UNIVERSITY OF CALGARY

Waste Heat Recovery and Utilization Potential from Data Centres in Alberta

by

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Abstract

Data centres in Alberta are poised to double the province's electricity demand. After data processing, most of that electricity becomes waste heat. This study quantifies the technically recoverable thermal energy from 11,879 MW of proposed data centres seeking grid interconnection in Alberta and models environmental and economic benefits of using recovered heat to displace natural gas for space heating. Using a recovery efficiency of 68%, each MW of IT load could offset approximately 1175 tCO_2e annually, equivalent to $65,280 per year in fuel costs when displacing natural gas. This research also explores how outdoor temperature impacts cooling system electricity consumption under an immersion cooling configuration. Using a Power Usage Effectiveness model, results show negligible differences across Canada and a 3% increase when compared to Dallas, TX. The study emphasizes how district heating can unlock waste heat recovery potential and help integrate Alberta's data centres into a sustainable energy transition.

Acknowledgement

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List of Abbreviations

- AESO: Alberta Electric System Operator
- AI: Artificial Intelligence
- DC: Data Centre
- IT: Information Technology
- PUE: Power Usage Effectiveness
- TIER: Technology Innovation and Emissions Reduction
- WHR: Waste Heat Recovery

Chapter 1: Introduction

1.1 Problem Identification

Alberta is vying to become a powerhouse in the global artificial intelligence (AI) data centre market with a goal of attracting C$100 billion in data centre (DC) investment over five years. The province touts many competitive advantages for DC developers, including abundant resources, competitive tax rates, cold climate, and business-friendly regulatory environment" (Government of Alberta, 2024a, p. 5). Already, developers are lining up with several projects over 100 MW announced (Sherry et al., 2025). Between Q1 2024 and Q1 2025, grid connection requests from data centres totaled 11,879 MW in Alberta (Alberta Electric System Operator, 2025a). This figure is significant given that Alberta's average internal load in 2024 was 10,112 MW (Alberta System Electric Operator, 2024). In other words, proposed data centres could potentially more than double the province's average electricity demand.

The scale and pace of DC growth would be expected to cause significant implications for electricity generation planning, grid reliability, and greenhouse gas emissions. The AESO announced in June 2025 that until 2028, they will only allow 1,200 MW of large load projects—defined as being equal or greater than 75 MW — to connect to the grid, including data centres (Alberta Electric System Operator, 2025b). That cap, established to manage demand and protect grid reliability, represents less than 10% of the load associated with projects in the queue, leading many DCs to consider generating their own power behind the fence.

It’s widely recognized that data centres use a large amount of electricity, but less attention is given to the unavoidable by-product of their energy consumption: waste heat. For facilities operating at hundreds of megawatts of IT load, this translates into a substantial quantity of thermal energy, which is typically released into the atmosphere through cooling towers. At the scale of over 11 GW of proposed data centres in Alberta, the potential for waste heat utilization is in the realm of billions of kilowatt-hours of recoverable energy annually. Given that Alberta is a province with long, cold winters and substantial heating demand, using waste heat for space heating can create a new revenue stream for DC operators without requiring an energy conversion. This is relevant because using heat for heating purposes is the most efficient application, especially since the temperature of waste heat is too low to convert to electricity. It also offers a decarbonization solution that could set Alberta apart in the race to become a data centre hub.

Alberta’s AI Data Centre Strategy (Government of Alberta, 2024a) includes three strategic pillars: Power Capacity, Sustainable Cooling, and Economic Growth. Under the second pillar, the intent to promote sustainable, innovative cooling systems and explore waste heat capture and utilization (Government of Alberta, 2024a, p. 9). This research aligns with that stated goal and contributes to formalizing this strategy into action.

Existing research on waste heat recovery focuses largely on industrial processes, district energy, and combined heat and power systems. There are several studies that focus on data centres, but there is a gap for Alberta-specific reports. Since utilizing waste heat relies on a network of transport infrastructure and off takers, each jurisdiction will face unique challenges and opportunities. Therefore, this research provides a WHR analysis specific to Alberta and is intended to provide guidance for policymakers and developers on the scale of economic and environmental benefits from capturing and reusing data centre waste heat in Alberta.

1.2 Research Questions

This research will answer two questions. Firstly, how does ambient temperature affect cooling system electricity consumption for data centres operating with identical immersion cooling systems? Cool climates are often seen as being advantageous due to potential energy savings, which is particularly relevant for Alberta with low average annual temperatures, with large seasonal variations. This is just one of several factors to consider when deciding where to locate a DC, but it is at the forefront of conversations surrounding DCs in Alberta. Other factors include water availability, cost of land, proximity to fibre optic networks, and electric grid capacity. Therefore, this research aims to quantify the potential energy savings from Alberta's cool climate and contrast them with other jurisdictions.

The second research question is, what are the technical, environmental and economic benefits of capturing waste heat from data centres in Alberta? Waste heat has historically been seen as a by-product, but it contains a vast amount of thermal energy. Capturing and utilizing waste heat comes with many challenges such as transport distance, demand and temperature matching, and the associated capital costs along with maintenance costs. However, if those hurdles are overcome, the benefits could be substantial. This project illustrates the scale of potential thermal energy that will result from Alberta's push to become a data centre hub. It is intended to encourage action to ensure that this energy is not wasted. As a global community, we are actively searching for solutions to cut emissions and slow down climate change—Alberta's potential doubling of its electricity generation capacity demands a commitment to maximizing the use of every unit of energy produced and displacing emissions wherever possible.

1.3 Interdisciplinary Approach

This project addresses the gap in research by quantifying the potential energy, emissions reductions, and economic value from recovering waste heat from large-scale data centres in Alberta, providing a benchmark for the theoretical environmental and economic value of this resource. It also demonstrates how ambient temperature affects cooling system electricity consumption across eight different locations in North America. This research takes an interdisciplinary approach by combining energy analysis, emissions calculations, and economic evaluation. From an energy perspective, it examines how recovered waste heat could offset existing heating demand, potentially reducing strain on the electricity grid and improving system efficiency. Environmentally, it quantifies potential reductions in Scope 2 greenhouse gas emissions, and economically, it provides a benchmark for the value of captured waste heat. Overall, it supports the following UN Sustainability Goals: Affordable and clean energy (SDG 7), Climate Action (SDG 13), and Industry, Innovation, and Infrastructure (SDG 9).

This project also responds to emerging policy and industry needs. With the global data centre industry under scrutiny for its energy use, jurisdictions around the world are exploring regulatory frameworks, incentives, and technical standards to manage their impact. Alberta is well-positioned given the wave of new facilities slated to be built, and decisions made now will influence whether the province can capture the full economic and environmental benefits of waste heat recovery and utilization.

By filling the research gap on data centre waste heat recovery in Alberta, this study aims to provide insights for policymakers, utilities, and developers. It could position waste heat from data centres as a strategic energy resource that can help meet heating demands, reduce emissions, and improve the overall efficiency of Alberta's energy system. District heating enhances the feasibility of waste heat utilization, which may increase attractiveness to data centre developers. Rather than viewing data centres as simply a burden on the electricity grid, this research considers how DCs can become part of an energy resource in an integrated, resilient, and sustainable energy future in Alberta.

Chapter 2: Background and Related Literature

2.1 Industry trends

The global data centre sector is undergoing rapid growth as demand for digital services, especially AI, accelerates. Between 2010 and 2022, internet traffic grew more than twentyfold, and the number of hyperscale data centres quadrupled worldwide (International Energy Agency, 2025). While efficiency gains have tempered some of the associated electricity demand, AI workloads and high-performance computing are reversing that trend. The IEA projects that electricity consumption from data centres, cryptocurrencies, and AI could exceed 1,000 TWh annually by 2026, representing roughly a 60% increase from 2022 levels (International Energy Agency, 2025). At the same time, increasing chip power densities are raising the thermal load per rack, making conventional air cooling less effective and driving a transition toward liquid and immersion cooling systems (Ebrahimi et al., 2014).

For Alberta, these trends have direct implications. Even with a colder climate, increased server rack densities mean that advanced cooling methods will be required to manage thermal loads efficiently (Ebrahimi et al. 2014). Liquid cooling improves thermal performance and enables recovery of higher-grade waste heat, creating opportunities to integrate data centres into district heating networks or other applications—an approach aligned with Alberta's focus on de-coupling economic growth and greenhouse gas emissions. By investing in the right infrastructure and aligning incentives for developers, Alberta can position itself to capture both the economic benefits of the expanding digital economy and the environmental advantages of energy system integration.

2.2 Cooling Systems

The rapid increase in chip power density and corresponding thermal density in AI data centres and high-performance computing (HPC), is exceeding the capabilities of conventional air-based cooling systems (Nadjahi et al., 2018; Ebrahimi et al., 2014). Traditional air-cooling struggles to manage server racks that are over 20 kW each, which is now regularly surpassed with AI computation (Ebrahimi et al., 2014). Indeed, today's average power density is approximately 15kw per rack, but it's expected that AI computational workloads will over 60kw per rack (Kleyman, 2024). A solution to these high heat density chips is immersion cooling, which works by fully submerging servers in thermally conductive dielectric fluids, enabling more efficient heat removal at higher temperatures than air-cooled systems (Nadjahi et al., 2018; Wang et al., 2024). Without WHR, immersion cooling rejects heat into the atmosphere, like air-cooling. However, it presents a better opportunity for heat capture due to the concentrated form of thermal energy and higher outlet temperatures. Overall, the industry is shifting towards immersion cooling to overcome high chip densities, but it has many other important benefits as well.

In terms of sustainability, immersion cooling offers significant energy and water savings compared to air cooling systems. By eliminating or greatly reducing the need for chillers, computer room air handlers (CRAH), or evaporative cooling towers, immersion systems can reduce cooling electricity consumption by 30–50% (Nadjahi et al., 2018; Ebrahimi et al., 2014). Moreover, water consumption is nearly eliminated in immersion-cooled facilities, which is a major difference from evaporative cooling (Haghshenas et al., 2023). Given that water scarcity and allocation is a big issue in many regions with existing DC hubs, immersion cooling offers a desirable alternative to water hungry air-cooling systems. Overall, immersion cooling improves Power Usage Effectiveness (PUE) and Water Usage Effectiveness (WUE), two core sustainability metrics used to measure the sector's environmental impacts. PUE is the ratio of all energy consumed by a data centre to the energy consumed by the servers specifically, demonstrating the efficiency of the DC (Vertiv, n.d.). WUE is a similar concept, but it compares total water consumed by a DC with the water consumed by IT equipment specifically, expressed in L/kwh (Tozzi, 2025).

Another advantage of immersion cooling is its ability to recover waste heat at higher temperatures than air-cooling. This allows direct use in applications such as district heating, industrial processes, or domestic hot water production without significant additional energy input (Luo et al., 2019; Zimmermann et al., 2012). In contrast, air cooling systems produce ultra low-grade heat, typically between 25-30 °C, which is too low for direct use and would require upgrading through heat pumps or other technologies before it can be useful, adding capital and operating costs (Ebrahimi et al., 2014; Luo et al., 2019). Multiple immersion cooling studies report outlet coolant temperatures in the high-grade range: the Aquasar project at ETH Zürich achieved 60–65 °C (Zimmermann et al., 2012), while a recent single-phase immersion cooling study measured facility water loop temperatures of 65 °C (Hnayno et al., 2023). These temperatures allow integration with district heating systems. Additionally, the stability of high outlet temperatures across seasons improves the Energy Reuse Effectiveness (ERE) metric, making heat recovery more predictable, easier to integrate with external networks, and potentially more economically viable under carbon pricing or energy efficiency incentive programs

(Ebrahimi et al., 2014). Overall, the output from any cooling system is the input for waste heat recovery— immersion cooling delivers a high-quality by-product that allows for more productive recovery.

As data centres shift towards higher density servers, immersion cooling provides a necessary solution for thermal management. Additionally, waste heat recovery with immersion-cooled data centres represents an emissions-reduction opportunity where hydrocarbons are used for heating, and a potential revenue stream through heat offtake agreements. As regulatory frameworks such as carbon pricing and industrial emissions benchmarks expand, these combined operational and sustainability benefits make immersion cooling an increasingly strategic choice for future-proofing data centre design (Haghshenas et al., 2023).

2.3 Waste Heat Recovery

Data centres ultimately convert nearly all the electricity they consume into heat after data processing (Luo et al., 2019). When conventional air-cooled systems are used, most of this thermal energy is simply released into the atmosphere. However, when a facility uses immersion or other forms of liquid cooling, much of that heat can be captured in a concentrated form. Liquid cooling directly transfers thermal energy from servers into a circulating fluid, which can leave the data centre at temperatures high enough for productive use—around 60 °C, as previously stated. At this temperature, the heat can be applied directly to many space heating applications without the need for temperature boosting from heat pumps. This reduces capital costs and ongoing energy use, making waste heat recovery technically feasible and economically attractive compared to lower-temperature waste heat streams.

The potential scale of recoverable energy from data centres is substantial, especially given Alberta's aggressive expansion plan. The cumulative waste heat could offset a significant portion of local heating demand, which fits well with Alberta's cold climate and large heating loads. Plus, reusing waste heat displaces greenhouse gas emissions that would have otherwise occurred from natural gas or electric heating. It also improves the overall efficiency of the energy system by extending and increasing the useful work from each unit of electricity produced. By leveraging WHR, data centres can be considered not only as energy consumers, but energy converters— transforming electrical energy into productive digital work *and* thermal energy.

2.3 Waste Heat Utilization

Based on available literature district heating is the most efficient and widely used application for data centre waste heat (Wahlroos et al., 2018; Yuan et al., 2023). In a district heating network, hot water is distributed through insulated pipelines to multiple buildings or neighbourhoods, supplying space heating and domestic hot water. As previously mentioned, immersion-cooled data centres can supply heat without further upgrading, so they are compatible with many existing district heating networks. However, proximity to an existing or planned district heating network and demand centre is essential for the economics and logistics to make sense.

Alberta has few established district heating networks, namely the University of Alberta's system and Calgary District Heating, which manages over 10 km's of pipeline and can provide heating for 15 million square feet, although it only serves 6 million square feet currently (Calgary District Heating, n.d.; University of Alberta, n.d.). Since district heating is not prevalent in Alberta, other WHR applications could be considered as well, including greenhouse heating, aquaculture heating, industrial process pre-heating, and domestic hot water production for nearby residential or commercial buildings (Pakere et al., 2023; Zhou et al., 2024). Each of these applications has different temperature requirements, demand patterns, and operational considerations, but immersion cooling's high outlet temperature and steady year-round operation make it adaptable to many of them.

Ultimately, leveraging a diverse network of waste heat off takers will likely yield the best results. While district heating can absorb large quantities of heat during colder months, demand drops off in the summer, creating periods of time that the waste heat wouldn't be used. By pairing district heating with other applications — such as year-round industrial processes, agricultural heating, or even absorption chilling for cooling demand — operators can maintain high utilization rates throughout the year. This combination could maximize the economic and environmental value of recovered heat, improve project feasibility by ensuring a stable demand profile, and position WHR as a reliable contributor to decarbonization strategies in jurisdictions with emissions-intensive heating. For this research, the focus will be on utilizing waste heat directly for district heating and how this could position Alberta as an attractive place to build a data centre.

2.4 Waste Heat Utilization: District Heating Case Studies

Nordic and European countries are leading the way in waste heat utilization. Stockholm, Sweden has an impressive district heating system with 2,800 kms of pipeline called Open District Heating, which is responsible for delivering over 90% of the district heating in Stockholm (UNEP Copenhagen Climate Centre, 2016). The physical infrastructure is accompanied by a competitive market that allows businesses to connect and sell their excess heat to the utility, Stockholm Exergi. In this market, payments are determined by the ambient temperature and based on the cost of Exergi producing comparable heat (UNEP Copenhagen Climate Centre, 2016). Over 30 data centres are connected to the network, which currently heats over 25,000 apartments (UNEP Copenhagen Climate Centre, 2016). The existence of the district heating network combined with a robust market for selling waste makes it much easier for businesses of all types to sell their waste heat. It opens doors for decarbonization and revenue streams.

Currently, the largest data centre district heating system in the world is under construction in Espoo, Finland, where Microsoft is building a 150 MW data centre hub. When operational, waste heat from these DCs will provide 100,000 homes with heat through the existing district heating network (Paulsson et al., 2025). It's reported that this ability to connect to district heating is one reason Microsoft chose this location (Paulsson et al., 2025). Elsewhere, promises of waste heat utilization have yet to come to fruition. Apple and Meta have fallen short on promises that their facilities in Denmark will provide heating for homes, exemplifying the real hurdles for projects to launch operations (Paulsson et al., 2025). A particularly tricky issue is that the price of land increases around dense populations or urban centres, which is where district heating is located. This is worth further research in the context of Alberta specifically.

Chapter 3: Methodology

3.1 Overview

A central component of the research is a computational spreadsheet that evaluates the influence of ambient temperature on immersion cooling electricity consumption across different locations and quantifies waste heat generation from DCs in Alberta. This method aims to compare technologies on an even playing field by using standardized indicators and measurements. **Error! Reference source not found.** is a basic block flow diagram of the energy flow in a data centre with waste heat recovery. It shows electricity as an input for the servers, which convert it into computational work. Electricity is also an input for the cooling system, which provides cool air, water, or coolant to the servers and removes the heat generated by the computational processing. Electricity is also an input for heat pumps, which increase the temperature of the rejected heat, before it is recovered and transported to an off taker where it can be used.

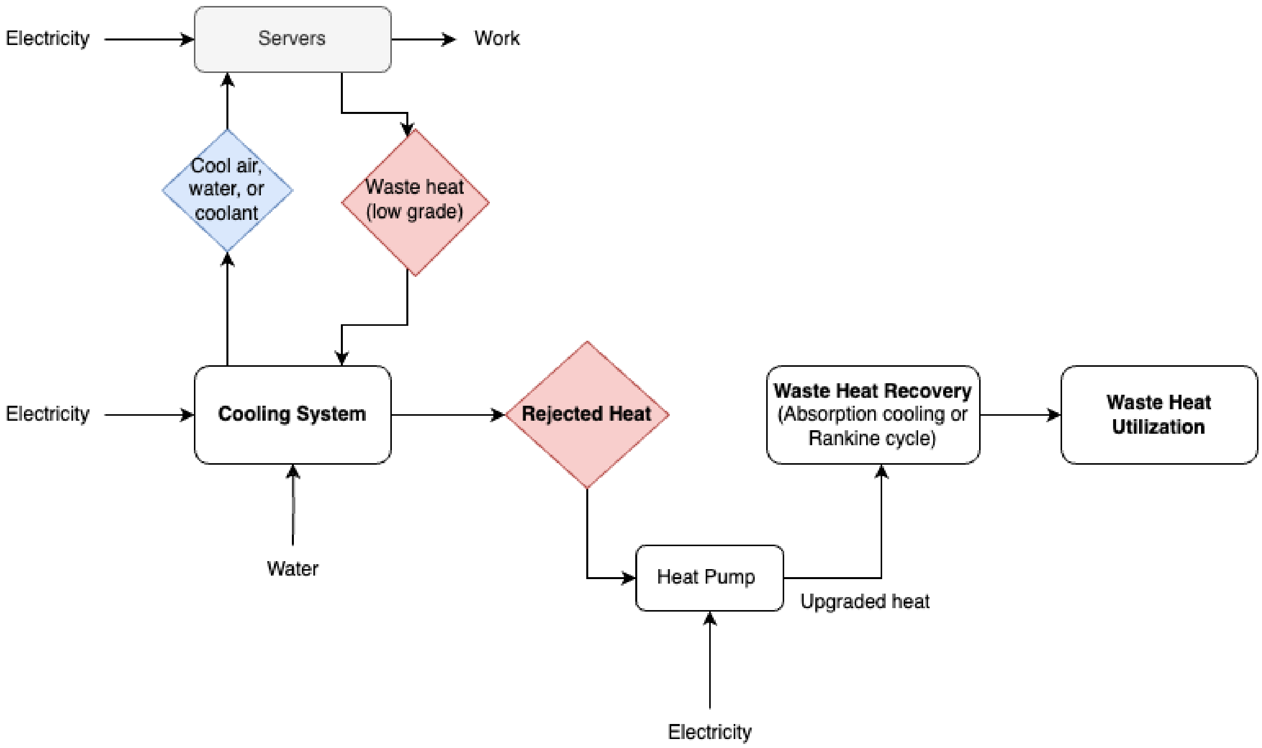


Figure 1: Block flow diagram of data centre with waste heat recovery and utilization. For context, this diagram shows a heat pump upgrading the waste heat, but if immersion cooling is used, this step is not required.

Two models were created in Microsoft Excel to answer both research questions. The research uses publicly available data to calculate 1) the energy used to cool data centres with immersion cooling systems, and 2) the economic and environmental benefits of waste heat utilization. For cooling system electricity consumption, eight locations (four within Alberta, and four across Canada and the US) are compared to show how ambient temperatures affect energy consumption. For WHR calculations, Alberta-specific data is used to find economic and environmental implications for that province.

3.2 Data Sources and Assumptions

The sources below provided the necessary data inputs for the two models described above.

- Hourly ambient temperature from the Typical Meteorological Year (TMY) data used in the National Solar Radiation Databased, published by National Renewable Energy Laboratory of the U.S. Department of Energy (Sengupta, 2018).
- Planned data centres in Alberta (Alberta Electric System Operator, 2025c)
- PUE value for immersion cooling (Centre of Expertise for Energy Efficiency in Data Centres, n.d.)
- Greenhouse gas emissions data (Environment and Climate Change Canada, 2024)

3.3 Emissions Intensity Assumptions

To estimate avoided greenhouse gas emissions from recovered waste heat, emissions intensities for Alberta grid electricity and marketable natural gas were used. The grid electricity intensity was taken from the most recent Alberta-specific data published by the Canada Energy Regulator and the Government of Alberta, which report 0.470 t CO_2e per MWh of electricity generated in 2023 (470 kg CO_2e/MWh (Government of Alberta, n.d.). For natural gas, an emission factor of 1,962 g CO_2/m^3 of marketable gas was used, which is the value published by Environment and Climate Change Canada for 2023, 2024, and 2025 (Environment and Climate Change Canada, 2024a). This corresponds to approximately 186 kg CO_2 per MWh of natural gas energy content, calculated using a higher heating value of 38 MJ/m^3 as shown below:

$$3{,}600 \text{ MJ/MWh} \div 38 \text{ MJ/m}^3 \cdot 1.962 \text{ kg CO}_2/\text{m}^3 = 186 \text{ kg CO}_2/\text{MWh}$$

To be conservative from an emissions perspective, **180 kg CO_2/MWh was used in the model**. Boiler efficiency is assumed to be 90% and electric heating is set to 99% efficiency.

3.4 Economic Assumptions

The price for natural gas in the model is set to \$2.78/ GJ. This assumption is based on the AECO C natural gas base case forecast, which estimates a price of \$2.71/GJ in 2025, increasing to \$4.37/GJ by 2034 (AECO-C Price, 2025). The assumption in this project's calculations was rounded to \$2.78/GJ (equivalent to \$10/MWh) for more simplistic comparison with electricity prices. This represents a conservative approach to valuing waste heat. Sensitivity analysis was performed on natural gas prices to demonstrate how the value of waste heat changes if natural gas prices increase to \$4.00/GJ and \$6.00/GJ. The price for grid electricity is assumed to be \$120/MWh, equivalent to 12c/kwh which reflects the delivered price of electricity.

3.5 System Boundaries and Functional Unit

The functional unit in the model is defined as 1 MW of IT load. This denotes the server load only, excluding ancillary systems, and is consistent with the convention commonly used in both academic literature and media when referring to data centre capacity. The source of electricity generated and supplied to the DC is outside of the scope of this study. This research is focused on large-scale AI data centres, which reflects the queue of projects in Alberta.

For WHR, the analysis applies a black-box approach to the data centre itself, with the system boundary drawn around the rejected waste heat. All data centres are assumed to use immersion cooling and operate 24/7 for all 8760 hours of the year, providing a consistent coolant outlet temperature of 60°C across all sites. Under this assumption, the primary driver of variation in the cooling system electricity consumption is the outdoor ambient air temperature, which determines how much active cooling is needed. By isolating the waste heat stream and modeling cooling demand as a function of ambient temperature, this approach allows for a location-specific assessment of energy and emissions displacement potential, independent of the DC's internal configuration.

3.6 Location Selection

The model evaluates cooling energy demand for a 1 MW data centre across eight geographically diverse locations. ***Figure 2*** is a map with numbered pins showing these specific locations: Grande Prairie, AB (1); Edmonton, AB (2); Calgary, AB (3); Pincher Creek, AB (4); Dallas, TX (5); Montreal, QC (6); Toronto, ON (7); and Ashburn, VA (8).

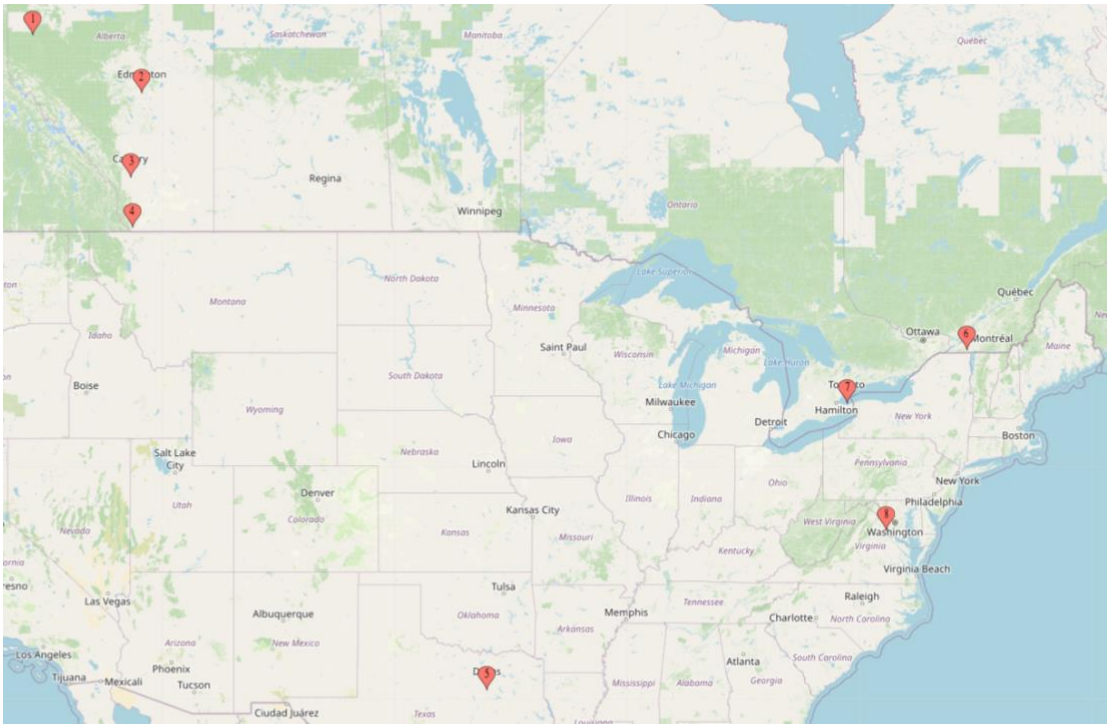


Figure 2: Eight locations were considered for various ambient temperature profiles.

These sites were selected to capture a range of ambient temperature profiles, providing insight into how location-specific climate conditions influence annual cooling system electricity consumption under an immersion cooling configuration. The Alberta locations were chosen based on the AESO's Project Map (Alberta Electric System Operator, 2025c), which identifies publicly announced data centres with grid connection requests, most of which are clustered around Edmonton and Calgary. Toronto and Montreal were included as they are actively pursuing data centre development and can be considered Canadian competitors to Alberta. Ashburn, Virginia, known as Data Center Alley, and Dallas, Texas, were also selected as prominent U.S. data centre hubs. Collectively, these locations enable a comparative assessment of how ambient temperature affects cooling requirements, testing the hypothesis that Alberta's cooler weather offers operational advantages over other regions.

3.7 Cooling System Electricity Consumption: Model and Assumptions

Research Question 1: Calculating Cooling System Electricity Consumption

$$E_{total} = E_{IT} + E_{cooling} + E_{auxiliary}$$

The equation above shows that total energy use in a data centre comprises three main loads: IT equipment, cooling systems, and auxiliary loads like office lighting. In this model, $E_{auxiliary}$ is excluded as it is comparatively negligible. IT load is modeled using the functional unit of 1 MW and assumes consistent loads for all hours of the year. Cooling system electricity consumption is the focus of this research question and is calculated using the Power Usage Effectiveness model and the assumptions below.

Cooling System Electricity Consumption Assumptions

- PUE Base= 1.05. Typical for immersion cooling systems under perfect conditions. Multiple studies are cited showing PUE values between 1.02-1.04 for immersion cooled data centres, so 1.05 is used as a conservative estimate (Haghshenas et al., 2023).
- Threshold Temperature= 22°C. Above this temperature, active cooling is needed. This threshold aligns with the ASHRAE Thermal Guidelines for Data Processing Environments, which recommend a temperature band of 18–22 °C for high-density equipment (ASHRAE, 2021). Although immersion cooling technologies can often tolerate higher coolant outlet temperatures, adopting 22 °C as the free cooling threshold takes a cautious approach that ensures equipment and operational safety.
- α= 0.0006. Empirical parameter to account for system conditions. This is a modelling assumption.

3.8 Cooling System Electricity Consumption Calculations

The calculations below are used to determine the amount of electricity consumed per hour by the immersion cooling system, based on ambient outdoor temperature.

1. $\mathrm{PUE(T)} = \mathrm{PUE}_{\mathrm{Base}} + \alpha \cdot \max(T_{\mathrm{ambient}} - T_{\mathrm{threshold}}, 0)$
2. $PUE(T) = 1.05 + 0.0006 \cdot \max(T_{\mathrm{ambient}} - 22, 0)$
3. $P_{\mathrm{cooling}} = (PUE(T) - 1) \cdot 1\ \mathrm{MW}$
4. $E_{\mathrm{cooling}}\ (\text{per hour}) = P_{\mathrm{cooling}} \cdot 1\mathrm{hr}$

To calculate cooling system electricity consumption, hourly temperature data for all 8,760 hours in the year were used. Active cooling was assumed to be required whenever the ambient temperature exceeded the threshold temperature of 22 °C. Below that threshold, cooling can be achieved with little electricity consumption. For each such hour, the cooling system electricity consumption was calculated by multiplying α by the difference between the ambient environmental temperature ($T_{ambient}$) and the threshold temperature ($T_{threshold}$). This value was then added to the base power usage effectiveness (PUE_{base}) to determine the instantaneous cooling power demand in megawatts (MW). The total electricity required for the cooling system was calculated by multiplying that figure by 1 hour and summing all 8760 hours to determine the annual energy required.

3.9 Waste Heat Recovery Assumptions and Calculations

Waste Heat Assumptions

Below are the assumptions used to calculate waste heat recovery. Waste heat transfer efficiency measures the amount of useful energy that a system can capture compared to the total waste heat available.

- Coolant outlet temperature = 60°C (Hnayno et al., 2023; Luo et al., 2019; Zimmermann et al., 2012)
- Heat Exchanger efficiency= 100% (Belkin, 2023)
- Waste Heat Transfer Efficiency = 68% (Luo et al., 2019)
- Hours per Month = 720, based on 30 days in each month
- Hours per Year = 8,760

Waste Heat Recovery Calculations

Table 1 shows the assumptions used to calculate monthly waste heat per 1 MW of IT load. The recovery efficiency refers to the heat exchanger efficiency of 100%, and the transfer efficiency is set to 68%.

Table 1: Assumptions for waste heat recovery and transfer calculation

E_IT (MW)	1
Recovery Eff	100%
Transfer Eff.	68%
Q (MW)	0.68
Q per month (MWh)	489.6

Below is the calculation used to quantify waste heat potential:

$$Q_{monthly} = P_{IT} \cdot \eta_{exchanger} \cdot \eta_{recovery} \cdot t$$

Variables:

- $Q_{monthly=}$ monthly recoverable heat (MWh)
- P_{IT}= IT load (MW)
- $\eta_{exchanger}$= heat exchanger effectiveness for immersion cooling systems (100%)
- $\eta_{recovery}$= recovery system efficiency (68%)
- t= hours per month

Substituting in values:

- $Q_{monthly}$= 1 MW · 1.0 · 0.68 · 720 hrs
- $Q_{monthly}$= 489.6 MWh

The analysis calculates that a 1 MW data centre will produce 490 MWh of recoverable waste heat per month. ***Figure 3*** shows the block flow diagram for this calculation below, where the functional unit of 1 MW is the input of electricity, coolant exits the servers at 60°C, and flows through the heat exchanger and transfer (or recovery) systems.

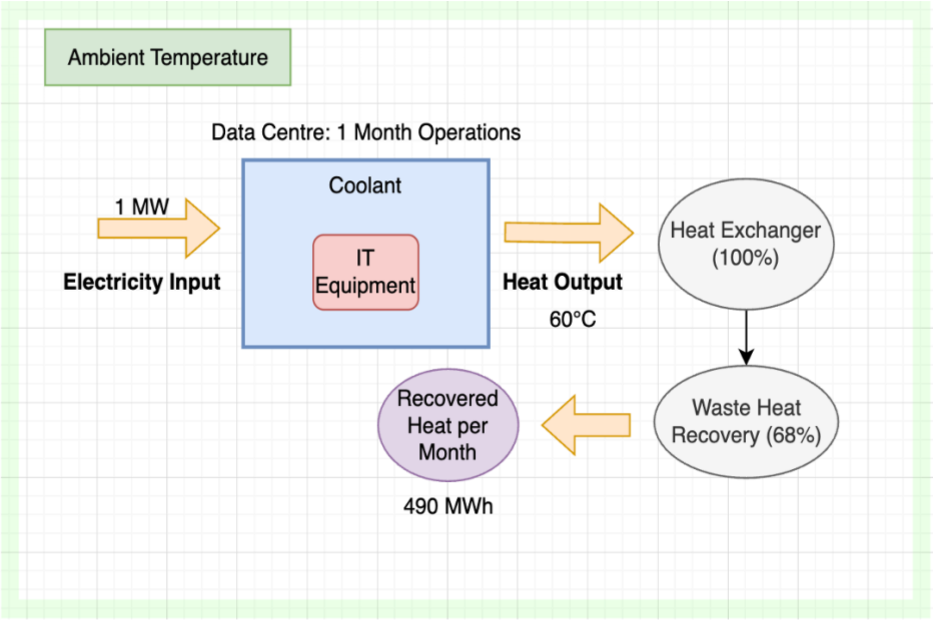


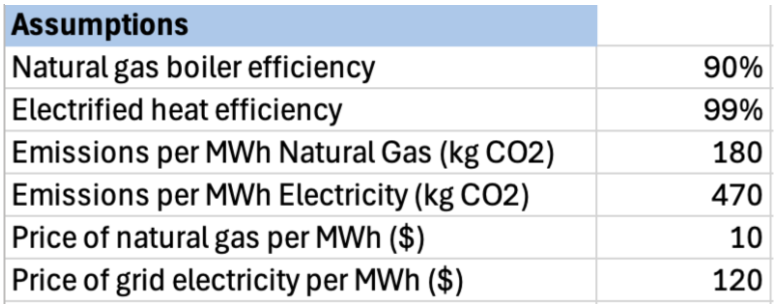
Figure 3: Schematic overview of the calculation flow for waste heat recovery potential.

3.10 Waste Heat Recovery: Emissions and Economic Analysis Assumptions

To estimate the potential emissions and cost displacement of recovered waste heat, this study calculates the monthly quantity of recoverable thermal energy (Q) available across relevant time periods (monthly or annually) depending on the specific analysis. The recoverable heat is then compared against the emissions and costs that would otherwise be incurred to deliver an equivalent energy service using two conventional scenarios: (1) heat produced by a natural gas boiler with 90% efficiency, and (2) electric resistance heating with 99% efficiency.

Table 2 denotes these assumptions along with the emission factors and price of fuel used in the environmental and economic analyses. Emissions are calculated using standard emissions intensities of 180 kg CO_2/MWh for natural gas combustion and 470 kg CO_2/MWh for Alberta grid electricity. Similarly, displaced energy costs are estimated using average prices of $10/MWh for natural gas and $120/MWh for grid electricity. This approach captures both the environmental and economic value of waste heat recovery by quantifying what would otherwise be emitted and spent to generate the same amount of heat through conventional means.

Table 2: Assumptions used in WHR calculations.



Assumptions	
Natural gas boiler efficiency	90%
Electrified heat efficiency	99%
Emissions per MWh Natural Gas (kg CO2)	180
Emissions per MWh Electricity (kg CO2)	470
Price of natural gas per MWh ($)	10
Price of grid electricity per MWh ($)	120

3.11 Limitations

This model calculates the amount of waste heat that is technically possible to recover and does not consider the economic or logistical barriers of utilizing the heat, as demonstrated in ***Figure 4*** below. In reality, factors like temperature, matching the timing between demand and generation, transport distance, and upfront cost of recovery systems cause serious hurdles to utilize the captured energy. However, this research effectively lays out the potential for economic and environmental benefits if we can overcome these hurdles. This is especially relevant in Alberta, where the large majority of DCs will be net-new builds so some hurdles like retrofitting would not apply.

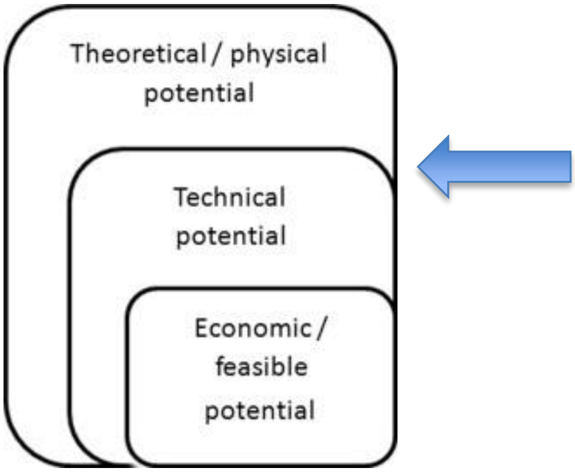


Figure 4: The model calculates the amount of waste heat that is technically available, which is necessarily higher than what is feasible and/or economically possible to use (Brueckner et al., 2014).

The model also simplifies the cooling system electricity consumption calculations and does not consider humidity, server rack layout, and demand spikes or shifting, among many other variables. Humidity largely impacts the ability to reject heat into the atmosphere, which is more impactful for traditional air-cooling systems than for a facility that is aiming to capture and reuse heat. Additionally, this study does not evaluate water usage in cooling systems, the global warming potential of coolants used in immersion cooling systems, upfront cost of waste heat recovery systems, and maintenance associated with immersion cooling and WHR.

Chapter 4: Results & Analysis

4.1 Cooling System Electricity Consumption Results

Based on the methodology and calculations applied, only the hours above the threshold temperature of 22°C contribute to an increase in cooling system electricity consumption. It was found that ambient temperature had a negligible impact on annual cooling system electricity consumption across Canadian locations, and only a small increase was seen in Dallas, TX, and Ashburn, VA. Consequently, Dallas had the highest electricity consumption, with more than 3,700 hours exceeding the threshold temperature, equivalent to ~42% of the year. Conversely, locations in Alberta only exceeded 22° for approximately 400 hours, or 4.5% of the year. ***Figure 5*** below shows hourly temperatures for a typical meteorological year in Grande Prairie, Montreal, and Dallas. These three locations are a geographically diverse selection of the eight locations, which are not all included in the graph to preserve visual clarity of the data.

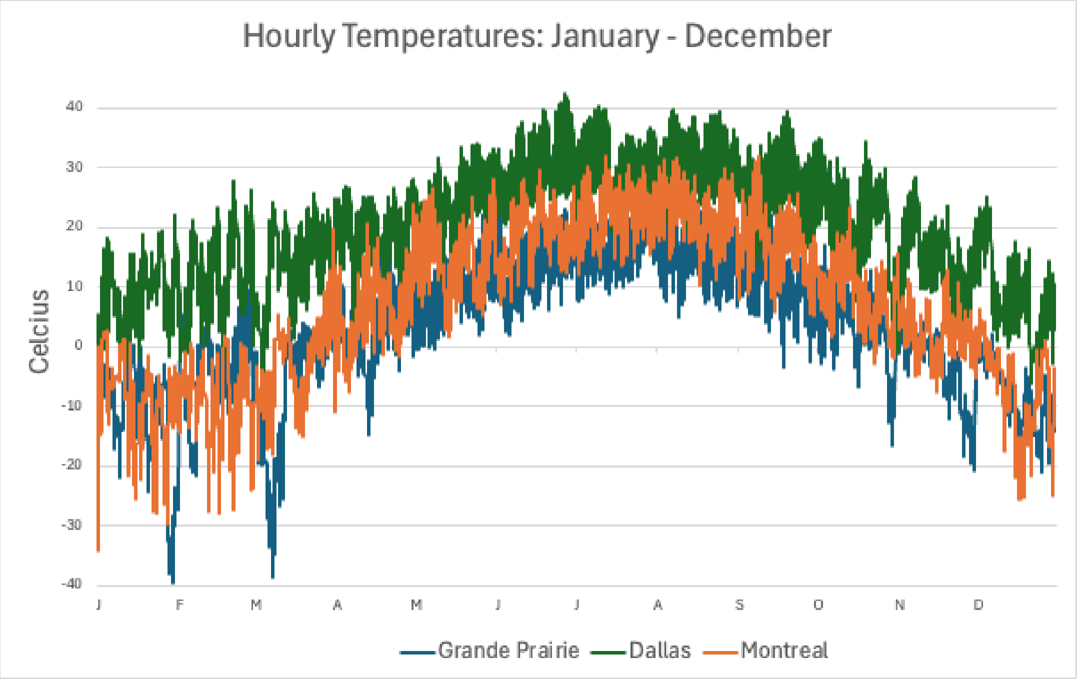


Figure 5: Hourly ambient temperatures for three geographically diverse locations.

Even though active cooling is needed for significantly more hours in Dallas, annual cooling system electricity consumption was only 3% higher than the most efficient location. ***Figure 6*** below shows the electricity demand increase associated with higher temperatures in the same locations as ***Figure 5.*** In ***Figure 6,*** Grande Prairie shows absolute values, the Montreal trendline is shifted upward by 0.01, and Dallas has been shifted upward by 0.02. The magnitude of variation is preserved, but absolute values should be read relative to the offset baselines. Once again, these three locations were selected to provide results across the study area without crowding the graph.

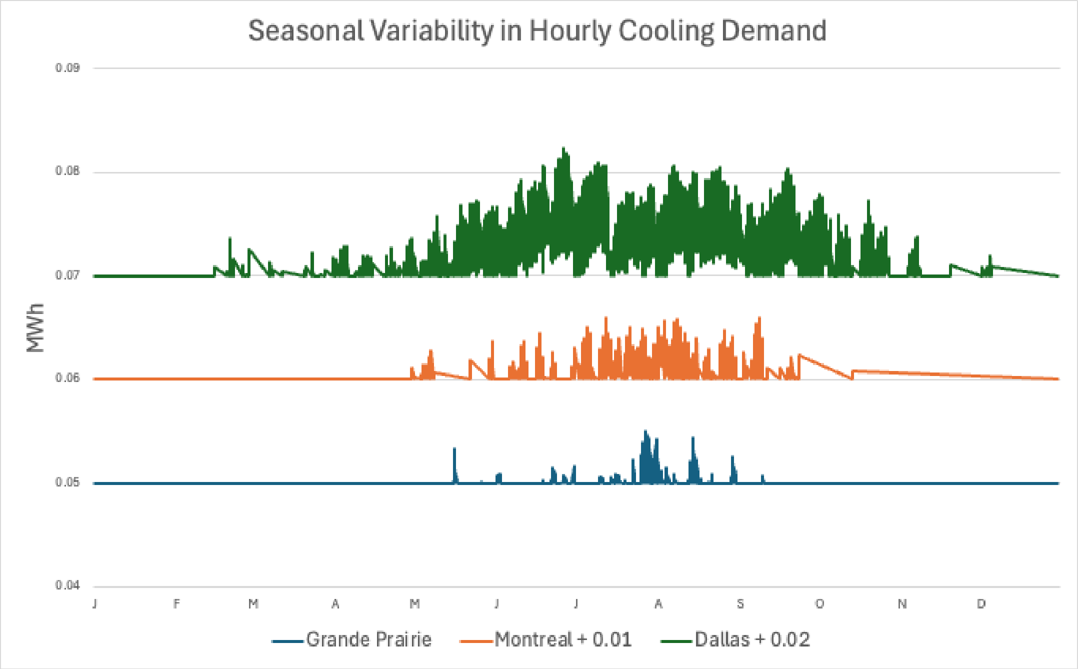


Figure 6: Hourly cooling demand for three locations, shown with vertically shifted baselines to separate overlapping lines and improve visual clarity.

Cooling demand shows a strong seasonal pattern, peaking in June, July, and August when sustained high temperatures drive increase loads. In Dallas, the location with the largest seasonal ambient temperature swing, peak hourly cooling demand rose to about 25% above its most efficient hour. In Grande Prairie, demand rose by 10%, and Montreal saw a 12% increase.

***Figure** 7* shows the annual electricity consumption of cooling systems across all eight locations at the functional unit of 1 MW of IT load. The results indicate that cooler climates reduce the number of hours that active cooling is needed, thereby lowering the total cooling energy use. However, the magnitude of these differences suggests that under the immersion cooling configuration, location-specific temperature impacts do exist but are not a dominant driver of total annual electricity demand.

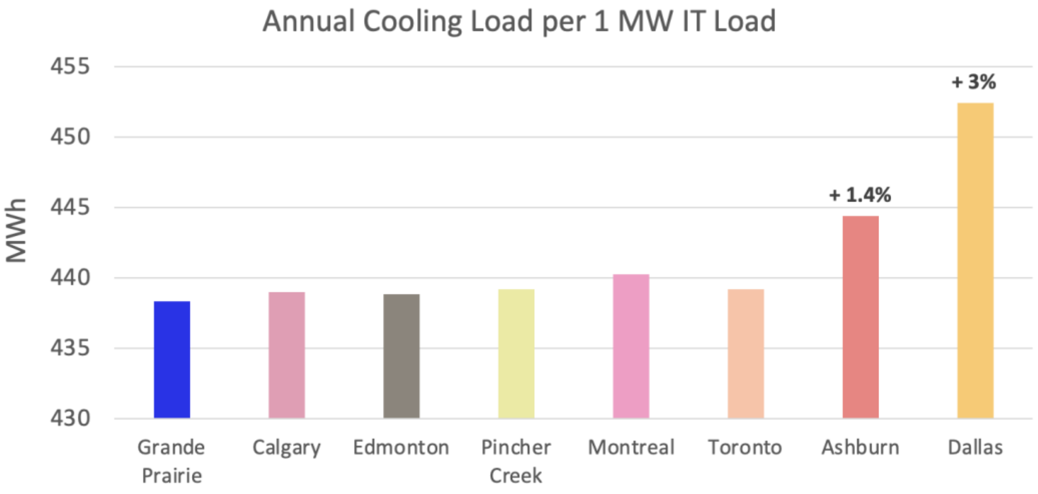


Figure 7: The total annual cooling system electricity consumption for a 1 MW data centre varies slightly across the eight locations. Dallas exhibits the highest demand, at approximately 3% above the lowest demand location, while Ashburn is 1.4% higher.

4.2 Waste Heat Recovery Emissions Results

Table 3 presents the annual GHG emissions reduction potential in Alberta for both natural gas and electric space heating displacement scenarios. On a per-MW basis, waste heat utilization can avoid approximately 2733 tCO_2e per year when replacing electric heating, and 1175 tCO_2e per year when replacing natural gas heating. Scaling these values to a 300 MW data centre increases the potential to roughly 819 $MtCO_2e$ and 352 $MtCO_2e$ per year, respectively. These results illustrate the substantial emissions benefits that can be realized at scale, particularly in jurisdictions with higher grid emissions intensities.

Table 3: Annual emissions displacement potential in Alberta per 1 MW IT load and scaled to a 300 MW data centre.

IT Load	1 MW (per year)	300 MW (per year)
Waste Heat Generation	5875 MWh	1,762,560 MWh
Displaced Emissions vs. Electric Heating	2733 tCO_2e	819,900 tCO_2e
Displaced Emissions vs. Natural Gas Heating	1175 tCO_2e	352,500 tCO_2e

Figure 8 illustrates the scale of potential emissions reductions if all proposed data centres that have applied for grid interconnection in Alberta were to capture and reuse their waste heat. If this recovered heat displaced space heating from natural gas boilers, annual emissions would be reduced by approximately 14 $MtCO_2$, equal to about **5% of Alberta's total 2023 emissions** (263.4 $MtCO_2e$). Replacing electric space heating instead would increase the potential reduction to 32.4 $MtCO_2$ per year. Since natural gas is the dominant fuel for space heating in Alberta, the electric heating displacement scenario is not as relevant. Alternatively, recovered waste heat could support electricity-fueled activities such as food processing, crop drying, and water preheating, though these opportunities are more dependent on local site conditions. In that scenario, the grid electricity displacement figures would apply.

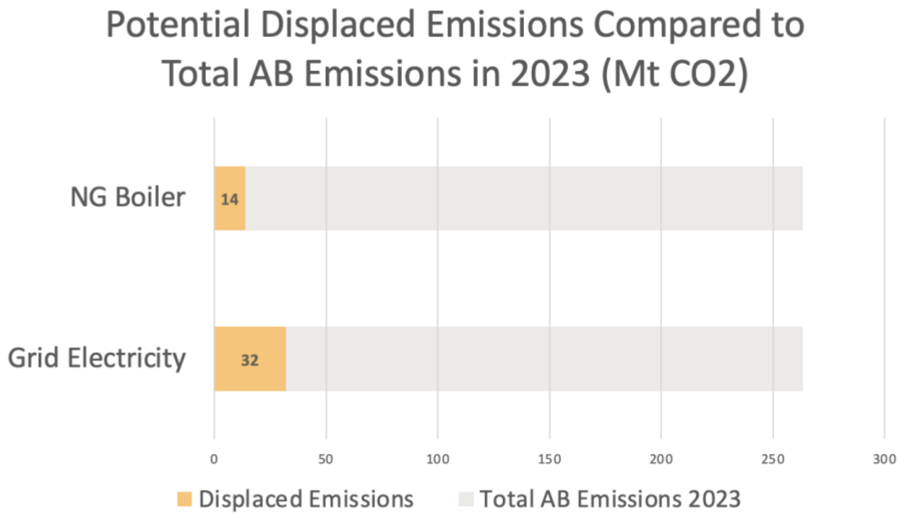


Figure 8: Annual GHG emissions avoided through waste heat recovery from all 11,879 MW of planned DCs in Alberta, shown for scenarios where waste heat displaces electric heating and natural gas heating.

4.3 Economic Results

In this analysis, the economic value of the waste heat is estimated based on the cost of providing the same heating service with conventional natural gas boilers or electric heating, using current gas and electricity prices. In practice, the actual value would depend on what an off taker is willing to pay. However, these two scenarios provide a useful benchmark for its potential market value. ***Figure 9*** shows that if waste heat is used to replace space heating from a natural gas boiler with 90% efficiency, assuming the price of natural gas is $10 per MWh ($2.78 per GJ), it would replace the equivalent of $5,440 per month for every 1 MW of IT load. When scaled up to a 300 MW data centre, this translates to **$1,632,000 per month or over $19M per year**. Since Alberta's heating is predominantly provided by natural gas, this is the most relevant economic figure.

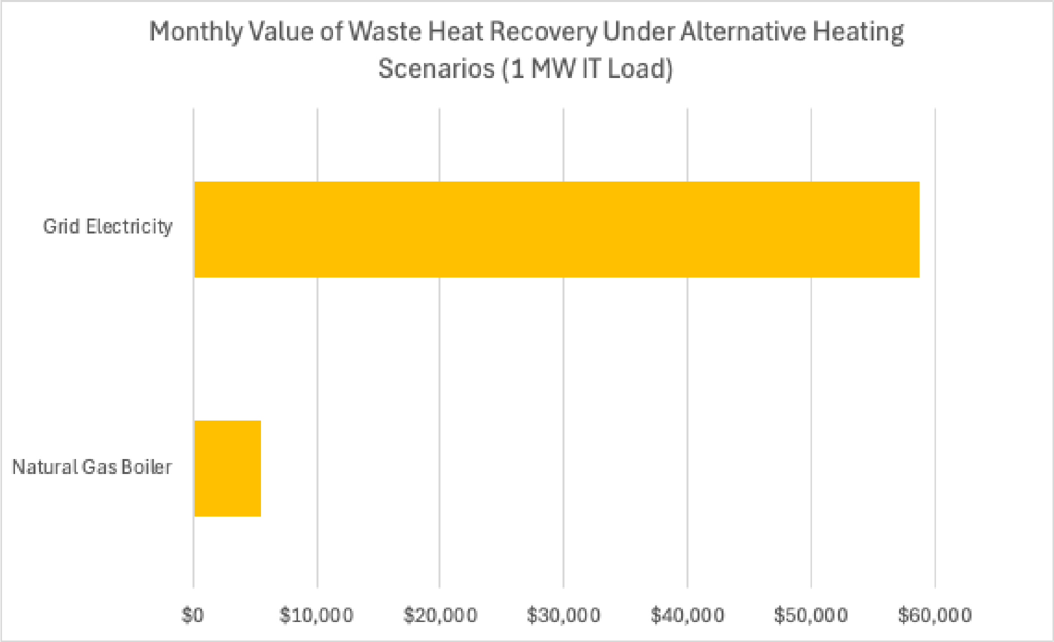


Figure 9: Economic value of waste heat based on replacement scenario. Waste heat would displace $58,752 worth of electricity or $5,440 worth of natural gas per month per 1 MW of IT Load.

A sensitivity analysis was applied to show how the economic results vary with increased natural gas prices. This considers waste heat as an equivalent unit of energy to natural gas space heating from an end user perspective. ***Figure 10*** demonstrates the annual value of waste heat from 1 MW of IT load at three price points: at $2.78/GJ it would be equivalent to $65,280, at 4.00/GJ it would be worth $94,003, and at $6.00/GJ, it would be valued at $141,004.

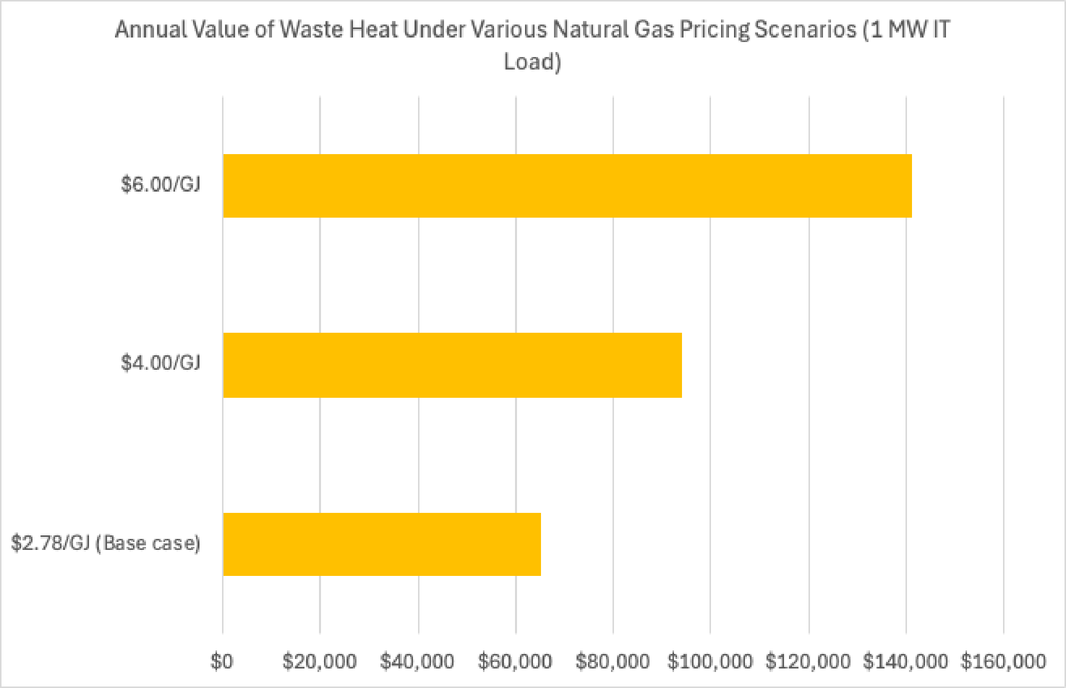


Figure 10: Annual value of waste heat displacing natural gas heating at three price points. The base case uses current prices.

4.4 Carbon Pricing Considerations

Alberta's Technology Innovation and Emissions Reduction (TIER) regulation is the province's industrial carbon pricing system, designed to reduce greenhouse gas emissions from large emitters. Facilities that emit 100,000 tonnes of CO_2e or more annually are required to meet an emissions intensity benchmark by implementing on-site reductions, using credits or offsets, or paying the TIER carbon price on excess emissions (Technology Innovation and Emissions Reduction, n.d.). ***Table 4*** denotes the increase in carbon pricing. In 2024, the carbon price under TIER was $80 per tonne, increasing by $15 annually to reach $170 per tonne by 2030.

Table 4: TIER emissions pricing scheme from 2024 to 2030.

Year	2024	2025	2026	2027	2028	2029	2030
Fund Price ($/tonne)	80	95	110	125	140	155	170

For new sectors such as data centres, a custom benchmark may be established, making TIER both a potential cost liability and an incentive for low-carbon innovations like waste heat recovery. ***Table 5*** shows the calculations to determine what size DC would be included in TIER if Scope 2 emissions from electricity is considered for grid-connected DCs. The minimum size to be included reach the 100,00 tCO$_2$ per year threshold and be included in TIER is a 32 MW data centre operating 24/7.

Table 5: Calculation for inclusion in the TIER program based on the 100,000 t CO2e threshold. A grid-connected data centre 32 MW or larger would be included in TIER.

TIER Emissions Threshold (kg CO$_2$)	TIER Carbon Emissions for Electricity (kg/ MWh)	Emissions Threshold (MWh/year)	Minimum Load to Hit Threshold (assuming 24/7 operations)
100,000,000	355.2	100,000,000 kg ÷ 355.2 kg/MWh = 281,531 MWh per year	281,568 MWh/year ÷ 8,760 MWh/year per MW = 32.1 MW

This calculation suggests that most data centres of the scale modelled in this study would fall under TIER, even though they are not yet classified as regulated facilities. The economic implications will depend on the emissions intensity benchmark ultimately set for the sector and whether individual facilities can achieve the required annual emissions reductions. Cooling system choice will also influence total energy use, and therefore emissions performance under TIER, because systems vary in efficiency and electricity demand. By contrast, location within Alberta will have little effect on annual cooling system electricity consumption under the assumed immersion cooling configuration, as shown in the results from the first research question.

4.5 Feasibility Considerations

Emissions reductions and cost benefits can only be realized if waste heat consistently replaces space heating. As previously mentioned, using waste heat from data centres for heating is typically the most efficient application due to its temperature and since there is no need for an energy conversion. A key factor influencing utilization rate is aligning waste heat generation and delivery with the timing and magnitude of space heating demand. ***Figure 11*** compares the space heating demand across Alberta's residential and commercial sectors with the waste heat generation from all DCs seeking grid interconnection in Alberta. In 2022 Alberta's residential and commercial sectors consumed 122 PJ and 137 PJ of natural gas for space heating, respectively (Natural Resources Canada, 2022). This translates to 33 TWh and 38 TWh, for a combined total of 71.9 TWh of space heating demand across the two sectors. The waste heat produced from the 11 GW of planned DCs annually equals 69.8 TWh, which is approximately equivalent to Alberta's space heating demand.

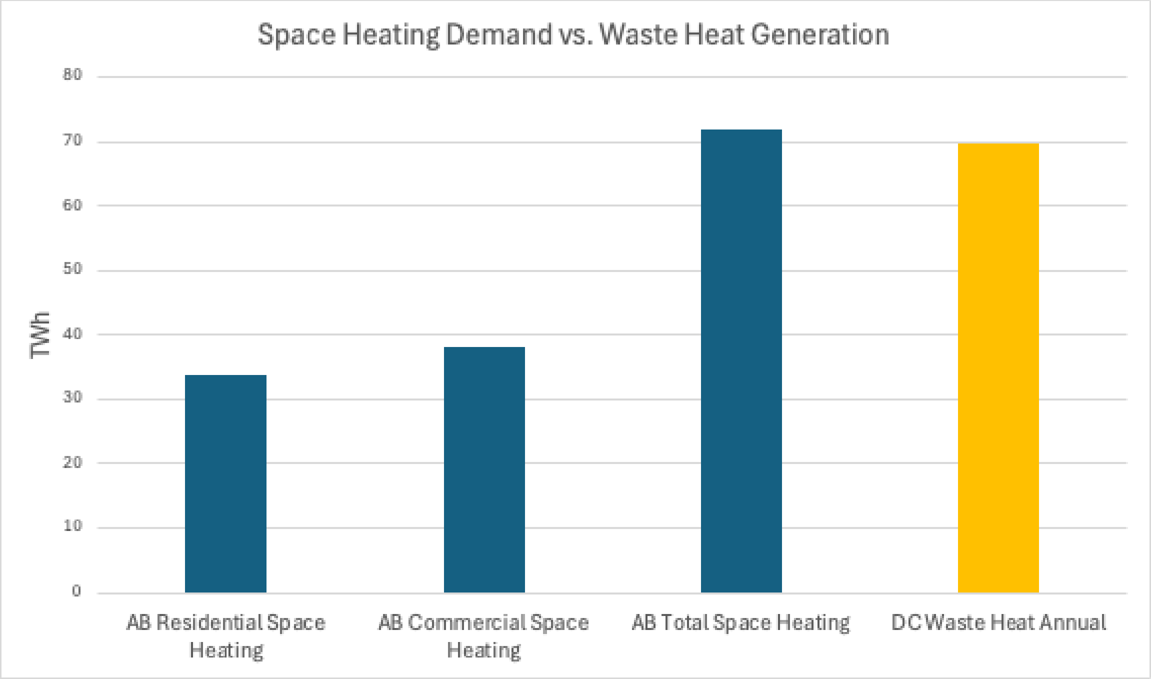


Figure 11: Space heating demand compared to potential waste heat generation from all DCs with grid connection requests.

While it would be virtually impossible to use all the waste heat due to the logistical barriers previously mentioned, the key takeaway is that Alberta's annual demand for space heating provides a strong offtake opportunity. Seasonal and daily variability in space heating demand would also be important to consider in future research.

Although this project focuses on Alberta, it is useful to compare it with Quebec and Ontario as alternative Canadian data centre hubs. In 2022, Quebec's residential and commercial sectors consumed a combined 300 PJ for space heating, while Ontario used 590 PJ (Natural Resources Canada, 2022). Both values exceed Alberta's consumption of 291 PJ, indicating that all three provinces have substantial potential markets for waste heat offtake. The main difference lies in the dominant energy source for space heating: Ontario relies more heavily on natural gas, whereas Quebec's heating is primarily electric. This is important from a decarbonization standpoint because using waste heat for space heating displaces the emissions associated with existing space heating.

Chapter 5: Discussion

This research explored two aspects of Alberta's data centre expansion: the influence of ambient temperature on immersion cooling system electricity consumption across North American climates and the environmental and economic potential of waste heat recovery in Alberta. Taken together, these findings challenge some assumptions about Alberta's cold climate advantage while presenting a compelling case for repositioning DCs not just as energy consumers but as integrated energy assets with digital and thermal value.

The cooling system electricity consumption analysis revealed only a 3% difference in total annual energy demand between the coolest and warmest climates under immersion cooling. This small uptick is likely because immersion cooling with waste heat recovery is not as sensitive to ambient temperature changes compared to air cooling systems that reject heat into the atmosphere. While Alberta's colder temperatures do reduce hours of active cooling, the overall advantage compared to warmer climates is relatively minor. It's important to acknowledge that without waste heat recovery, heat would need to be rejected into the atmosphere. This step is also dependent on ambient temperatures and humidity and presents another variable that is not considered under a WHR configuration. Therefore, under an immersion cooling and WHR system, the cold climate advantage that is often cited in Alberta does not appear to be as important. Instead, other factors in site selection such as electricity cost, grid capacity, cost of land, fibre network availability, and as this research suggests, the availability and value of waste heat offtake, become more important.

Under an assumption of 68% heat recovery efficiency, every 1 MW of IT load can generate approximately 5,875 MWh per year of recoverable heat at around 60 °C. When scaled to Alberta's pipeline of 11,879 MW in proposed DC capacity, this nearly matches the 70 TWh annual demand for commercial and residential space heating. This opens the door for a significant decarbonization opportunity. With appropriate district heating and offtake infrastructure in place, Alberta's data centres could meet a significant share of space heating needs and displace existing fossil fuel consumption. This emphasizes the importance of siting DCs near a facility that can use the recovered heat to reduce transport distances and improve utilization rates.

Environmentally, displacing natural gas heating with WHR could result in emissions reductions of approximately 14 Mt CO_2 per year—representing around 5 percent of Alberta's total existing emissions in 2023. This is an upper bound for displacement and would realistically be reduced when feasibility factors are taken into consideration. From an economic standpoint, the monthly value of heat replacement ranges from about CA$5,440 per month per MW IT load (for natural gas displacement) to upwards of CA$58,752 per month per MW IT load (if replacing electric heating). These figures suggest that for large-scale DC facilities, WHR could translate into significant annual revenue streams, even if offtake prices are lower than natural gas prices.

To realize the full economic and environmental benefits of WHR and utilization, significant investment into district heating or waste heat transport infrastructure would be required. Alberta's investment in carbon capture and storage provides an insightful benchmark for existing cost of abatement. The Government of Alberta's Carbon Capture

Incentive Program (CCIP) is slated to spend \$3.2 - \$5.3 billion on CCUS projects between 2024 and 2035 (Government of Alberta, 2024). Already, they have contributed roughly \$1.2 billion towards the Alberta Carbon Trunk Line (ACTL) and the Quest carbon capture projects. The former is estimated to sequester 10-12 Mt of CO_2 per year, while Quest has captured and stored 8 Mt since 2015 (Government of Alberta, 2024). For context, the ACTL involves building over 400kms of pipeline and underground permanent carbon storage. By comparison, this research suggests that offsetting natural gas fired heating with waste heat from all proposed DCs in Alberta would be equivalent to 14 Mt of CO_2 emissions displacement per year. As previously mentioned, this is the technical quantity of waste heat— operational barriers would greatly reduce the amount of waste heat delivered to an end user and the associated emissions displacement. The key finding, however, is that this quantity of waste heat offers a significant decarbonization opportunity and merits exploring the cost and benefits of investing in WHR and utilization systems alongside CCUS.

Despite this potential, implementation of WHR faces serious hurdles, namely Alberta's limited district heating infrastructure to distribute recovered heat. Seasonal demand matching is another challenge that may reduce utilization rates unless summertime uses are incorporated. There is significant capital cost associated with heat transmission infrastructure, including pipelines, heat exchangers, and integration with existing systems. Additionally, the market for purchasing recovered heat from DCs is nascent; standardized contractual frameworks and pricing mechanisms are not yet widely established.

Viewed in the broader Canadian context, Alberta's combination of high heat demand and reliance on natural gas heating positions it uniquely. While a cold climate is not a unique advantage for Alberta compared to other Canadian jurisdictions, enabling the infrastructure and commercial incentives to support a pathway for WHR utilization and a revenue stream for DC developers could be the competitive edge that sets Alberta apart.

Chapter 6: Conclusions and Limitations

6.1 Summary of Results

Regarding the first research question, results show that under an immersion cooling configuration with a threshold for active cooling of 22°C, cooling system electricity consumption does not vary significantly between locations in Alberta or across Canada. Of the eight locations considered, Dallas, TX had the highest electricity consumption for cooling, which was 3% higher than the most efficient location. The second research question addressed waste heat recovery. Results demonstrate that for every 1 MW of IT load, an immersion-cooled data centre running 24/7 generates 5875 MWh of recoverable waste heat per year. By replacing natural gas fired space heating, this would offset 1175 tCO_2e and be equivalent to $65,280 of fuel costs annually.

6.2 Limitations

Several limitations are present in the results of this study, which uses numbers based on the technical availability of waste heat in the best-case scenario. First, the modelling assumes a constant IT load and coolant outlet temperature year-round, which does not reflect real-world variability in server loads. In practice, fluctuations in data centre loads could influence both cooling energy requirements and waste heat availability. Second, the analysis does not evaluate the distance between data centres and potential heat loads and users. This could significantly affect the practical utilization rate of waste heat and the associated economic and environmental outcomes. Third, the economic estimates presented in this study are based on the value of displaced energy costs (natural gas and electricity). They do not consider the capital or operating expenses from installing waste heat recovery systems, building or expanding district heating infrastructure, or leveraging other off takers such as greenhouses or industrial co-location. As a result, the figures represent potential gross value, not net profit from implementing WHR. Fourth, the analysis does not match the seasonal and daily demand patterns for heating with the year-round availability of waste heat. This may inflate the quantity of total recoverable heat that could be used in practice, especially during warmer months when heating demand is low.

Finally, the study does not consider barriers such as regulatory complexity, contractual structures for heat sales, or the maturity of the market for recovered heat in Alberta. These factors can significantly influence adoption rates and should be considered in any comprehensive feasibility assessment, especially when developers and the province are racing to build these facilities as quickly as possible.

6.3 Future Research

There are many opportunities for future research to provide a more granular assessment of the WHR landscape in Alberta. A detailed map of Alberta's planned data centres compared to its heating demand loads, large commercial or industrial users, and other potential off takers would provide a much-needed picture of where WHR could be most efficiently implemented.

An investigation into district heating in Alberta would be worthwhile. This could include a district heating suitability assessment, an evaluation of costs and financing pathways, offtake market structure, and policy recommendations. Ultimately, district heating can unlock the usefulness of recovered waste heat, so it's necessary to understand the costs of building those networks and providing the other side of the equation to this project. HeatNet NWE is a project that is part of the European Regional Development Fund focused on developing pilot networks for district heating and provides many helpful resources (HeatNet, n.d.).

Another research area is modelling seasonal balancing strategies to align the supply of waste heat with heating demand. Thermal storage is an essential consideration in this area and could help manage gaps in supply and demand, as well as applications that take heat year-round. Ultimately, applying a utilization rate to the numbers in this research would improve accuracy.

From a policy perspective, it would be interesting to analyze different mechanisms to accelerate WHR adoption in Alberta. This could include compliance pathways under TIER, provincial or federal grants, pilot studies or projects, and mandating some form of WHR. The goal would be to understand what would motivate private companies to invest in WHR and what level of investment is required from the government to get projects off the ground. Within this, a particularly interesting question is how WHR stacks up to CCUS in terms of cost per tonne of CO_2e displaced versus sequestered. This analysis should incorporate both capital and operational costs for each technology to help guide investment prioritization in Alberta's broader decarbonization strategy.

Finally, future research could provide a lifecycle assessment (LCA) for immersion cooling systems themselves. This includes assessing the environmental impacts associated with dielectric fluids, which carry global warming potential if they leak, the manufacturing and operation of equipment, and disposal or recycling options at end-of-life. The LCA could also be scaled up to the data centre itself, taking a circular economy approach to examine where all the servers and equipment will end up at end of life.

6.4 Conclusions

The key takeaway from this study is that data centres are not simply large electricity consumers, but rather distributed energy assets that can contribute thermal energy as well as digital services. While infrastructure, economic, and policy barriers exist, the province can capture the opportunity with strong cooperation between policymakers, utilities, and industry. If successful, WHR can complement other large-scale decarbonization efforts and attract more developers to build data centres in Alberta.

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