotope, a prominent industry player, boasts a substantial 96% reduction in water usage, a 40% decrease in power usage, and a 40% reduction in CO2 emissions achieved with their liquid cooling systems (*Precision Liquid Cooling from the Cloud to the Edge*, n.d.). Another manufacturer, Submer, claims a massive 95% reduction in cooling operating expenditure, a halving of building capital costs, and a savings of between 25% to 40% on the total cost of ownership (TCO) facilitated by their liquid cooling solutions (*Submer | Smart Solutions for Next Generation Datacenters*, n.d.).

However, while these industry claims are promising, it is important to interpret them in the context of other variables. Factors such as power requirements, geographic

location, scale of operation, and the specific technologies used can significantly impact these results. Furthermore, while these figures speak to the energy and cost efficiency of liquid cooling systems, they do not present a comprehensive picture of their overall environmental impact, including resource extraction, manufacturing, use, and end-of-life disposal or recycling.

Comprehensive LCA and LCC studies of liquid cooling systems for data centers remain sparse. This lack of holistic analysis presents an opportunity to test the assertions that liquid cooling is more energy-efficient than traditional air cooling, reducing energy consumption and operating costs in the long run. However, the specific environmental implications of liquid cooling, especially within a comparative LCA context with traditional air cooling, remain underexplored. The void of life cycle analysis in the academic literature regarding the liquid cooling of data centers presents an opportunity for further study.

Research Questions, Hypotheses, and Specific Aims

The research questions of this study were:

1. How do the carbon footprints of liquid and conventional air cooling methods in data centers compare when evaluated through a comprehensive LCA?
2. How does adopting liquid cooling in data centers influence the facility design and use of resources such as energy, water, and structural components?
3. What are the cost implications of transitioning from traditional air cooling methods to liquid cooling in data centers, considering both upfront and operational costs?
4. How big of an impact does renewable energy procurement play in the context of whole life carbon emissions?

5. How does the operational efficiency of the cooling systems affect data center design after the power source has been decarbonized?

In addressing these questions, this study examined the following hypotheses:

- H1: Data centers with liquid cooling systems exhibit a 50% reduction in embodied and operational carbon emissions over their life cycle compared to those with traditional air cooled systems when evaluated through LCA.
- H2: Adopting liquid cooling systems in data centers results in significant changes in facility design, leading to near-zero water use (95% reduction), and a 50% reduction in data center building size.
- H3: Liquid cooling systems may have higher upfront costs than traditional air cooling systems. However, the smaller building size and the lower operational costs due to increased energy and water efficiency make liquid cooling a cost-neutral solution when TCO is evaluated over a 20-year life cycle.

Specific Aims

The specific aims of this research on the life cycle assessment (LCA) of air cooling and liquid cooling systems on data center facilities were to:

1. Collect a comprehensive inventory of materials and equipment used in the construction, installation, and operation of data center facilities utilizing both air and liquid cooling systems.
2. Define the functional units that will be used in the LCA to standardize the comparison between air and liquid cooling systems.

3. Establish the system boundaries for the LCA, delineating the stages of the cooling systems' life cycle to be included in the analysis, from manufacturing and installation to operation and end-of-life disposal.
4. Set the assumptions and limitations underpinning the LCA, including the scope of data considered, the environmental impact categories assessed, and any inherent uncertainties in the analysis.
5. Develop LCA models detailing the carbon emissions of both air and liquid cooling systems.
6. Compile and analyze cost data associated with the construction and operations of data centers with both air and liquid cooling systems.
7. Using data gathered and models developed, perform a detailed comparative analysis of air and liquid cooling systems in terms of environmental impacts, including embodied and operational carbon emissions.
8. Conduct a sensitivity analysis if renewable energy were to be procured, reducing the operational emissions, and what impact that has on the results.

Chapter II

Methods

To test my hypotheses, the research methodology involved conducting a comparative LCA and LCC analysis. This included not only the operational phase but also the environmental impacts throughout the life cycle of the data center facility. I collected data on the manufacturing, transportation, installation, operation, maintenance, and end-of-life disposal or recycling of the building elements and cooling systems.

Life Cycle Assessment (LCA)

The comparative LCA adhered to the ISO 14040 and 14044 standards, covering all stages of the building life cycle from A1 to C5. The primary objective was to compare a data center equipped with a liquid cooling system and another utilizing air cooling mechanisms. This LCA, encompassing the entire life cycle, provided an in-depth evaluation of the environmental impacts associated with each cooling methodology. Results were compared using an LCA program with two models: a data center model with evaporative air cooling (the business-as-usual or baseline) and a liquid cooled data center model. This study considered land use, concrete and steel structural elements, mechanical, electrical, and plumbing (MEP) for each cooling system, and operational energy and water use. Some methodological details are:

- I used One Click LCA software to create the data center models.

- The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1) impact assessment method was utilized within the One Click LCA software.
- A geography or temperature and humidity levels of a region in North America was selected.
- Functional unit was defined as 1 MW of computing capacity. The scale of the data center models was 10 MW data halls on a campus consisting of five data halls for a total of 50 MW capacity data center.
- System boundaries included major raw materials, utilities, manufacturing, consumer market for data, use phase, energy production, and end of life. The IT and networking equipment, minor raw materials, retail sales, and networking use phase were excluded.

Life Cycle Inventory (LCI)

The LCI stage, the data collection phase, is the most significant determinant of LCA results. Primary data were collected from manufacturers and industry experts through Environmental Product Declarations (EPDs). Traditional air cooled data centers are common, and data were readily available. Liquid cooled systems are novel and were more challenging to obtain. Since the IT and the network equipment remain unchanged between the two models, data on the IT equipment production is not required and, therefore, were excluded.

The data covered various aspects of the facility operations, including but not limited to energy use, water use, carbon emissions, and other environmental factors, as

well as embodied carbon of material and cost data related to the installation and construction of the data center and cooling systems. Secondary data were sourced from relevant databases, industry reports, and academic papers. Collected data included:

- Total energy consumption, energy used by the IT equipment, energy used by the cooling systems, peak power draw, and Power Usage Effectiveness (PUE). These data allowed evaluation of energy efficiency by comparing total energy with energy from IT equipment.
- Environmental data included carbon emissions and water use.
- Design and construction data included: building square foot, upfront and embodied emissions from the structure and envelope of the building, and the MEP systems related to the cooling.
- Upfront and operational costs were collected or estimated from industry sources.
- Grid and renewable energy data were obtained from sources such as the U.S. EPA's EGRID database.

Life Cycle Cost (LCC) Analysis

An LCC analysis was conducted to assess the economic implications of transitioning from air cooling to liquid cooling. The analysis examined both systems' immediate and long-term operational costs, considering factors such as energy and water usage. As part of the economic analysis of data centers, I considered primary inputs, including capital, operating, energy, and water costs. The data collection encompassed:

- Capital costs including the construction and installation of cooling systems from equipment manufacturers, suppliers, and construction cost databases.

- Operational costs derived from industry reports, operational data from existing data centers, and interactions with industry experts.
- The cost of energy consumption and water usage obtained from utility companies and regional energy and water price databases.

For the LCC analysis, the following steps were employed:

- The study period was defined as 20 years, the typical lifespan of a data center facility.
- The results were compared, and the cost-effectiveness of both cooling methods was analyzed.

This LCC analysis was conducted in parallel with the LCA, providing a holistic view of the financial and environmental implications of both cooling systems throughout the data center's life cycle.

One Click LCA and the Life Cycle Carbon Tool

One Click LCA is a software tool designed to streamline the process of conducting LCAs for buildings, infrastructure, and construction products. It enables users to calculate environmental impacts such as carbon emissions, material efficiency, and energy use over a project’s entire life cycle. One Click LCA automates much of the analysis process by integrating with industry databases and design tools, making it easier for sustainability professionals to assess the environmental performance of their projects. The tool supports various certification schemes, including LEED, and is aligned with the ISO 14040 and ISO 14044 international standards, making it a widely adopted solution for the building industry.

The educational license for One Click LCA that I was able to obtain was restricted to the Life Cycle Carbon Tool, which limited the scope of analysis to carbon related impacts of projects. The Life Cycle Carbon Tool focuses specifically on calculating the carbon footprint of buildings and construction projects throughout their entire life cycle, from material extraction and manufacturing to construction, use, and eventual demolition or recycling. This tool is primarily used to quantify embodied carbon and operational carbon emissions, offering insights into how design choices and material selection affect a building's overall carbon impact. While this is a valuable feature for assessing environmental performance, the restriction to only carbon related aspects excluded the other environmental impact categories, such as water use, biodiversity, or resource depletion, which would be available in the full One Click license. This limitation meant that I only performed partial environmental analyses focused on carbon and did not perform comprehensive LCAs.

Data Sources and Methodologies

Data quality assessment is critical to ensuring the accuracy and reliability of the carbon footprint analyses of liquid and air cooled data centers. Primary data, such as Environmental Product Declarations (EPDs) and direct measurements from manufacturers, were prioritized to ensure high quality inputs. Where primary data were unavailable, secondary data from databases and industry reports were utilized, with attention to transparency and alignment with ISO 14040 and 14044 standards. Any limitations or assumptions related to data gaps were clearly documented.

Given the current limitations in data availability and Product Category Rules

(PCR) development, several methodologies and data sources were utilized to estimate the environmental impact of mechanical, electrical, and plumbing (MEP) systems:

- TM65 methodology:
    - Basic Calculation: This involves straightforward estimations using readily available data, but with lower accuracy.
    - Mid-level Calculation: provides a more detailed assessment using more specific data points, which are often estimated if not directly available.
- Generic data sources:
    - Platforms like One Click offer generic data that can be used for preliminary assessments of MEP systems. This data, while not specific to any one product, can provide a baseline for environmental impact.
- Weight-based calculations:
    - Often used as a last resort, weight-based calculations provide a very rough proxy for environmental impact based on the material composition and total weight of the systems. This method is the least preferred due to its high level of generalization and low accuracy, however it is a common current industry practice.
- Preferred but unavailable data sources. Ideally, the assessment of MEP systems would rely on:
    - Product-Specific EPDs: These would provide the most accurate and relevant environmental impact data for individual MEP systems but are not yet available due to the lack of PCRs.

- Industry-wide EPDs: These would offer a broader view of environmental impacts across an industry segment, providing useful benchmarks and averages that could be used for comparison. However, these too are unavailable for cutting-edge MEP systems

The assessment of the environmental impact of MEP systems in data centers faces significant challenges due to the lack of specific EPDs and the ongoing development of PCRs. In this landscape, methodologies like TM65 offer alternative routes for assessment, though they come with limitations in precision and specificity. As the industry progresses and more specific PCRs are developed, it will become possible to generate more accurate and meaningful EPDs, enhancing the ability of data center designers and operators to make environmentally informed decisions. Meanwhile, exploring generic databases and improving the granularity of available methods can partially mitigate these challenges.

CIBSE TM65 Methodology

TM65, developed by CIBSE (the Chartered Institution of Building Services Engineers), provides methodologies for quantifying embodied carbon in building services. This tool fills a significant gap in the LCA of building services equipment by offering a standardized approach to calculating carbon emissions associated with the manufacture, transportation, installation, maintenance, and disposal of MEP equipment.

While TM65 provides a robust framework, it is fundamentally a bridging solution until more specific PCRs are developed for various types of MEP equipment in data centers. PCRs are essential for creating product-specific environmental declarations and ensuring comparability between products. In the absence of such rules, TM65 offers a

reliable method for assessing environmental impacts that can inform design decisions, facilitate regulatory compliance, and support the pursuit of sustainability certifications.

The evaluation of the environmental impact of Mechanical, Electrical, and Plumbing (MEP) systems in data centers is currently hindered by several significant challenges:

- Lack of EPDs: MEP systems, particularly those incorporating advanced, cutting-edge technologies, do not yet have EPDs. This absence is due to the nascent stage of PCRs development for these systems.
- PCR Development: Although there is ongoing development of PCRs, they have not yet been established for these advanced MEP systems. This gap makes it difficult to create standardized and reliable EPDs that could help in assessing their environmental impact comprehensively.
- Absence of Integrated Software Solutions: Currently, there is no software that offers a comprehensive database of MEP systems, which further complicates the process of environmental impact assessment.
- Necessity of Using TM65: Due to these limitations, the use of methodologies like TM65 becomes essential. TM65 provides a structured approach to estimate environmental impacts in the absence of specific data, although it is not as precise as product-specific EPDs.

Interpretation, Comparison, and Sensitivity Analysis

To ensure the robustness of the models and their results, I performed a comparative analysis of the two distinct models. This comparison aimed to evaluate their

respective impacts on environmental sustainability and identify potential opportunities for improvements in both environmental and financial aspects. I altered key parameters within the models to understand how changes in these values impact the overall results. Parameters such as temperature and humidity, which affect the efficiency of both air and liquid cooling systems, were among the primary variables considered in the sensitivity analysis. This allowed me to assess the relative performance of air and liquid cooling systems under varying seasons and environmental circumstances.

Sensitivity analyses play a critical role in evaluating the life cycle carbon results for liquid and conventional air cooled data centers. The analyses were designed to test how changes in key parameters – such as procuring renewable energy and variability in cooling demands – affect the overall carbon footprint of data centers with the respective cooling systems. One sensitivity analysis explored how adopting a higher percentage of renewable energy in data center operations would influence the carbon footprint. Another sensitivity analysis zeroed out the B6 operational energy and focused on how the embodied carbon is affected by the different cooling systems. These sensitivity analyses provided a better understanding of the potential benefits and limitations of each cooling technology under varying operational conditions, providing insight into how these factors impact the sustainability of data center design and operation.

Additionally, I explored other factors, including the proportion of renewable energy utilized and the effects of geographic differences, such as cold climate operation. These evaluations aimed to broaden my understanding of the environmental and economic performance of air-cooled and liquid-cooled data centers under various scenarios.

One of these analyses focused on integrating renewable energy procurement into these models and examined how it may influence the overall results. The hypothesis for this sensitivity analysis was that operational emissions would decrease with the introduction of renewable energy procurement, leading to a bias towards embodied carbon reductions. This hypothesis emerged from recognizing that renewable energy sources, unlike traditional fossil fuels, do not contribute significantly to carbon emissions during their operational phase.

Research Limitations

This research was subject to several limitations related to data availability, analysis methods, research scope, and resources. The primary challenge was the availability and quality of data. Although data on traditional air-cooled data centers are relatively abundant, information about emerging liquid cooling technologies can be scarce and potentially proprietary, making data collection challenging. EPDs, a vital primary data source, may not comprehensively cover all HVAC components (*MEP 2040*, n.d.). Given the time and resource-demanding nature of LCA and LCC analyses, these challenges may amplify, particularly during the data collection phase.

The LCA and LCC methodologies, while robust, might not fully represent real-world data center operations due to necessary assumptions and scope limitations. This could lead to underestimating environmental and economic impacts, especially with the exclusion of minor raw materials, IT equipment, and network use phases. Inherent LCA limitations include complexity, data, expertise requirement, potential lack of transparency, and uncertainties in data and modeling. The key to addressing these limitations lies in maintaining consistency in LCA methodology and transparency in the

data used, enabling reproducible results that instill trust in the data and facilitate accurate accounting (Balaji et al., 2023).

EPDs are standardized documents that provide quantifiable information about the environmental impacts of a product throughout its life cycle, following defined Product Category Rules (PCRs). Achieving comparability across EPDs can be challenging due to variations in data quality, scope, geographical coverage, and methodologies used in their creation. Differences in assumptions, functional units, or life cycle stages can lead to inconsistencies that may skew the results of the carbon footprints. ISO 14025 governs the structure and content of EPDs.

Current State of PCRs for MEP Equipment

The development of PCRs for MEP equipment in data centers is currently in its nascent stages. This lack of comprehensive PCRs poses significant challenges in assessing and comparing the environmental impacts of such equipment accurately. Without standardized PCRs, manufacturers might use different life cycle stages, assumptions, and metrics in their EPDs, which leads to inconsistent data that complicates the decision-making process for data center designers and operators.

The absence of well-defined PCRs for data center MEP equipment, particularly advanced cooling technologies, impedes the ability to:

- Evaluate performance accurately: Without standard benchmarks, it becomes difficult to gauge the true environmental impact of different MEP systems.

- Drive improvements: Consistent and comparative environmental impact data incentivize manufacturers to innovate and reduce the environmental footprints of their products.
- Support regulatory compliance: Regulators rely on standardized information to set and enforce environmental standards and policies.

Uncertainty

LCA relies heavily on data, and the accuracy of its outcomes is strongly influenced by the quality of the input information:

> The building industry is fragmented and there are constraints in data collection in terms of availability of the human and financial resources as well as the time available to complete the project. Often, missing data and unrepresentative data influence the credibility of LCA results and lead to uncertainty in building LCA results (Warrier et al., 2024, p. 2).

In the general practice of whole building LCAs, the material quantity is obtained from the Bill of Materials (BOMs). The environmental information of materials is taken from databases of Environmental Product Declaration (EPD) datasets. Resch et al. (2021, p. 1) noted that:

> Climate change effects of material use in construction, operation, and end-of-life phases are estimated from production, transport, construction-waste incineration, biogenic carbon-sequestration, and cement carbonation, and there is uncertainty in every step of the process.

Outcomes may be influenced by uncertainties arising from factors such as variations in data, measurement inaccuracies, flawed estimates, incomplete datasets, and assumptions used in modeling (Figure 5). Researchers have proposed various frameworks to categorize and explain the different forms of uncertainty encountered in LCAs. Clavreul et al. (2012, p. 3) pointed out that:

A well-established one was introduced by Huijbregts (1998) and divides uncertainties into three groups: (1) parameter uncertainties refer to the uncertainty in values due to inherent variability, measurement imprecision or paucity of data; (2) scenario uncertainties are due to the necessary choices made to build scenarios; and (3) model uncertainties are due to the mathematical models underlying LCA calculations.

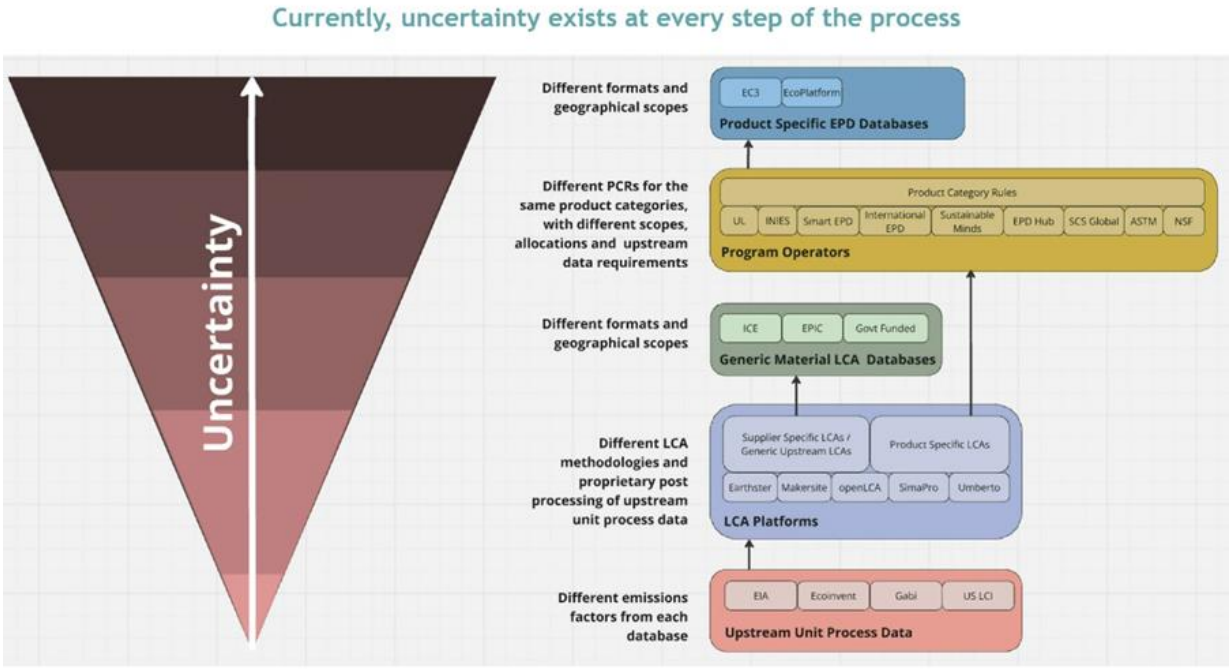


Figure 5. Uncertainty at every step.

(Stacey Smedley, Building Transparency)

Functional Unit

Selecting an appropriate functional unit is critical as it provides a reference to which all inputs and outputs are normalized. This unit provides a standard reference that enables the normalization of all inputs and outputs, allowing for a consistent basis for comparison between liquid and conventional air cooling systems.

This thesis employed 1 MW of computing capacity as the functional unit, chosen for its relevance in assessing the environmental impacts of cooling technologies in data

centers. As the data center industry often measures facility power in terms of megawatts, this functional unit aligns well with industry norms and is both widely recognized and scalable. It directly reflects the power needed to support a defined level of computational workload, enabling this study's results to be interpretable and actionable for stakeholders in data center operations. By focusing on 1 MW, the analysis can easily be scaled up or down, adapting to facilities of different sizes while focusing specifically on cooling demands tied to computational loads. Using 1 MW as a functional unit also emphasized the primary role of cooling systems in managing the substantial heat output from computing activities, ensuring the LCA accurately captures environmental impacts associated with maintaining stable computing performance in data centers.

While industry practice often quantifies data center power in MW, it is essential to recognize that this measure can have ambiguities. Power capacity figures, which appear in industry directories, news, and permits, may lack clarity on whether they represent only the maximum attainable IT load or the total operational power capacity of the entire facility, including cooling and auxiliary systems (Masanet et al., 2024). This lack of precision in defining MW can introduce uncertainties in environmental analyses, potentially affecting the accuracy of comparisons and overall energy demand estimations.

Traditional Space Conditioning Functional Unit

DeMarco and Fortier (2022) discussed the choice of the functional unit extensively, particularly in the context of space conditioning systems. Their analysis highlighted several key considerations for selecting a functional unit, including that it should reflect the primary service provided by the system under study. For air

conditioning systems in typically buildings, this often means focusing on the thermal comfort provided per unit of conditioned space. This is extremely important when comparing air conditioning systems themselves.

However, this thesis compared the environmental impact that different cooling technologies have on data center facilities. The choice of 1 MW of computing capacity reflects the primary output of data centers, computational power, rather than the physical space or thermal comfort achieved. By choosing 1 MW of computing capacity, this analysis aligned the functional unit with the operational focus of data centers, and all relevant energy and cooling requirements are accounted for within the system boundaries. This operational performance-based functional unit normalizes a consistent measure of computational performance, allowing for the comparability and relevance of results.

The choice of 1 MW of computing capacity as the functional unit provides a clear, relevant, and scalable measure for evaluating environmental impacts of different cooling technologies in data centers. This approach contrasts with DeMarco and Fortier's (2022) methodology, which is appropriate for space conditioning systems and comparability of the air conditioning units themselves. The space conditioning method would be more difficult for the industry to adopt as a useful comparison since the thermal properties of the chips would influence the heat generated. The 1 MW of computing capacity enables a direct comparison of different cooling technologies under a standardized performance metric. This facilitates a clear understanding of how each cooling method performs in terms of energy efficiency, water usage, and carbon emissions per unit of computing capacity. It is important that the functional unit be tailored to the specific product or operational context of the system being studied. By

aligning the functional unit with the core output of data centers, my analysis ensured that the LCA results are both meaningful and actionable within the industry.

Computing Capacity in MW for AI Workloads

In data centers supporting AI workloads, defining capacity in MW is especially useful for standardizing environmental impact assessments. AI-driven applications, such as machine learning and natural language processing, require high computational intensity and resource demands, often relying on energy-dense hardware like GPUs and specialized accelerators (Kachris, 2024). These workloads necessitate robust power for both IT equipment and cooling infrastructure, as AI applications involve high data throughput, extensive memory capacity, and dense processing architectures (Masanet et al., 2024). Computing capacity in MW captures not only the direct power for IT operations but also the essential cooling, networking, and storage demands required to sustain these compute-intensive tasks.

For high-performance AI data centers, Power Usage Effectiveness (PUE), the ratio of total facility energy to IT energy, serves as a key indicator of power distribution efficiency between computational tasks and supporting infrastructure. In AI environments, optimizing PUE is challenging but impactful; improvements in cooling efficiency allow more power to be devoted to computational processes, which effectively enhances the data center's productivity. In GPU-heavy configurations common in AI facilities, high power consumption is paired with significant computational throughput, demonstrating that even though AI applications demand substantial power, they can be efficiently managed with precise cooling strategies, which the MW functional unit helps

to assess. For LCA purposes, MW thus provides a practical basis to measure the environmental impacts of AI-driven workloads across different cooling methods, offering insights into energy efficiency, water use, and emissions on a per-MW basis.

Limitations of MW of Compute as a Proxy for Computing Power

Although MW is a convenient metric for evaluating data center energy demands, it has notable limitations when used as a proxy for computing power, especially in AI-intensive environments. It is often unclear if the capacity denotes the peak IT load—commonly used as a market convention—or the total design power capacity, which includes auxiliary systems (Masanet et al., 2024). This inconsistency can lead to significant uncertainties in environmental assessments, as analysts may interpret capacity figures in varying ways, affecting the comparability of different facilities.

Further, MW does not account for actual power utilization rates. Many data centers are designed with surplus capacity for redundancy and future growth, resulting in average power usage well below the maximum stated capacity. Without accurate data on utilization, which is rarely disclosed publicly, using MW as a functional unit can lead to overestimations in energy consumption, particularly in AI-focused data centers with variable and workload-dependent energy demands.

The MW measure encapsulates the total available power rather than the specific computing power delivered, which varies based on hardware configurations and workload types. In AI-driven data centers, for example, GPUs consume more energy per MW than CPUs but offer higher computational throughput for parallel tasks, making MW an approximate rather than exact proxy for computing output. This variability

complicates environmental impact assessments, as 1 MW in a GPU-intensive AI data center will not produce the same computational efficiency as 1 MW in a general-purpose facility (Kachris, 2024). While MW remains a valuable and scalable measure, these limitations must be considered in order to contextualize results effectively, particularly when comparing cooling technologies in AI data centers.

System Boundary

This comparative LCA study focused on stages A1 to A3 (embodied carbon) and B6 (operational energy use) of the building life cycle (Table 1; Figure 6). This included concrete and steel structural elements, mechanical, electrical, and plumbing (MEP) for each cooling system, and operational energy and water use. Some methodological details are:

- Northern Virginia, also known as Data Center Alley, was the region selected.
- The grid selected was the SERC Virginia/Carolina e-grid region. The SERC (Southeast Electric Reliability Council) region is one of the geographic regions defined by the U.S. EPA within the eGRID (Emissions & Generation Resource Integrated Database).
- The scale of the data center models was 10 MW data halls on a campus consisting of five data halls for a total of 50 MW capacity data center.
- The system boundary included major raw materials, utilities, manufacturing, consumer market for data, use phase, and energy production (Figure 6). The IT and networking equipment, minor raw materials, retail sales, networking use phase, and end of life phases were excluded, as shown in red in Figure 6.

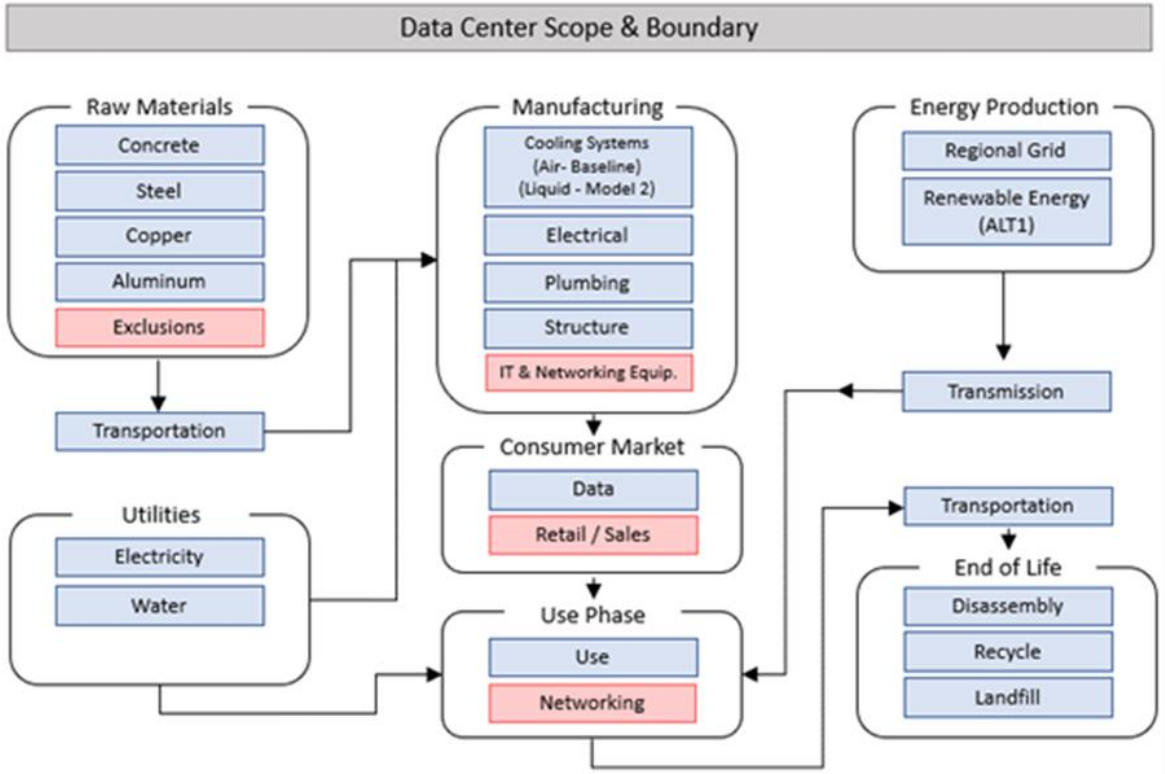


Figure 6. LCA scope and boundaries.
(exclusions in red).

Table 1. Life cycle system boundary.

Product Stage			Construct-ion Process Stage		Use Stage							End-of-Life Stage				Benefits and loads beyond the system boundary		
Raw material supply	Transport	Manufacturing	Transport to building site	Installation into building	Use/application	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	D	D
x			x	x	x					x	x	x				Excluded		

Inclusions marked by 'x'

Descriptions of the life cycle stages and analysis scope are provided Table 2. The Assessed Impact Categories are described in Table 3.

Table 2. Description of life cycle stages and analysis scope.

A1-A3 Construction Materials	Raw material supply (A1) includes emissions generated when raw materials are taken from nature, transported to industrial units for processing and processed. Loss of raw material and energy are also taken into account. Transport impacts (A2) include exhaust emissions resulting from the transport of all raw materials from suppliers to the manufacturer's production plant as well as impacts of production of fuels. Production impacts (A3) cover the manufacturing of the production materials and fuels used by machines, as well as handling of waste formed in the production processes at the manufacturer's production plants until end-of-waste state.
A4 Transportation to site	A4 includes exhaust emissions resulting from the transport of building products from manufacturer's production plant to building site as well as the environmental impacts of production of the used fuel.
A5 Construction/installation process	A5 covers the exhaust emissions resulting from using energy during the site operations, the environmental impacts of production processes of fuel and energy and water as well as handling of waste until the end-of-waste state.
B1-B5 Maintenance and material replacement	The environmental impacts of maintenance and material replacements (B1-B5) include environmental impacts from replacing building products after they reach the end of their service life. The emissions cover impacts from raw material supply, transportation and production of the replacing new material as well as the impacts from manufacturing the replacing material as well as handling of waste until the end-of-waste state.
B6 Energy use	The considered use phase energy consumption (B6) impacts include exhaust emissions from any building level energy production as well as the environmental impacts of production processes of fuel and externally produced energy. Energy transmission losses are also taken into account.

B7 Water use	The considered use phase water consumption (B7) impacts include the environmental impacts of production processes of fresh water and the impacts from waste water treatment.
C1-C4 Deconstruction	The impacts of deconstruction include impacts for processing recyclable construction waste flows for recycling (C3) until the end-of-waste stage or the impacts of pre-processing and landfilling for waste streams that cannot be recycled (C4) based on type of material. Additionally, deconstruction impacts includes emissions caused by waste energy recovery.
D External impacts/end-of-life benefits	Excluded. The external benefits include emission benefits from recycling recyclable building waste. Benefits for re-used or recycled material types include positive impact of replacing virgin based material with recycled material and benefits for materials that can be recovered for energy cover positive impact for replacing other energy streams based on average impacts of energy production.

Adopted from One Click LCA.

Table 3. Assessed impact categories.

Impact category	Unit	Description
Global warming potential (greenhouse gases)	$kgCO_2$ eq	Describes changes in local, regional, or global surface temperatures caused by an increased concentration of greenhouse gases in the atmosphere. Greenhouse gas emissions from fossil fuel burning has been strongly correlated with two other impact categories: acidification and smog. Often called “carbon footprint”.
Primary energy	kWh	

Adopted from One Click LCA.

Assumptions

The model assumptions for the two distinct cooling systems, each with a 50 MW IT load, examined in this study are contrasted in (Table 4).

Table 4. Model assumptions.

	Evaporative	Immersion
IT Load	50 MW (5 - 10 MW data halls)	50 MW (5 - 10 MW data halls)
Data Hall Cooling	25 evaporative cooling AHUs per data hall	4 immersion tanks per data hall
Makeup Water Storage	Two storage tanks per data hall	None
Space	Area (m3)	Area (m3)
Total Building Area	20,000	7,820
IT Rack Space	11,406	3,521
Mechanical Rooms	3,178	283
All Other (Elect, Admin, etc)	5,415	4,016
Power	Consumption (MWh/year)	Consumption (MWh/year)
Mechanical & Electrical Load	39,420	17,520
IT Load	438,000	438,000
PUE	1.09	1.04
Water	Mliters/year	Mliters/year
Water Consumption	31,374,000	0
Lifespan	Years	Years
Building	60	60
Mech Equipment	15-25	15

Author's assumptions, aggregated and anonymized from private industry data.

Calculations of annual energy consumption in the two models required assumptions of their respective Coefficients of performance (COPs). COPs in advanced data center cooling systems, such as evaporative spray-cooling and immersion cooling, significantly outperform those of traditional expansion air-based cooling methods, offering markedly higher energy efficiency and reduced operational costs. Chen et al. investigated the application of advanced spray-cooling technology for evaporative systems in data centers, concluding that the system's coefficient of performance (COP) is "significantly influenced by the inlet water temperature, with potential COP values ranging from 3 to 15" (Chen et al., 2017, p. 310). In a related study, Lui and Yu (2024) examined immersion cooling systems, demonstrating that as server power increases, both COP and power usage effectiveness (PUE) improve. In one of their experiments, COP rose from 19.0 to 26.7, while PUE decreased from 1.053 to 1.037, indicating enhanced cooling efficiency and reduced energy overhead with increasing power loads (Liu & Yu, 2021). These considerations advised how energy consumption was calculated.

Cooling Requirement for the Evaporative System

The evaporative cooling system must dissipate the heat from the nominal IT load of 50 MW. The energy consumption calculation using COP follows as:

- Given a COP of 11.11, the power input required to provide 50,000 kW of cooling can be calculated as: Power Input (kW) = Cooling Requirement (kW) / COP
- Plugging in the values: Power Input =50,000 kW / 11.11 ≈ 4,500 kW
- This means the cooling system would require 4,500 kW (4.5 MW) of continuous power to provide the necessary cooling.

- To find the annual energy consumption, the continuous power requirement was multiplied by the number of hours in a year (8,760 hours), so Annual Energy Consumption = 4,500 kW × 8,760 hours/year = 39,420,000 kWh/year = 39,420 MWh/year

IT load and cooling power requirements:

- The IT load was assumed as 50 MW, which corresponds to 438,000 MWh/year (since 50 MW × 8,760 hours/year = 438,000 MWh/year).
- The evaporative cooling system, with a COP of 11.11, requires 4.5 MW of continuous power to meet the cooling demand of 50 MW, resulting in 39,420 MWh/year of energy consumption (Table 4).

Total facility energy consumption:

- The total facility energy consumption is the sum of the IT load and the cooling system's energy consumption (mechanical and electrical loads): Total Facility Energy = IT Load + Cooling System Energy
- Substituting the values: Total Facility Energy = 438,000 MWh/year + 39,420 MWh/year = 477,420 MWh

Calculating PUE:

- Power Usage Effectiveness (PUE) is defined as the ratio of total facility energy consumption to IT load energy consumption: PUE = Total Facility Energy Consumption / IT Load Energy Consumption
- Substituting the values: PUE = 477,420 MWh/year / 438,000 MWh/year ≈ 1.09

In summary:

- With a COP of approximately 11.11, the evaporative cooling system would consume 39,420 MWh/year to meet the 50 MW cooling requirement.
- With a COP of 11.11 for the evaporative cooling system, the PUE is approximately 1.09. This PUE reflects the additional 39,420 MWh/year needed for cooling and other facility needs on top of the IT load.
- While still extremely efficient, this COP is lower than that of the immersion cooling system (COP of 25), reflecting the higher energy use required to maintain cooling in the evaporative setup, which aligns with the overall PUE of 1.09 for the evaporative-cooled system.

Cooling Requirements for the Immersion System

The immersion cooling system must also dissipate the heat from the nominal IT load of 50 MW:

Energy consumption calculation using COP:

- Given a COP of 25, the power input required to provide 50,000 kW of cooling can be calculated as: Power Input (kW) = Cooling Requirement (kW) / COP
- Plugging in the values: Power Input =50,000 kW / 25 ≈ 2,000 kW
- This means the cooling system would require 2,000 kW (2 MW) of continuous power to provide the necessary cooling.

Convert to annual energy consumption:

- To find the annual energy consumption, the continuous power requirement was multiplied by the number of hours in a year (8,760 hours):

  Annual Energy Consumption = 2,000 kW × 8,760 hours/year =

17,520,000 kWh/year = 17,520 MWh/year

IT load and cooling power requirements:

- The IT load is given as 50 MW, which corresponds to 438,000 MWh/year (since 50 MW × 8,760 hours/year = 438,000 MWh/year).
- The immersion cooling system, with a COP of 25, requires 2 MW of continuous power to meet the cooling demand of 50 MW, resulting in 17,520 MWh/year of energy consumption (Table 4).

Total facility energy consumption:

- The total facility energy consumption is the sum of the IT load and the cooling system's energy consumption (mechanical and electrical loads):
  Total Facility Energy = IT Load + Cooling System Energy
- Substituting the values: Total Facility Energy = 438,000 MWh/year + 17,520 MWh/year = 455,520 MWh

Calculating PUE:

- Power Usage Effectiveness (PUE) is defined as the ratio of total facility energy consumption to IT load energy consumption: PUE =
  Total Facility Energy Consumption / IT Load Energy Consumption
- Substituting the values: PUE = 455,520 MWh/year / 438,000 MWh/year ≈ 1.04

Summary:

- With a COP of approximately 25, the immersion cooling system would consume 17,520 MWh/year to meet the 50 MW cooling requirement.

- The PUE for the immersion cooling system is approximately 1.04. This reflects the lower energy consumption for cooling, resulting in a more efficient setup compared to the evaporative system.
- The higher COP of the immersion system (COP of 25 vs. COP of 11.11 for evaporative) aligns with the lower overall PUE of 1.04, indicating its greater energy efficiency.

Life Cycle Inventories

The foreground data collected for this LCA was extracted from various sources to ensure a representative dataset. Key sources included manufacturers' product specifications, Environmental Product Declarations (EPDs), and construction estimates. This dataset was further enhanced with anonymized client-provided data, public product information, relevant peer-reviewed journal articles, and where necessary, informed assumptions based on industry norms. The collected foreground data was then aligned and matched with process data available in the One Click LCA platform. The One Click LCA database provides a comprehensive repository of verified background data, enhancing the reliability of the comparative analysis.

Foreground data and Bill of Materials (Tables 5 and 6) are presented here to ensure transparency and reproducibility. Additionally, Appendices 1 and 2 provide detailed documentation of all background and foreground data sources, including data quality assessments, assumptions, and any methodological considerations.

Table 5. Foreground data and bill of materials for the air cooled model.

Bill of Materials - Evaporative Air Cooled System									
Resource	**Quantity**	**Unit**	**Thickness mm**	**Comment**	**Service life**	**Omniclass**	**Construction**	**Resource type**	**esiMasterformat**
Electricity use									
Electricity, USA, SERC Virginia/Carolina (eG	39420000	kWh						Electricity - HVAC	1
Electricity, USA, SERC Virginia/Carolina (eG	438000000	kWh						Electricity - IT	1
Building systems and installations									
Galvanized steel pipes, DN 25 mm, (1 in), 2.5	180583	lbs			60	21-04 50 Electrical	Electrification	Pipes (water, heating, sewage)	33
PVC plastic pipe, 0% recycled content	56537	lbs			30	21-04 50 Electrical	Electrification	Plastic profiles and products	6
Air handling unit (AHU), commercial grade, 3	125	unit			15	21-04 30 HVAC	Evaporative System	HVAC components and equipment	23
Centrifugal chillers, 13.8 kg/unit, CenTraVac	60	unit			20	21-04 30 HVAC	Evaporative System	HVAC components and equipment	23
Pendent fire sprinklers, 0.0944 kg/unit, GL11	999.999	unit			As building	21-04 40 Fire Protection	Fire suppression	Other metals	5
Polyvinyl chloride (PVC) pipe for drainage a	22046.2	lbs			60	21-04 40 Fire Protection	Fire suppression	Pipes (water, heating, sewage)	33
Cast Iron Pipes	4561.38	lbs			35	21-04 20 Plumbing	Fresh water distribution	Water heating and handling equipm	22
Copper pipes, Type L, DN 100 mm, (4 in), 8.0	38423.6	lbs			60	21-04 20 Plumbing	Fresh water distribution	Pipes (water, heating, sewage)	33
Aluminium, extruded, 2660-2840 kg/m3 (Alu	10800	lbs	0.508		30	21-04 30 HVAC	Hot Aisle Containment	Aluminium	5
Fabricated hollow structural steel sections,	93762	lbs			30	21-04 30 HVAC	Hot Aisle Containment	Structural steel and steel profiles	5
Perforated aluminium foil laminated to kraft	23571	sq ft			30	21-04 30 HVAC	Hot Aisle Containment	Plastic membranes	7
Steel truss connector plates, ASTM A653,	25434	lbs			30	21-04 30 HVAC	Hot Aisle Containment	Structural steel and steel profiles	5
Wall panel, polycarbonate, 0.47in, 74.3lbs/ft3	5022	sq ft	12		30	21-04 30 HVAC	Hot Aisle Containment	Partitioning systems (without windo	8
Air handling unit, with heat recovery through	8.1696	unit			25	21-04 30 HVAC	HVAC	HVAC components and equipment	23
Copper pipes, Type L, DN 100 mm, (4 in), 8.0	5054.79	lbs			60	21-04 30 HVAC	HVAC	Pipes (water, heating, sewage)	33
Glass Fiber Reinforced Polymer Water Stor	5240.01	lbs			35	21-04 30 HVAC	HVAC	Water heating and handling equipm	22
Glass wool insulation for pipes, unfaced, pe	28465.1	lbs			As building	21-04 30 HVAC	HVAC	Glass wool insulation	7
Polyvinyl chloride (PVC) pipe for drainage a	67111.9	lbs			60	21-04 30 HVAC	HVAC	Pipes (water, heating, sewage)	33
Ventilation ducting, per m linear, D: 500 mm	112691	lbs			25	21-04 30 HVAC	HVAC	HVAC components and equipment	23
Galvanized steel pipes, DN 25 mm, (1 in), 2.5	28671.5	lbs			60	21-04 60 Communications	Telecommunication	Pipes (water, heating, sewage)	33
PVC plastic pipe, 0% recycled content	23776	lbs			30	21-04 60 Communications	Telecommunication	Plastic profiles and products	6
Polypropylene (PP) pipe for drainage and se	5422.14	lbs			60	21-04 20 Plumbing	Wastewater and rainwater draina	Pipes (water, heating, sewage)	33
Polyvinyl chloride (PVC) pipe for drainage a	29571.3	lbs			60	21-04 20 Plumbing	Wastewater and rainwater draina	Pipes (water, heating, sewage)	33
Columns and load-bearing vertical									
Reinforcement steel (rebar), generic, 90% re	4995.06	lbs		4 lbs/ft3 (65 kg/m3)	As building	21-02 10 10 10 02. Floor Structural Fr	Reinforced concrete shear wall,	Reinforcement for concrete (rebar	5
Ready-mix concrete, 5000 psi, 34.5 Mpa (Inc	184433	lbs	203.2		As building	21-02 10 10 10 02. Floor Structural Fr	Reinforced concrete shear wall,	Ready-mix concrete for external wa	3
Reinforcement steel (rebar), generic, 90% re	265334	lbs		20.28 lbs/ft3 (325 kg/m3)	As building	21-02 10 10 10 02. Floor Structural Fr	Precast concrete column, 17.7 x	Reinforcement for concrete (rebar	5
Precast concrete, structural	1959460	lbs	203.2		As building	21-02 10 10 10 02. Floor Structural Fr	Precast concrete column, 17.7 x	Structural concrete (beams, colum	3
External walls and facade									
Fibre cement boards, 1300 kg/m3 (81.16 lbs/f	14458	sq ft	9.53		As building	21-03 20 10. Wall Finishes	Fiber cement sheet cladding	Fibre cement products	6
Precast concrete, insulated wall panel	14458	sq ft	90		As building	21-02 20 10. Exterior Walls	Precast concrete sandwich exte	Concrete wall elements	3
Precast concrete, insulated wall panel	14458	sq ft	80		As building	21-02 20 10. Exterior Walls	Precast concrete sandwich exte	Concrete wall elements	3
Foundation, sub-surface, basement									
Ready-mix concrete, 5000 psi, 34.5 Mpa (Inc	528	cu yd	203.2		As building	21-01 10 10. Standard Foundations	Footing foundations for hard sc	Ready-mix concrete for external wa	3
Ready-mix concrete, 2500 psi, 17.2 Mpa (Ind	1300	cu yd	50		As building	21-01 10 10. Standard Foundations	Concrete cleanliness per GFA	Ready-mix concrete for lightweight	3
Styrofoam insulation, 1.8 pcf, Styrofoam Hic	3752	sq ft	152.4	Styrofoam insulation, 1.8	As building	21-01 10 10. Standard Foundations	Frost insulation (XPS)	XPS (extruded polystyrene) insulati	7
Reinforcement steel (rebar), generic, 90% re	138891	lbs			As building	21-01 10 10. Standard Foundations	Footing foundations for hard sc	Reinforcement for concrete (rebar	5
Floor slabs, ceilings, roofing decks									
Ready-mix concrete, 5000 psi, 34.5 Mpa (Inc	215278	sq ft	101.6	Ready-mix concrete, gen	As building	21-01 40 10. Standard Slabs-on-Grad	Ground slab, reinforced concret	Ready-mix concrete for external wa	3
Reinforcement steel (rebar), generic, 90% re	389777	lbs		reinforcement steel, 1.81	As building	21-01 40 10. Standard Slabs-on-Grad	Ground slab, reinforced concret	Reinforcement for concrete (rebar	5
EPDM membrane roofing, 0.1in	215278	sq ft	1		30	21-02 10 20 20. Roof Decks, Slabs, a	Hollow-core roof slab assembly	Plastic membranes	7
EPS insulation, 1.02in	215278	sq ft	238		As building	21-02 10 20 20. Roof Decks, Slabs, a	Hollow-core roof slab assembly	EPS (expanded polystyrene) insulat	7
Precast concrete, structural	16093700	lbs	265	75 lbs/sqft, 365 kg/m2	As building	21-02 10 20 20. Roof Decks, Slabs, a	Hollow-core roof slab assembly	Structural concrete (beams, colum	3
Reinforcement steel (rebar), generic, 90% re	583230	lbs		18.7 lbs/ft3 (300 kg/m3) c	As building	21-02 10 10 10 01. Floor Structural Fra	Precast concrete beam, 15.7 x 17	Reinforcement for concrete (rebar	5
Precast concrete, structural	4665840	lbs	203.2		As building	21-02 10 10 10 01. Floor Structural Fra	Precast concrete beam, 15.7 x 17	Structural concrete (beams, colum	3
Fiberglass asphalt shingle roofing system, 1	215278	sq ft			20	21-02 30 10. Roofing	Roof covering, asphalt shingles	Bitumen and other roofing	7
Water use									
Tap water, conventionally treated (One Click	0	cu ft						Water	1
Windows and doors									
Steel door, 86x36x1.34in	4306	sq ft	34.04		30	21-02 20 50. Exterior Doors and Gril	External door, steel	Metal and industrial doors	8
Aluminium window frame, 50in x 58in, YOW 3	16141.3	lbs		Average weight 1.4 kg/m,	As building	21-02 20 20. Exterior Windows	Window, metal framed, double p-	Aluminium frame windows	8
Flat glass, clear, tinted and low-iron (Nation-	18764	sq ft	20		35	21-02 20 20. Exterior Windows	Window, metal framed, double p-	Regular glass panes	8

Table 6. Foreground data and bill of materials for the liquid cooled model.

Bill of Materials - Immersion Liquid Cooled System									
Resource	**Quantity**	**Unit**	**Thickness mm**	**Comment**	**Service life**	**Omniclass**	**Construction**	**Resource type**	**csiMaster format**
Electricity use									
Electricity, USA, SERC Virginia/Carolina (eGRID)	17520000	kWh/year						Electricity - HVAC	1
Electricity, USA, SERC Virginia/Carolina (eGRID)	438000000	kWh/year						Electricity - IT	1
Building systems and installations									
PVC plastic pipe, 0% recycled content	22106	lbs			30	21-04 50 Electrical	Electrification	Plastic profiles and products	6
Galvanized steel pipes, DN 25 mm, (1 in), 2.57 kg/r	70608.3	lbs			60	21-04 50 Electrical	Electrification	Pipes (water, heating, sewage)	33
Pendent fire sprinklers, 0.0944 kg/unit, GL112 Pen	391.001	unit			As building	21-04 40 10. Fire Suppres	Fire suppression	Other metals	5
Polyvinyl chloride (PVC) pipe for drainage and se	8620.1	lbs			60	21-04 40 10. Fire Suppres	Fire suppression	Pipes (water, heating, sewage)	33
Cast Iron Pipes	1783.51	lbs			35	21-04 20 Plumbing	Fresh water distributio	Water heating and handling equipmer	22
Copper pipes, Type L, DN 100 mm, (4 in), 8.02 kg/r	15023.7	lbs			60	21-04 20 Plumbing	Fresh water distributio	Pipes (water, heating, sewage)	33
Air handling unit, with heat recovery through plate	3.1943	unit			25	21-04 30 HVAC	HVAC	HVAC components and equipment	23
Copper pipes, Type L, DN 100 mm, (4 in), 8.02 kg/r	1976.43	lbs			60	21-04 30 HVAC	HVAC	Pipes (water, heating, sewage)	33
Glass Fiber Reinforced Polymer Water Storage T	2048.85	lbs			35	21-04 30 HVAC	HVAC	Water heating and handling equipmer	22
Glass wool insulation for pipes, unfaced, per mete	11129.9	lbs			As building	21-04 30 HVAC	HVAC	Glass wool insulation	7
Polyvinyl chloride (PVC) pipe for drainage and se	26240.8	lbs			60	21-04 30 HVAC	HVAC	Pipes (water, heating, sewage)	33
Ventilation ducting, per m linear, D: 500 mm (19.69	44062.5	lbs			25	21-04 30 HVAC	HVAC	HVAC components and equipment	23
Stainless steel metal sheets and coils, 0.012-0.12 i	25355	lbs	0.3		15	21-04 30 HVAC	Immersion System	Stainless steel	5
Petroleum-based hydraulic engine lubricant (One	42990	lbs			15	21-04 30 HVAC	Immersion System	Explosives and other chemicals	9
PVC plastic pipe, 0% recycled content	9296	lbs			30	21-04 60 Communicatio	Telecommunication	Plastic profiles and products	6
Galvanized steel pipes, DN 25 mm, (1 in), 2.57 kg/r	11210.6	lbs			60	21-04 60 Communicatio	Telecommunication	Pipes (water, heating, sewage)	33
Polypropylene (PP) pipe for drainage and sewera	2120.06	lbs			60	21-04 20 Plumbing	Wastewater and rainwa	Pipes (water, heating, sewage)	33
Polyvinyl chloride (PVC) pipe for drainage and se	11562.4	lbs			60	21-04 20 Plumbing	Wastewater and rainwa	Pipes (water, heating, sewage)	33
Columns and load-bearing vertical struc									
Reinforcement steel (rebar), generic, 90% recycle	3554.58	lbs		4 lbs/ft3 (65 kg/m	As building	21-02 10 10 10 02. Floor S	Reinforced concrete s	Reinforcement for concrete (rebar)	5
Reinforcement steel (rebar), generic, 90% recycle	120285	lbs		20.28 lbs/ft3 (325	As building	21-02 10 10 10 02. Floor S	Precast concrete colu	Reinforcement for concrete (rebar)	5
Ready-mix concrete, 5000 psi, 34.5 Mpa (Industry	131246	lbs	203.2		As building	21-02 10 10 10 02. Floor S	Reinforced concrete s	Ready-mix concrete for external walls	3
Precast concrete, structural	888289	lbs	203.2		As building	21-02 10 10 10 02. Floor S	Precast concrete colu	Structural concrete (beams, columns	3
External walls and facade									
Fibre cement boards, 1300 kg/m3 (81.16 lbs/ft3)	11663	sq ft	9.53		As building	21-03 20 10. Wall Finishes	Fiber cement sheet cla	Fibre cement products	6
Precast concrete, insulated wall panel	11663	sq ft	90		As building	21-02 20 10. Exterior Wall	Precast concrete sanc	Concrete wall elements	3
Precast concrete, insulated wall panel	11663	sq ft	80		As building	21-02 20 10. Exterior Wall	Precast concrete sanc	Concrete wall elements	3
Foundation, sub-surface, basement and									
Ready-mix concrete, 5000 psi, 34.5 Mpa (Industry	210	cu yd	203.2		As building	21-01 10 10. Standard Fou	Footing foundations f	Ready-mix concrete for external walls	3
Ready-mix concrete, 2500 psi, 17.2 Mpa (Industry	510	cu yd	50		As building	21-01 10 10. Standard Fou	Concrete cleanliness p	Ready-mix concrete for lightweight ap	3
Styrofoam insulation, 1.8 pcf, Styrofoam Highloac	2670	sq ft	152.4	Styrofoam insula	As building	21-01 10 10. Standard Fou	Frost insulation (XPS)	XPS (extruded polystyrene) insulatio	7
Reinforcement steel (rebar), generic, 90% recycle	54306.6	lbs			As building	21-01 10 10. Standard Fou	Footing foundations f	Reinforcement for concrete (rebar)	5
Floor slabs, ceilings, roofing decks, bea									
Ready-mix concrete, 5000 psi, 34.5 Mpa (Industry	84174	sq ft	101.6	Ready-mix concr	As building	21-01 40 10. Standard Slal	Ground slab, reinforce	Ready-mix concrete for external walls	3
Reinforcement steel (rebar), generic, 90% recycle	152403	lbs		reinforcement st	As building	21-01 40 10. Standard Slal	Ground slab, reinforce	Reinforcement for concrete (rebar)	5
EPDM membrane roofing, 0.1in	84174	sq ft	1		30	21-02 10 20 20. Roof Dec	Hollow-core roof slab	Plastic membranes	7
EPS insulation, 1.02in	84174	sq ft	238		As building	21-02 10 20 20. Roof Dec	Hollow-core roof slab	EPS (expanded polystyrene) insulatic	7
Precast concrete, structural	6292670	lbs	265	75 lbs/sqft, 365 k	As building	21-02 10 20 20. Roof Dec	Hollow-core roof slab	Structural concrete (beams, columns	3
Reinforcement steel (rebar), generic, 90% recycle	258032	lbs		18.7 lbs/ft3 (300 k	As building	21-02 10 10 10 01. Floor St	Precast concrete bear	Reinforcement for concrete (rebar)	5
Precast concrete, structural	2064260	lbs	203.2		As building	21-02 10 10 10 01. Floor St	Precast concrete bear	Structural concrete (beams, columns	3
Fiberglass asphalt shingle roofing system, 12.7 kg	84174	sq ft			20	21-02 30 10. Roofing	Roof covering, asphal	Bitumen and other roofing	7
Water use									
Tap water, conventionally treated (One Click LCA	0	cu ft						Water	1
Windows and doors									
Steel door, 86x36x1.34in	1683	sq ft	34.04		30	21-02 20 50. Exterior Doo	External door, steel	Metal and industrial doors	8
Aluminium window frame, 50in x 58in, YOW 350 X7	11480.6	lbs		Average weight 1	As building	21-02 20 20. Exterior Win	Window, metal framed,	Aluminium frame windows	8
Flat glass, clear, tinted and low-iron (National Gla:	13346	sq ft	20		35	21-02 20 20. Exterior Win	Window, metal framed,	Regular glass panes	8

Chapter III

Results

The comparison between evaporative air-cooled and liquid immersion-cooled data centers revealed a significant finding: energy consumption, particularly during the operational phase, is the dominant factor in environmental impacts for both cooling methods. However, this first comparison, the base case model with power from the grid, highlighted the advantages of immersion cooling over evaporative cooling in terms of energy efficiency, water usage, and overall carbon emissions.

The life cycle carbon footprint of the modeled evaporative cooling system far exceeded that of the immersion cooling system. The total emissions for evaporative cooling was projected to reach 1,102,278,407 kg CO2e over 60 years, more than double the 489,014,668 kg CO2e attributed to immersion cooling (Table 7). The primary contributor to this discrepancy was the B6 stage, or the energy consumption during the operational phase, which accounted for over 98% of the total emissions in both systems.

While energy consumption was the dominant factor, material phases (A1-A3) also contributed to the overall environmental burden. The evaporative cooling system requires more infrastructure, particularly in the form of HVAC systems, leading to higher embodied carbon emissions (7,704,073 kg CO2e) compared to the immersion system (3,118,373 kg CO2e) (Table 7). The compact nature of immersion cooling systems, which require less physical space and fewer auxiliary components like fans and pumps, resulted in significantly lower emissions during both the construction phase and material replacement over time (B4-B5).

Table 7. Building life cycle carbon footprint utilizing grid power.

		Evaporative Cooling Grid Power	Immersion Cooling Grid Power
Stage	Category	Global warming kg CO2e	Global warming kg CO2e
A1-A3	Construction Materials	7,704,073	3,118,373
A4	Transportation to site	201,893	81,355
A5	Construction/installation process	200,754	80,837
B4-B5	Material replacement and refurbishment	3,249,144	1,127,405
B6	Energy consumption	1,089,955,116	484,424,496
B7	Water use	509,461	0
C1-C4	End of life	457,965	182,202
	Total	1,102,278,407	489,014,668
	Per MW	22,045,568	9,780,293
	Carbon Intensity	918.57 kg CO2e / m2 / year	1042.23 kg CO2e / m2 / year

Life cycle carbon footprint of each system over 60 years.

Interestingly, when carbon intensity in kg CO2e per m² per year is examined, evaporative cooling shows a lower value (918.57 kg CO2e) compared to immersion cooling (1,042.23 kg CO2e). This difference arises because immersion cooling's more compact systems allow for higher computing densities within the same physical footprint, intensifying energy use per square meter. This highlights a critical limitation of using area as an intensity metric. Carbon intensity per square meter failed to reflect the efficiency of computing performance achieved. Evaporative cooling showed a lower carbon intensity by area, it did not account for the higher computing capacity achieved with immersion cooling systems. A more appropriate intensity metric, such as emissions per unit of computational output (i.e., MW of compute capacity), would provide a clearer picture of the relative efficiencies and environmental impacts.

Tables 8 and 9 illustrate the life cycle global warming potential (kg CO2e) for each system by life cycle stage. Figures 7 and Figure 8 further highlight the total life cycle impact by resource type, emphasizing that immersion cooling not only reduces energy-related emissions but also lowers material and water usage impacts, even though it may be hard to see when dwarfed by the B6 stage.

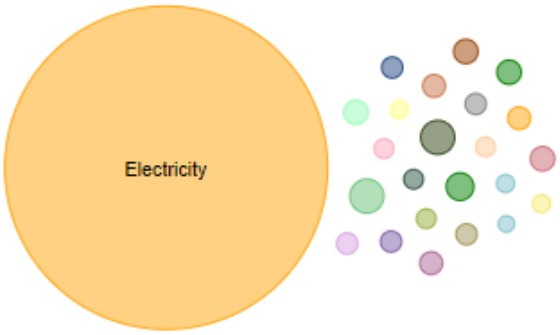
Air: Evaporative Cooling on Grid Power

Evaporative air cooling over its life cycle demonstrated high energy consumption due to the mechanical energy required to operate fans, pumps, and auxiliary systems necessary for moving and cooling air. The life cycle assessment demonstrated that the B6 energy consumption stage is the largest contributor to the global warming potential of the evaporative cooling system (Table 8). The additional water use further exacerbated the environmental impact, emphasizing the inefficiency of this traditional cooling method, especially over extended operational periods.

Table 8. Evaporative cooling global warming (kg CO2e) life cycle stages.

Item	Value	Unit	Percentage %
A1-A3 Materials	7,700,000	kg CO_2e	0.7 %
A4 Transport	200,000	kg CO_2e	0.02 %
A5 Construction	200,000	kg CO_2e	0.02 %
B4-B5 Replacement	3,200,000	kg CO_2e	0.29 %
B6 Energy	1,100,000,000	kg CO_2e	98.88 %
B7 Water	510,000	kg CO_2e	0.05 %
C2 Waste transport	110,000	kg CO_2e	0.01 %
C3 Waste processing	350,000	kg CO_2e	0.03 %
C4 Waste disposal	810	kg CO_2e	0.0 %

These results are broken down by material and operation components in Figure 7.



XPS (extruded polystyrene) insulation
Ready-mix concrete for external walls and floors
Fibre cement products
Structural concrete (beams, columns, piling)
Plastic membranes
Aluminium frame windows
Metal and industrial doors
Aluminium
HVAC components and equipment
Glass wool insulation
Plastic profiles and products
Electricity
Ready-mix concrete for lightweight applications
Reinforcement for concrete (rebar)
Concrete wall elements
Bitumen and other roofing
EPS (expanded polystyrene) insulation
Regular glass panes
Structural steel and steel profiles
Partitioning systems (without windows)
Pipes (water, heating, sewage)
Water heating and handling equipment
Other metals
Water

Item	Value	Unit	Percentage %
Electricity	1,100,000,000	kg CO_2e	98.88 %
HVAC components and equipment	3,400,000	kg CO_2e	0.31 %
Structural concrete (beams, columns, piling)	3,200,000	kg CO_2e	0.29 %
Ready-mix concrete for external walls and floors	1,200,000	kg CO_2e	0.11 %
EPS (expanded polystyrene) insulation	550,000	kg CO_2e	0.05 %
Reinforcement for concrete (rebar)	520,000	kg CO_2e	0.05 %
Pipes (water, heating, sewage)	510,000	kg CO_2e	0.05 %
Water	510,000	kg CO_2e	0.05 %
Plastic profiles and products	340,000	kg CO_2e	0.03 %
Other resource types	2,100,000	kg CO_2e	0.19 %

Figure 7. Total life cycle impact by resource type, evaporative cooling.

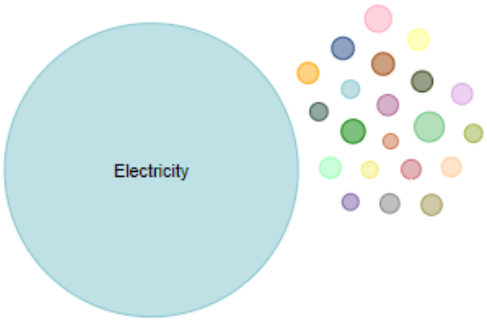
Liquid: Immersion Cooling on Grid Power

The immersion cooling system reduced energy consumption which directly translated into a smaller carbon footprint during the B6 operational phase. Since immersion cooling does not rely on water for its operation, it also demonstrated zero water usage, which represented a significant sustainability advantage.

The life cycle analysis revealed that immersion cooling results in a considerably lower carbon footprint than evaporative cooling. The B6 operational energy consumption remained the most significant factor, but immersion cooling's superior energy efficiency greatly reduces this absolute impact (Table 9, Figure 8).

Table 9. Immersion cooling global warming (kg CO2e) life cycle stages.

Item	Value	Unit	Percentage %
A1-A3 Materials	3,100,000	kg CO_2e	0.64 %
A4 Transport	81,000	kg CO_2e	0.02 %
A5 Construction	81,000	kg CO_2e	0.02 %
B4-B5 Replacement	1,100,000	kg CO_2e	0.23 %
B6 Energy	480,000,000	kg CO_2e	99.06 %
C2 Waste transport	44,000	kg CO_2e	0.01 %
C3 Waste processing	140,000	kg CO_2e	0.03 %
C4 Waste disposal	360	kg CO_2e	0.0 %



XPS (extruded polystyrene) insulation
Ready-mix concrete for external walls and floors
Fibre cement products
Structural concrete (beams, columns, piling)
Plastic membranes
Aluminium frame windows
Metal and industrial doors
Explosives and other chemicals
Pipes (water, heating, sewage)
Water heating and handling equipment
Other metals
Ready-mix concrete for lightweight applications
Reinforcement for concrete (rebar)
Concrete wall elements
Bitumen and other roofing
EPS (expanded polystyrene) insulation
Regular glass panes
Stainless steel
HVAC components and equipment
Glass wool insulation
Plastic profiles and products
Electricity

Item	Value	Unit	Percentage %
Electricity	480,000,000	kg CO_2e	99.06 %
Structural concrete (beams, columns, piling)	1,300,000	kg CO_2e	0.27 %
HVAC components and equipment	850,000	kg CO_2e	0.17 %
Ready-mix concrete for external walls and floors	460,000	kg CO_2e	0.09 %
Stainless steel	230,000	kg CO_2e	0.05 %
Reinforcement for concrete (rebar)	220,000	kg CO_2e	0.05 %
EPS (expanded polystyrene) insulation	210,000	kg CO_2e	0.04 %
Pipes (water, heating, sewage)	200,000	kg CO_2e	0.04 %
Regular glass panes	180,000	kg CO_2e	0.04 %
Other resource types	920,000	kg CO_2e	0.19 %

Figure 8. Total life cycle impact by resource type, immersion cooling.

This base case analysis emphasized that while both cooling systems depend heavily on energy consumption during their operational phases, immersion cooling offers a more energy-efficient solution. When relying on grid power, immersion cooling exhibited a lower overall carbon footprint.

Sensitivity Analysis – Change to Renewable Power

In the first sensitivity analysis, a change in power source was evaluated. The analysis transitioned from the grid power of SERC Virginia/Carolina (eGRID), which is primarily reliant on fossil fuels, to NERC New York Upstate (eGRID) as a proxy for renewable energy. This shift allowed for the assessment of how transitioning to a lower-carbon grid impacts data centers. Table 10 outlines the life cycle carbon footprints of both cooling technologies when powered by this renewable energy proxy.

Table 10. Building life cycle carbon footprint with renewable energy proxy.

		Evaporative Cooling Renewable Power	Immersion Cooling Renewable Power
Stage	Category	Global warming kg CO2e	Global warming kg CO2e
A1-A3	Construction Materials	7,704,073	3,118,373
A4	Transportation to site	201,893	81,355
A5	Construction/installation process	200,754	80,837
B4-B5	Material replacement and refurbishment	3,249,144	1,127,405
B6	Energy consumption	592,908,336	263,514,816
B7	Water use	509,461	0
C1-C4	End of life	457,965	182,202
	Total	605,231,627	268,104,988
	Per MW	12,104,633	5,362,100
	Carbon Intensity	504.36 kg CO2e / m2 / year	571.41 kg CO2e / m2 / year

Life cycle carbon footprint of each system over 60 years.

When powered by a grid with lower carbon sources, in this case with hydro and nuclear, both cooling systems showed substantial reductions in operational carbon emissions.

Air: Evaporative Cooling on Renewable Power

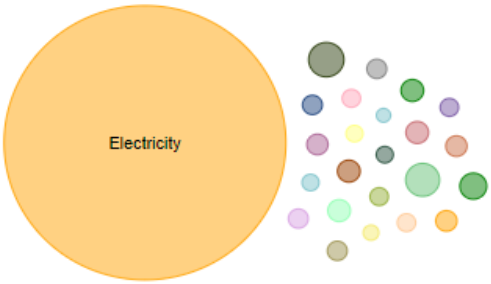
When powered by renewable energy sources, evaporative air cooling exhibited a significant reduction in carbon emissions. The B6 stage, which accounts for energy consumption, saw a nearly 50% reduction in carbon footprint, dropping from 1,089,955,116 kg CO2e (Table 7) to 592,908,336 kg CO2e (Table 10). This reduction is largely attributed to the replacement of carbon-intensive grid power with lower carbon renewable energy. Despite this substantial improvement, the system's fundamental inefficiencies remained. Evaporative air cooling continues to rely heavily on mechanical cooling processes and water use, which kept its overall energy demand and environmental impacts higher than optimal.

In the case of evaporative air cooling, the shift to renewable energy dramatically decreased carbon emissions (Table 11). Despite the lower carbon footprint, the system's energy inefficiency remained a limiting factor, as its reliance on mechanical cooling processes and evaporative water use persisted, resulting in higher overall energy demand.

Table 11. Evaporative cooling global warming (kg CO2e) life cycle stages.

Item	Value	Unit	Percentage %
A1-A3 Materials	7,700,000	kg CO_2e	1.27 %
A4 Transport	200,000	kg CO_2e	0.03 %
A5 Construction	200,000	kg CO_2e	0.03 %
B4-B5 Replacement	3,200,000	kg CO_2e	0.54 %
B6 Energy	590,000,000	kg CO_2e	97.96 %
B7 Water	510,000	kg CO_2e	0.08 %
C2 Waste transport	110,000	kg CO_2e	0.02 %
C3 Waste processing	350,000	kg CO_2e	0.06 %
C4 Waste disposal	810	kg CO_2e	0.0 %

Even with renewable energy inputs, evaporative cooling's global warming potential remained heavily influenced by its high operational energy demands (Figure 9). Renewable energy mitigates the carbon intensity of the electricity consumed, but the inefficiency of the cooling process itself persists.



XPS (extruded polystyrene) insulation
Ready-mix concrete for external walls and floors
Fibre cement products
Structural concrete (beams, columns, piling)
Plastic membranes
Aluminium frame windows
Metal and industrial doors
Aluminium
HVAC components and equipment
Glass wool insulation
Plastic profiles and products
Electricity
Ready-mix concrete for lightweight applications
Reinforcement for concrete (rebar)
Concrete wall elements
Bitumen and other roofing
EPS (expanded polystyrene) insulation
Regular glass panes
Structural steel and steel profiles
Partitioning systems (without windows)
Pipes (water, heating, sewage)
Water heating and handling equipment
Other metals
Water

Item	Value	Unit	Percentage %
Electricity	590,000,000	kg CO_2e	97.96 %
HVAC components and equipment	3,400,000	kg CO_2e	0.56 %
Structural concrete (beams, columns, piling)	3,200,000	kg CO_2e	0.53 %
Ready-mix concrete for external walls and floors	1,200,000	kg CO_2e	0.19 %
EPS (expanded polystyrene) insulation	550,000	kg CO_2e	0.09 %
Reinforcement for concrete (rebar)	520,000	kg CO_2e	0.09 %
Pipes (water, heating, sewage)	510,000	kg CO_2e	0.08 %
Water	510,000	kg CO_2e	0.08 %
Plastic profiles and products	340,000	kg CO_2e	0.06 %
Other resource types	2,100,000	kg CO_2e	0.35 %

Figure 9. Total life cycle impact by resource type, evaporative cooling.

Evaporative cooling's reliance on water remained unchanged, continuing to drive water usage impacts. While the carbon benefits of renewable energy are clear, this system's operational inefficiency limits the extent of its environmental performance improvements.

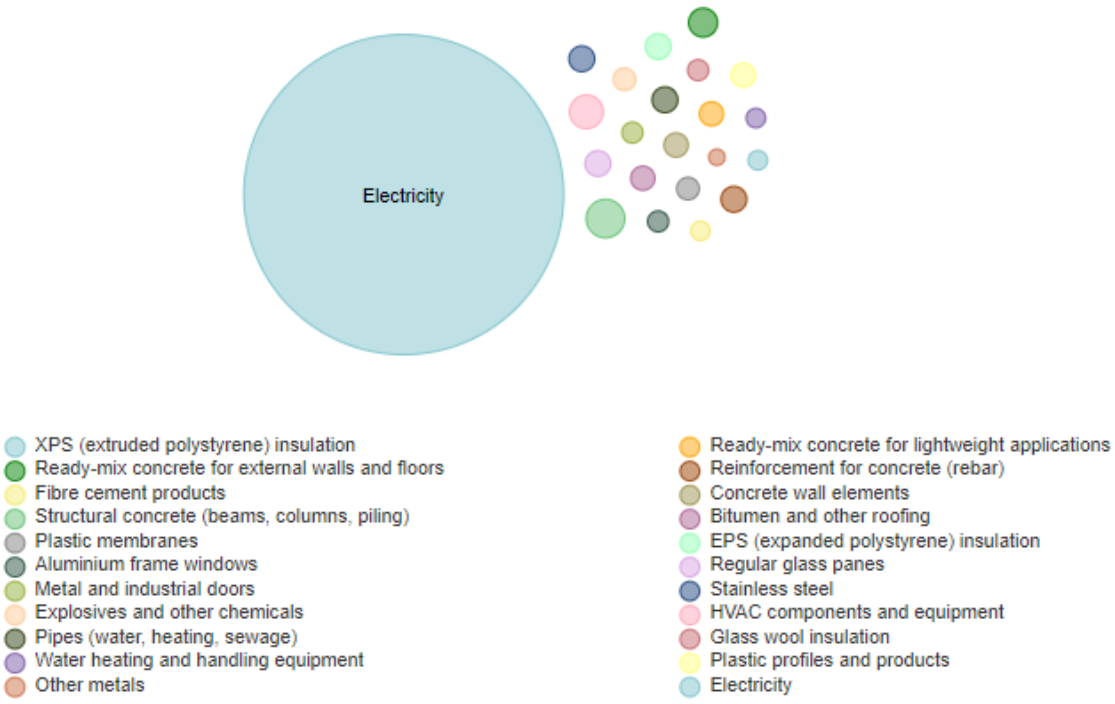
Liquid: Immersion Cooling on Renewable Power

For the liquid immersion cooling system, the transition to renewable energy sources amplified its efficiency advantages. Already more energy-efficient than evaporative cooling under grid power, immersion cooling's carbon emissions from energy consumption (B6) dropped from 484,424,496 kg CO2e (Table 7) to 263,514,816 kg CO2e (Table 10). This represented a more than 45% reduction in emissions. Coupled with its near-zero water use and reduced reliance on mechanical systems, the immersion cooling system's environmental footprint shrunk further, positioning it as a more desirable solution when paired with renewable energy.

Table 12. Immersion cooling global warming (kg CO2e) life cycle stages.

Item	Value	Unit	Percentage %
A1-A3 Materials	3,100,000	kg CO_2e	1.16 %
A4 Transport	81,000	kg CO_2e	0.03 %
A5 Construction	81,000	kg CO_2e	0.03 %
B4-B5 Replacement	1,100,000	kg CO_2e	0.42 %
B6 Energy	260,000,000	kg CO_2e	98.29 %
C2 Waste transport	44,000	kg CO_2e	0.02 %
C3 Waste processing	140,000	kg CO_2e	0.05 %
C4 Waste disposal	360	kg CO_2e	0.0 %

Table 12 and Figure 10 illustrate that the B6 stage was still dominant even on a grid with lower carbon sources. Immersion cooling consistently performed better than evaporative cooling due to its lower absolute energy consumption, irrespective of the energy source.



Item	Value	Unit	Percentage %
Electricity	260,000,000	kg CO_2e	98.29 %
Structural concrete (beams, columns, piling)	1,300,000	kg CO_2e	0.49 %
HVAC components and equipment	850,000	kg CO_2e	0.32 %
Ready-mix concrete for external walls and floors	460,000	kg CO_2e	0.17 %
Stainless steel	230,000	kg CO_2e	0.09 %
Reinforcement for concrete (rebar)	220,000	kg CO_2e	0.08 %
EPS (expanded polystyrene) insulation	210,000	kg CO_2e	0.08 %
Pipes (water, heating, sewage)	200,000	kg CO_2e	0.07 %
Regular glass panes	180,000	kg CO_2e	0.07 %
Other resource types	920,000	kg CO_2e	0.34 %

Figure 10.Total life cycle impact by resource type, immersion cooling.

Sensitivity Analysis – Zero Out B6 Energy Consumption

In this sensitivity analysis, a hypothetical scenario was created where B6 energy consumption was eliminated, representing a situation where data centers are powered entirely by clean renewable energy and operational energy does not contribute to carbon emissions. This analysis helped focus on the embodied carbon and life cycle impacts of the core and shell of the building and the evaporative air-cooled and liquid immersion-cooled systems, excluding the influence of operational energy consumption.

Table 13. Building life cycle carbon footprint, zero out B6 stage.

		Evaporative Cooling Renewable Power	Immersion Cooling Renewable Power
Stage	Category	Global warming kg CO2e	Global warming kg CO2e
A1-A3	Construction Materials	7,704,073	3,118,373
A4	Transportation to site	201,893	81,355
A5	Construction/installation process	200,754	80,837
B4-B5	Material replacement and refurbishment	3,249,144	1,127,405
B6	Energy consumption	0	0
B7	Water use	509,461	0
C1-C4	End of life	457,965	182,202
	Total	12,323,290	4,590,172
	Per MW	246,466	91,803
	Carbon Intensity	10.27 kg CO2e / m2 / year	9.78 kg CO2e / m2 / year

Life cycle carbon footprint of each system over 60 years.

This sensitivity analysis showed that even without considering operational energy consumption, the overall environmental performance of liquid immersion cooling remains superior to evaporative air cooling. The total emissions for the evaporative cooling system are 12,323,290 kg CO2e compared to 4,590,172 kg CO2e for immersion

cooling—a difference driven primarily by the embodied carbon of materials and components required for each system and the water usage of the evaporative system.

Air: Evaporative Cooling With No B6 Energy Consumption

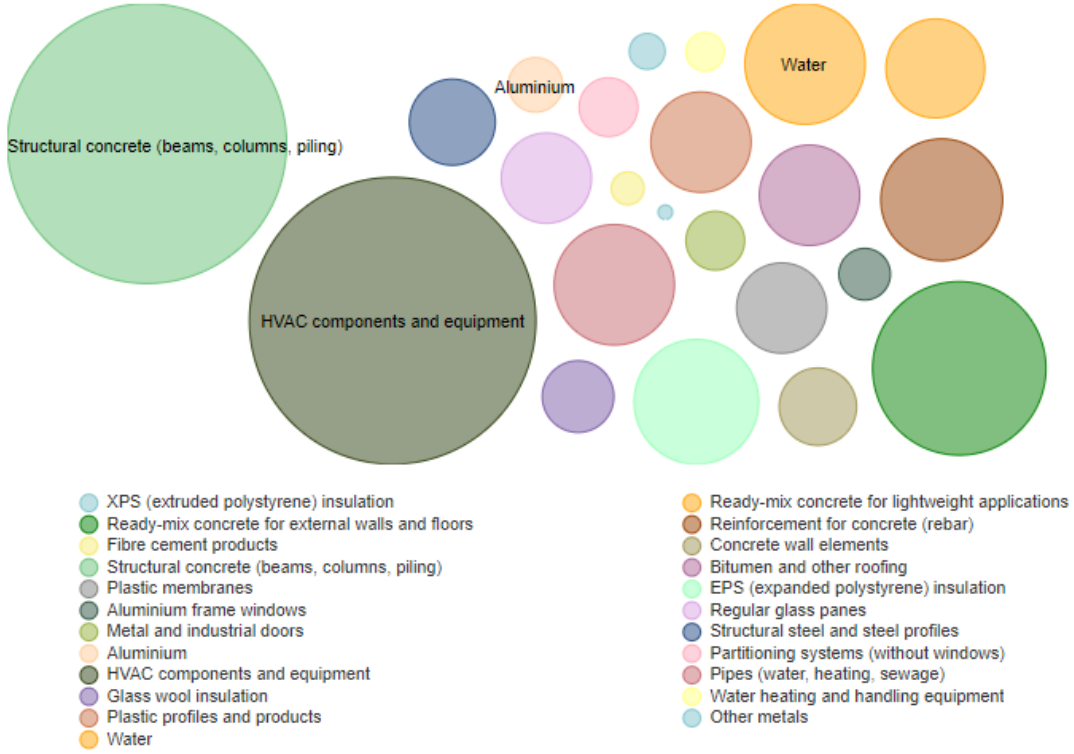
When B6 energy consumption is zeroed out, the focus shifted to the embodied impacts of the cooling systems. For evaporative air cooling, significant emissions remained due to the embodied carbon of air handling units, fans, and evaporative cooling processes. As shown in Table 14, even without operational energy emissions, evaporative cooling still produced substantial carbon emissions from its materials and construction phases (A1-A3).

Table 14. Evaporative cooling global warming (kg CO2e) life cycle stages.

Item	Value	Unit	Percentage %
A1-A3 Materials	7,700,000	kg CO_2e	62.52 %
A4 Transport	200,000	kg CO_2e	1.64 %
A5 Construction	200,000	kg CO_2e	1.63 %
B4-B5 Replacement	3,200,000	kg CO_2e	26.37 %
B7 Water	510,000	kg CO_2e	4.13 %
C2 Waste transport	110,000	kg CO_2e	0.86 %
C3 Waste processing	350,000	kg CO_2e	2.85 %
C4 Waste disposal	810	kg CO_2e	0.01 %

The reliance on large mechanical systems, such as fans and pumps, means that the construction of these components contributed heavily to the system's overall carbon footprint. Furthermore, water use remained a persistent factor, adding to the life cycle

impacts of this system. As shown in Figure 11, the reliance on water for evaporative cooling continued to affect the system's environmental performance, even though energy-related emissions were eliminated.



Item	Value	Unit	Percentage %
HVAC components and equipment	3,400,000	kg CO_2e	27.63 %
Structural concrete (beams, columns, piling)	3,200,000	kg CO_2e	26.06 %
Ready-mix concrete for external walls and floors	1,200,000	kg CO_2e	9.43 %
EPS (expanded polystyrene) insulation	550,000	kg CO_2e	4.44 %
Reinforcement for concrete (rebar)	520,000	kg CO_2e	4.22 %
Pipes (water, heating, sewage)	510,000	kg CO_2e	4.17 %
Water	510,000	kg CO_2e	4.13 %
Plastic profiles and products	340,000	kg CO_2e	2.72 %
Bitumen and other roofing	330,000	kg CO_2e	2.68 %
Other resource types	1,800,000	kg CO_2e	14.52 %

Figure 11.Total life cycle impact by resource type, evaporative cooling.

Liquid: Immersion Cooling With No B6 Energy Consumption

In contrast, the liquid immersion cooling system showed a much lower embodied carbon footprint when B6 energy was zeroed out. As reflected in Table 15, the total carbon emissions for immersion cooling were 62% lower than evaporative cooling (4,590,172 kg CO2e vs. 12,323,290 kg CO2e). The compact design of the immersion system, which requires fewer mechanical components, resulted in reduced material used during construction.

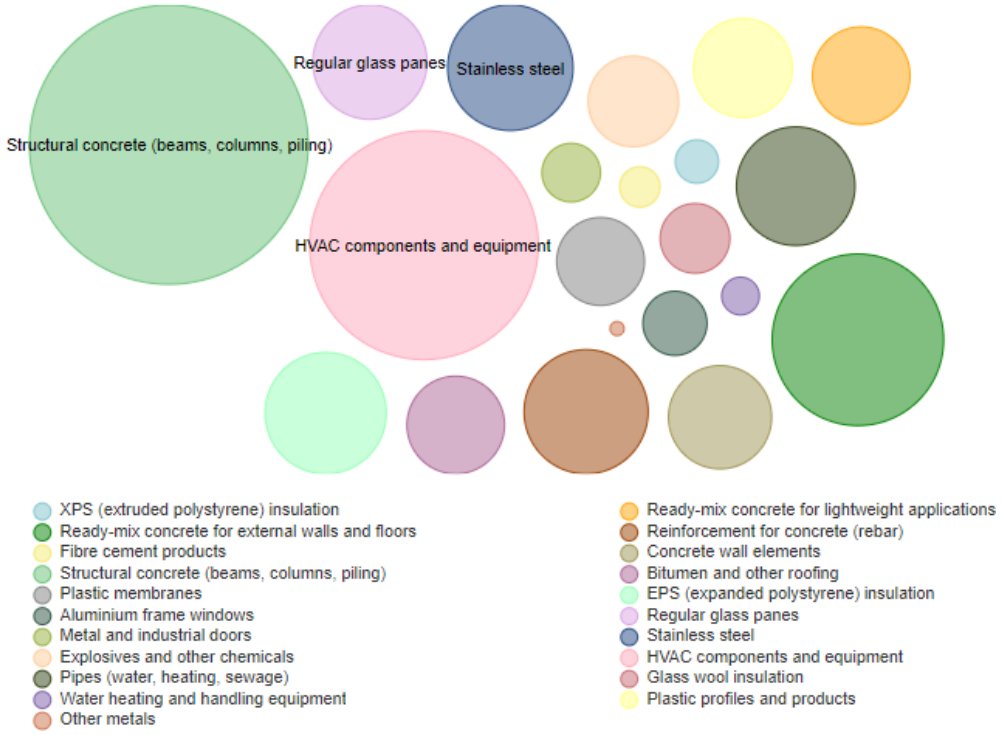
Figure 12 highlights the global warming potential of immersion cooling across its life cycle stages, emphasizing that the system's construction and materials required significantly less carbon-intensive infrastructure. Additionally, because immersion cooling does not rely on water for cooling, it avoided the environmental impacts associated with water use, further enhancing its sustainability profile.

Table 15. Immersion cooling global warming (kg CO2e) life cycle stages.

Item	Value	Unit	Percentage %
A1-A3 Materials	3,100,000	kg CO_2e	67.94 %
A4 Transport	81,000	kg CO_2e	1.77 %
A5 Construction	81,000	kg CO_2e	1.76 %
B4-B5 Replacement	1,100,000	kg CO_2e	24.56 %
C2 Waste transport	44,000	kg CO_2e	0.95 %
C3 Waste processing	140,000	kg CO_2e	3.01 %
C4 Waste disposal	360	kg CO_2e	0.01 %

The sensitivity analysis indicated that even when B6 energy consumption is eliminated, the liquid immersion system maintains a clear environmental advantage over

the evaporative air-cooled system, particularly in terms of embodied carbon and water use. Figure 12 illustrated that when B6 energy was not skewing the results, the other resources used in the core & shell and HVAC components became more apparent.



Item	Value	Unit	Percentage %
Structural concrete (beams, columns, piling)	1,300,000	kg CO_2e	28.47 %
HVAC components and equipment	850,000	kg CO_2e	18.57 %
Ready-mix concrete for external walls and floors	460,000	kg CO_2e	10.04 %
Stainless steel	230,000	kg CO_2e	5.02 %
Reinforcement for concrete (rebar)	220,000	kg CO_2e	4.83 %
EPS (expanded polystyrene) insulation	210,000	kg CO_2e	4.66 %
Pipes (water, heating, sewage)	200,000	kg CO_2e	4.37 %
Regular glass panes	180,000	kg CO_2e	4.01 %
Concrete wall elements	150,000	kg CO_2e	3.21 %
Other resource types	770,000	kg CO_2e	16.82 %

Figure 12.Total life cycle impact by resource type, immersion cooling.

Liquid immersion cooling's lower embodied carbon and resource requirements make it the more sustainable choice, even in scenarios where operational energy consumption is entirely carbon neutral. This sensitivity analysis highlighted the importance of considering both operational and embodied impacts when assessing the full life cycle performance of data center cooling technologies.

Carbon Footprint Comparison

I compared all the carbon footprints in the above models and sensitivity analyses to draw comprehensive inferences. Figure 13 demonstrates the proportional contributions of different life cycle stages to the total carbon footprint of both cooling systems. The evaporative system's operational energy consumption (B6) significantly outweighed its embodied carbon from construction materials, transportation, and installation.

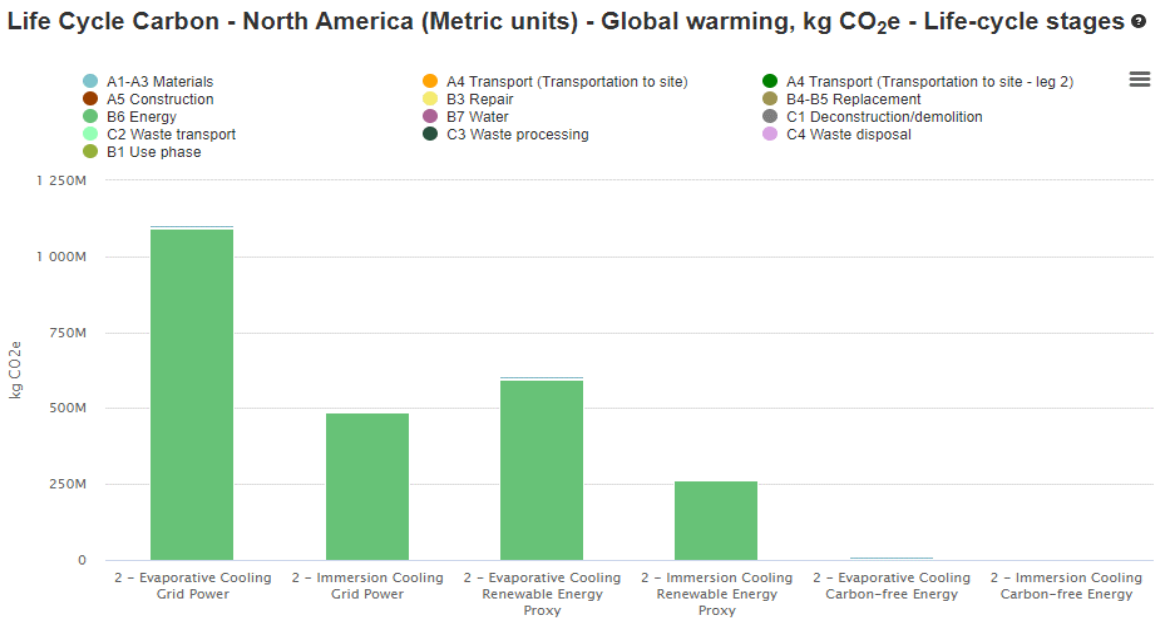


Figure 13.Carbon footprint comparison of life cycle stages (kg CO2e).

Figure 14 highlights the breakdown of life cycle carbon emissions by major system components, showcasing the stark difference in operational and embodied carbon between evaporative and immersion cooling systems. The other components are barely visible on the graph because operational energy dominates so completely.

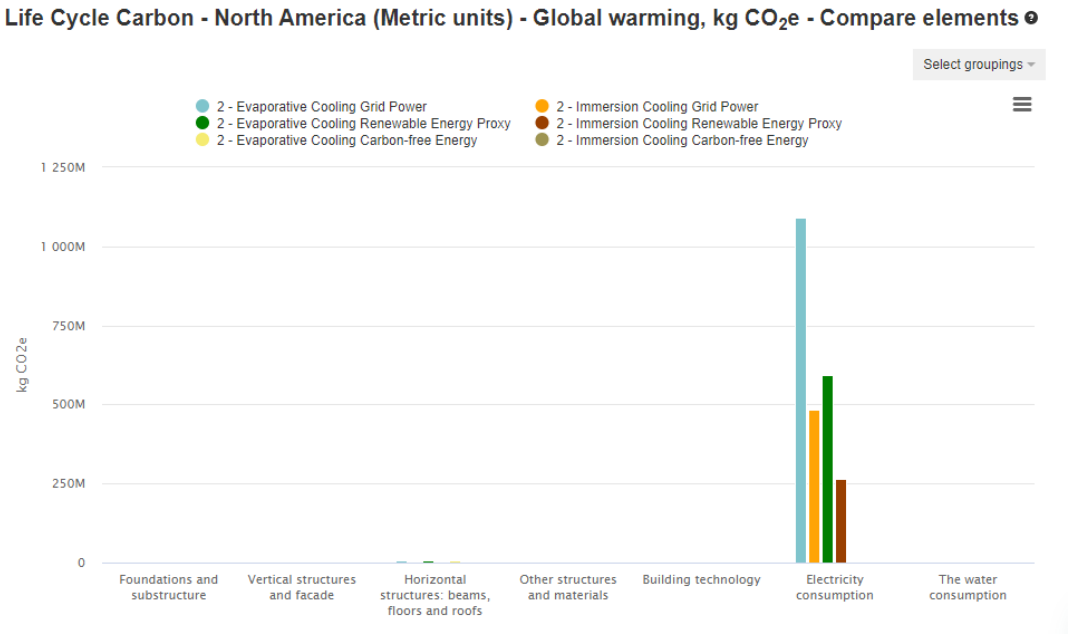


Figure 14.Life cycle carbon comparing elements.

When removing the B6 operational energy consumption to assess the embodied impacts alone, the disparity between the two systems shifts focus from operational efficiency to the material impacts of the core and cooling systems. Figure 15 shows that the evaporative cooling system's larger core & shell and reliance on equipment, such as fans and pumps, increased its embodied carbon footprint. Even without considering energy consumption, the evaporative system still showed a higher total footprint due to its material intensive design.

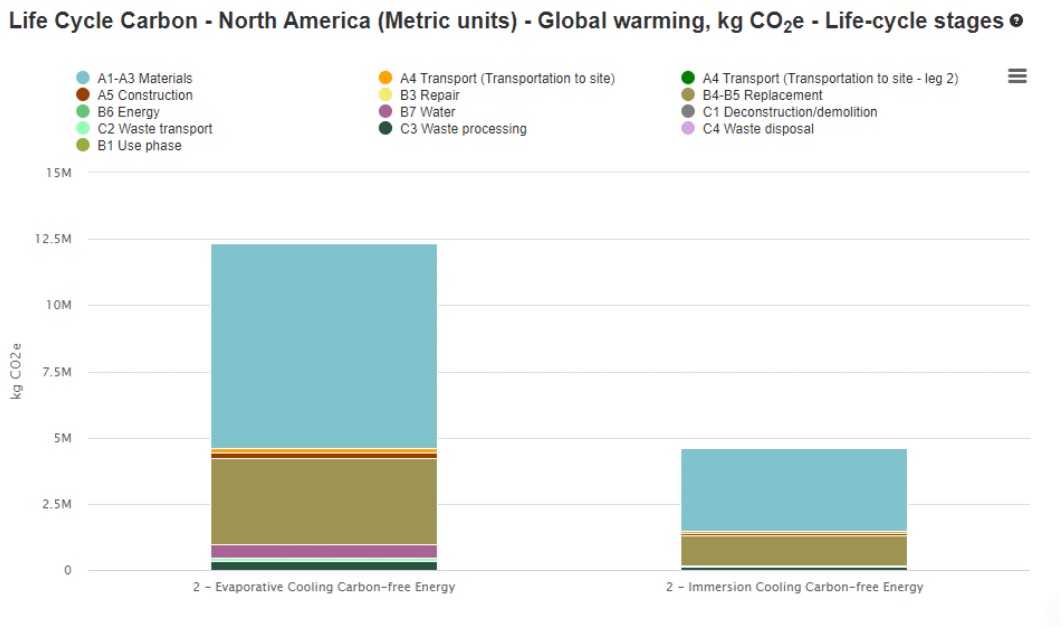


Figure 15.Life cycle carbon by life cycle stage (without B6).

Figure 16 isolated the contribution of construction materials and cooling systems, demonstrating that the compact nature of the immersion system leads to less embodied carbon. Compared to the more infrastructure-heavy evaporative system, the minimized use of steel and concrete in the immersion system significantly reduced its environmental impact.

In Figure 17, without operational emissions, the liquid immersion system's lower embodied carbon footprint is evident in every category.

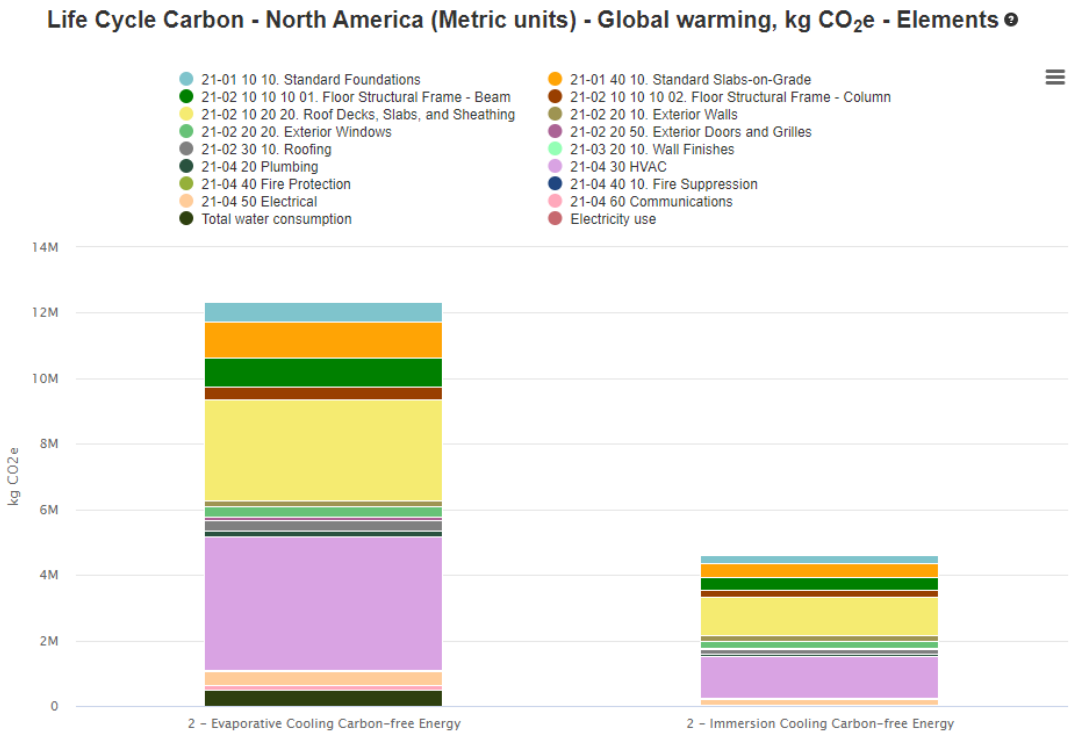


Figure 16.Life cycle carbon by element (without B6).

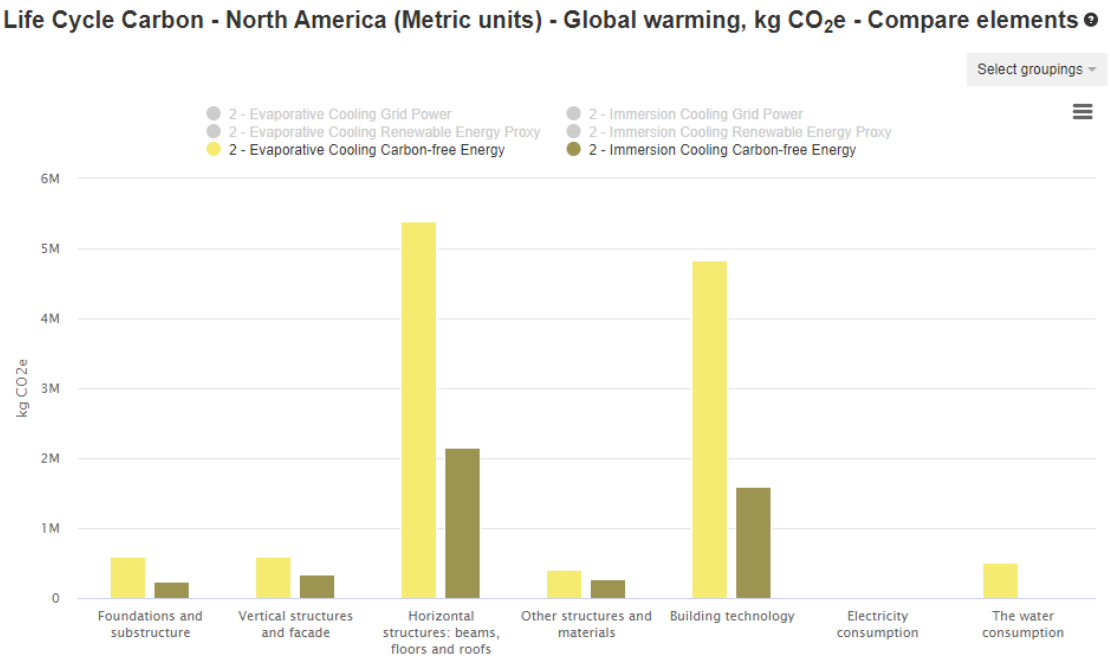


Figure 17.Life cycle carbon comparing elements (without B6).

Intensity vs Absolute Metrics

The comparison between evaporative cooling and immersion cooling, based on grid power, revealed an important trend: immersion cooling consistently results in lower overall emissions, but exhibits higher carbon intensity on a per-square-meter basis. Total emissions for immersion cooling are significantly lower than for evaporative cooling, with immersion cooling generating 489,014,668 kg CO_2e compared to 1,102,278,407 kg CO_2e for evaporative cooling. This represented a substantial 55.6% reduction in the overall global warming impact. On a per MW basis, immersion cooling similarly demonstrated lower emissions, with 9,780,293 kg CO_2e/MW compared to 22,045,568 kg CO_2e/MW for evaporative cooling, also a 55.6% reduction.

However, despite these lower absolute emissions, immersion cooling showed an increase in carbon intensity on a per-square-meter basis. Immersion cooling resulted in 1,042.23 kg CO_2e/m^2/year, while evaporative cooling produces 918.57 kg CO_2e/m^2/year, reflecting a 13.5% higher intensity in immersion cooling. This higher carbon intensity can be attributed to several factors, including the higher concentration of cooling equipment and the energy density typically associated with immersion cooling. Immersion cooling is more spatially efficient, requiring less floor space but concentrating more energy consumption in a smaller area, leading to a higher intensity of emissions per square meter. Additionally, immersion cooling is often applied in high-density compute environments, where more computing power is packed into less space, resulting in higher energy use per unit area, even though total emissions and per-MW emissions are significantly reduced. This analysis showed that while immersion cooling significantly

reduces overall CO2e emissions and improves efficiency on a per MW basis, it resulted in an increase in carbon intensity per square meter.

Scaled Results

If the liquid immersion-cooled model were scaled up to match the size of the evaporative air-cooled data center at 20,000 m2, it would dramatically increase its power density. Immersion cooling systems, being more efficient and compact, enable higher computational density by efficiently dissipating heat from densely packed servers. Based on my analysis and industry data, liquid immersion-cooled data centers generally required 30-60% less space than conventional air-cooled systems. Therefore, when scaled up to a facility of 20,000 m2, the liquid-cooled data center could potentially support approximately 120 to 160 MW of computing capacity compared to the air-cooled system's 50 MW.

This outcome highlights the primary advantage of liquid immersion cooling: its ability to cool a significantly larger number of servers within the same footprint. However, it also introduces a critical point of consideration, Jevons Paradox. By increasing the efficiency and density of the cooling system, immersion cooling allows for a much higher computational capacity within the same facility size. Consequently, operators may choose to maximize the potential of this increased capacity, resulting in a substantial rise in overall energy consumption rather than a net reduction. The potential for efficiency to drive increased demand perfectly exemplifies Jevons Paradox, where improvements in energy efficiency lead to higher total resource consumption due to expanded use.

In this context, immersion cooling significantly reduced the operational energy required for cooling and minimizes water usage, but it may inadvertently lead to greater overall energy consumption if the additional capacity is fully utilized for computational purposes. Therefore, despite its clear advantages in cooling efficiency and sustainability, the broader implications of increased energy demand must be managed through thoughtful operational strategies to avoid negating the environmental benefits.

Life Cycle Cost

In comparing the life cycle costs of air-cooled versus liquid-cooled data centers, several key factors must be considered, including capital expenditure (CapEx), operational expenditure (OpEx), and energy consumption.

Capital Expenditure (CapEx)

The capital costs for air-cooled and liquid-cooled systems vary significantly based on the density and size of the data center. A baseline analysis comparing traditional air cooling to liquid cooling systems shows that the initial costs for both can be comparable at low rack densities (e.g., 10 kW per rack). For instance, a study by Schneider Electric found that at a 10 kW per rack density, the capital costs of a 2 MW air cooled and an immersive liquid cooled data center are approximately the same. However, as rack densities increase, liquid cooling systems can achieve up to 14% savings in CapEx due to the increased compaction and reduced infrastructure requirements (*Capital Cost Analysis, Schneider Electric*, n.d.).

Haghshenas et al. (2023) highlighted that liquid cooling systems tend to reduce overall facility size, allowing for a two-thirds reduction in occupied space. This space-

saving advantage leads to reduced construction costs, especially in regions where space is limited or expensive. Additionally, liquid cooling eliminates the need for extensive air-handling units and ducting, further reducing the capital investments associated with traditional air cooling (Haghshenas et al., 2023).

CapEx can range from $7-$12 million per MW (Haghshenas et al., 2023; Major et al., 2022). A case study analyzing a 36 MW direct evaporative-cooled data center showed significant operational efficiency with lower capital costs due to fewer complex components like mechanical refrigeration. The 50 MW evaporative-cooled system would consume significant amounts of water annually resulting in long-term costs associated with water usage. The capital cost for building a large-scale evaporative-cooled data center is generally around $10-$12 million per MW for basic configurations, including power redundancy, IT equipment, and cooling infrastructure. This equates to approximately $500-$600 million for a 50 MW facility, depending on redundancy and climate conditions (*Capital Cost Analysis, Schneider Electric*, n.d.).

Immersion cooling is shown to offer CapEx savings of 10%-14% at higher rack densities compared to traditional evaporative cooling. For instance, when operating at 20-40 kW per rack, a study demonstrated CapEx savings of 10%-14% compared to conventional air cooling at 10 kW per rack (*Capital Cost Analysis, Schneider Electric*, n.d.). A comparative analysis between evaporative-cooled and two-phase immersion-cooled systems for a 36 MW data center revealed savings of $3 million per MW (Major et al., 2022).

The reduced space requirements are another benefit of immersion cooling. A case study showed that immersion cooling systems can reduce the building footprint by as

much as 60%, which has substantial implications for both CapEx and operational costs. Immersion cooling's ability to reduce physical infrastructure also contributes to lower embodied carbon and reduced construction material use. The capital cost for an immersion-cooled data center would be $450-540 million for a 50 MW facility, reflecting a 10%-14% CapEx saving over a similarly sized evaporative-cooled center (*Capital Cost Analysis, Schneider Electric*, n.d.; Haghshenas et al., 2023).

Operational Expenditure (OpEx)

The operational costs of liquid cooling systems are significantly lower compared to traditional air cooling systems, primarily due to their higher energy efficiency. Studies indicate that immersion cooling can reduce energy consumption by 50%, resulting in substantial cost savings over the life of the data center. “Immersion cooling systems operate with a power usage effectiveness (PUE) as low as 1.02 to 1.04, compared to air cooling, which typically operates with a higher PUE” (*Capital Cost Analysis, Schneider Electric*, n.d.; Haghshenas et al., 2023). This reduced energy consumption directly translates into lower operational costs over time.

Energy savings are a significant factor in life cycle cost analysis. Liquid cooling systems reduce the need for energy-intensive HVAC systems and provide more effective heat dissipation. The higher thermal capacity of liquids allows for greater computing power in a smaller space, which also decreases cooling-related energy demands.

One downside of liquid cooling systems is the difficulty and cost of retrofitting existing air-cooled data centers. Haghshenas et al. (2023) cautioned that retrofitting air-cooled systems with immersion cooling is generally not recommended due to the high costs involved in replacing or modifying the infrastructure. These costs include changes

to the physical space, installation of new cooling systems, and potential downtime during the upgrade process.

To provide an example comparison of life cycle costs between an air-cooled system with a Power Usage Effectiveness (PUE) of 1.09 and an immersion cooling system with a PUE of 1.04, this section breaks down the energy consumption and cost differences over a typical 10-year lifespan of a 1 MW data center. For this scenario, assume the the data center operates continuously throughout the year, with a constant IT load of 1 MW and an average U.S. commercial electricity rate of $0.11 per kWh.

The efficiency difference between the two systems, reflected in their PUE values, directly impacts the total energy consumed. In the case of the air-cooled system, a PUE of 1.09 results in total energy consumption of 1.09 MW for every 1 MW of IT load, factoring in the overhead required for cooling and infrastructure. This translates into an annual energy consumption of 9,548 MWh. Conversely, the immersion-cooled system, with a lower PUE of 1.04, consumes 9,110 MWh annually due to its more efficient cooling process.

When considering these consumption figures in terms of annual energy costs, the air-cooled system incurs $1,050,324 per year, while the immersion-cooled system costs $1,002,144 annually. Over a 10-year period, the total energy cost for the air-cooled system amounts to $10,503,240, compared to $10,021,440 for the immersion-cooled system. This results in energy cost savings of $481,800 in favor of the immersion-cooled system over the decade.

If these results were scaled up to a 50 MW data center, the financial operational impact would be significantly magnified. For the air-cooled system, the total annual

energy consumption would increase to 477,420 MWh, resulting in an annual cost of approximately $52,516,200. Over a 10-year period, this would total $525,162,000. In contrast, the immersion-cooled system would consume 455,520 MWh annually, with an energy cost of $50,107,200 per year, leading to a 10-year total of $501,072,000. Scaling to 50 MW, the immersion-cooled system would result in total savings of approximately $24,090,000 over a decade.

These savings show the long-term financial benefits associated with immersion cooling, driven by its higher energy efficiency. Upfront costs could be partially offset by reduced space and infrastructure needs, as immersion cooling allows for higher rack densities. Over a 10-year period, the immersion-cooled system demonstrates significant energy savings compared to the air-cooled alternative. This analysis highlights how marginal improvements in efficiency can result in long-term financial and operational benefits, reinforcing the importance of cooling decisions in data center design.

Cost of Carbon

The operational costs of liquid cooling systems are lower compared to traditional air cooling systems, primarily due to their higher energy efficiency. Studies indicate that immersion cooling can reduce energy consumption by 50%, resulting in substantial cost savings over the system's life cycle. By including the cost of carbon, the immersion-cooled system provides even greater savings. When factoring in the cost of carbon at $50 per metric ton, the 10-year life cycle cost scenario for a 1 MW data center is as follows:

Air-cooled system (PUE 1.09): $14,470,038

Immersion-cooled system (PUE 1.04): $13,243,574

Total savings over 10 years: $1,226,463

Chapter IV

Discussion

The rapid expansion of data centers, driven by AI and high-performance computing, has placed unprecedented demands on energy resources, particularly in cooling systems. This thesis presented a comparative life cycle assessment between liquid and evaporative air cooling systems, revealing several key insights regarding energy consumption, carbon emissions, water use, and long-term sustainability. The results confirmed the initial hypotheses: liquid cooling demonstrated significant environmental advantages over conventional air cooling, with reductions in both operational and embodied carbon emissions. However, these results are context-dependent, and the practical implementation of liquid cooling involves trade-offs, particularly concerning upfront costs and system complexity.

Energy Consumption and Cooling Efficiency

One of the most significant findings of this study was the superior energy efficiency of liquid cooling systems, particularly in high-density computing environments. Liquid immersion cooling, by directly engaging with heat-generating components, achieves more effective heat transfer compared to air, resulting in a reduction of cooling-related energy consumption by as much as 50%. This advantage becomes increasingly critical as data center power densities rise, driven by AI and machine learning workloads.

The performance of liquid cooling systems must be considered in the context of local environmental conditions and data center operational needs. In regions where free cooling is available, such as cold or temperate climates, evaporative air cooling may remain a viable and lower-cost option. Additionally, the carbon footprint of either system is heavily influenced by the source of electricity. Regions with renewable energy grids may see less relative benefit from liquid cooling, as operational emissions are already minimized. Conversely, in regions where fossil fuels dominate, liquid cooling's energy savings can substantially reduce total emissions.

Embodied Carbon and Data Center Design

The life cycle perspective adopted in this thesis highlights the importance of considering embodied carbon, particularly as operational emissions decrease with the adoption of renewable energy sources. Liquid cooling systems contribute to a smaller data center footprint, requiring less mechanical infrastructure (e.g., fans, HVAC systems) and allowing for more compact facility designs. As demonstrated in the case study, immersion cooling systems can reduce overall building size by 60%, leading to significant reductions in the embodied carbon from construction materials such as concrete and steel.

This smaller footprint is particularly valuable as hyperscale data centers seek to integrate sustainability into design without sacrificing performance. The reduction in building size not only lowers the embodied carbon but also contributes to lower capital expenditures (CapEx) over the long term, offsetting the higher initial costs associated with liquid cooling technology.

Water Usage and Sustainability Impacts

Water use is another critical factor in the comparison of cooling technologies. Air cooling systems, particularly evaporative models, are water-intensive and can strain resources in areas prone to drought or water scarcity. Liquid cooling, especially dielectric immersion systems, eliminates the need for large amounts of water, making it a more sustainable option in arid regions. This supports the conclusion that liquid cooling not only reduces energy consumption but also minimizes water-related environmental impacts, positioning it as a key technology for sustainable data center operations.

Jevons Paradox and the Future of Data Center Cooling

The study also mentioned the implications of the Jevons Paradox, where improvements in energy efficiency may lead to increased overall energy demand due to reduced costs and expanded capacities. While liquid cooling offers clear energy savings, these improvements could incentivize further expansion of data centers and computational workloads, particularly in the context of AI and blockchain technologies. This paradox suggests that without careful management of energy demand and infrastructure growth, the overall environmental benefits of liquid cooling could be diminished by increased usage.

To mitigate this, policymakers and data center operators must adopt strategies that balance efficiency gains with controlled growth in computing capacities. Leveraging liquid cooling within the broader context of renewable energy procurement and enhanced data management strategies can ensure that these efficiency improvements lead to net reductions in energy consumption and emissions.

Limitations and Future Research

While the findings presented are robust, this research acknowledges certain limitations. The availability of primary data for liquid cooling systems is limited, as these technologies are still emerging in commercial applications. As liquid cooling systems become more prevalent, future studies should incorporate more comprehensive primary data, particularly concerning the long-term maintenance and end-of-life phases of these systems.

Additionally, this thesis focused on cooling technologies but did not explore the broader life cycle impacts of other data center components, such as IT equipment and storage systems. Future research should aim to integrate these factors into a holistic LCA framework, offering a more complete picture of data center sustainability.

Conclusions

This thesis provided a clear comparison of liquid and air cooling systems in data centers from an LCA and LCC perspective. Liquid cooling emerged as the more sustainable solution, offering significant reductions in both operational and embodied carbon emissions. It also reduces water use and facilitates more compact, resource-efficient data center designs. However, its success depends on several contextual factors, including local climate conditions, energy grid composition, and the future management of data center growth.

In conclusion, liquid cooling represents a critical opportunity for reducing the environmental impact of data centers. However, to fully realize its potential, it must be integrated into broader strategies that promote renewable energy use and manage the growing demand for computational power.

Appendix 1

Air Cooled Data Sources

Appendix 1 provides detailed data sources and references used to model the evaporative air-cooled data center scenario in this thesis. It includes material inventories, equipment specifications, and EPD data.

Table 16. Air cooled bill of materials.

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Electricity use									
Electricity, USA, SERC Virginia/Carolina	39420000	kWh						Electricity - HVAC	1
Electricity, USA, SERC Virginia/Carolina	438000000	kWh						Electricity - IT	1
Building systems and installations									

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Galvanized steel pipes, DN 25 mm, (1 in), 2.57	180583	lbs			60	21-04 50 Electrical	Electrification	Pipes (water, heating, sewage)	33
PVC plastic pipe, 0% recycled content	56537	lbs			30	21-04 50 Electrical	Electrification	Plastic profiles and products	6
Air handling unit (AHU), commercial grade, 3800	125	unit			15	21-04 30 HVAC	Evaporative System	HVAC components and equipment	23
Centrifugal chillers, 13.8 kg/unit, CenTraVacT	60	unit			20	21-04 30 HVAC	Evaporative System	HVAC components and equipment	23
Pendent fire sprinklers, 0.0944 kg/unit	999.999	unit			As building	21-04 40 Fire Protection	Fire suppression	Other metals	5
Polyvinyl chloride (PVC) pipe for drainage	22046.2	lbs			60	21-04 40 Fire Protection	Fire suppression	Pipes (water, heating, sewage)	33
Cast Iron Pipes	4561.38	lbs			35	21-04 20 Plumbing	Fresh water distribution	Water heating and handling equipment	22
Copper pipes, Type L, DN 100 mm, (4 in)	38423.6	lbs			60	21-04 20 Plumbing	Fresh water distribution	Pipes (water, heating, sewage)	33

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Aluminium, extruded, 2660-2840 kg/m3	10800	lbs	0.508		30	21-04 30 HVAC	Hot Aisle Containment	Aluminium	5
Fabricated hollow structural steel	93762	lbs			30	21-04 30 HVAC	Hot Aisle Containment	Structural steel and steel profiles	5
Perforated aluminium foil laminated to	23571	sq ft			30	21-04 30 HVAC	Hot Aisle Containment	Plastic membranes	7
Steel truss connector plates, ASTM	25434	lbs			30	21-04 30 HVAC	Hot Aisle Containment	Structural steel and steel profiles	5
Wall panel, polycarbonate, 0.47in, 74.3lbs/ft3	5022	sq ft	12		30	21-04 30 HVAC	Hot Aisle Containment	Partitioning systems (without windows)	8
Air handling unit, with heat recovery	8.1696	unit			25	21-04 30 HVAC	HVAC	HVAC components and equipment	23
Copper pipes, Type L, DN 100 mm (4 in)	5054.79	lbs			60	21-04 30 HVAC	HVAC	Pipes (water, heating, sewage)	33
Glass Fiber Reinforced Polymer Water	5240.01	lbs			35	21-04 30 HVAC	HVAC	Water heating and handling equipment	22

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Glass wool insulation for pipes, unfaced, per	28465.1	lbs			As building	21-04 30 HVAC	HVAC	Glass wool insulation	7
Polyvinyl chloride (PVC) pipe for drainage	67111.9	lbs			60	21-04 30 HVAC	HVAC	Pipes (water, heating, sewage)	33
Ventilation ducting, per m linear, D: 500 mm	112691	lbs			25	21-04 30 HVAC	HVAC	HVAC components and equipment	23
Galvanized steel pipes, DN 25 mm, (1 in), 2.57	28671.5	lbs			60	21-04 60 Communications	Telecommunication	Pipes (water, heating, sewage)	33
PVC plastic pipe, 0% recycled content	23776	lbs			30	21-04 60 Communications	Telecommunication	Plastic profiles and products	6
Polypropylene (PP) pipe for drainage and	5422.14	lbs			60	21-04 20 Plumbing	Wastewater and rainwater drainage	Pipes (water, heating, sewage)	33
Polyvinyl chloride (PVC) pipe for drainage	29571.3	lbs			60	21-04 20 Plumbing	Wastewater and rainwater drainage	Pipes (water, heating, sewage)	33
Columns and load-bearing vertical structures									

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Reinforcement steel (rebar), generic, 90%	4995.06	lbs		4 lbs/ft3 (65 kg/m3)	As building	21-02 10 10 10 02. Floor Structural Frame -	Reinforced concrete shear wall, 7.8 in (200	Reinforcement for concrete (rebar)	5
Ready-mix concrete, 5000 psi, 34.5 Mpa	184433	lbs	203.2		As building	21-02 10 10 10 02. Floor Structural Frame -	Reinforced concrete shear wall, 7.8 in (200	Ready-mix concrete for external walls and	3
Reinforcement steel (rebar), generic, 90%	265334	lbs		20.28 lbs/ft3 (325 kg/m3) of reinforcemen	As building	21-02 10 10 10 02. Floor Structural Frame -	Precast concrete column, 17.7 x 17.7 in	Reinforcement for concrete (rebar)	5
Precast concrete, structural	1959460	lbs	203.2		As building	21-02 10 10 10 02. Floor Structural Frame -	Precast concrete column, 17.7 x 17.7 in	Structural concrete (beams, columns	3
External walls and facade									
Fibre cement boards, 1300 kg/m3 (81.16	14458	sq ft	9.53		As building	21-03 20 10. Wall Finishes	Fiber cement sheet cladding	Fibre cement products	6
Precast concrete, insulated wall panel	14458	sq ft	90		As building	21-02 20 10. Exterior Walls	Precast concrete sandwich external wall	Concrete wall elements	3
Precast concrete, insulated wall panel	14458	sq ft	80		As building	21-02 20 10. Exterior Walls	Precast concrete sandwich external wall	Concrete wall elements	3

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Foundation, sub-surface, basement and retaining									
Ready-mix concrete, 5000 psi, 34.5 Mpa	528	cu yd	203.2		As building	21-01 10 10. Standard Foundations	Footing foundations for hard soils (sand	Ready-mix concrete for external walls and	3
Ready-mix concrete, 2500 psi, 17.2 Mpa	1300	cu yd	50		As building	21-01 10 10. Standard Foundations	Concrete cleanliness per GFA	Ready-mix concrete for lightweight applications	3
Styrofoam insulation, 1.8 pcf, Styrofoam	3752	sq ft	152.4	Styrofoam insulation, 1.8 pcf, Styrofoam	As building	21-01 10 10. Standard Foundations	Frost insulation (XPS)	XPS (extruded polystyrene) insulation	7
Reinforcement steel (rebar), generic, 90%	138891	lbs			As building	21-01 10 10. Standard Foundations	Footing foundations for hard soils (sand	Reinforcement for concrete (rebar)	5
Floor slabs, ceilings, roofing decks, beams									
Ready-mix concrete, 5000 psi, 34.5 Mpa	215278	sq ft	101.6	Ready-mix concrete, generic, 4400/5400	As building	21-01 40 10. Standard Slabs-on-Grade	Ground slab, reinforced concrete (4400/5400	Ready-mix concrete for external walls and	3
Reinforcement steel (rebar), generic, 90%	389777	lbs		reinforcement steel, 1.81 lb per sqft of slab	As building	21-01 40 10. Standard Slabs-on-Grade	Ground slab, reinforced concrete (4400/5400	Reinforcement for concrete (rebar)	5

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
EPDM membrane roofing, 0.1in	215278	sq ft	1		30	21-02 10 20 20. Roof Decks, Slabs, and	Hollow-core roof slab assembly	Plastic membranes	7
EPS insulation, 1.02in	215278	sq ft	238		As building	21-02 10 20 20. Roof Decks, Slabs, and	Hollow-core roof slab assembly	EPS (expanded polystyrene) insulation	7
Precast concrete, structural	16093700	lbs	265	75 lbs/sqft, 365 kg/m2	As building	21-02 10 20 20. Roof Decks, Slabs, and	Hollow-core roof slab assembly	Structural concrete (beams, columns	3
Reinforcement steel (rebar), generic, 90%	583230	lbs		18.7 lbs/ft3 (300 kg/m3) of reinforcemen	As building	21-02 10 10 10 01. Floor Structural Frame -	Precast concrete beam, 15.7 x 17.7 in (400	Reinforcement for concrete (rebar)	5
Precast concrete, structural	4665840	lbs	203.2		As building	21-02 10 10 10 01. Floor Structural Frame -	Precast concrete beam, 15.7 x 17.7 in (400	Structural concrete (beams, columns	3
Fiberglass asphalt shingle roofing	215278	sq ft			20	21-02 30 10. Roofing	Roof covering, asphalt shingles	Bitumen and other roofing	7
Water use									
Tap water, conventionally treated (One Click	0	cu ft						Water	1

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Windows and doors									
Steel door, 86x36x1.34in	4306	sq ft	34.04		30	21-02 20 50. Exterior Doors and Grilles	External door, steel	Metal and industrial doors	8
Aluminium window frame, 50in x 58in	16141.3	lbs		Average weight 1.4 kg/m, average	As building	21-02 20 20. Exterior Windows	Window, metal framed, double pane	Aluminium frame windows	8
Flat glass, clear, tinted and low-iron (National	18764	sq ft	20		35	21-02 20 20. Exterior Windows	Window, metal framed, double pane	Regular glass panes	8

Author's assumptions, aggregated and anonymized from private industry data.

Table 17. Air cooled data sources.

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	PCR	Download EPD
Air handling unit, with heat	50 000 m3/h (29428.9 ft3/min)			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2019	LOCAL	One Click LCA	EN15804+A1	
Aluminium window frame	50in x 58in	YOW 350 XT, YOW 225 H, YOW	YKK AP	UL Environment	4786832322.107.1	Aluminum Window System, YKK	ISO 14040, EN15804+A1	Third-party verified (as per ISO	2015	USA	GaBi	IBU/UL PCR Part A: Calculation	Download EPD
Cast Iron Pipes				Quartz	CP175	Quartz 2015	ISO 14040	Third-party verified (as per ISO	2015	USA	GaBi	LCIA: TRACI 2.1, GWP IPCC	
Concrete cleanliness per GEA	with US industry average concrete EPD			-		One Click LCA One Click				USA	Other		
Copper pipes	Type L, DN 100 mm, (4 in), 8.02 kg/m		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
EPDM membrane roofing	0.1in			Quartz	CP071	Quartz 2015	ISO 14040	Third-party verified (as per ISO	2015	USA	GaBi	LCIA: TRACI 2.1, GWP IPCC	

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	PCR	Download EPD
EPS insulation	1.02in			Quartz	CP120	Quartz 2015	ISO 14040	Third-party verified (as per	2015	USA	GaBi	LCIA: TRACI 2.1, GWP	
Electricity, USA, Vermont			eGRID	One Click LCA		LCA study for country		Internally verified	2022	vermont, USA	One Click LCA		
Electrification system for data	incl. One Click LCA			-		One Click LCA One				northAmerica	Other		
External door, steel	U: 0.20, for USA and Canada			-		One Click LCA generic				northAmerica	Other		
Fiber cement sheet cladding	Fiber cement sheet cladding			-		One Click LCA generic				northAmerica	Other		
Fiberglass asphalt shingle	12.7 kg/m2		Asphalt Roofing	UL Environment	4787168709.101.1	EPD Asphalt Shingle Roofing	ISO 14040	Third-party verified (as per	2016	northAmerica	GaBi	ASTM PCR Asphalt shingles	Download EPD

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	PCR	Download EPD
Fibre cement boards	1300 kg/m3 (81.16 lbs/ft3)			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2019	LOCAL	One Click LCA	EN15804+A1	
Fire suppression system for data	incl. One Click LCA generic			-		One Click LCA One				northAmerica	Other		
Flat glass, clear, tinted and			National Glass Associations	ASTM	EPD-121	EPD Flat Glass	ISO 14040	Third-party verified (as per ISO	2019	USA	GaBi	NSF GANA PCR for Flat Glass	Download EPD
Footing foundations for hard soils	with US industry average concrete EPD			-		One Click LCA One				northAmerica	Other		
Fresh water distribution system	incl. One Click LCA generic			-		One Click LCA One				northAmerica	Other		
Frost insulation (XPS)	Frost insulation is placed			-		One Click LCA generic				northAmerica	Other		

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	PCR	Download EPD
Galvanized steel pipes	DN 25 mm, (1 in), 2.57 kg/m,		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
Glass Fiber Reinforced				Quartz	CP176	Quartz 2015	ISO 14040	Third-party verified (as per	2015	USA	GaBi	LCIA: TRACI 2.1, GWP	
Glass wool insulation for	L = 0.035 W/mK, d= 6		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
Ground slab, reinforced	with US industry average concrete EPD			-		One Click LCA generic				northAmerica	Other		
HVAC system for data centers	incl. One Click LCA			-		One Click LCA One				northAmerica	Other		
Hollow-core roof slab	with US industry average EPDs			-		One Click LCA One				northAmerica	Other		

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	PCR	Download EPD
PVC plastic pipe	0% recycled content			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2019	LOCAL	One Click LCA	EN15804+A1	
Pendent fire sprinklers	0.0944 kg/unit	GL112 Pendent	Reliable Sprinkler Autom	ASTM	EPD-372	EPD Reliable® Sprinkler Model	ISO 14040	Third-party verified (as per ISO	2023	southCarolina, USA	ecoinvent	ISO 21930:2017	Download EPD
Polypropylene (PP) pipe for	DN 200 mm (8 in), 9.95 kg/m,		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
Polyvinyl chloride (PVC) pipe for	DN 200 mm (8 in), 12.68 kg/m		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
Polyvinyl chloride (PVC) pipe for	DN 500 mm (20 in), 61.98 kg/m		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
Precast concrete beam, 15.7 x 17.7 in	with US industry average concrete EPD			-		One Click LCA generic				northAmerica	Other		

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	PCR	Download EPD
Precast concrete column, 17.7 x	with US industry average concrete			-		One Click LCA generic				northAmerica	Other		
Precast concrete sandwich	for USA and Canada			-		One Click LCA generic				northAmerica	Other		
Precast concrete, insulate				ASTM	EPD-016	Architectural and Insulate	ISO 14040	Third-party verified (as per	2015	northAmerica	USLCI	ASTM PCR for Preparing an	Download EPD
Precast concrete, structura				ASTM	EPD-017	Structural Precast Concrete	ISO 14040	Third-party verified (as per	2015	northAmerica	USLCI	ASTM PCR for Preparing an	Download EPD
Ready-mix concrete	5000 psi, 34.5 Mpa		Industry average	NRMCA	-	NRMCA Member National	ISO 14040	Third-party verified (as per	2020	USA	ecoinvent	-	Download EPD
Ready-mix concrete	2500 psi, 17.2 Mpa		Industry average	NRMCA	-	NRMCA Member National	ISO 14040	Third-party verified (as per	2020	USA	ecoinvent	-	Download EPD

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	PCR	Download EPD
Reinforced concrete shear	5000 psi, 34.5 Mpa, with US			-		One Click LCA generic				northAmerica	Other		
Reinforcement steel (rebar),	90% recycled content, A615			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2018	LOCAL	One Click LCA	EN15804+A1	
Roof covering, asphalt shingles	for USA and Canada			-		One Click LCA generic				northAmerica	Other		
Steel door	86x36x1.34in			Quartz	CP127	Quartz 2015	ISO 14040	Third-party verified (as per	2015	USA	GaBi	LCIA: TRACI 2.1, GWP	
Styrofoam insulation	1.8 pcf	Styrofoam Highload 40,	Dow	UL Environment	4786548101.101.1	Styrofoam Insulation, Dow	ISO 14040	Third-party verified (as per	2014	northAmerica	ecoinvent	PCR Building Envelope	Download EPD
Telecommunication system	incl. One Click LCA			-		One Click LCA One				northAmerica	Other		

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	PCR	Download EPD
Ventilation ducting	per m linear, D: 500 mm (19.69			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2019	LOCAL	One Click LCA	EN15804+A1	
Wastewater and rainwater drainage	incl. One Click LCA generic			-		One Click LCA One Click				northAmerica	Other		
Window, metal framed, double	U: 0.32, for USA and Canada			-		One Click LCA generic				northAmerica	Other		

Author's assumptions, aggregated and anonymized from private industry data.

Appendix 2

Liquid Cooled Data Sources

Appendix 2 provides detailed data sources and references used to model the immersion liquid-cooled data center scenario in this thesis. It includes material inventories, equipment specifications, and EPD data.

Table 18. Liquid cooled bill of materials.

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Electricity use									
Electricity, USA, SERC Virginia/Carolina	17520000	kWh/year						Electricity - HVAC	1
Electricity, USA, SERC Virginia/Carolina	438000000	kWh/year						Electricity - IT	1
Building systems and installations									

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
PVC plastic pipe, 0% recycled content	22106	lbs			30	21-04 50 Electrical	Electrification	Plastic profiles and products	6
Galvanized steel pipes, DN 25 mm, (1 in), 2.57	70608.3	lbs			60	21-04 50 Electrical	Electrification	Pipes (water, heating, sewage)	33
Pendent fire sprinklers, 0.0944 kg/unit	391.001	unit			As building	21-04 40 10. Fire Suppression	Fire suppression	Other metals	5
Polyvinyl chloride (PVC) pipe for drainage	8620.1	lbs			60	21-04 40 10. Fire Suppression	Fire suppression	Pipes (water, heating, sewage)	33
Cast Iron Pipes	1783.51	lbs			35	21-04 20 Plumbing	Fresh water distribution	Water heating and handling equipment	22
Copper pipes, Type L, DN 100 mm, (4 in)	15023.7	lbs			60	21-04 20 Plumbing	Fresh water distribution	Pipes (water, heating, sewage)	33
Air handling unit, with heat recovery	3.1943	unit			25	21-04 30 HVAC	HVAC	HVAC components and equipment	23
Copper pipes, Type L, DN 100 mm, (4 in)	1976.43	lbs			60	21-04 30 HVAC	HVAC	Pipes (water, heating, sewage)	33

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Glass Fiber Reinforced Polymer Water	2048.85	lbs			35	21-04 30 HVAC	HVAC	Water heating and handling equipment	22
Glass wool insulation for pipes, unfaced, per	11129.9	lbs			As building	21-04 30 HVAC	HVAC	Glass wool insulation	7
Polyvinyl chloride (PVC) pipe for drainage	26240.8	lbs			60	21-04 30 HVAC	HVAC	Pipes (water, heating, sewage)	33
Ventilation ducting, per m linear, D: 500 mm	44062.5	lbs			25	21-04 30 HVAC	HVAC	HVAC components and equipment	23
Stainless steel metal sheets and coils, 0.012-	25355	lbs	0.3		15	21-04 30 HVAC	Immersion System	Stainless steel	5
Petroleum-based hydraulic engine	42990	lbs			15	21-04 30 HVAC	Immersion System	Explosives and other chemicals	9
PVC plastic pipe, 0% recycled content	9296	lbs			30	21-04 60 Communications	Telecommunication	Plastic profiles and products	6
Galvanized steel pipes, DN 25 mm, (1 in), 2.57	11210.6	lbs			60	21-04 60 Communications	Telecommunication	Pipes (water, heating, sewage)	33

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Polypropylene (PP) pipe for drainage and	2120.06	lbs			60	21-04 20 Plumbing	Wastewater and rainwater drainage	Pipes (water, heating, sewage)	33
Polyvinyl chloride (PVC) pipe for drainage	11562.4	lbs			60	21-04 20 Plumbing	Wastewater and rainwater drainage	Pipes (water, heating, sewage)	33
Columns and load-bearing vertical									
Reinforcement steel (rebar), generic	3554.58	lbs		4 lbs/ft3 (65 kg/m3)	As building	21-02 10 10 10 02. Floor Structural Frame -	Reinforced concrete shear wall, 7.8 in (200	Reinforcement for concrete (rebar)	5
Reinforcement steel (rebar), generic	120285	lbs		20.28 lbs/ft3 (325 kg/m3) of reinforceme	As building	21-02 10 10 10 02. Floor Structural Frame -	Precast concrete column, 17.7 x 17.7 in	Reinforcement for concrete (rebar)	5
Ready-mix concrete, 5000 psi, 34.5 Mpa	131246	lbs	203.2		As building	21-02 10 10 10 02. Floor Structural Frame -	Reinforced concrete shear wall, 7.8 in (200	Ready-mix concrete for external walls and	3
Precast concrete, structural	888289	lbs	203.2		As building	21-02 10 10 10 02. Floor Structural Frame -	Precast concrete column, 17.7 x 17.7 in	Structural concrete (beams, columns	3
External walls and facade									

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Fibre cement boards, 1300 kg/m3 (81.16	11663	sq ft	9.53		As building	21-03 20 10. Wall Finishes	Fiber cement sheet cladding	Fibre cement products	6
Precast concrete, insulated wall panel	11663	sq ft	90		As building	21-02 20 10. Exterior Walls	Precast concrete sandwich external wall	Concrete wall elements	3
Precast concrete, insulated wall panel	11663	sq ft	80		As building	21-02 20 10. Exterior Walls	Precast concrete sandwich external wall	Concrete wall elements	3
Foundation, sub-surface, basement and retaining									
Ready-mix concrete, 5000 psi, 34.5 Mpa	210	cu yd	203.2		As building	21-01 10 10. Standard Foundations	Footing foundations for hard soils (sand	Ready-mix concrete for external walls and	3
Ready-mix concrete, 2500 psi, 17.2 Mpa	510	cu yd	50		As building	21-01 10 10. Standard Foundations	Concrete cleanliness per GFA	Ready-mix concrete for lightweight applications	3
Styrofoam insulation, 1.8 pcf, Styrofoam	2670	sq ft	152.4	Styrofoam insulation, 1.8 pcf, Styrofoam	As building	21-01 10 10. Standard Foundations	Frost insulation (XPS)	XPS (extruded polystyrene) insulation	7
Reinforcement steel (rebar), generic	54306.6	lbs			As building	21-01 10 10. Standard Foundations	Footing foundations for hard soils (sand	Reinforcement for concrete (rebar)	5

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Floor slabs, ceilings, roofing decks									
Ready-mix concrete, 5000 psi, 34.5 Mpa	84174	sq ft	101.6	Ready-mix concrete, generic, 4400/5400	As building	21-01 40 10. Standard Slabs-on-Grade	Ground slab, reinforced concrete (4400/5400	Ready-mix concrete for external walls and	3
Reinforcement steel (rebar), generic	152403	lbs		reinforcement steel, 1.81 lb per sqft of slab	As building	21-01 40 10. Standard Slabs-on-Grade	Ground slab, reinforced concrete (4400/5400	Reinforcement for concrete (rebar)	5
EPDM membrane roofing, 0.1in	84174	sq ft	1		30	21-02 10 20 20. Roof Decks, Slabs, and	Hollow-core roof slab assembly	Plastic membranes	7
EPS insulation, 1.02in	84174	sq ft	238		As building	21-02 10 20 20. Roof Decks, Slabs, and	Hollow-core roof slab assembly	EPS (expanded polystyrene) insulation	7
Precast concrete, structural	6292670	lbs	265	75 lbs/sqft, 365 kg/m2	As building	21-02 10 20 20. Roof Decks, Slabs, and	Hollow-core roof slab assembly	Structural concrete (beams, columns	3
Reinforcement steel (rebar), generic	258032	lbs		18.7 lbs/ft3 (300 kg/m3) of reinforceme	As building	21-02 10 10 10 01. Floor Structural Frame -	Precast concrete beam, 15.7 x 17.7 in (400	Reinforcement for concrete (rebar)	5
Precast concrete, structural	2064260	lbs	203.2		As building	21-02 10 10 10 01. Floor Structural Frame -	Precast concrete beam, 15.7 x 17.7 in (400	Structural concrete (beams, columns	3

Resource	Quantity	Unit	Thickness mm	Comment	Service life	Omniclass	Construction	Resource type	csiMasterformat
Fiberglass asphalt shingle roofing	84174	sq ft			20	21-02 30 10. Roofing	Roof covering, asphalt shingles	Bitumen and other roofing	7
Water use									
Tap water, conventionally treated (One Click	0	cu ft						Water	1
Windows and doors									
Steel door, 86x36x1.34in	1683	sq ft	34.04		30	21-02 20 50. Exterior Doors and Grilles	External door, steel	Metal and industrial doors	8
Aluminium window frame, 50in x 58in	11480.6	lbs		Average weight 1.4 kg/m, average	As building	21-02 20 20. Exterior Windows	Window, metal framed, double pane	Aluminium frame windows	8
Flat glass, clear, tinted and low-iron (National	13346	sq ft	20		35	21-02 20 20. Exterior Windows	Window, metal framed, double pane	Regular glass panes	8

Author's assumptions, aggregated and anonymized from private industry data.

Table 19. Liquid cooled data sources.

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Product Category Rules (PCR)	Download EPD
Air handling unit, with heat	50 000 m3/h (29428.9 ft3/min)			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2019	LOCAL	One Click LCA	EN15804+A1	
Aluminium window frame	50in x 58in	YOW 350 XT, YOW 225 H, YOW	YKK AP	UL Environment	4786832322.107.1	Aluminum Window System, YKK	ISO 14040, EN15804+A1	Third-party verified (as per ISO	2015	USA	GaBi	IBU/UL PCR Part A: Calculation	Download EPD
Cast Iron Pipes				Quartz	CP175	Quartz 2015	ISO 14040	Third-party verified (as per ISO	2015	USA	GaBi	LCIA: TRACI 2.1, GWP IPCC	
Concrete cleanliness per GFA	with US industry average concrete EPD			-		One Click LCA One Click				USA	Other		
Copper pipes	Type L, DN 100 mm, (4 in), 8.02 kg/m,		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
EPDM membrane roofing	0.1in			Quartz	CP071	Quartz 2015	ISO 14040	Third-party verified (as per ISO	2015	USA	GaBi	LCIA: TRACI 2.1, GWP IPCC	

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Product Category Rules (PCR)	Download EPD
EPS insulation	1.02in			Quartz	CP120	Quartz 2015	ISO 14040	Third-party verified (as per ISO	2015	USA	GaBi	LCIA: TRACI 2.1, GWP IPCC	
Electricity, USA, Iowa			eGRID	One Click LCA		LCA study for country specific		Internally verified	2022	iowa, USA	One Click LCA		
Electrification system for data centers	incl. One Click LCA generic			-		One Click LCA One Click				northAmerica	Other		
External door, steel	U: 0.20, for USA and Canada			-		One Click LCA generic construc				northAmerica	Other		
Fiber cement sheet cladding	Fiber cement sheet cladding, 3/8			-		One Click LCA generic construc				northAmerica	Other		
Fiberglass asphalt shingle roofing	12.7 kg/m2		Asphalt Roofing Manufacturers Associat	UL Environment	4787168709.101.1	EPD Asphalt Shingle Roofing System	ISO 14040	Third-party verified (as per ISO	2016	northAmerica	GaBi	ASTM PCR Asphalt shingles, built-	Download EPD

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Product Category Rules (PCR)	Download EPD
Fibre cement boards	1300 kg/m3 (81.16 lbs/ft3)			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2019	LOCAL	One Click LCA	EN15804+A1	
Fire suppression system for data	incl. One Click LCA generic			-		One Click LCA One Click				northAmerica	Other		
Flat glass, clear, tinted and			National Glass Association	ASTM	EPD-121	EPD Flat Glass	ISO 14040	Third-party verified (as per ISO	2019	USA	GaBi	NSF GANA PCR for Flat Glass -	Download EPD
Footing foundations for hard soils	with US industry average concrete EPD			-		One Click LCA One Click				northAmerica	Other		
Fresh water distribution system	incl. One Click LCA generic			-		One Click LCA One Click				northAmerica	Other		
Frost insulation (XPS)	Frost insulation is placed around			-		One Click LCA generic construc				northAmerica	Other		

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Product Category Rules (PCR)	Download EPD
Galvanized steel pipes	DN 25 mm, (1 in), 2.57 kg/m, wall		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
Glass Fiber Reinforced Polymer				Quartz	CP176	Quartz 2015	ISO 14040	Third-party verified (as per ISO	2015	USA	GaBi	LCIA: TRACI 2.1, GWP IPCC	
Glass wool insulation for pipes,	L = 0.035 W/mK, d= 6 inch, 50		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
Ground slab, reinforced concrete	with US industry average concrete EPD			-		One Click LCA generic construc				northAmerica	Other		
HVAC system for data centers	incl. One Click LCA generic			-		One Click LCA One Click				northAmerica	Other		
Hollow-core roof slab assembl	with US industry average EPDs			-		One Click LCA One Click				northAmerica	Other		

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Product Category Rules (PCR)	Download EPD
PVC plastic pipe	0% recycled content			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2019	LOCAL	One Click LCA	EN15804+A1	
Pendent fire sprinklers	0.0944 kg/unit	GL112 Pendent	Reliable Sprinkler Automatic	ASTM	EPD-372	EPD Reliable® Sprinkler Model	ISO 14040	Third-party verified (as per ISO	2023	southCarolina, USA	ecoinvent	ISO 21930:2017	Download EPD
Polypropylene (PP) pipe for drainage	DN 200 mm (8 in), 9.95 kg/m, wall		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
Polyvinyl chloride (PVC) pipe for	DN 200 mm (8 in), 12.68 kg/m,		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
Polyvinyl chloride (PVC) pipe for	DN 500 mm (20 in), 61.98 kg/m,		One Click LCA	One Click LCA	-	One Click LCA	EN15804+A1, EN15804+A2	Internally verified	2023	LOCAL	One Click LCA	EN15804+A1, EN15804+A2	
Precast concrete beam, 15.7 x 17.7 in	with US industry average concrete EPD			-		One Click LCA generic construc				northAmerica	Other		

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Product Category Rules (PCR)	Download EPD
Precast concrete column, 17.7 x 17.7 in	with US industry average concrete EPD			-		One Click LCA generic construc				northAmerica	Other		
Precast concrete sandwich external	for USA and Canada			-		One Click LCA generic construc				northAmerica	Other		
Precast concrete, insulated wall				ASTM	EPD-016	Architectural and Insulated Wall	ISO 14040	Third-party verified (as per ISO	2015	northAmerica	USLCI	ASTM PCR for Preparing an EPD	Download EPD
Precast concrete, structural				ASTM	EPD-017	Structural Precast Concrete	ISO 14040	Third-party verified (as per ISO	2015	northAmerica	USLCI	ASTM PCR for Preparing an EPD	Download EPD
Ready-mix concrete	5000 psi, 34.5 Mpa		Industry average ready-mix concrete	NRMCA	-	NRMCA Member National and	ISO 14040	Third-party verified (as per ISO	2020	USA	ecoinvent	-	Download EPD
Ready-mix concrete	2500 psi, 17.2 Mpa		Industry average ready-mix concrete	NRMCA	-	NRMCA Member National and	ISO 14040	Third-party verified (as per ISO	2020	USA	ecoinvent	-	Download EPD

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Product Category Rules (PCR)	Download EPD
Reinforced concrete shear wall,	5000 psi, 34.5 Mpa, with US industry			-		One Click LCA generic construc				northAmerica	Other		
Reinforcement steel (rebar), generic	90% recycled content, A615			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2018	LOCAL	One Click LCA	EN15804+A1	
Roof covering, asphalt shingles	for USA and Canada			-		One Click LCA generic construc				northAmerica	Other		
Steel door	86x36x 1.34in			Quartz	CP127	Quartz 2015	ISO 14040	Third-party verified (as per ISO	2015	USA	GaBi	LCIA: TRACI 2.1, GWP IPCC	
Styrofoam insulation	1.8 pcf	Styrofoam Highload 40, Styrofoa	Dow	UL Environment	4786548101.101.1	Styrofoam Insulation, Dow 2014	ISO 14040	Third-party verified (as per ISO	2014	northAmerica	ecoinvent	PCR Building Envelope	Download EPD
Telecommunication system for data	incl. One Click LCA generic			-		One Click LCA One Click				northAmerica	Other		

Resource name	Technical specification	Product	Manufacturer	EPD program	EPD number	Environment Data Source	Standard	Verification	Year	Country	Upstream database	Product Category Rules (PCR)	Download EPD
Ventilation ducting	per m linear, D: 500 mm (19.69			One Click LCA	-	One Click LCA	EN15804+A1	Internally verified	2019	LOCAL	One Click LCA	EN15804+A1	
Wastewater and rainwater drainage	incl. One Click LCA generic			-		One Click LCA One Click				northAmerica	Other		
Window, metal framed, double pane,	U: 0.32, for USA and Canada			-		One Click LCA generic construc				northAmerica	Other		

Author's assumptions, aggregated and anonymized from private industry data.

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