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Closed-Loop Cryptocurrency Mining in Alberta

by

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ABSTRACT

In the highly connected age of information and data, the push for the development of 'clean data' has necessitated sustainability strategies for data centers. Green innovations are increasingly implemented to reduce the formidable power consumption of inefficient computing processes while heat reuse solutions repurpose the large volumes of server waste heat, decreasing facility footprint. This project examined the efficiency optimization potential of co-located power generation and greenhouse waste heat reuse for cryptocurrency data center platforms in Alberta. The proposed 45 MW data center capitalized on favorable climatic conditions to reduce energy requirements, improving facility efficiency and decreasing theoretical PUE values from 2.13 to 1.51. Resultant waste heat sufficiently supplied year-round heating to an 8.34-acre greenhouse suitable for commercial cannabis growth. The total annual avoided emissions for this proposed system were calculated at 70,000 tonnes of CO_2, illustrating the potential of integrated economizer cyles and waste heat reuse in Alberta.

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To my family, endless thanks for the dog walks.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF TERMS AND ABBREVIATIONS

AB - Alberta, Canada

AESO - Alberta Electrical System Operator

AI – Artificial Intelligence

ASHRAE - The American Society of Heating, Refrigeration and Air Conditioning Engineers

ASIC – Application-Specific Integrated Circuit

Baseload - The minimum amount of power required to supply the electrical grid

Bitcoin – Digital Currency

BTC – Bitcoin currency code

CAD – Canadian Dollars

CF - Capacity Factor

Cloud Computing – Using remote servers to store, manage and process data

CO_2 - Carbon Dioxide

CO_2e - Carbon Dioxide equivalent

CRAC - Computer Room Air Conditioner

CPU - Central Processing Unit

CRAH - Computer Room Air Handler

DC - Data Center

DCiE – Data Center Infrastructure Efficiency

ERE - Energy Reuse Effectiveness

ERF - Energy Reuse Factor

EPA - The United States Environmental Protection Agency

FPGA – Field Programmable Gate Array

GHG - Greenhouse Gas

GPU - Graphics Processing Unit

GW - Gigawatt

HVAC - Heating, Ventilation and Air Conditioning

ICT Sector – Information and Communications Technology sector

IT – Information Technology

kWh – Kilowatt-hour

MW - Megawatt

MWh - Megawatt-hour

PDU - Power Distribution Unit

PUE - Power Usage Effectiveness

UPS - Uninterruptible Power Supply

US - United States of America

USD – US Dollars

WSC – Warehouse Scale Computing

1 CHAPTER ONE – INTRODUCTION

1.1 Introduction

Data centers (DCs) are significant users of energy at approximately 3% (416 TW) of global electricity consumption and 2% of global greenhouse gas emissions (Danilak, 2017). As the fastest growing division of the information and communications technology (ICT) sector, data center energy consumption is expected to double every four years (Avgerinou, Bertoldi, & Castellazzi, 2017). Escalating demand for computing and storage capacity has led to increasing power consumption, operating costs and greenhouse gas emissions. The environmental cost of data has become a pressing issue and a significant challenge for future data center development. From cryptocurrency mining to machine learning, the current and future applications of data centers are immense and considerable focus will be exerted on efficiency optimization to reduce both the environmental and financial burden of digitization. Innovations in data center platform design improve data center sustainability and capitalize on external temperatures, while intelligent heat reuse is increasingly implemented to minimize waste heat generated by computational processes. Given the suitability of Alberta to future data center development, this paper reviews energy conservation and efficiency technologies applicable to local data centers and investigates whether a closed-loop gas-to-cryptocurrency design with integrated heat reuse can become a model for sustainable data centers in Canada. Combining industrial design and agriculture, this form of industrial symbiosis has the potential to increase efficiency for a diverse set of data center types, agricultural crops, and energy sources.

1.2 Sustainability Pillars

The work of this project is multi-disciplinary, touching on the environmental and energy burden associated with technological development and the sustainability opportunities for efficient data center design.

This research tackles the energy dimension through the investigation of energy use in the fast-growing data center sector. Data centers are the factories of the digital age and digitization, data analysis technology and artificial intelligence are reshaping the way industries function worldwide. The scale of digital transformation requires an emphasis not only on data center reliability and profitability but also energy responsibility. The design, construction, and operation of data center platforms determine energy use and efficiency optimization at the scale of data centers has significant implications for global energy consumption. Through the analog of cryptocurrency mining and the co-located greenhouse, the system energy balance was analyzed to determine potential energy and emissions savings relevant to data center development in Alberta. The three co-located systems; the power plant, the data center, and the greenhouse were extensively researched to understand efficiency gaps and relative energy consumption. This report highlights the energy generation, consumption and reuse possible in a co-located closed-loop data center design.

Along with the financial implications of energy consumption, anthropogenic climate change concern is a key driver of the push towards data center sustainability. As the number of applications of data centers grows, so do the associated greenhouse gas emissions. Energy sourcing, data center location and efficiency measures are the requisite strategies needed to pioneer environmentally responsible data management. Data center sustainability processes are discussed and calculated for the theoretical case, illustrating the potential for avoided emissions. The challenge of meeting processing power demand while reducing greenhouse gas emission intensity represents the environmental dimension of this analysis.

Finally, the technology dimension is represented throughout the analysis. The scale of technological development is limited by the financial and environmental implications of energy consumption, thus technological development must advance hand in hand with sustainable design. Environmental stewardship and sustainability have become key business parameters for data center developers and operators, setting a precedent for future technological development.

1.3 Research Objectives

The purpose of this study was to determine the feasibility of integrated greenhouse waste heat reuse for data center operations in Alberta and to estimate the potential scale and impact of supported integrated agricultural production from an unconventional combined heat and power scheme. Three primary objectives were outlaid:

Objective 1: To delineate the energy consumption issues of the data center and cryptocurrency sector and characterize the relevant efficiency metrics

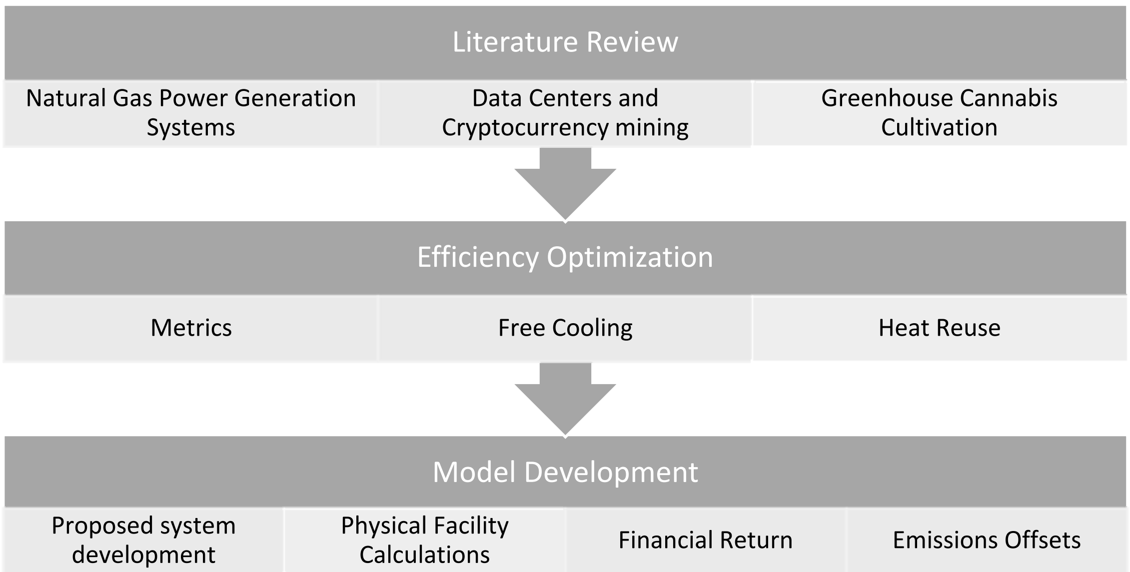
Objective 2: Explore the efficiency improvement methods for data centers and understand the applications of facility optimization in the reduction of data center economic and environmental footprint

Objective 3: Develop a model to determine the feasibility of integrated greenhouse waste heat reuse in cryptocurrency operations in Alberta. The purpose of the model is three-fold; to determine the size of greenhouse area supported by waste heat, the degree of data center waste heat reuse, and the potential cost and avoided emissions from waste heat reuse.

1.4 Research Methodology

To tackle the objectives outlaid in this project, the key analysis steps to were followed.

Figure 1 - Research Methodology



2 CHAPTER TWO – DATA CENTERS

Over the previous decades, the global computational landscape has undergone revolutionary change resulting in monumental increases in concentrated processing power. The heavy lifting of storing, processing and managing data has shifted to high-density computing facilities known as data centers that house the critical technological applications and data of organizations. Centralized data facilities fitted with technology infrastructure and hardware uphold the major functions of all major business processes, financial transactions, communication, university, municipal and governmental systems (Shehabi, et al., 2016).

Nearly all institutions are reliant on the electronic exchange of data and data center requirements vary in degree. Large organizations require tens or hundreds of data centers to support their operations (Shehabi, et al., 2016). Data center activity encompasses traditional enterprise services such as email, file sharing, communications, streaming, internet and hosting facilities as well as data consolidation and analysis, storage, cryptocurrency transacting and high-performance computing. The transformative disciplines of artificial intelligence, machine learning, and deep learning are reliant on data centers. While the global total number of data centers has declined in recent years, the outsourcing of critical computational applications to hyper-scale facilities developed by cloud service providers will likely contribute to an overall increase in total data center area for the foreseeable future.

Typical data center design includes standard physical information technology (IT) components such as routers, switches, firewalls, storage systems, servers and application delivery controllers. Data center size is contingent on intended purpose thus data centers have diverse configurations. Layout can vary by function as network topology and supporting equipment are customized to the service provided (Johnson, B., 2013). Depending on the level of computational support required, data centers can range from a small number of servers to warehouse-style facilities with tens of thousands of servers and while some building standards exist, not all data centers follow recommended building codes (Johnson, B., 2013). The physical design and logistical layout of data center infrastructure are optimized for capacity, power and temperature control requirements, yet must often be flexible to accommodate demand fluctuations. Dedicated service providers may be classified as ‘mission-critical’ facilities, where service interruptions can cause catastrophic disruption to organization or business. As a result, critical building systems in comprehensive DCs include power supply redundancy, backup power generation equipment, heating, ventilation, and air conditioning (HVAC) systems as well as extensive fire protection and security systems (Bell, 2005). Environmental factors, such as humidity and temperature are carefully controlled to protect IT equipment (Johnson, B., 2013).

2.1 Processors

From the early days of the computing industry, Moore’s law forecasted the increase in computing power in correlation with the biennial doubling of transistors on the microchip. In line with Moore’s predictions, computational power has grown steadily and rapidly over time, driving the success of the IT revolution (Waldrop, 2016). Until recently, as the processing efficiency and capability of computing chip devices increased, the associated cost, size, and power consumption decreased (Waldrop, 2016).

As the ‘brain’ of a computing device, computational processing units (CPUs) were developed to carry out general program functions. Flexible and multi-functional, CPU processors are capable of a wide array of complex computational tasks. Dual and multi-core CPUs increased the number of operations that could be run in tandem. Modern multi-core CPUs have between 1-12 cores, but basic design remains largely similar to early CPUs (Baltazar, 2018). The rise of the graphics processing unit (GPU) coincided with the need for processing units that could perform simple tasks in parallel. GPUs today have thousands of processing cores, and despite lower overall processing capability, GPU efficiency rapidly outpaced CPUs in task-specific functionality. In big data processes, thousands of gigabytes of data are generated every second, thus instantaneous and efficient processing is critical (Schlegel, 2015). Further advances in microchip development led to specialized single-purpose chip design of Field Programmable Gate Arrays (FPGAs) and Application Specific Integrated Circuits (ASICs). ASICs are developed and manufactured to perform specific functions; ASICs used in bitcoin mining perform the task-specific intensive blockchain hash computations and cannot be used for any other purpose. The efficiencies of ASIC chips are due to the singular functioning of the chip, as a result, ASICs can compute hashes up to 100,000 times faster than CPUs (Asaad, et al., 2012). The demand for leading-edge microprocessors has escalated dramatically with the advent of data mining, machine learning, and deep learning, where intense hashing operations require processing power delivered from high-end GPUs and ASICs. It is estimated that by the end of 2018, 25% of chips used in machine learning data centers will be FPGAs and ASICs, and operations will be measured with a performance per watt metric in consideration of microchip heat output (Deloitte, 2017).

It is now well understood that the limits of Moore's law have been reached. At microscopic transistor sizes, heat production caused by the speed of electron transfer through increasingly smaller infrastructure causes wear to transistors and exceeds temperature thresholds creating heat dissipation challenges (Waldrop, 2016). To accommodate for the escalating demand in computing performance, server density in enterprise applications has also increased dramatically over the past decade, accelerating heat and power issues (Fruehe, 2005). Server enterprises, the single largest client for advanced processing chips, subsequently shed large volumes of heat creating power and cooling challenges for many IT organizations. As a result, data center administrators must determine how to supply large amounts of power to systems and how to contend with the excessive amounts of heat generated.

2.2 Data Center Size

Data centers are classified based on both size and performance. The International Data Corporation (IDC) categorizes data centers into five types by size, however (Horner & Azevedo, 2016) adopt a sixth type to account for the most sophisticated type of data centers.

The smallest classification type, server closets, support small businesses or individual projects and are often managed by non-experts. Slightly larger, server rooms (5-25 servers) support similar processes at larger companies and are often managed by dedicated IT staff. Localized data centers (26-100 servers) are used in business-critical applications requiring some degree of redundancy in their power and cooling systems, however, downtime is not catastrophic at this size classification. Mid-tier data centers (101-499 servers) are utilized by large and medium-sized organizations, hosting operational systems such as HR, email, internal data storage. In this size of facility, downtime can impact business functioning. therefore, mid-tier data centers necessitate some degree of power supply redundancy. Enterprise data centers (500+ servers) are independent off-site facilities used to support core business operations for organizations such as banks, finance, and health care companies. Service interruptions causing downtime may be catastrophic and enterprise data centers have a high degree of redundancy in their design. Lastly, hyper-scale data centers, also called server farms or warehouse-scale computers (WSCs) are classified as having 5000 or more servers. Hyperscale data centers are generally built by information and communications technology companies (ICTs) and host data and cloud services. The architecture of hyper-scale facilities allows for a high degree of homogeneity that emphasizes efficiency (Ganeshalingam, Shehabi, & Desroches, 2017).

Table 1 - Data Center Taxonomy

Classification	*Taxonomy*	*Servers*	*Dimensions (ft^2)*
Small Data Centers	Server Closet	1-4	≥100
	Server Rooms	5-25	101-1000
Mid-size Data Centers	Localized Data Center	26-100	1001-2000
	Mid-tier Data Center	101-499	2001-20000
Large Data Centers	Enterprise Data Center	500+	20000+
	Hyperscale Data center	5000+	20000+

Modified from (Ganeshalingam, Shehabi, & Desroches, 2017)

The Uptime Institute's Tier Classification System classifies data center performance and redundancy. For mission-critical facilities, service interruption may have severe business consequences ranging from lost revenue to loss of life, thus tier classification is enhanced by a certification process to ensure facility performance to business demand (Turner, Seader, Renaud, & Brill, 2008). A Tier 4 classification represents the highest level of redundancy and the lowest degree of downtime for data centers and is designated as fully redundant.

Table 2 - Data Center Tier Classification

Tier	*Uptime*	*Redundancy*	*Downtime (h/y)*
1	99.671%	No redundancy	28.8
2	99.741%	Partial redundancy	22
3	99.982%	Fault tolerant	1.6
4	99.99%	Fully redundant	0.43

Modified from (Matko & Brezovec, 2018)

2.3 Data Center Siting Considerations

Data center site selection is constrained by stringent reliability requirements (Covas, Silva, & Dias, 2013). Industry criteria for site selection include a number of underlying considerations; energy, bandwidth, ease of doing business, taxation, political stability, sustainability, natural disasters, energy security, GDP per capita and water availability per capita (Cushman & Wakefield, 2016) as well as climate and man-made hazards (Covas, Silva, & Dias, 2013). Client distance factors are less important, as data centers can be located at greater distances from ultimate users.

The reliability of critical power infrastructure is the overriding concern for operators in data center site selection. As a critical consumer of energy, power availability and cost are the main drivers of data center operators. Access to economic, reliable energy with stable rates characteristic of baseload generation is essential to data center operations. In siting data centers, operators look to maintain redundancy in supply. The type or origin of electricity may factor into site selection, with a growing number of DCs moving toward 'green' power supply from renewable sources. Proximity to the generation source results in decreased distribution losses and less required infrastructure, subsequently lowering facility cost/MW (Intel, 2014).

The availability and reliability of fiberoptic and communications infrastructure is another high-ranking consideration for data center site selection. Market connectivity is an important driver of facility location given the requirement for high-speed and high-volume data transmission. Like power supply, infrastructure reliability is critical to sustained operations, and network traffic is limited by infrastructure quality. In addition to adequate capacity, the infrastructure must be flexible to allow for expansion as data center demand grows over time.

Environmental conditions including both climate and natural hazards can affect data center reliability and cost. Due to high server heat output, cool climates are an asset that can be used to decrease temperature control demands. Climate affects data center efficiency and can also impact facility design and construction. Intensive cooling requires more infrastructure, increasing both the initial capital expenditure and lifetime operational expenditure (Intel, 2014). In suitable climates, 'free cooling', the use of external ambient air at sufficiently low temperature, can be utilized as a method to significantly reduce energy costs. Cold, dry climates provide optimal conditions for data center efficiency. Suitable locations for data centers are seismically stable and have a low proclivity for natural hazards such as floods, tornadoes, hurricanes, and volcanoes. High winds can be problematic for DCs using external air for cooling, and poor air quality resulting from dust storms, heavy pollen, corrosives (ex. salt from ocean air), fumes, chemical pollutants, and other fine particulate matter can require costly filtering equipment and filter upkeep (Intel, 2014).

Additional factors considered during site selection include political stability and economic incentives. Cushman & Wakefield (2016) found that in the selection of a data center site political stability is the second most important risk factor. Political unrest can impede data center reliability as conflict can disrupt the supply of primary sources of energy. Taxation and regulation may incentivize location selection and socioeconomic factors determine the availability of a sustaining workforce.

Using a flexible risk assessment methodology, Cushman & Wakefield (2016) developed a Data Center Risk Index. Thirty-seven countries were ranked according to ten top risk factors affecting successful data center operation. The five highest-ranking countries; Iceland, Norway, Switzerland, Finland, and Sweden are located in Northern Europe. These countries offer both politically and geologically stable environments for business with strong energy security and a significant proportion of renewable energy generation (Cushman & Wakefield, 2016). The index rankings are representative of the industry trend to seek out sustainable low-cost energy sources to lower data center footprint. Data center hubs like Sweden, Norway, and Finland capitalize on reliable, low-cost energy, taxation advantages, strong connectivity, low natural hazard risk, and political stability.

Following closely behind, Canada ranks sixth in the index and possesses many of the same attributes that make Northern European countries highly valued targets for data center expansion. Canada is energy secure, with competitively low energy prices for electricity generated from hydropower and natural gas. Canada possesses the cool climate necessary for free cooling and is geologically stable with low natural hazard risk. It ranks high in political and economic stability and has strong legislated privacy protection, ensuring the privacy of data stored on servers in Canadian data centers. Canada's work permit and immigration processes are friendly to foreign tech workers, a benefit to the Canadian tech sector, where 37.6% of the workforce holds immigrant status (Vu, Lamb, & Zafar, 2019).

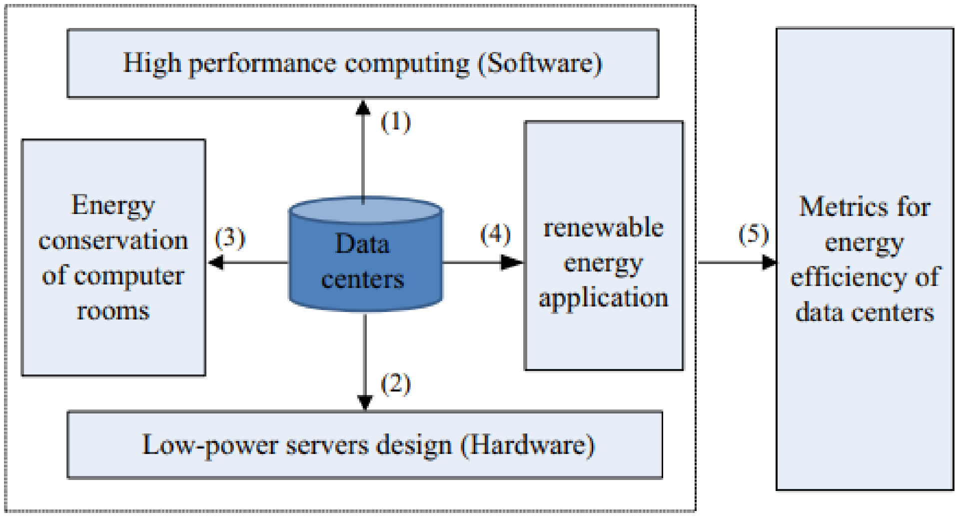
The province of Alberta is one of the most cost-competitive locations for data center investment in North America. Alberta's energy market is the only deregulated market in Canada, resulting in some of the lowest electricity prices in the region. Abundant natural gas resources provide a significant proportion of baseload power. Recent oversupply driven by limited export demand and contentious pipeline restrictions has resulted in low prices allowing for competitive long-term rate negotiation. A favorable exchange rate and low relative construction costs provide further incentive. Additionally, with no sales, capital, payroll or equipment taxes and a low commercial property tax rate, businesses and employees in Alberta benefit from the lowest overall taxation rate in Canada (Government of Alberta, 2018). Alberta also enjoys a stable, upgraded electricity grid and broad telecommunications network featuring a high speed, low latency network (Invest Alberta, N.d.). The province also boasts a highly competent workforce; the city of Calgary maintains the highest concentration of high-tech workers in Canada, a reflection of the technical professionals employed in Alberta's resource sector (Vu, Lamb, & Zafar, 2019). Lastly, Alberta's cool and dry climate minimizes temperature control cost, with less than 10% of the year necessitating the use of air conditioning (Invest Alberta, N.d.).

2.4 Data Center Energy Efficiency

With data availability, security and bandwidth requirements necessitating uninterrupted power supply, data centers are energy-intensive operations. Handling the concentrated heat produced by computing infrastructure and hardware contributes to the need for serious power (Yole Developpement, 2016). Typical data center power densities range from 538-2153 W/m^2 reaching up to 10,000 W/m^2. In comparison, modern high-tech office power densities are considerably lower, ranging from 108-161 W/m^2 (Whitehead, Andrews, Shah, & Maidment, 2014). Data center temperature control systems consume on average 40% of energy delivered to the facility; with the most efficient cooling systems consuming 24% of total facility energy and least efficient at 61% (Ni & Xuelian, 2017). The Smart 2020 Report estimated that emissions for the ICT sector will grow 180% over the 20-year period from 2000-2020, while data center emissions growing 240% over the same period (The Climate Group, 2008). The rapid expansion of data centers, development of hyper-scale facilities and evolution of component and facility design have resulted in significant capital and operational cost increase for data centers (The Climate Group, 2008). As the primary source of power generation, fossil fuels account for the majority electricity generated globally thus efficiency optimization for data centers is vital in decreasing both economic and environmental footprints.

Given the high volumes of sensitive data handled, security is paramount in data center operation. Administrators are vigilant to maintain the anonymity of data center locations for data security and competitive purposes. Data center secrecy often extends to energy use, meaning that oversight is scarce and energy use is difficult to track. No appropriate legislative framework or policies monitor or limit data center energy consumption and emissions, though some region-specific legislation is under consideration (Avgerinou, Bertoldi, & Castellazzi, 2017).

Figure 2 - Energy Conservation Framework



(Rong, Zhang, Xiao, Li, & Hu, 2016)

To improve economic and environmental burdens, data center platforms focus on efficiency optimization. As illustrated in Figure 2, data centers can be 'greened' through four main methods; the incorporation of high-performance computing, low power server design, energy conservation, and renewable energy application. High-performance computing optimizes facility efficiency through supercomputer architecture and the adoption of artificial intelligence software. Low power server design facilitates hardware improvements to reduce energy consumption. Energy conservation of computer rooms involves the incorporation of innovative and efficient cooling methods, such as free cooling and liquid cooling. And lastly, renewable energy application refers to both the incorporation of renewable energy sourcing and the direct application of thermal energy generated by the facility. This project focuses on the two latter forms of efficiency improvements, energy conservation, and renewable energy application.

2.5 Efficiency Metrics

2.5.1 PUE

Power usage effectiveness (PUE) is an industry-standard metric used to benchmark the energy performance of a data center. PUE is the efficiency ratio of the total power consumption of a data center and the power consumed by the IT equipment (The Green Grid, 2012b).

$$PUE = \frac{Total\ Facility\ Energy\ (kW)}{IT\ Equipment\ Energy\ (kW)}$$

$$PUE = \frac{Power\ Distribution + Cooling + Lighting + Miscelaneous + IT\ (kW)}{IT\ \ (kW)}$$

$$1.0 \leq PUE \leq \ \infty$$

PUE characterizes how effectively power and cooling are dispatched to the IT equipment. IT equipment energy is encompassed by the computing, storage, and network equipment as well as by the monitors, workstations, and switches used in data center oversight and control. Facility energy includes the described IT equipment and other component loads including but not limited to power delivery components, cooling system components and miscellaneous component loads such as lighting (The Green Grid, 2012b). The three main processes covered by the PUE measurement are the energy delivered to the IT equipment, energy lost during this power distribution, and the energy required by the cooling and infrastructure.

PUE is not a productivity metric nor is it a comprehensive efficiency metric (The Green Grid, 2012b), and PUE does not express the full environmental burden of the facility or IT equipment (The Green Grid, 2010). PUE values can be used to identify operational efficiency improvement opportunities and demonstrating whether operational design and processes are improving over time. Further, PUE metrics can be used to compare analogous data centers and can serve as a design target for new data centers (The Green Grid, 2012b). Continual PUE monitoring is often integrated into building management systems to monitor operating efficiency (Horner & Azevedo, 2016).

Calculated PUE values can range from 1.0 to infinity. PUE has an ideal value of 1.0, at which 100% of power delivered to the data center is exclusively used by computing equipment. A value of 1.0 is a theoretical minimum as all facilities experience some efficiency losses due to lighting and power distribution. At this time, a comprehensive data set for global data center PUE values are lacking and the true variance in PUE across data centers is unknown. Industry-wide measurements of PUE vary, an EPA survey of 61 DCs showed PUEs varying from 1.25 to 3.75, with an average of 1.92 (Energy Star, 2010). A 2013 self-reporting Uptime Institute survey showed an average PUE of 1.65 (Avgerinou, Bertoldi, & Castellazzi, 2017). At 1.92, the data center infrastructure value (DCiE) shows that slightly less than half (48%) of the energy reaching the facility is used by IT equipment in computational processes, at 1.65 this value is 40%. Ultra-low PUE benchmarks are achieved by large technology organizations such as Google, Facebook, and Amazon with resources and expertise required to engineer optimized facilities. In 2015, Google reported a trailing 12-month fleet average PUE of 1.12 (Google, N.d.), and Facebook's two largest data centers reported TTM values of 1.08 and 1.09 (Horner & Azevedo, 2016). Efficiency levels are illustrated in Table 3. Trends predict a general decrease in PUE across all data center sizes (Shehabi, et al., 2016), yet the lack of oversight means that reliable energy data is difficult to ascertain as PUE values are largely self-reported (Avgerinou, Bertoldi, & Castellazzi, 2017).

Table 3 - PUE Efficiency

PUE	*Infrastructure Efficiency (DCiE)*	*Level of Efficiency*
3.0	33%	Very inefficient
2.5	40%	Inefficient
2	50%	Average
1.5	67%	Efficient
1.2	83%	Very Efficient

Modified from (42U, N.d.)

Table 4 - PUE and Redundancy Values for Efficiency Scenarios

		2020 PUE			
DC Type	2014 PUE	Current Trends	Improved Management	Best Practices	Redundancy
Room	2.5	2.35	2.00	2.00	N+0.5N
Closet	2.0	2.00	1.70	1.50	N+1
Localized	2.0	1.88	1.70	1.50	N+1
Midtier	1.9	1.79	1.70	1.40	N+0.2N
High-end	1.7	1.60	1.51	1.30	N+0.5N
Hyperscale	1.2	1.13	1.13	1.10	N

Modified from (Shehabi, et al., 2016)

PUE values can be significantly influenced by data center location. The efficiency of mechanical and computational systems varies with climate, informing the amount of temperature control required to ensure temperature does not exceed operational limits. Local climate dictates the ability to capitalize on external temperatures used in innovative cooling processes. Climate parameters, such as weather, ambient temperature, and relative humidity can affect energy consumption and processor performance. As illustrated in Table 5, countries with cooler climates, such as Nordic and Continental European countries, as well as Canada and northern United States, experience lower average PUE values.

Table 5 - Geographical Zoning with Temperature and Relative Humidity Data

Geographical Zones	Countries	Temperature Range (°C)	RH Range (%)	Average PUE	Number of Data Centres
Nordic countries	Denmark, Finland, Norway, Sweden	18–26	20–80	1.71	13
UK and Republic of Ireland	England, Scotland, Wales, Northern Ireland, Republic of Ireland.	17–30	8–80	1.83	116
Northern/Central Europe	Austria, Belgium, France, Germany, Hungary, Luxembourg, The Netherlands, Portugal, Poland, Switzerland	14–28	16–75	1.72	122
Southern Europe/ Mediterranean	Gibraltar, Greece, Italy, Malta, Spain, Turkey, Monaco, Romania, Bulgaria	16–26	20–80	2.00	30
Non EU	Republic of Mauritius, US	-	-	-	5

(Avgerinou, Bertoldi, & Castellazzi, 2017)

PUE is a relevant metric for several significant reasons. PUE is influenced by operational expenditures; a decrease in PUE value corresponds to a decrease in utility costs. PUE can also impact capital expenditures as peak PUE reflects the design requirements necessary to accommodate facility peak load. PUE impacts sustainability, as global energy consumption for computing processing grows, energy management and efficiency are critical for data centers. Lastly, PUE is representative of power grid demand (Keisling, 2017). Despite its usefulness, PUE is not a proxy for environmental performance or 'greenness' (Horner & Azevedo, 2016). IT load for two comparable data centers may be identical, however energy consumption from IT hardware and associated data center infrastructure varies and is translated into different PUE values (Oro, Taddeo, & Salom, 2018). PUE does not measure energy consumption or emissions, and efficiency measures such as heat reuse can increase PUE. Oro, Taddeo, and Salom (2018) found heat reuse implementation increased energy consumption with respect to the reference case (no heat reuse), reaching PUE values of 2.2 in some cases. To better delineate data center sustainability and energy efficiency, operators must look towards further sustainability metrics.

2.5.2 ERE

Energy Reuse Effectiveness (ERE) is a ratio used by data center engineering analysis purposes to characterize energy recovery (Wahlroos, Parssinen, Rinne, Syri, & Manner, 2018). ERE incorporates energy reuse into the PUE equation and is the measurement of the ratio of the total energy required to run the data center facility less the amount of reuse energy to the energy consumed by the IT equipment (National Renewable Energy Laboratory, 2011). ERE is calculated using the following equations.

$$ERE = \frac{Total\ Facility\ Energy - Reuse\ Energy\ (kW)}{IT\ Equipment\ Energy\ (kW)}$$

$$ERE = \frac{Power\ Distribution + Cooling + Lighting + Miscelaneous + IT - Reuse\ (kW)}{IT\ \ (kW)};\ 0 \leq ERE \leq\ \infty$$

ERE only considers energy reused outside the control volume (the boundary around the data center) (Patterson, 2010). Energy reuse within the control volume (i.e., heat to run a chiller) is captured by the PUE value, but an external use (i.e., heat into a district heating system) can be measured with ERE. ERE has a lower limit of 0.0, where 100% of the energy delivered to the facility is reused in external applications.

In the effort to ‘green’ data centers there is a push to acquire power from renewable sources, however, the source of power does not impact data center efficiency. Minimizing waste through efficiency optimization and heat reuse is an area of environmental protection and cost savings and both PUE and ERE provide context to waste heat reutilization and reductions in power draw.

2.5.3 ERF

The relationship between PUE and ERE is defined by the Energy Reuse Factor (ERF). ERF is a ratio of energy reuse over the total energy of the data center. Similar to ERE, the ERF refers to energy reuse as energy used outside the control volume, and total energy as energy used within the control volume.

$$ERF = \frac{Reuse\ Energy\ (KW)}{Total\ Energy\ (KW)}$$

$$ERF = \frac{Reuse\ Energy\ (KW)}{Power\ Distribution + Cooling + Lighting + Miscelaneous + IT\ (KW)};\ 0 \leq ERF \leq\ 1.0$$

ERF values range from 0.0 to 1.0; an ERF of 0 indicates no energy is reused and 1.0 indicates all energy is reused outside of the data center.

$$ERE = (1 - ERF)\ x\ PUE$$

Low PUE values are indicative of data center performance and generally represent more efficient operations. Yet at their most efficient, data centers still consume tremendous amounts of power, most of which is converted to heat. In order to generate further sustainability gains, it is necessary to look beyond internal facility efficiency to the implementation of waste heat reuse.

2.6 Efficiency Optimization in Data Centers

This project explores data center ‘greening’ through energy conservation and heat reuse. Decreasing energy consumption of server rooms is directly related to temperature control requirement. Improvements to cooling systems have been a developing focal point in data center design. The introduction of ‘free cooling’ where external ambient air is used to in place of traditional computer room air conditioners (CRACs) has had a significant impact on data center siting.

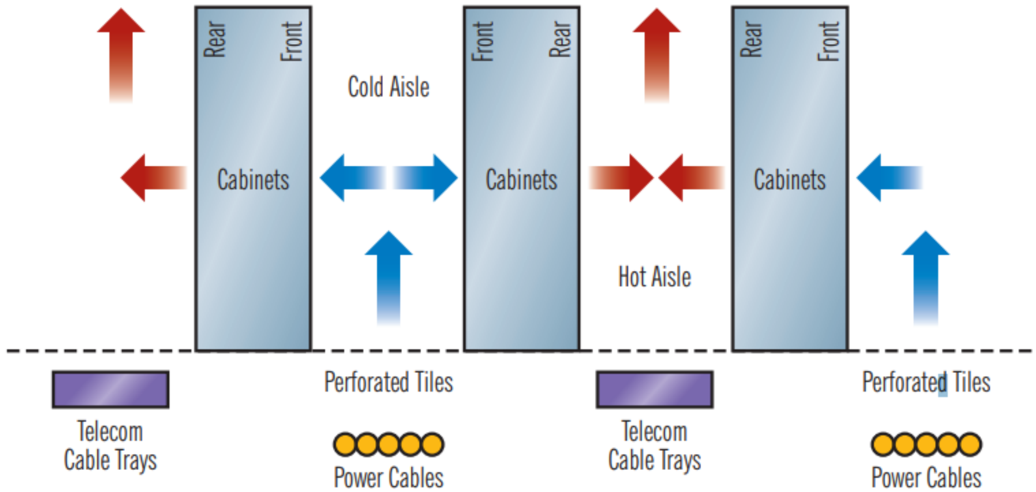
Data center layout is designed to manage heat dissipation and maintain functional working temperatures for data center equipment and prevent equipment overheating. Data-driven heat production negatively affects servers, shortening lifespan and overburdening internal server cooling fans. Temperature is the main threat to electronic components and the primary cause of component failure in DCs (55%) followed by vibration (20%), humidity (19%) and dust (6%) (Anandan & Ramalingam, 2008). Traditionally, data center temperature has been controlled using air-cooling systems requiring pumps or fans. For data center designers and engineers, providing ideal conditions for equipment while minding efficiency is a challenge.

2.6.1 Data Center Energy Conservation

2.6.1.1 Operating Temperatures

Air cooling systems in typical data centers are dependent on server rack layout, which are most commonly arranged into ‘hot’ and ‘cold aisles’ (Nadjahi, Louahlia, & Lemasson, 2019). In cold aisles, the front sides of the server racks face forward, and chilled air provided by the computer room air conditioner (CRAC) unit is distributed through perforated tiles in the floor or ceiling. Heated server air is exhausted to the hot aisle, where air is captured and returned to the CRAC intake. Containment strategies used to isolate hot and cold aisle air are vital to avoid increasing overall temperature and cooling demand. The heat in the CRAC is absorbed into a chiller or cooling tower loop for ultimate dissipation to the environment.

Figure 3 - Hot Aisle/Cold Aisle Cabinet Configuration



(Anixter, 2012)

Thermal guidelines are set for data process environments by the American Society of Heating and Refrigerating and Air-Conditioning Engineers (ASHRAE) with an ideal supply air temperature between 18-27°C and relative humidity of 60% (American Society of Heating, Refrigerating and Air-Conditioning Engineers TC 9.9, 2016). Previous concerns regarding equipment functioning led operators to set maximum operating temperatures at 22°C, with some data centers operating at temperatures as low as 13°C (Miller, 2008). High power cost prompted operators to begin running DCs at higher temperatures and data center equipment was found to have more temperature resiliency than assumed. ASHRAE guidelines were revised to cover wider temperature ranges (American Society of Heating, Refrigerating and Air-Conditioning Engineers TC 9.9, 2016). Higher operating temperatures reduce the dependency on CRAC/CRAH cooling. To date, some large-scale data center operators run at the upper end of the ASHRAE guidelines, with a number of highly efficient data centers operating at 35°C (Humphries, 2012). Research illustrates that failure rates for modern, well-designed servers do not increase when operated at the upper range of ASHRAE guidelines, however older classes of equipment are not compatible with the modified temperature range and thus experience a decrease in reliability when operated at higher temperatures. ASHRAE's Environmental Class Definitions classify data centers based on operational functioning are outlined in Table 5.

Table 6 - 2011 ASHRAE Thermal Guidelines for Data Centers

Class	IT Equipment Type	Rec. operating range	Allowable operating range	Max dew point	Environmental control
A1	Enterprise servers, storage products	18-27℃	15-32℃	17℃	Tightly controlled
A2	Volume servers, storage products, personal computers, workstations	18-27℃	10-35℃	21℃	Some control
A3	Same as above	18-27℃	5-40℃	24℃	Some control
A4	Same as above	18-27℃	5-45℃	24℃	Some control

(American Society of Heating, Refrigerating and Air-Conditioning Engineers TC 9.9, 2016)

2.6.1.2 Free Cooling

Cooling systems are critical infrastructure for any data center facility. Traditional air-cooling methods for data centers are energy-intensive, requiring between 30-50% of data center energy consumption (Bai, Gu, & Qi, 2018). Designated cooling equipment systems consist of computer room air conditioners (CRACs) and computer room air handlers (CRAHs) and the requisite chillers, pumps, and fans. These systems operate by cooling and cycling the same air over servers, dissipating heat through heat transfer to the moving air.

Upon exiting the server, system air is typically between 10-15 degrees warmer than server inlet air temperatures (Petschke, 2015). This temperature differential is referred to as the airside temperature difference and determines the degree of cooling required (Petschke, 2015). Low recommended operating temperatures previously restricted the applicability of free cooling economizer cycles, but as ASHRAE values for operating temperatures were adjusted to accommodate higher server inlet temperatures, the opportunities for free cooling increased (Zhang, Shao, Xu, Zou, & Tian, 2014).

Heated server exit air is collected and returned to the CRAC/CRAH where it is cooled via compression refrigeration to the designated inlet temperature. Innovative passive cooling techniques using air and liquid-based cooling systems largely bypass the power-hungry compressor cycles, drastically reducing facility power consumption. This project focuses on 'free cooling', a passive air-based cooling technique that uses natural air temperatures to bypass the requirement for power-hungry chillers and air conditioning.

'Free cooling', or the 'economizer cycle' utilizes ambient external air and natural air flows for cooling within the data center (Zhang, Shao, Xu, Zou, & Tian, 2014). Free cooling is dependent on climate and is divided into two main types: direct free cooling, where outdoor air is directly applied within the facility, and indirect free cooling, where cooling from external air is transferred via heat exchanger (Nadjahi, Louahlia, & Lemasson, 2019). The ability to apply direct airside economization is an advantage for data center developers as this system drastically decreases or eliminates the need for a CRAC cooling system. Direct free cooling has the highest theoretical efficiency of all free cooling systems, however direct air economizer cycles must include air quality and humidity control. Air quality issues can impede server functioning, and outdoor air must be filtered to avoid damage IT equipment from particulate matter. If external temperatures are too cold, warm air from the data center is combined in to maintain acceptable server inlet temperatures. Humidity is an additional concern in the use of free cooling, as server functioning is negatively impacted by excessive dryness or dampness. Elevated humidity can increase the probability of conductive failures or corrosion in electronic equipment and air that is excessively dry damage equipment through electrostatic discharge (Nadjahi, Louahlia, & Lemasson, 2019).

Free cooling can be applied in many locations, however cooler northern climates permit a greater number of free cooling hours. Data centers in cooler climates can take advantage of cold outdoor temperatures and direct airside economizer modes have been demonstrated to significantly reduce PUE, with energy savings of up to 49% (Nadjahi, Louahlia, & Lemasson, 2019). Intel found a 67% decrease in power consumption when economizer mode was used at 91% the year (Atwood & Miner, 2008). Modeling multiple modes for Chicago, Atlanta and Phoenix, an analysis of economizer modes showed that free cooling provided more savings relative to the conventional cooling systems. In the air economizer mode, total cooling energy was reduced by 51.7-54.7% (Sujatha & Abimannan, 2011). Reasonable site selection may lead to 12-15% decrease in total energy consumption and the associated financial implications are an important consideration for developers in the siting of new data centers (Rong, Zhang, Xiao, Li, & Hu, 2016).

Hyperscale data centers such as those developed by ICT companies like Yahoo!, Facebook and Google rely heavily on free cooling, with ultra-low PUE values around 1.1 (Gough, Steiner, & Saunders, 2015). Free cooling technology is developing rapidly and has been cited as the most suitable tech to improve data center energy efficiency (Nadjahi, Louahlia, & Lemasson, 2019). Cold, dry climates are the most advantageous for free cooling, however most data center locations have daily temperatures below set facility temperatures and can benefit from partial free cooling. It is likely that the use of economizer cycles will be recommended in future ASHRAE standards, and some American planning and development authorities have already begun to implement economizer mode requirements (National Renewable Energy Laboratory, 2011).

2.7 Heat Reuse

A byproduct of many industrial processes, waste heat has been identified as one of the world's largest sources of energy and a massively undervalued resource (Jones, 2018). In data centers, inefficient server processes shed significant amounts of waste heat, most of which is lost to the atmosphere. Both internal and external reutilization of waste heat directly reduce energy requirement and carbon dioxide emissions through the offset of additional fuels (often carbon-based). Avoided emissions through waste heat reuse is therefore an economic, environmental and technically sustainable practice that appeals to consumers, clients and regulators focusing on green industrial practice (Wahlroos, Parssinen, Manner, & Syri, 2017). The co-generation of electricity and heat is not a new concept, and heat reuse within the ICT sector has become increasingly common. As remaining opportunities for physical microchip-based improvements decrease and. Future improvements in facility efficiency are likely to come from outside the confines of the data center in the form of energy reuse (Unica, 2018).

Nordic countries lead in waste heat reuse adoption for several identifiable reasons. The cool temperate climate is ideal for free cooling and results in high heat demand in both residential and commercial sectors. After the oil crises of the 1970s, governments in Nordic countries mandated the development of district heating networks, later opening heat grids to industries producing large volumes of waste heat (Unica, 2018). Industrial waste heat in district heating made up 10% of Finland’s grid in 2018 (Tiitinen, 2019) and 8% Sweden’s grid in 2017 (Johannesson, 2017). District Heating utilities in Finland estimated DCs as the second-largest potential source for heat (Wahlroos, Parssinen, Manner, & Syri, 2017). Data centers in these regions are therefore intentionally located proximal to district heating networks. Outside of district heating, waste heat reuse is more complex due to the barriers to implementation.

Two significant barriers impede waste heat reutilization; heat demand and quality. Given that heat transmission is not feasible over long distances, any data center design involving the implementation of waste heat reuse must be situated near a heat uptake source. Wahlroos, Parssinen, Rinne, Syri, and Manner (2018) outlined several specific uses for waste heat; space heating, floor heating, domestic hot water heating, melting snow, preheating feed water in power plants and industrial processes, drying biomass, water desalination, and energy production. The demand for space heating from district heating networks is seasonal, thus demand and profitability of waste heat fluctuates throughout the year. The additional energy and infrastructure required for the implementation of heat reuse for district heating systems increase overall electricity consumption and capital expenditure, subsequently increasing the PUE value. Reuse energy is accounted for in the ERE value, and small-scale, location-specific solutions (swimming pools, greenhouses, nearby buildings and industrial processes) generally do not require significant heavy investment in comparison to district heating systems (Wahlroos, Parssinen, Rinne, Syri, & Manner, 2018).

The second consideration for heat reuse is heat quality. Heat from data centers is categorized as low-grade heat, with waste heat captured from air-cooled DCs between 25-35℃, and between 50-60℃ from liquid-cooled data centers (Wahlroos, Parssinen, Rinne, Syri, & Manner, 2018). For heat reuse implementation, a low-grade heat application must be available otherwise low-quality heat must be upgraded with heat pumps to increase usability. Heat demand and quality in conjunction with investment and infrastructure cost are the largest barriers to heat reuse implementation, however other factors can influence heat reuse adoption. As two separate entities, data center and district operators may have opposing priorities must work collaboratively

(Wahlroos, Parssinen, Rinne, Syri, & Manner, 2018). As discussed previously, data center security is a primary operational concern which must be considered when implementing waste heat reuse (Unica, 2018). For privacy and security reasons, data centers reveal limited data on energy utility and heat reuse, and the lack of transparency is considered to be a significant factor in the slow adoption of commercial waste heat reuse (Wahlroos, Parssinen, Manner, & Syri, 2017). Currently, the scale of waste heat reutilization is limited considering the economic potential of the resource.

2.8 Bitcoin Mining

To date, the largest data center facilities in Alberta are cryptocurrency mining operations, which have been selected as the analog to represent local data center in this model. Bitcoin mining operations have been drawn to Alberta in search of cool climate and low, predictable power rates. Toronto-based Hut 8 mining, Canada's largest cryptocurrency mining company operates two bitcoin mining data centers in Drumheller and Medicine Hat (Hut 8 Mining Corp., 2019)

Bitcoin is a peer-to-peer digital currency that operates on a cryptographic protocol, maintained on an immutable public ledger called the 'blockchain'. As a decentralized currency, bitcoin is not issued by a central authority, instead, bitcoin is transacted and secured through a process called 'mining'. In order to add 'blocks' of transactional data, specialized computers solve complex computational problems, the 'proof of work' scheme that results in the solution of the problem or the 'hash'. Bitcoin mining is undertaken using high-performance ASIC chips, requiring an immense amount of power and cooling.

The cost of energy is a limiting factor in bitcoin mining. As with all currencies, the value of bitcoin fluctuates over time, impacting the overall processing power of active bitcoin miners. The bitcoin proof of work algorithm increases in difficulty over time as the remaining amount of bitcoin decreases, known as the difficulty adjustment. The solve rate (~every 10 minutes) remains approximately the constant regardless of available network mining power, thus an increase in value corresponds to the need for more powerful hardware to maintain a comparable success rate (O'Dwyer & Malone, 2013). To remain competitive, bitcoin hardware must have a high hash rate and low energy footprint. In 2018, it was estimated that the production of one bitcoin equaled costs of up to $2500 USD ($3,318 CAD) in power (Roberts, 2018).

Similar to other types of data centers, Bitcoin mining facilities divulge little about their operations. The efficiency of mining operations is largely undisclosed, and PUE claims are not independently verified. The global power consumption of Bitcoin was a minimum of 4.2 GW in 2018, consuming between a minimum of 37 TWh and estimated actual of 69 TWh per year, or 0.31% of global energy consumption (Digiconomist, 2019). While Bitcoin mining may be a lucrative use of Alberta's cheap and abundant natural gas, the value in Bitcoin's secure and open-source virtual ledger, the blockchain, has potential for other practical future applications. The blockchain can be used to host authentication, logistics and financial transactions (Patriquin, 2019).

3 CHAPTER THREE – GREENHOUSES

As discussed previously, applications for data center heat reuse outside of district heating are limited largely by heat demand and quality. In Canada, greenhouses require considerable volumes of heat to enable year-round crop production and greenhouse operators in Alberta are beholden to utility costs and inefficient heating systems. Unlike heat reuse in municipal and industrial applications which require access to a district heating system, commercial greenhouses and data centers can be co-located adjacent to natural gas power generation. Co-location minimizes losses to electricity distribution, heat transportation, and associated heat loss. The newly developing Cannabis industry represents a potential candidate for the implementation of heat reuse. In the following section, the energy use of greenhouses and cannabis cultivation will be discussed.

The heating requirement for greenhouses is dependent upon structure heat loss which occurs through conduction loss, convection loss, and radiation loss. Often, heat transfer occurs via a combination of methods, as such heat demand is calculated through combining losses into a coefficient in a heat loss equation (Worley, 2014). Approximately two-thirds of Alberta's greenhouses are located in southern Alberta, with the Medicine Hat/Redcliff region holding the largest proportion (45.2%) of total greenhouse area (Laate, 2018). Despite cold temperatures, the region extending from Calgary, AB to Estevan, SK is known as the sunbelt region of Canada, with the highest number of available sunshine hours per year. Medicine Hat is the sunniest city in Canada with a cumulative average of 2544.3 hours of bright sunshine per year (Government of Canada, 2019). As of 2017, there were 230 greenhouse facilities covering 1.53 million m^2 (153 Ha) in Alberta (Laate, 2018), though this figure does not include new acreage devoted to Cannabis cultivation. The recent legalization of Cannabis has dramatically increased the demand for regulated cannabis cultivation, with the development of highly automated mega-greenhouses positioning Alberta as a leader in cannabis greenhouse innovation.

3.1 Energy Use

Cannabis cultivation has come under fire for its high consumption of resources. Substantial expenditures of energy are associated with high-tech greenhouse cultivation of cannabis (Small, 2018). Mills (2012) found that 1 kg of cannabis produced indoors is associated with the release of 4600 kg of CO_2 emissions, equivalent to operating 3 million cars annually. Commercial cannabis cultivation in Alberta's fast-growing cannabis market has a considerable energy draw; as such, the environmental costs of cannabis production are substantial. Legalization has likely had an impact on electricity consumption in Alberta. Lehman and Johnstone (2010) found a 50% rise in per-capita residential electricity use in cultivation communities post-legalization in Humboldt County, California. Inexpensive land and energy prices, low taxation rates, friendly policy, sunshine and the young population of Alberta support the development of indoor growing facilities for one of the most rapidly expanding industries in the Western world (Gerson, 2018).

For temperate climates, energy is the largest overhead cost in agricultural greenhouse production due to the specific conditions that must be maintained within the facility (Hassanien, Hassanien, Li, & Lin, 2016). In Alberta, natural gas and coal are the primary sources of electricity generation for greenhouse production. Greenhouse profitability is limited by energy and fuel costs and impacted by emissions taxes. Energy cost reduction is thus an area of consequence for growers, who aim to increase energy efficiency through energy use reduction or optimization of production. Several main actions can be taken to improve greenhouse efficiency, including a reduction in the total greenhouse energy use, incorporation of sustainable fuel sources, energy-efficient design and the development of flexible control systems.

Heat reuse may potentially decrease the energy intensity of indoor cannabis production. A recent whitepaper published by UC Berkeley suggests that greenhouse cultivation of cannabis can require up to 2,000 kWh/pound as a result of lighting, temperature, humidity and ventilation control. The high unit value of cannabis offsets the high economic production cost, however, the environmental cost is rarely accounted for (O'Hare, Sanchez, & Alstone, 2013). As a result of high energy consumption of indoor cannabis cultivation, the Boulder Board of County Commissioners in Colorado authorized Resolution 2014-41, requiring cannabis growers to offset 100% of electricity and associated production fuels with renewable energy or payment into the Energy Impact Offset Fund (Boulder County, 2014). Similar incentives for energy reduction exist in several other American states.

3.2 Data Center Heat Reuse & The Greenhouse

Several studies have analyzed the feasibility of greenhouses for localized data center waste heat reuse. Additionally, data center heat reuse has been applied in some commercial operations.

A report published by the Canadian Agricultural Energy End-Use and Analysis Center explored the implications of heat and energy use as a by-product of unrelated operations. According to the review, system type was dependent on the distance between the greenhouse and the heat source. Heat derived from compressor plants when co-located could be piped, filtered and released to the greenhouse at low cost. Liquid heat transfer using heat exchangers was feasible for greater distances, low but led to higher financial cost. To forecast cost savings of heat reuse systems, an economic analysis comparing projected lifetime natural gas cost for the greenhouse against the cost of the required heat reuse infrastructure is necessary (Canadian Agricultural Energy End-use Data and Analysis Center, 2002).

Environmentally Opportunistic Computing (EOC) is the conceptualization of data centers as distributed heat providers or nodes. Computational load is distributed across multiple data center nodes and vented to heat adjacent buildings and facilities. Integration of environmentally opportunistic computing is used to offset heating demands on the facility HVAC or water systems (Ward, Goedke, Brenner, & Go, 2012). The initial prototype for EOC was developed at Notre Dame's Center for Research Computing, in South Bend, Indiana. Eight server racks generating 150 000 BTUs/h of heat inside a containerized data center were used to heat a historic conservatory and greenhouse, resulting in substantial hardware cooling cost savings of $35,000 (Alger, 2010). Hot air expelled into the greenhouse was measured to develop a thermodynamic model to determine real-world utility. The developed model was simplistic, yet effectively predicted EOC performance and captured trends in experimental data (Ward, Goedke, Brenner, & Go, 2012). Based on this prototype, further research at Notre Dame expanded on the decentralized node approach to offset building energy needs and found that integrating data center nodes with free cooling reduces the overall energy consumption (Woodruff, Brenner, Buccellato, & Go, 2014).

Parker and Kiessling (2016) studied the possibilities of low-grade heat recycling for food production at the European Spallation Source. Overall greenhouse heating demand in Sweden is 0.5 TWh and a reduction in energy use can result in improvements to greenhouses sustainability. The increase in yield generated through heat reuse use decreased the amount of fossil fuel-derived fertilizers required. Parker and Kiessling analyzed the impact of indirect energy use of fertilizers, which accounted for nearly one-fifth of greenhouse energy use. Co-location of on-land aquaculture allowed for a nutrient loop, decreasing total fertilizer requirements. This study showed the value of a direct relationship between a waste heat producer and consumer could have a value of up to €0.05/kWh ($0.075/kWh CAD) and low-quality heat reuse can significantly lower energy costs (Parker & Kiessling, 2016). Heat recycling was shown to be a widely available resource well-suited to agricultural production and expandable to other low-grade heat sources such as solar and geothermal heating. A similar proof of concept project was studied in Helsinki, Finland. Lightweight rooftop greenhouses were coupled with micro data centers to extend the growing season. The analysis showed that server waste heat would outpace heat demand, even during the coldest months. The issue of snow for rooftop construction in Finland was relevant to building concerns for Canada, however, radiated heat was expected to reduce snow burden and was predicted to melt at a higher rate with increased data center exhaust (Pervila, Remes, & Kangasharju, 2012).

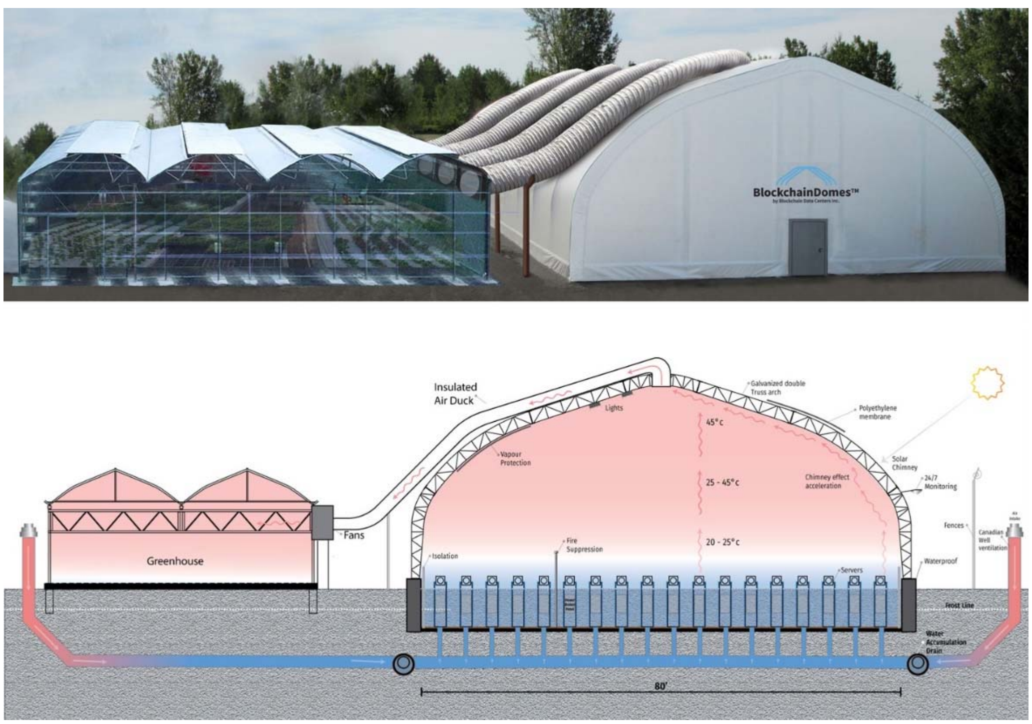
In northern Sweden, the Boden Hydro66 data center was modeled to study the feasibility of data center heat reuse co-location with an associated greenhouse. It was found that exiting heat temperatures (35°C) aligned with target crops that have a relatively low heat requirement (Sandberg, et al., 2017). Using computational fluid dynamics, this study modeled the heat transfer between the data center and the greenhouse, the study found that a 1 MW data center could support a greenhouse of 625 m^2 at a low temp of -10°C. At -30°C, the greenhouse supported was 212 m^2. During the summer, a greenhouse with a length of 3,750-5,000 m^2 was viable. Seasonal temperature variation dictated the calculated greenhouse area that could be supported by waste heat. Due to significant temperature differentials at the Boden location, maximum greenhouse size was dependent on winter temperatures, and year-round operation would likely require additional heating from a separate source. This study suggests that edible mushroom crops are well suited to waste heat reuse due to low-temperature requirements, as well as low demand for lighting, fertilizer and pesticide input. Mushrooms simultaneously provide high protein and other health benefits, thus making them a competitive and low-GHG replacement crop in a time where there is growing recognition of the environmental consequences of highly inefficient animal protein production systems. (Sandberg, et al., 2017).

Existing greenhouse data center heat reuse is currently being implemented in some commercial data mining operations. The Czech cryptocurrency NakamotoX has developed specialized housing for Bitcoin servers with the ability to distribute heat directly to a five-acre tomato greenhouse. Dubbed 'cryptomatoes', the developed system is considered an 'energy cycle loop', as electricity generated for mining activities is made from local biowastes. NakamotoX's initial plans were to grow medical-grade Cannabis in their facilities, however legislative hurdles resulted in the use of vegetable crops (Suberg, 2018).

United American Corp.'s BlockchainDome concept is the first retail facility that uses servers as heat sources distributing residual heat through a cascading set of greenhouse applications. In sharing heat generated from cryptocurrency operations (estimated at up to 5,000 BTUs/h/server), the BlockchainDome supports a set of auxiliary greenhouses for agricultural operations such as cultivation and drying heat (United American Corp., 2018). BlockchainDome houses up to 1,000 ASIC servers in a semi-permanent steel-framed structure that uses passive cooling using heat prevention and natural cooling. Through a Canadian well natural cooling system, ambient air is drawn into the Canadian well and cooled naturally through geothermal exchange. Each individual server is cooled by a devoted vertical ventilation tube. The negative pressure created by server fans enhances the chimney effect, causing heat to rise to the apex of the structure where it is collected and transferred with a blower to a series of greenhouses; a tropical greenhouse, a temperate greenhouse, and an agricultural drying greenhouse. The described configuration is shown in Figure 4. Through the use of natural cooling and heat gain prevention, the BlockchainDome requires no additional electricity to maintain the preferred temperature range. Each dome has an input of 1.5 MW and produces 5,000,000 BTU/h of heated air. The

BlockchainDome system eliminates the need for the typical cooling systems associated with Tier 3 data centers and by keeping both capital and operating costs to a minimum, agricultural and mining activities become more competitive. In July of 2018, United announced their intention to deploy 25 BlockchainDomes across Quebec, filing a power license request at 5 MW at the large-power preferential rate. As of May 2019, United faced legal difficulties due to agricultural zoning violations at its initial 8.5 MW BlockchainDome Heat Campus, which houses 5,000 mining servers.

Figure 4 - BlockchainDome Heat Generation Station Rendering



(United American Corp., 2018)

Other data center-greenhouse operations in Canada include a small nutrient cycling project in St. Francois Xavier, Manitoba. The Myera Group utilizes the heat generated from approximately 30 computers mining bitcoin to help warm lettuce and other crops in an indoor growing operation (Samson, 2018). Water from on-site Arctic Char aquaculture fertilizes the crops. The company aims to create a global campus using technology to create sustainable food systems. Another Canadian start-up, Heatmine, hopes to use its waste heat for buildings and central heating systems. In field tests, Heatmine units warmed churches and greenhouses across Quebec, where the technology reduced food production costs. The units provide 75,000 BTU per hour, sufficient to heat 300 m^3 for 24 hours per day (Deign, 2018). Winter testing of the system will incorporate 750 Heatmine units and is slated for the upcoming year.

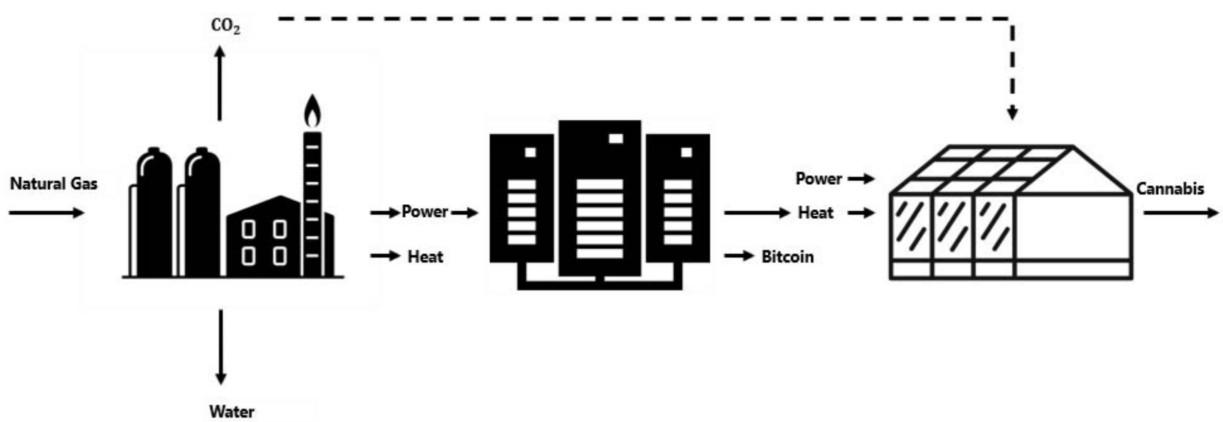
In June of 2019, Koinedge Farms have announced the intention to develop a cryptomining-greenhouse facility in Happy Valley-Goose Bay, Labrador. Taking advantage of temperature and hydropower from Muskrat Falls, Koinedge anticipates a 523-tonne offset from avoided emissions created by produce importation. Upon approval from Newfoundland and Labrador Hydro, Koinedge planned a pilot-ready project ready in three months (Koinedge Farms, 2019).

4 CHAPTER FOUR - METHODOLOGY

To develop a case for local data center heat reuse it was necessary to examine industries active in Alberta that could be integrated to create a closed-loop system. As the data center analog, cryptocurrency mining was modeled after Hut 8, a Bitcoin mining company with operations in Drumheller and Medicine Hat. Cannabis production modeled by Aurora Cannabis acts as the co-located large consumer of low-grade heat. Both Hut 8 and Aurora Cannabis have active or developing operations in Medicine Hat. As such, Medicine Hat was selected as the proposed location for the modeled system. In addition to the favorable climate conditions for greenhouse operations, the region sits above the Medicine Hat-Hatton gas field, one of Alberta's largest natural gas fields. Medicine Hat also operates its own electricity grid, an advantage that facilitated the negotiation of Hut 8's competitive ten-year power contract.

All temperature and solar irradiance values used in the analysis were supplied by the Alberta Climate Information Service (Alberta Agriculture and Forestry, 2019) and the Government of Canada historical climate data (2019). The modeled system is represented in Figure 5. Power is generated through a natural gas power plant which supplies the electricity for the bitcoin mining operation. The bitcoin mining data center incorporates a free cooling economizer cycle capitalizing on low ambient external temperatures. Low-grade server waste heat is reused in the greenhouse facility, and a proportion of captured CO_2 is used to supplement plant growth. The system reduces CO_2 emissions in two ways – firstly, it drastically reduces cooling energy required and secondly, it offsets the energy required to heat the greenhouse, decreasing GHG output through avoided emissions. All figures and data were prepared by the author unless otherwise cited.

Figure 5 – Proposed Closed-Loop Cryptocurrency Mining System Schematic



This project aims to develop a simplified methodology to determine the greenhouse area and avoided emissions supported by waste heat reuse and free cooling from a cryptocurrency mining operation in Medicine Hat, Alberta. This analysis follows a similar methodology developed by Anderson and Pearce (2011) in their study of the technical and economic viability of industrial waste heat reuse in greenhouses for northern climates and adheres to the following steps.

- Power output supply to the cryptocurrency mining facility is determined from the proposed modular gas engine system.
- Free cooling CO_2 emissions and cost savings are calculated for the cryptocurrency facility
- Availability of waste heat is determined based on cryptocurrency mining facility size and processing capacity
- Previously derived formulas from Anderson and Pearce (2011) are utilized to calculate the maximum greenhouse footprint for the set threshold temperature derived from historical temperature data
- Representative temperature and solar irradiation data are used to determine actual heat load against heat output. CO_2 and cost savings are calculated for the greenhouse.
- Yearly estimated cannabis yield for the greenhouse is estimated using industry averages
- Bitcoin mining returns are estimated based on the current bitcoin price and processing power.

4.1 Power Generation

The project will be sized to the pre-expansion capacity of the Hut 8 Medicine Hat facility, as operations of this size have been successfully demonstrated in Alberta. Medicine Hat's Unit 16 power plant is primarily powered by a 43 MW GE LM6000 Gas turbine generator, completed in June 2016 for a final project cost of $55.7 million. For this project, a modular gas engine system has been deemed the appropriate generation method due to the high efficiency over a wide range of outputs and the ease of facility assembly. Gas engines have lower exhaust volume and higher CO_2 emissions, making the exhaust easier to handle and distribute to greenhouses (Wärtsilä, 2018b).

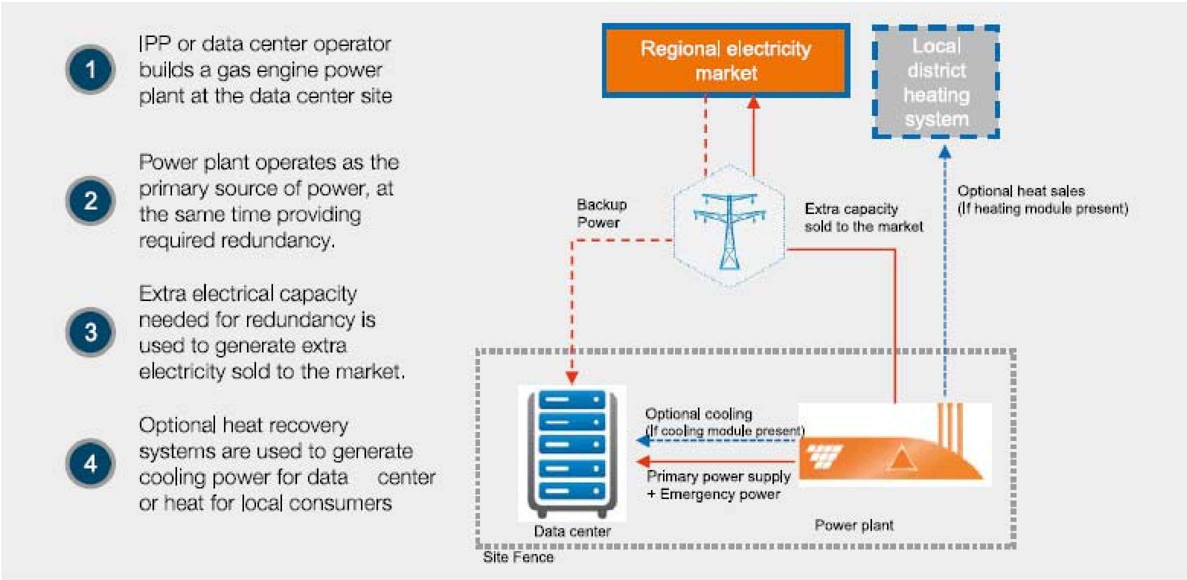
Gas turbines have been the technology of choice in conventional large power plant generation (Araner, 2018), but for the purposes of cryptocurrency mining, modular gas engine systems provide improved efficiency and redundancy. Smaller in size, modular gas engines are connected to form generating sets that run in parallel to generate electricity (Araner, 2018). In a multi-generator system, maintenance downtime causes a temporary decrease in the amount of available power, however full operational shutdown is unlikely to occur. The flexibility of this type of system is advantageous over traditional gas turbines as gas engines are adaptable to fluctuations in load and demand characteristic of data center operations. While cryptocurrency mining does not experience the same variation in operational demand, the ability to incorporate renewable energy from intermittent sources has resulted in the need for flexible power. A total of 3,697MW of renewable energy projects are proposed for the Medicine Hat region according to the most recent project list released by the AESO (Alberta Electric System Operator, 2019). Gas engines can accommodate rapid starts, ramp-up times and can operate efficiently at partial loads (Wärtsilä, N.d.). Recent innovation in gas engine design has reached new levels of efficiency, outpacing gas turbines and the lower gas pressures required reduces infrastructure and safety requirements as well as the capital and operational expenditures through the elimination of fuel gas compression allowing units to be sited closer to consumers (Grosshauser, 2016).

A self-generation power model is selected for this project, where electricity is generated from an on-site natural gas power supply rather than sourced from the grid. Dedicated electricity generation allows for a reduction in facility power redundancy and offers protection against fluctuations in electricity price and availability. The carbon emission footprint of natural gas combustion is smaller than electricity drawn from Alberta's grid, simply because Alberta's grid is in still partially reliant (45%) on electricity generation from coal-fired power (National Energy Board, 2019).

In addition, redundant capacity intended for maintenance support or surplus load can be sold to the grid at high demand times, creating an additional revenue flow. As seen during the 'crypto winter' of 2018, cryptocurrency values can decrease to values where mining is not economic. At low bitcoin values, priority in this system can be given to grid in times when the grid value of electricity is higher than the resulting bitcoin return.

The requirement for uninterruptible energy supply in a gas-to-cryptocurrency configuration may be an economic opportunity for surplus natural gas in the province, creating a supplementary local market for natural gas in the near term. The flexibility of a modular plant allows for the incorporation of contracted power from intermittent renewable sources such as wind and solar. Medicine Hat's geographical location makes it well suited to take advantage of future advances in both wind and solar energy, clean sources of electricity that can further minimize data center operational impact (Moore, 2017). A mixed power supply model would prioritize cheaper power from wind or solar sources and fill the gap between demand and supply with natural gas generation, similar to the operations of 'wind chasing' natural gas engine power plants.

Figure 6 - Self-Generation Model for Gas-Fired Data Center Power Plant



(Wärtsilä, 2018b)

Specifications for a modular gas engine system were derived from Wärtsilä's Modular Block system which incorporates high-efficiency gas engines in prefabricated expandable enclosures allowing for quick delivery and installation (Wärtsilä, 2019). Flexible units can be added to scale to data center needs or redeployed to other facility locations.

Medium-speed engines are applied in The Modular block configuration. Medium speed technology is typically used in engines over 4MW. While their larger and sturdier size calls for higher construction and installation costs, medium-speed solutions better able to start quickly and accept loads. Slower wear of components makes medium-speed less expensive to maintain. Lower lifecycle costs and flexibility make medium-speed engines the preferred technology for multi-MW gas-fired data center plants (Wärtsilä, 2018b). The Wärtsilä 20V34SG gas engine model is used in this case study, with an electrical output of 9.4 MW and an efficiency of 49% when operating as a flexible baseload plant (Wärtsilä, 2016). Power specifications for the 20V34SG gas engine are available in Appendix A.

To best approximate the system on the Hut 8 Medicine Hat plant (48 MW), 5 gas engines at 9.4 MW are required (47 MW). Multi-unit configuration allows for near 100% plant availability.

Operating a series of engines creates high-level redundancy and reliability; downtime for one generator means that 37.6 MW are still available to the facility. The Wärtsilä White Paper on power supply for data centers illustrates plant availability when capacity matches the maximum load is 96.5%, while adding a standby unit increases availability to 99% (2018b). For the economic purposes of this project, the plant capacity will be sized to maximum load, thus the availability of 96.5% was used. Associated reliability data can be found in Appendix B.

At the 60 Hz system rating that Canada operates the 20V34SG gas engine is rated at 9,389 kW. From the facility size specifications, the yearly power output is calculated at 397,309 MWh or 1,430,315 GJ. At 49% efficiency, 2.77 Bcf of natural gas is required annually. Using the Alberta Government CO_2 emissions factor (Government of Alberta, 2015), a total of 150,257 tonnes of CO_2 emissions were generated by this system. Further power generation values are available in Appendix D – Project Power Plant Specifications.

4.2 Bitcoin Cryptocurrency Mining Data Center

For the purposes of the model, uptime for the cryptocurrency mining facility was assumed to be 100%. True uptime fluctuates when equipment requires servicing, however no published specifications on cryptocurrency mining uptime were available thus it was assumed that servers would be actively mining for all times where power was available. Calculations were completed to understand the component-specific energy consumption and determine the total heat output of the cryptocurrency data center. This analysis was undertaken strictly for the cryptocurrency data center in order to contextualize the volume of heat created by the facility and the feasibility of heat reuse. Excluded from the analysis was the heat output from the power generation plant, however, it was determined that should data center heat output be insufficient to supply a commercial-scale greenhouse, heat from the gas combustion process can be supplemented.

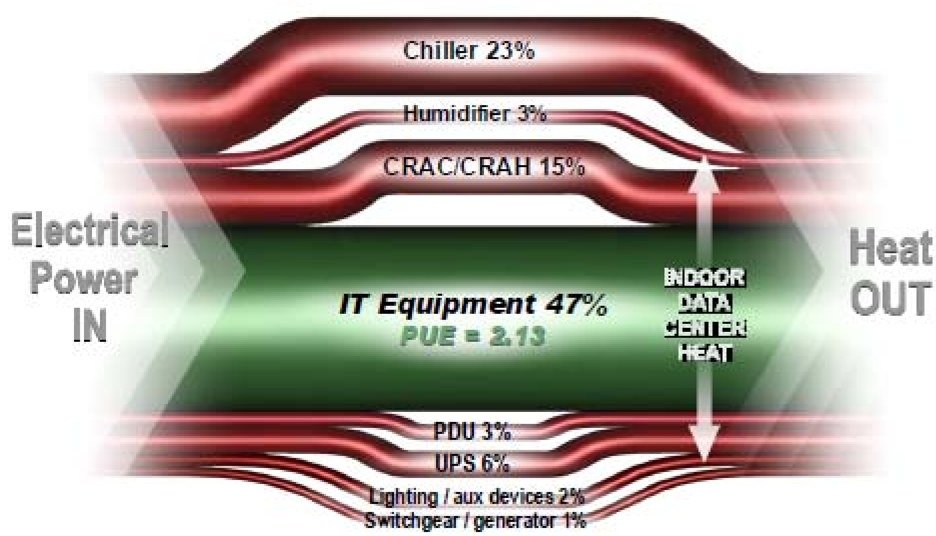
With an on-site power generation capacity of 45.4 MW, the calculations estimated the heat output from a Bitcoin mining operation created by operation of this size. By determining the power distribution by component, the general heat output can be estimated from the facility. For the purposes of this study, transmission losses from on-site electrical generation are negligible and assumed to be zero.

As cryptocurrency mining is notoriously secretive, disclosure of mining operational efficiency is rare and limited published sources delineating energy consumption, footprint and equipment sizing are available. To emulate the power consumption of a cryptocurrency mining operation, values were modeled from APC White Papers (Rasmussen, 2011), (Rasmussen, 2003) and modified to better represent the estimated consumption of cryptocurrency mining data centers.

4.2.1 Cryptocurrency Mining Energy Consumption

The distribution of data center energy consumption for the typical data center is illustrated in Figure 7, which describes electrical energy consumption by component for a typical high-availability dual-path data center operating at an average 30% load.

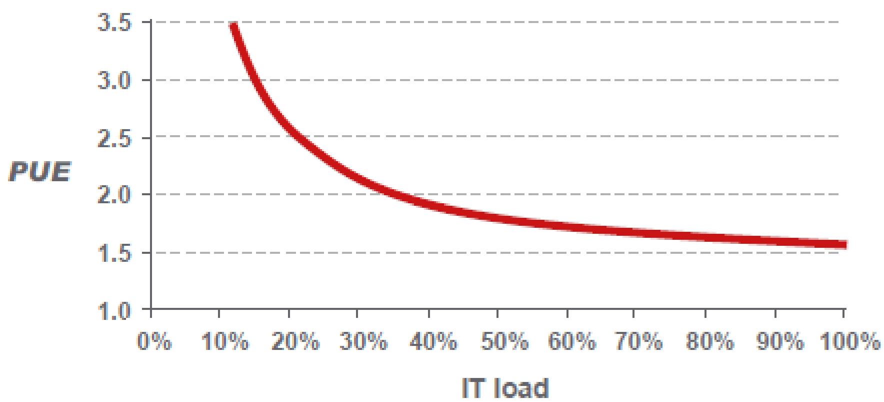
Figure 7 – Typical Data Center Component Power Consumption Distribution



(Rasmussen, 2011)

As shown in Figure 7, the resulting PUE value of the reference data center operating at 30% load is 2.13. Typical data centers generally operate at a low load with large margins to accommodate for fluctuations and customer demand and maintain service under all operating conditions. Commercial cryptocurrency mining is reliant on function-specific ASIC processors operating near or at full loads. To solve and 'win' the complex cryptographic problems used to validate the blockchain, crypto mining operations run at continuous maximum output; server loads near 100%. As a non-mission critical activity, it is assumed that this bitcoin mining operation does not require an uninterruptible power supply (UPS). As previously discussed, self-generated power from a multi-unit power supply is already highly redundant and full power failure requiring operational redundancy is highly unlikely. In the case of service interruption, the temporary disconnection of mining servers has limited negative outcome as cryptocurrency mining operations are not considered mission-critical.

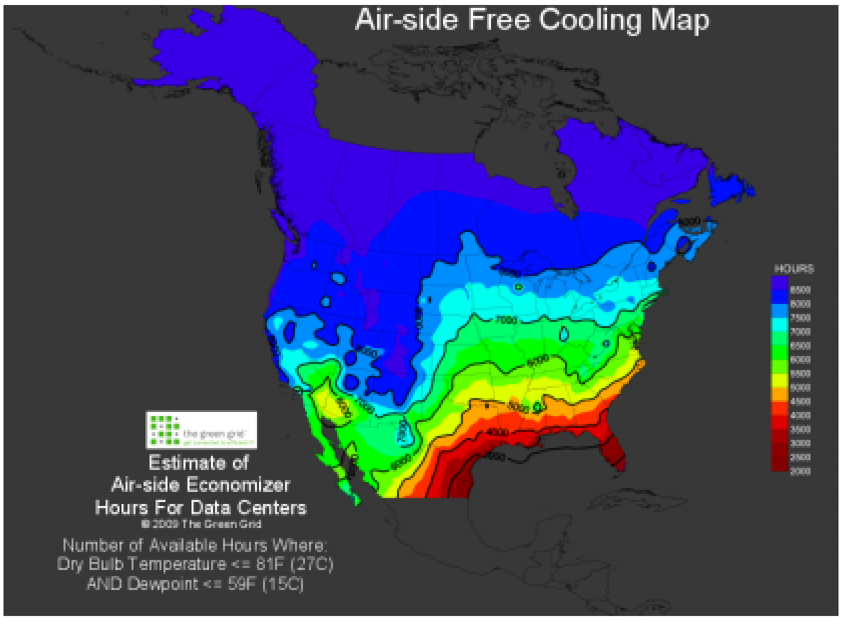
Figure 8 - Power Usage Effectiveness (PUE) and IT Load



(Rasmussen, 2011)

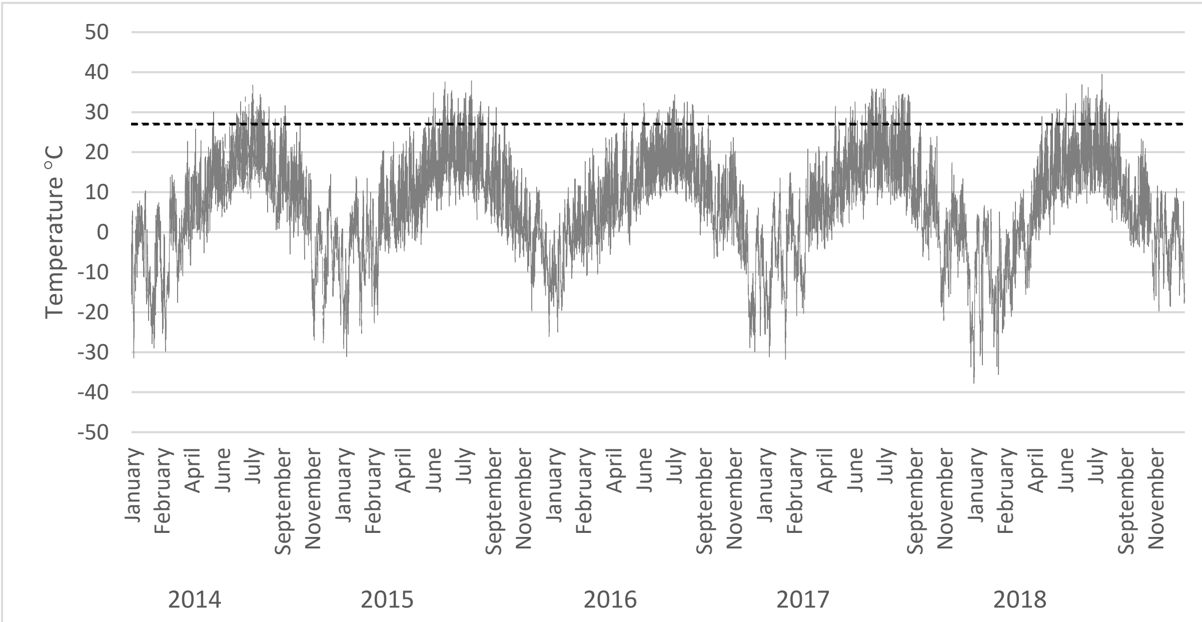
To determine the power consumption per component, a power consumption model was developed that incorporated the use of a free cooling economizer mode. As illustrated by Figure 8, as IT load increases to 100%, PUE decreases to approximately 1.6. The energy consumption reduction from free cooling was estimated at 50% based on academic and industry literature. In the free cooling power consumption model, the power consumed by the chiller and CRAC/CRAH components was decreased by 50%. As illustrated in Figure 9, free cooling hours in Medicine Hat fall within the contour for a minimum of 8000 hours of at server inlet temperatures of 27°C, the upper recommended server inlet temperature (American Society of Heating, Refrigerating and Air-Conditioning Engineers TC 9.9, 2016). From the five-year historical temperature data from 2014-2018, average hourly temperature was below the 27°C for 8400 hours, meaning free cooling is feasible for approximately 95.9% of the year. Figure 10 illustrates the average hourly temperatures and the set facility temperature at 27°C. Energy consumption calculations are elaborated further in Appendix E – Bitcoin Mining Data Center Energy Consumption.

Figure 9 - North America Air-Side Free Cooling Map (27°C)



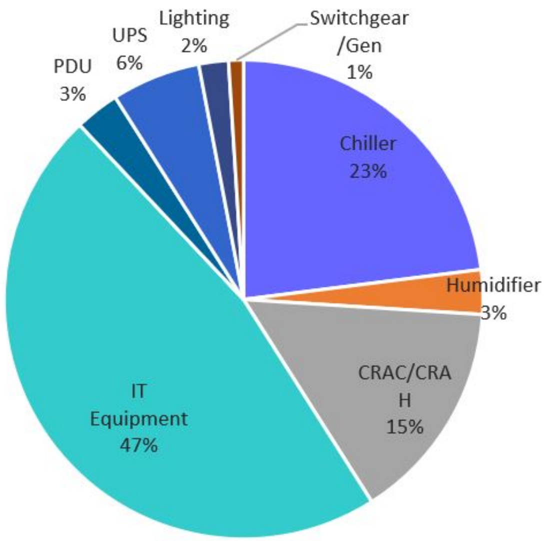
(The Green Grid, 2012a)

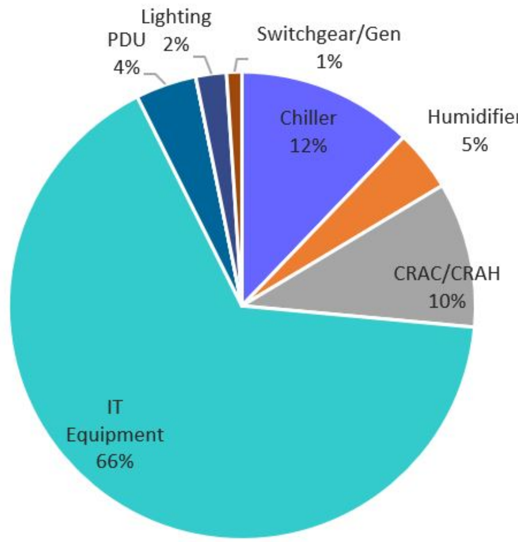
Figure 10 - Medicine Hat Average Hourly Temperatures 2014-2018



Free cooling economizer mode using outdoor air requires the use of additional fans and humidification. When compared to the total energy draw of the chiller/air conditioning system, requisite increases in power consumption are small. To account for the increase in air distribution and humidity control, a 2% increase in power for fans and a 1% increase in humidification are estimated. Assuming a linear relationship, it can be estimated that an increase of IT energy consumption (DCiE) from 47% to 66%, the PDU energy consumption will increase by an equivalent degree from 3% to 4.2%. The modified component-specific energy consumption for the theoretical cryptocurrency mining facility is shown in Figure 11. Through the incorporation of free cooling and elimination of the UPS, the PUE of the facility decreases to 1.512 operating at full capacity, falling within the range of efficient data centers at a DCiE of 66%. The cost and emissions offset of incorporating the economizer cycle were calculated at $7,337,734 and 33,353 tonnes CO_2.

Figure 11 - Energy Consumption for Data Centers and Cryptocurrency Mining





4.2.2 Heat Output

To determine the heat generated from this system available to the greenhouse, total heat output methodology as defined by Rasmussen in the APC whitepaper was used.

Table 7 - Data Center Heat Output Calculation Sheet

Item	Data required	Heat output calculation	Heat output subtotal
IT Equipment	Total IT load power in Watts	Same as total IT load power in watts	____________ Watts
UPS with Battery	Power system rated power in Watts	(0.04 x Power system rating) + (0.06 x Total IT load power)	____________ Watts
Power Distribution	Power system rated power in Watts	(0.02 x Power system rating) + (0.02 x Total IT load power)	____________ Watts
Lighting	Floor area in square feet, or Floor area in square meters	2.0 x floor area (sq ft), or 21.53 x floor area (sq m)	____________ Watts
People	Max # of personnel in data center	100 x Max # of personnel	____________ Watts
Total	Subtotals from above	Sum of heat output subtotals	____________ Watts

(Rasmussen, 2003)

Heat generated by the air conditioner unit is excluded as heat is vented to the outdoors, thus no thermal load from the CRAC/CRAH is added to the facility. The heat output of both the UPS and PDUs are fixed losses proportional to operating power and can be considered functionally consistent across brand and models. Heat output from lighting and employees in the facility are estimated using standard values. As discussed previously, power consumption from the UPS was struck from this equation as it was not considered relevant to the facility.

To estimate the floor area, the Hut 8 Medicine Hat facility was used as a point of reference. At this facility, Bitfury Blockbox containerized data centers are utilized as modular data centers; further facility and server specifications can be found in Appendix C. Each 1.1 MW Blockbox contains 176 air-cooled mining servers in 395.3ft^2 with hot and cold aisles external to the units delivering a total hash rate of 14PH/s drawing 6.3kW of power. Using the power supplied to the IT equipment, the total server area for the Hut 8 facility was calculated at 2,432 ft^2. According to IBM, IT equipment occupies between 30-35% of total data center space, thus the final area was estimated at 8,109 ft^2. The remaining 65-70% is 'white space' for fans, CRAC units, PDUs, and access aisles (IBM, N.d.). Estimated number of employees was evaluated from the analogous Hut 8 Medicine Hat bitcoin mining operation. From the Rasmussen heat output equation, the total heat load of the cryptocurrency facility was estimated at 1,004,681 GJ per year. Additional calculated heat output values are located in Appendix F – Bitcoin Mining Data Center Heat Output.

4.3 Greenhouse

To determine the size of greenhouse supported by the cryptocurrency facility waste heat, previously derived formulas developed by Anderson & Pearce (2011) were utilized to understand the energy balance of the greenhouse. Equation 1 is used by the American Society of Agricultural and Biological Engineers (ASABE) in sizing greenhouse heating systems.

$$E_r = AU(T_i - To) + 1800VN(T_i - To) \tag{1}$$

Where E is the Energy required, A is the total surface area of the greenhouse structure in m^2, V is the greenhouse volume in m^3, U is the heat loss coefficient in W/m^{2}K and N is the ventilation rate in s^{-1}. T_i and T_o are the determined internal and external temperatures. Optimal growth temperatures for Cannabis vary between 20-25°C, thus T_i is set to 20°C to allow for upwards adjustments to achieve optimal production. Ventilation rate and thermal coefficient are constants consistent with Anderson & Pearce (2011). The ventilation rate of 2.1 x 10^{-4} s^{-1} is representative of a mid-range new glass greenhouse, while the thermal coefficient of 4 W/m^2 K is within the suggested range for new double-walled glass greenhouses (Anderson & Pearce, 2011). The physical dimensions of the greenhouse, the height (h), roof height (G) and roof angle were also kept consistent with the values generated by Anderson & Pearce (2011).

Table 8 – Greenhouse Supported Area Input and Output Data

Input Data		*Output Data*	
U	4 W/m^2	Length	183.73m
T_i	20°C	Area	8.34 Acres
T_o	-13.5°C		
N	2.10$E^{-04}$$s^{-1}$		
h	4 m		
G	2 m		
θ	30°		

Modified from (Anderson & Pearce, 2011)

Re-arranging the ASABE equation for the linear dimension, Equation 2 is generated to determine the length of the greenhouse.

$$L = \frac{-4hU\Delta T + \sqrt{(4hU\Delta T)^2 - 4\left\{\left(h + \frac{G}{2}\right) 1800N\Delta T + \frac{U\Delta T}{cos\theta}\right\}(-Er)}}{2\left[\left(h + \frac{G}{2}\right) 1800N\Delta T + \frac{U\Delta T}{cos\theta}\ \right]} \tag{2}$$

Average hourly temperature differentials from Medicine Hat climate monitoring stations were calculated over a five-year period from 2014-2018 and quartile temperatures were determined for each season. Greenhouse area was calculated for each quartile temperature. At the first winter quartile temperature (-13.5°C), it was found that based on the assumptions, the cryptocurrency mining facility could support an 8.34-acre greenhouse for 92% of the year.

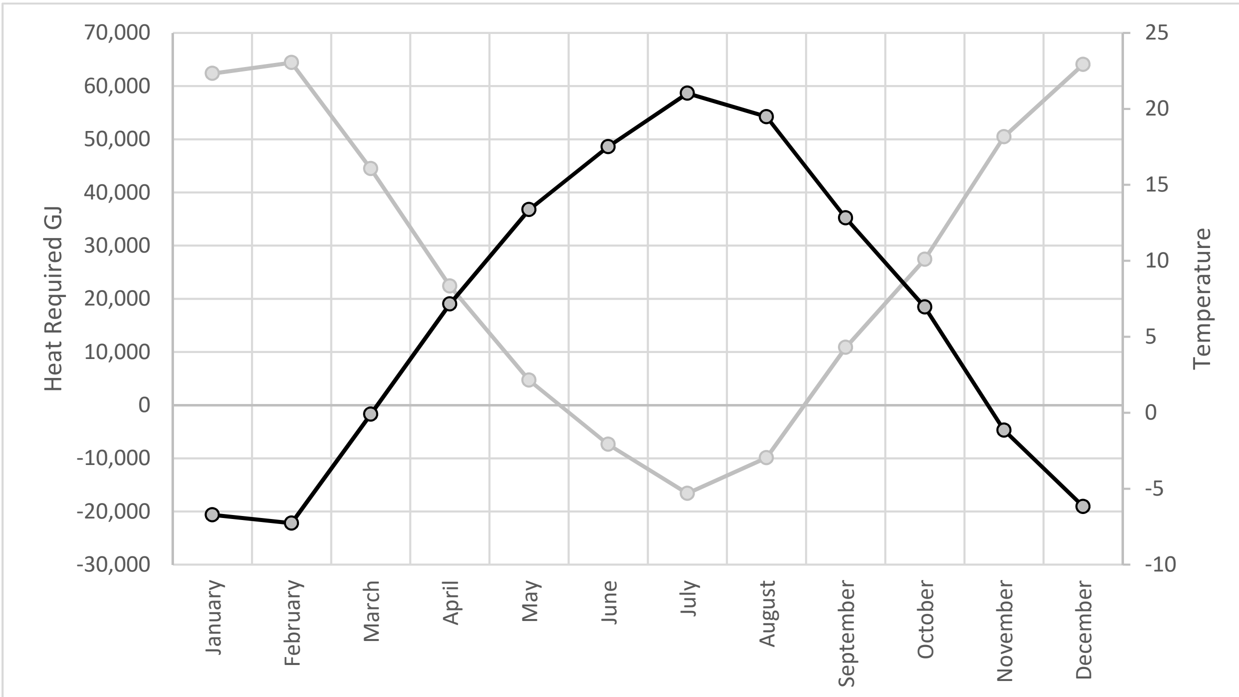
Supplementary data for the greenhouse sizing is found in Appendix G – Waste Heat Greenhouse Sizing.

Utilizing the ASABE energy equation, heat demand for the 8.34-acre greenhouse at a constant temperature of -13.5°C is 982,050 GJ. The actual heating demand for the majority of the year is lower than the calculated value as hourly temperatures are largely higher than the first winter quartile temperature. To calculate the actual demand, the hourly averaged temperatures and averaged hourly solar irradiance information was collected. Equation 3 was modified from Anderson and Pearce (2011) to calculate the total required heat.

$$Q_{actual} = 3600 \sum_{n}^{12} M_n \left(\sum_{j}^{24} AU(T_i - T_{njavg}) + 1800(T_i - Tnjavg)\gamma \; - \; snjavg\beta \right) \tag{3}$$

The bracketed portion of this equation is the summation of the hourly heating requirement. T_{njave} and s_{njave} represent the hourly average temperature and average solar irradiation at hour j in month n. The absorptivity constant, β for tomato canopy was used Anderson and Pearce (2011) and in this analysis. Tomato plants have similar cultivation characteristics to cannabis and suitable analogs for canopy absorptivity. When the resulting Q value is negative, heat was not required and would be vented from the greenhouse. Negative values occurred during the warmest hours of the summer months, where heat was still required but over the period of the month, more heat overall was vented than consumed. Figure 12 illustrates the overall monthly heating demand against the average monthly temperatures.

Figure 12 - Greenhouse Average Monthly Heating Requirement



The summation of equation 3 results in a total heat requirement of 317,145 GJ annually, representing 31% of the total heat output of the data center. This value can reach 40%, as heat demand varies with yearly temperatures and solar irradiance values. The calculated ERE at this greenhouse size was 1.18, with an ERF of 0.22, showing a total of 22% energy reuse based on the total cryptocurrency data center energy consumption. The offset cost and emissions were calculated at $7,329,589 CAD and 33,316 tonnes CO_2.

Figure 13 illustrates the estimated yearly heating requirement calculated for 2018 using annual hourly temperature and solar irradiance values. Heat demand for the greenhouse is represented against the heat output from the cryptocurrency mining facility. For the purposes of this project, it was assumed that the heat output of the cryptocurrency mining facility was constant, however, heat output may fluctuate over the course of the year. Heat output was assumed to be reused externally in the greenhouse, however, a portion of the server waste heat may be reused internally during extreme temperatures to warm incoming external air to temperatures better suited for electronic equipment functioning. As shown by Figure 13, the heat demand is occasionally higher than the heat available. These peaks represent the 8% of the year for which ambient external temperatures are lower than -13.5°C. These winter cold snaps are illustrated in detail by the January 2018 heat demand in Figure 14. Over the winter months, approximately 20 days would potentially require supplemental heating from a backup heating system. As the greenhouse was sized to the first winter quartile rather than the maximum cold temperature, a backup generator may be required to maintain constant temperatures within the greenhouse. Additional data on greenhouse heat demand is found in Appendix H – Greenhouse Heat Demand.

Figure 13 - 2018 Yearly Heat Demand and Data Center Heat Output

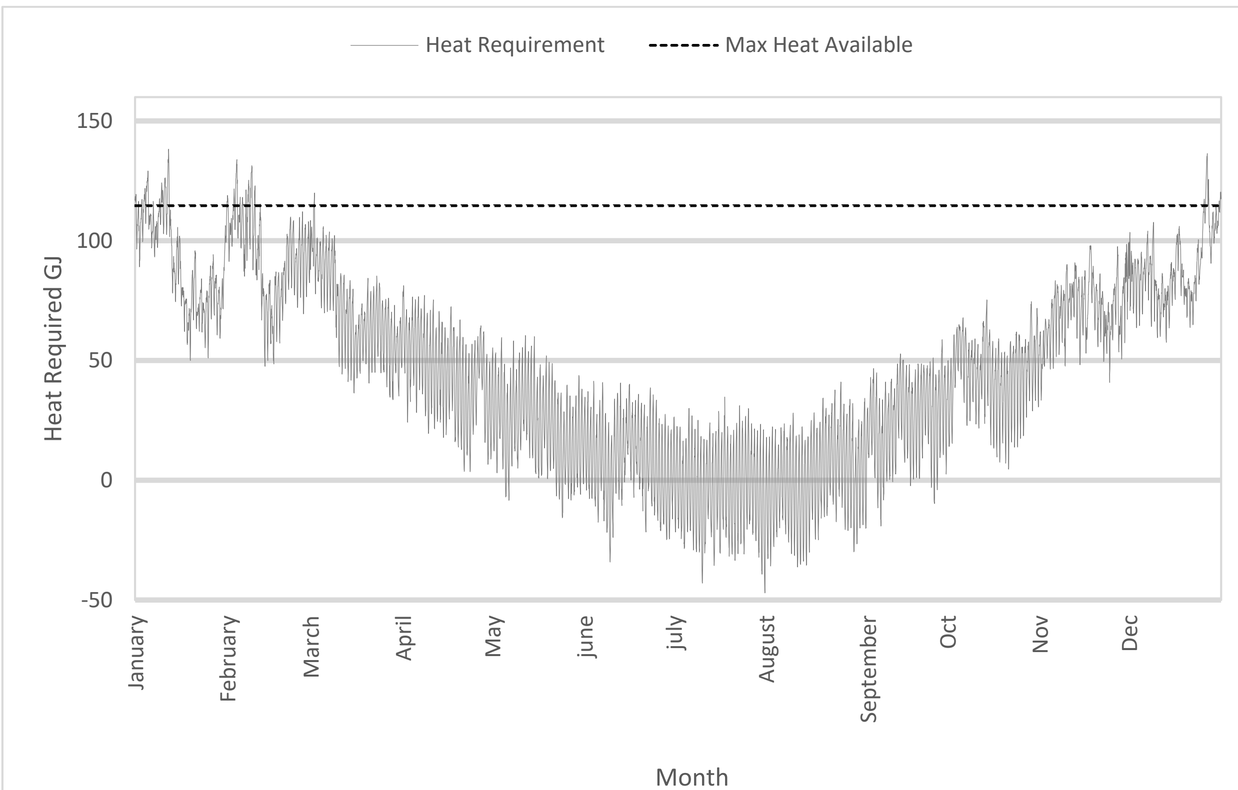
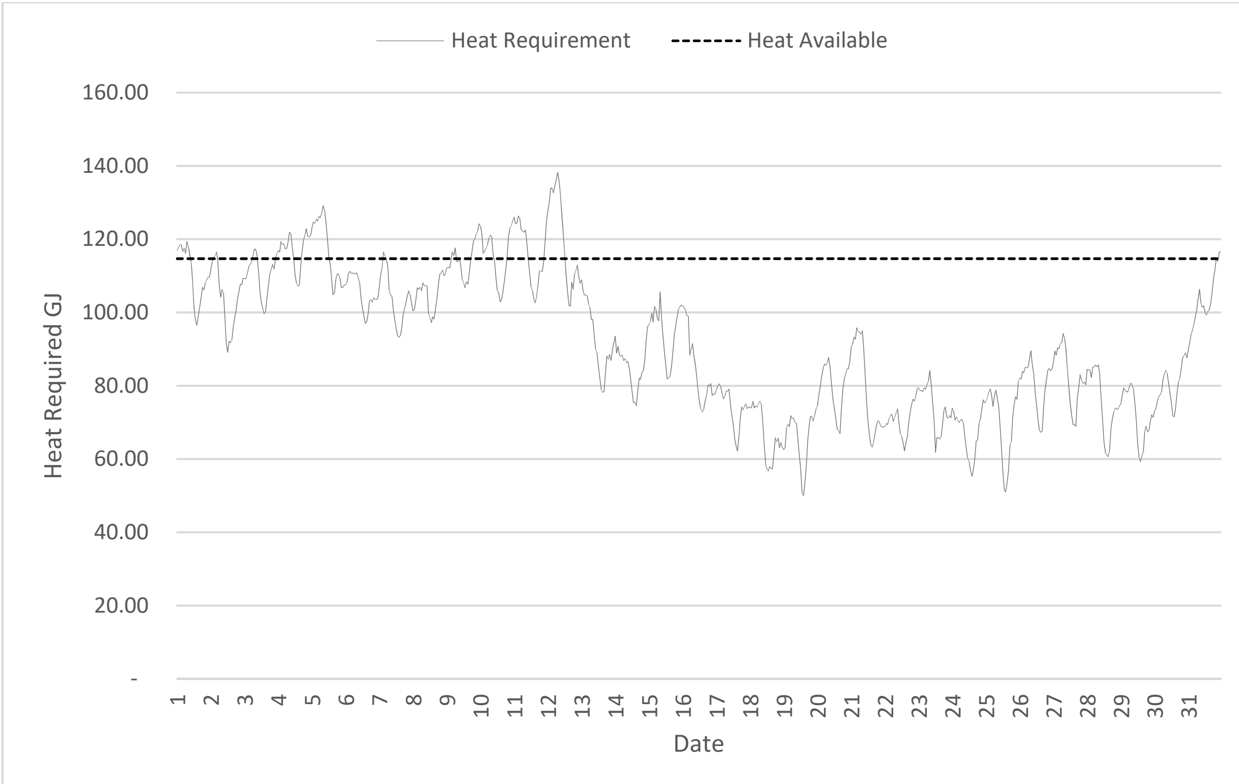


Figure 14 - January 2018 Hourly Heating Demand



4.4 CO_2 Supplementation

Carbon dioxide enrichment is an industry-wide practice utilized to increase yields in commercial greenhouse cultivation. As an essential component of photosynthesis, greenhouse growers typically supplement CO_2 to increase plant growth and vigor, shortening the growing period and increasing yield (Blom, Straver, Ingratta, Khosla, & Brown, 2012). CO_2 in greenhouse air can be rapidly depleted by growing plants and the amount of CO_2 supplementation varies with crop, stage of crop growth, light intensity, temperature, ventilation, and economics. CO_2 for enrichment is primarily derived by burning carbon-based fuels with low levels of impurities.

Doubling CO_2 levels in cannabis cultivation has been found to increase crop yield by up to 30% (Chandra, Lata, Khan, & Elsohly, 2008). Typical concentration for greenhouse cultivation is between 750-1500 ppm, increasing yields by 30-50% and reducing time to harvest (Smith, 2016). Recommended concentrations for enhancing bloom is 1,400 ppm (Banks, 2017).

To approximate the amount of CO_2 required to supplement cannabis grown in the 8.34-acre greenhouse modeled, an increase of 1000 ppm from an ambient level of 400 to 1400 ppm was assumed. For the theoretical volume of the greenhouse, enrichment was calculated for a combined sunlight and grow light configuration estimated at 18 hours of light per day Accounting for photosynthesis and the natural air exchange rate, 0.50-0.60 kg of CO_2/hr/100 m^2 is required to be supplemented into a standard glass greenhouse when supplementing 1000 ppm (Blom, Straver, Ingratta, Khosla, & Brown, 2012). A calculated total of 778 tonnes of CO_2 is required to maintain a constant level of 1400 ppm during lit hours. CO_2 is captured from flue gas, cooled and reused in the greenhouse from the natural gas processing facility. This amount represents a very small proportion of the total CO_2 emissions generated from the natural gas facility thus does not create a significant CO_2 offset opportunity, however, it does represent potential cost savings for the greenhouse.

Due to the void of published research on cannabis greenhouse cultivation, grey literature resources were used to determine enrichment concentrations. Calculated CO_2 enrichment values are found in Appendix I – Greenhouse CO_2 Enrichment.

4.5 Greenhouse Yield

To estimate annual crop yields for the modeled greenhouse, average yields were estimated from literature and corporate data. Greenhouse cultivation of cannabis is a newly legalized industry, and as such, academic literature on production and yields for greenhouse cultivation methods are scarce. Estimating harvestable canopy required assumptions based on productive greenhouse area. It was assumed that one-third of greenhouse area was dedicated whitespace for walkways, equipment and facility infrastructure (Caulkins, Cohen, & Zamarra, 2016). Harvestable or “flowering” cannabis in a large-scale production facility was assumed to make up two-thirds of the total canopy area. The resulting harvestable canopy area is 15,000 m^2. Table 8 highlights yield averages for multiple cultivation styles. Only the greenhouse-specific averages are applicable to yield estimations for this project. To compare yields with industry averages, yield/m^2 was calculated from Aurora Cannabis facility yields and averaged over their eleven Canadian facilities. Using Aurora Cannabis average yields, estimated yearly yield was calculated at 17,924 kg/y at a value of $137,588,025 CAD. This value falls within the yield range generated by the values in Table 8.

Table 9 - Cannabis Yield Estimations

Row	Source	Cultivation Style	Output per plant (grams)	Plants per square meter	Weight per Square Meter (grams)	Seasons per year	Output per square meter per year (grams)
#1	UNODC Morocco	Outdoor rain-fed	76	1	76	2	152
#2	UNODC Morocco	Outdoor irrigated	4	30	127	2	254
#3	M. Starks (1990)	Unspecified outdoor	227-454	0.66	152-304	1	152-304
#4	M. Thomas (2002)	Outdoor	About 500	1	500	1	500
#5	Cannabis-seedbank.nl website	Outdoor	10-200	40 X 10 g	300-600		
#6	Cannabis-seedbank.nl website	Greenhouse		1-10	50-250	3-6	

(Caulkins, Cohen, & Zamarra, 2016)

Yield calculations are complex for a number of reasons. Yield figures are not standardized, and limited research exists for greenhouse-based cannabis cultivation. Yield varies by the number of harvests per year, which is impacted by greenhouse infrastructure, lighting, cultivated strain, and production intensity. Estimations are often calculated using greenhouse area, however ancillary space for clone rooms, drying rooms, walkways, and other white spaces account for a portion of total facility area. Accurate square footage representative of total area against total canopy area occupied by mature plants is essential. Yield can also vary dependent on the type of harvesting, whether the facility harvests dry flowers or extracts medicinal compounds for other uses from the entire plant (Backer, et al., 2019). Additional yield data is found in Appendix J – Greenhouse Cannabis Yield Estimations.

4.6 Bitcoin Return

Estimations on bitcoin return were made using power consumption data and server component specifications. A simple financial model was developed to calculate monthly return and payback period. Hash rate specifications derived from the server information sheets of Hut 8s mining operation in conjunction with the estimated number of mining servers, power consumption, and capital costs were used. The developed model allows for multiple input values for Bitcoin value, bitcoin difficulty change, and power cost. Additionally, a cut-off point was incorporated for which the power price achieves greater profitability than Bitcoin mining. This illustrates the price for which the power plant may sell electricity into the grid rather than continue mining to achieve the greatest return.

At the modeled bitcoin value of $10,850 USD (14449.49$ CAD), a net monthly profit of $ 2,000,000 was estimated at a payback period of 13.1 months, assuming a constant average Bitcoin price over the year. Forecasting long-term Bitcoin price is extremely speculative due to the volatility of Bitcoin value and the ever-increasing difficulty of the bitcoin algorithm. The estimated value assumes a net difficulty change of 0 for the year, however, payback period for difficulty increase at 2%, 5% and 10% over a range of Bitcoin values was also modeled as illustrated in Figure 15. The return rate was consistent with the values calculated in the online Bitcoin Mining Calculator used for verification (Diab, N.d.). The specific data used to calculate bitcoin return can be found in Appendix K – Estimated Bitcoin Return. Pertinent system values are illustrated in Figure 16.

Figure 15 - Bitcoin Mining Payback Period

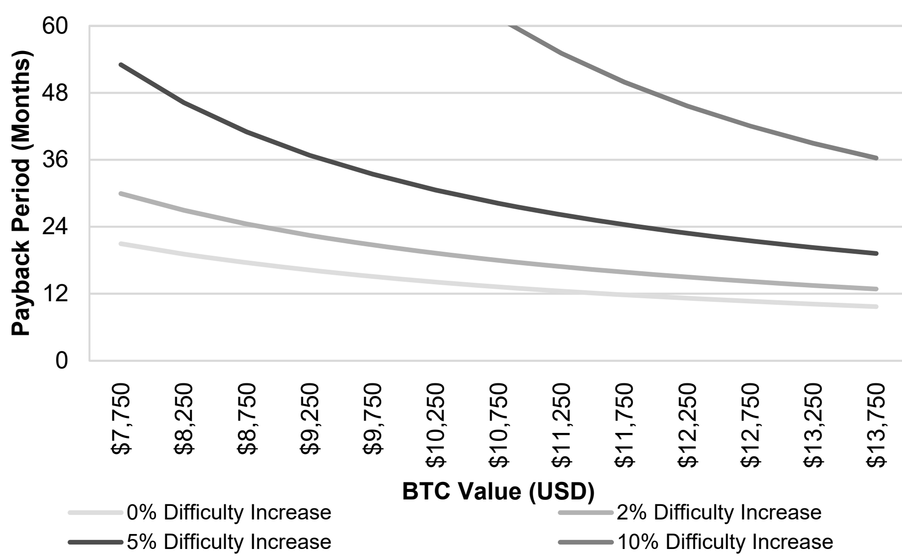
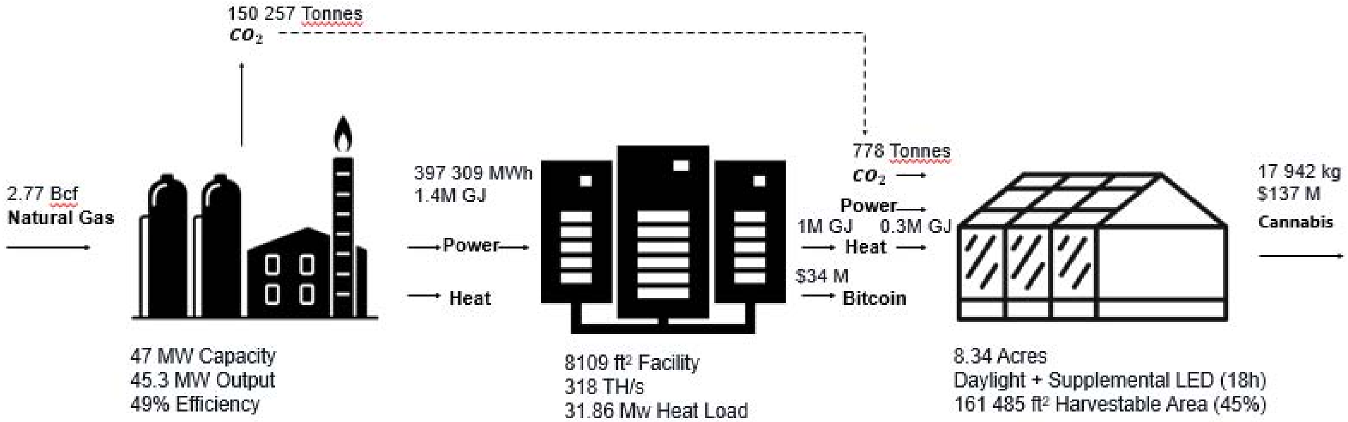


Figure 16 – Closed-loop Cryptocurrency Mining System Calculated Outputs



5 CHAPTER FIVE – CONCLUSION

The case study modeled in this project estimated the avoided emissions resulting from the incorporation of efficient cooling system design and heat reuse. The chosen location of Medicine Hat, Alberta lends itself to a high degree of free cooling, where external temperatures can be suitably used within the economizer cycle for an estimated 96% of the year. The incorporation of free cooling decreased the estimated PUE value from a 2.13 to 1.51 landing the facility within the range of 'efficient' data center classification with a DCiE of 66%. Through the co-location of a greenhouse, waste heat reuse generated a facility ERE of 1.18 and ERF of 0.22, offsetting of 22% of total facility energy use. The total avoided emissions for this proposed system were calculated at 70,000 tonnes of CO_2, with a cost savings of approximately \$15,000,000 CAD. This includes the avoided cost and emissions for the decreased cooling energy demand in the cryptocurrency mining facility, the heating of the 8.34-acre greenhouse, and the CO_2 used in the greenhouse enrichment process.

At 8.34 acres, the theoretical greenhouse is larger than most commercial food production greenhouses in Alberta. The designated client for large scale agricultural greenhouses is thus the newly-legalized cannabis industry. Cannabis yield for the supported greenhouse size was estimated at approximately 18,000 kg/year currently valued at \$137,000,000 CAD. Monthly bitcoin return at the current bitcoin value was estimated at \$2,663,040 CAD with a payback period of 13.1 months; however, the volatility of the bitcoin price would require more sophisticated modeling to generate credible long-term returns.

The fluctuations in seasonal temperatures result in a high heat demand for the greenhouse in the winter and a tradeoff exists between the amount of heat reuse and facility sizing. The theoretical greenhouse is sized to the first winter quartile temperature of -13.5°C. At this size, the greenhouse is sufficiently heated for 92% of the year, based on historical average hourly temperatures, reusing 32% of the total heat output of the cryptocurrency mining facility. Should the greenhouse be sized to satisfy the minimum yearly temperature, (the coldest night on the coldest day) the greenhouse area decreases to 4.82 acres. The consequence of year-round cultivation is the oversupply of heat, as the greenhouse heat demand decreases with increasing temperature, yet the heat output of the cryptocurrency facility remains largely constant. Enlarging the greenhouse to utilize a greater proportion of the waste heat is possible, however, would require the incorporation of a suitable back-up heating system for year-round production. Alternatively, the greenhouse can be utilized to extend the growing season, a possibility for food crops but an unlikely solution for large volume cannabis producers. Additional utility for surplus heat may be incorporated, such as agricultural drying, a necessary step in cannabis production.

This project is a very high-level examination of a cogeneration system with integrated agriculture in Alberta. The suitability of Alberta's climate, economic and geopolitical characteristics are enhanced by the competitive cost of power in the province. With a current overabundance of natural gas production and limited export markets, the requirement for uninterruptible energy supply in a gas-to-cryptocurrency configuration may create a new end-user for natural gas in Alberta. Active cryptocurrency mining in the province is one of the many kinds of data centers whose carbon footprint can be partially mitigated through heat reuse. The avoided emissions and capital savings from the proposed closed-loop co-generation model illustrate a tangible benefit for data center operators in Alberta. Greenhouses, particularly large-scale greenhouses such as cannabis production facilities are significant consumers of power thus a synergistic model such as the one proposed can aid in offsetting associated carbon footprint. The ability to expand greenhouse production to lower-margin greenhouse crops such as tomatoes, cucumbers, leafy greens, or non-greenhouse crops such as mushrooms represents an opportunity for sustainable food production systems in countries with temperate climates. The increasing understanding of the impacts of the average animal protein-heavy diet has led to an emphasis on plant-based eating in order to reduce individual carbon footprint. The development of more local, sustainable and year-round food production supports this goal, particularly in countries with cooler climates such as Canada.

Our daily functioning on a personal and global scale is reliant upon data centers. As the degree and difficulty of functions performed by data centers increases, efficiency optimization is critical to facilitate sustainable data center platforms. As this project illustrates, Alberta is well-positioned to make significant contributions in the development of net-zero data center facilities through the use of free cooling economizer cycles and integrated greenhouse waste heat reuse.

5.1 Project Limitations

Both the cryptocurrency and cannabis industries are newly developing, highly competitive industries. Both industries are highly secretive due to the nature of their activities, and as a result, published or standardized values for facility design, component power usage, and crop yields were restricted to available data. Corporations were reluctant to disclose relevant facility metrics or non-responsive to requests for data. Data availability was a significant limitation and going forward the developed model would benefit from future academic work and industry data.

Fluctuations in efficiency, power use, and heat losses are more complex than can be accurately modeled through the developed methodology. More detailed results for waste heat transfer would be possible using sophisticated dynamic fluid modeling techniques. The intention of the simplified equations was to demonstrate a baseline understanding of the degree of heat production and utility for reuse. Developing more accurate values that reflect inevitable variation in the described processes would require a more elaborate framework.

The full economic implications of a closed-loop design necessitate a full financial analysis. Characterizing the utility and practicality of the proposed design relies largely on the joint financial benefit to the producer of both the cryptocurrency operator and the greenhouse grower. Fluctuations in value and the implications of future cryptocurrency relevance, as well as the potential for cannabis legalization in countries where production values are significantly lower may dismiss any financial benefit from the proposed scheme.

5.2 Recommendations

In order to develop a more comprehensive understanding of the efficiency optimization advantages, partnership with industry stakeholders is recommended. Expertise from dedicated data center and greenhouse technology professionals and more accurate and scenario-specific data will improve the credibility and build on the conclusions of this analysis.

Examining the applicability of internal heat reuse within the cryptocurrency facility would provide a better understanding of heat output fluctuations and total available heat to the greenhouse. Understanding not only the allowable but recommended operating temperatures for the designated IT equipment is required to understand the internal heat reuse requirement.

A life cycle analysis for the heat reuse crop would allow for energy intensity and emissions comparison to crops grown in Alberta's non-heat reuse facilities or for crops purchased here but grown elsewhere. Analysis of the different production scenarios would provide a better understanding of sustainability gains for the crop.

5.3 Future Research

A void of data on data center energy consumption exists, specifically in relation to cryptocurrency mining. Academic research on energy use and efficiency would provide a better understanding of the implications of the rapidly expanding ICT sector and allow for more accurate analysis of average facility performance. Similarly, limited academic resources for greenhouse specific cannabis production exist. Research on cannabis consumption and production has been largely limited by legislative restrictions. Indoor and outdoor cultivation techniques have been studied to some degree. Only two countries, Canada and Uruguay, have fully legalized the production, sale, and consumption of cannabis. The opportunity for research on large-scale high-tech greenhouse cultivation has thus been limited.

The legality of cannabis in Canada thus comes with strict conditions for cannabis productions from Health Canada. Regulations include stringent controls on production inputs for the safety of consumers and growers. Analyzing production regulations for licensed producers would outline possible limitations of heat reuse and requirements for waste heat integration.

The development of a pilot project would examine the feasibility on a larger scale. A retrofitted facility could be used to demonstrate waste heat reuse at scale and identify potential problem areas and deficiencies in design or concept. Exploration of innovative technology solutions is potentially in line with the philosophies of technology-focused organizations, who may be willing to partner with an academic research institution.

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APPENDIX A Wärtsilä 34SG Technical Data

Main technical data

Wärtsilä 34SG generating sets for data center applications

Generating set		12V34SG	16V34SG	20V34SG
Number of cylinders		12	16	20
Cylinder bore	mm	340	340	340
Piston stroke	mm	400	400	400
Startup system		Direct injection of compressed air		
Operation in 50 Hz systems				
Speed	rpm	750	750	750
Rated electrical power	kW	5840	7840	9810
Operation in 60 Hz systems				
Speed	rpm	720	720	720
Rated electrical power	kW	5590	7510	9400
Starting performance				
Time to synchronize from start command	sec	15	15	15
Time to full load from start command	sec	< 60	< 60	< 60

GENERAL CONDITIONS

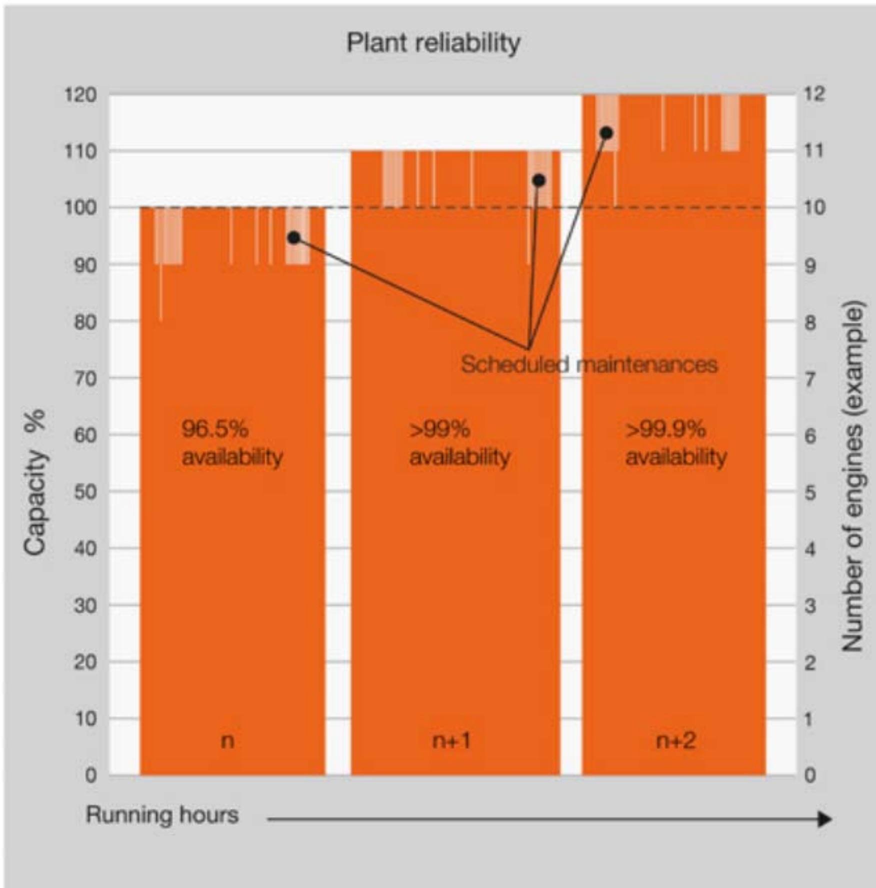
Rated electrical power is given at generator terminals and ISO 3046 conditions.

All Wärtsilä engines, in a standard configuration, have engine-driven lubricating oil, low and high temperature circuit cooling water pumps. Gas LHV > 28 MJ/Nm^3. Gas methane number > 80. Gas pressure > 5.1 bar(g) at plant inlet.

Please contact Wärtsilä for project-specific performance figures in case the gas does not fulfil the aforementioned criteria.

(Wärtsilä, 2018a)

APPENDIX B Wärtsilä Modular Gas Engine Reliability



(Wärtsilä, 2016)

APPENDIX C Bitfury Mining Technical Specifications

Blockbox

Parameter	Description
Container dimensions in closed position (length x width x height)	40' × 8' × 9.6' (12.2 m × 2.5 m × 2.9 m)
Door opening	7' 8" × 8' 6" (2.4 m × 2.6 m)
Weight	26,455 lb (12 T) of equipped weight in basic configuration
Power supply	1.1 MW ±5% 1.5 MW transformer with two 700 A three-phase leads is recommended
Internet connection	Reliable internet connection with at least 2 Mbps and maximum 50 ms latency to the www.bitfury.com
Installation	50–60 cm between the footing and the container underside
Backup power supply	Diesel generating set or a 40 kW commercial uninterrupted power supply unit
Backup internet connection	1.5 Mbps
Ambient temperature range	−40 to 113°F (−40 to +40°C)

(Bitfury, 2018a)

Tardis Server

Hashboards installed	5	6	7	8
Power consumption	6.3 kW	6.3 kW	6.3 kW	6.3 kW
Hashrate	67 TH/s	72 TH/s	76 TH/s	80 TH/s
Efficiency	94 mJ/GH	88 mJ/GH	83 mJ/GH	79 mJ/GH
Weight	34 kgs	37 kgs	40 kgs	44 kgs

(Bitfury, 2018b)

APPENDIX D Project Power Plant Specifications

Power Plant Specifications

Engine Type	*Wärtsilä 20V34SG*	
Capacity	*MW*	9.4
Generating sets		5
Total Output	*MW*	47
Capacity Factor	*%/day*	96.5%
Actual Output	*MW*	45.355
Yearly Output	*MWh*	397,309.80
	GJ	1,430,315.28

Power Plant Outputs

Output (kWh)	Efficiency	Btu	Heat Rate	Heat Emitted
kWh	*kWh*	*kWh*	*BTU/kWh*	*BTU*
397,309,800.00	49.0%	3,412.00	6,963.27	2,766,573,546,122.45

Natural Gas Required

MMBTU	*Bcf*	*m³*
2,766,573.55	2.77	78,340,638.69

Emissions Factor

g/m³ CO_2
1,918.00

CO_2

g	*Tonnes*
150,257,345,009.41	150,257.35

APPENDIX E Bitcoin Mining Data Center Energy Consumption

Typical Data Center Energy Consumption by Component at 30%				Data Center Energy Consumption at 100% Load				Proposed DC Energy Consumption at 95% Load					
Component	Energy Consumption (30% load)	MW	W	Energy Consumption (100% load)	MW	W	Free Cooling Reduction	Energy Consumption (100% load) + Free cooling	Energy Consumption (100% load) + Fans + Hum	MW	W	MW Operating at 100%	Energy Consumption at 100%
Chiller	23.0%	10.42	10,419,000.00	23.0%	10.419	10,419,000.00	50%	11.50%	11.50%	5.21	5,209,500.00	5.51	12.2%
Humidifier	3.0%	1.36	1,359,000.00	3.0%	1.359	1,359,000.00		3.0%	4.00%	1.81	1,812,000.00	1.92	4.2%
CRAC/CRAH	15.0%	6.80	6,795,000.00	15.0%	6.795	6,795,000.00	50%	7.50%	9.50%	4.30	4,303,500.00	4.55	10.1%
IT Equipment	47.0%	21.29	21,291,000.00	62.50%	28.3125	28,312,500.00		62.50%	62.50%	28.31	28,312,500.00	29.96	66.1%
PDU	3.0%	1.36	1,359,000.00	3.0%	1.359	1,359,000.00		3.99%	3.99%	1.81	1,807,180.85	1.91	4.2%
UPS	6.0%	2.72	2,718,000.00	-	-	-		-	-	-	-	-	-
Lighting	2.0%	0.91	906,000.00	2.0%	0.906	906,000.00		2.0%	2.0%	0.91	906,000.00	0.96	2.1%
Switchgear/Gen	1.0%	0.45	453,000.00	1.0%	0.453	453,000.00		1.0%	1.0%	0.45	453,000.00	0.48	1.1%
total	100.00%	45.3	45,300,000.00	109.50%	49.6035	49,603,500.00		91.49%	94.49%	42.80	42,803,680.85	45.30	100.0%
PUE			2.13			1.75					1.51	1.51	

100% load

PUE	Total MW	IT Load	Energy Consumption	Consumption increase	PDU	Multiplier
1.6	45.3	2831.25%	62.50%	75.20%	0.039893617	1.058320198

ERE

Total Facility Energy/year	Energy reuse/year	IT Energy	Calculated ERE	Calculated ERF
396,828,000.00	88,095,963.89	262,481,929.75	1.18	0.22

Calculated Total Heat Output from Mining

Component	Data Required	Value	Calculated Heat Load (W)
IT Equipment	Total IT Load (W)	29,963,690.61	29,963,690.61
PDU	Power System Rating (W)	1,912,576.00	1,874,324.48
Lighting	Floor Area	8,109.00	16,218.00
People	Max # Personnel	40.00	4,000.00
Total			31,858,233.09

Total (MW)	31.86
Total MWh (1 y operation)	279,078.12
Total kWh (1y operation)	279,078,120.00
Total GJ from DC	1,004,681.24
Proportion of NG Power Plant	70%

APPENDIX F Bitcoin Mining Data Center Heat Output

Typical Data Center Energy Consumption by Component at 30% Load				Data Center Energy Consumption at 100% Load				Proposed DC Energy Consumption at 95% Load					
Component	Energy Consumption (30% load)	MW	W	Energy Consumption (100% load)	MW	W	Free Cooling Reduction	Energy Consumption (100% load) + Free cooling	Energy Consumption (100% load) + Fans + Hum	MW	W	MW Operating at 100%	Energy Consumption at 100%
Chiller	23.0%	10.42	10,419,000.00	23.0%	10.419	10,419,000.00	50%	11.50%	11.50%	5.21	5,209,500.00	5.51	12.2%
Humidifier	3.0%	1.36	1,359,000.00	3.0%	1.359	1,359,000.00		3.0%	4.00%	1.81	1,812,000.00	1.92	4.2%
CRAC/CRAH	15.0%	6.80	6,795,000.00	15.0%	6.795	6,795,000.00	50%	7.50%	9.50%	4.30	4,303,500.00	4.55	10.1%
IT Equipment	47.0%	21.29	21,291,000.00	62.50%	28.3125	28,312,500.00		62.50%	62.50%	28.31	28,312,500.00	29.96	66.1%
PDU	3.0%	1.36	1,359,000.00	3.0%	1.359	1,359,000.00		3.99%	3.99%	1.81	1,807,180.85	1.91	4.2%
UPS	6.0%	2.72	2,718,000.00	-	-	-		-	-	-	-	-	-
Lighting	2.0%	0.91	906,000.00	2.0%	0.906	906,000.00		2.0%	2.0%	0.91	906,000.00	0.96	2.1%
Switchgear/Gen	1.0%	0.45	453,000.00	1.0%	0.453	453,000.00		1.0%	1.0%	0.45	453,000.00	0.48	1.1%
total	100.00%	45.3	45,300,000.00	109.50%	49.6035	49,603,500.00		91.49%	94.49%	42.80	42,803,680.85	45.30	100.0%
PUE			2.13			1.75					1.51	1.51	

100% load

PUE	Total MW		IT Load	Energy Consumption	Consumption increase	PDU	Multiplier
1.6	45.3		2831.25%	62.50%	75.20%	0.039893617	1.058320198

ERE

Total Facility Energy/year	Energy reuse/year	IT Energy	Calculated ERE
396,828,000.00	88,095,963.89	262,481,929.75	1.18

Calculated Total Heat Output from Mining

Component	Data Required	Value	Calculated Heat Load (W)
IT Equipment	Total IT Load (W)	29,963,690.61	29,963,690.61
PDU	Power System Rating (W)	1,912,576.00	1,874,324.48
Lighting	Floor Area	8,109.00	16,218.00
People	Max # Personnel	40.00	4,000.00
Total			31,858,233.09

Total (MW)	31.86
Total MWh (1 y operation)	279,078.12
Total kWh (1y operation)	279,078,120.00
Total GJ from DC	1,004,681.24
Proportion of NG Power Plant	70%

Facility Floor Area

	# Blockbox	Blockbox MW	Blockbox Footprint (ft2)	Tardis Servers	Power Consumption (W)	Servers/rack	Free air flow	Cost
	kWh	MW	ft^2		W		CFM ft^3/min	$ USD
Blockbox	1	1.1	395.3	176.00	6300		1,500.00	$ 704,000.00
Hut 8	40	48.00	15,812.00	7,040.00	44,352,000.00	6	10,560,000.00	$ 28,160,000.00
Case	27.00	29.96	10,673.10	4,752.00	29,937,600.00	6	7,128,000.00	$ 19,008,000.00

Blockbox floor area

Dimensions	Length	Width	Height	Area	Area	Volume	Volume
		m	m	m^2	ft^2	m^3	ft^3
box	12.20	2.50	2.90	30.50	328.18	88.45	3,123.17
door	2.40	2.60		6.24	67.14		
total				36.74	395.32		

Server Area

Bitfury Tardis	Total Servers	Server Racks	Height	Width	Depth	Area		IT space	Total Area	Cost	Hashrate
			mm	mm	mm	mm^2	ft^2		ft^2	$USD	TH/s
Server	1	0.00	264.00	483.00	591.00	285,453.00	3.07			4,000.00	67
Blockbox	176	29.33	264.00	483.00	591.00	285,453.00	90.10	23%	395.30	704,000.00	11,792
Hut 8	7,040	1,173.33	264.00	483.00	591.00	285,453.00	3,603.86	30%	12,012.88	28,160,000.00	471,680
Case	4,752	792.00	264.00	483.00	591.00	285,453.00	2,432.61	30%	8,108.69	19,008,000.00	318,384

Total Heat dissipation

Heat Load						Server Inlet Temper	Server Exit Temperature Low differential	High differential
	MW	W	Wh	GJ	BTU/h	℃	℃	℃
Servers	29.9	29963690.61	2.62482E+11	944934.9471	102,240,380.69	27	37	42
Other	1.9	1,894,542.48	16596192094	59746.29154	6,464,448.81			
Total	31.8	31,858,233.09	2.79078E+11	1004681.239	108,704,829.50			
		6300			98,281,986.28			
					952,254.31			

heating btu/h	ΔT	constant	Correction Factor	Heat dissipation		41.36
BTU/h	℃			CFM ft^3/min	CFH ft^3/h	
108,704,829.50	10	1.08	0.999	10,075,337.33	604,520,239.69	
108,704,829.50	15	1.08	0.999	6,716,891.55	403,013,493.13	
108,506,129.91	14.36	1.08	0.999	7,016,251.62	420,975,097.28	

servers	Server CFM from Spec		
4752	1500	7,128,000.00	within range, so delta T is between 10-15 degrees

APPENDIX G Waste Heat Greenhouse Sizing

Energy available (W)	*W*		**31,854,852.92**				
Yearly energy available	*Wh*		**279,048,511,579.2**				
Yearly energy available	*Mwh*		**279,048.5**		**Winter**		
			0 Quartile	**1st Quartile**	**2nd Quartile**	**3rd Quartile**	**4th Quartile**
Heat loss coefficient	*U*	*W/m²k*	4	4	4	4	4
Temperature greenhouse	T_i	℃	20	20	20	20	20
Temperature external	T_o	℃	-37.8	-13.5	-5.6	0.6	17.7
Temperature difference	Δ*T*	*k*	57.8	33.5	25.6	19.4	2.3
Ventilation rate	*N*	s^{-1}	0.00021	0.00021	0.00021	0.00021	0.00021
Height of greenhouse	*h*	*m*	4	4	4	4	4
Length of side of pitched roof	*G*	*m*	2	2	2	2	2
Roof pitch angle	*θ*	*degrees*	30	30	30	30	30
Greenhouse Size							
$L = \frac{-4hU\Delta T + \sqrt{(4hU\Delta T)^2 - 4\left\{\left(h+\frac{G}{2}\right)1800N\Delta T + \frac{U\Delta T}{cos\theta}\right\}(-Er)}}{2\left[\left(h+\frac{G}{2}\right)1800N\Delta T + \frac{U\Delta T}{cos\theta}\right]}$							
(-4hUΔT)			-3,699.20	-2,144.00	-1,638.40	-1,241.60	-147.20
(4hUΔT)^2			13,684,080.64	4,596,736.00	2,684,354.56	1,541,570.56	21,667.84
4(h+G/2)1800NΔT + UΔT/cos0 -E			-204,902,313,619.57	-118,758,261,353.90	-90,752,581,810.74	-68,773,440,903.45	-8,153,552,272.06
2(H+(G/2))*1800NΔT+UΔT/cos0)			3,216.19	1,864.05	1,424.47	1,079.48	127.98
square root			452,676.48	344,619.87	301,256.15	262,249.85	90,297.14
Calculated Values							
Calculated greenhouse side length	*m*		139.60	**183.73**	210.34	241.79	704.41
Calculated greenhouse side length	*ft*		458.00	602.78	690.08	793.28	2,311.05
Area (m2)	*m²*		19,487.95	**33,755.42**	44,241.34	58,462.60	496,190.43
Area (ft2)	*ft²*		209,766.59	363,340.33	476,209.87	629,286.27	5,340,949.73
Surface Area	*m²*		128,572.45	**221,773.35**	290,178.51	382,877.10	3,228,034.03
Area (Acres)	*acres*		4.82	**8.34**	10.93	14.45	122.61
Volume (m3)	*m³*		97,439.76	**168,777.10**	221,206.71	292,313.02	2,480,952.17
Volume (ft3)	*ft³*		3,441,055.95	5,960,312.51	7,811,848.56	10,322,946.56	87,614,081.75
cos30			0.15	0.15	0.15	0.15	0.15
length of roof triangle	*m*		25.93	25.93	25.93	25.93	25.93
pitched roofs			5.38	**7.09**	8.11	9.32	27.16
Energy							
$E_r = AU(T_i - To) + 1800VN(T_i - To)$							
4Lh+((L^2)/cos0)UΔT			50,597,296.56	29,326,658.61	22,411,512.94	16,984,436.59	2,016,209.88
1800(h+(G/2))(L^2)NΔT			3,687,509.50	2,137,224.36	2,140,573.08	2,143,589.83	2,156,939.82
Energy	*W*		54,284,806.06	31,463,882.97	24,552,086.02	19,128,026.42	4,173,149.70
Energy available	*W*		31,854,852.92	31,854,852.92	31,854,852.92	31,854,852.92	31,854,852.92
Differential			-22,429,953.14	390,969.95	7,302,766.90	12,726,826.50	27,681,703.22
Percentage	%		-70.41	1.23	22.93	39.95	86.90
Energy required	*MWh*		470,649.27	272,791.87	212,866.59	165,839.99	36,181.21
Energy Available	*MWh*		276,181.57	276,181.57	276,181.57	276,181.57	276,181.57
Proportion of E available	%		170%	99%	77%	60%	13%

APPENDIX H Greenhouse Heat Demand

Inputs

Temp Initial	20
Surface Area (A)	221,773.35
Volume (V)	168,777.10
U	4
N	0.00021
Beta	0.71
Area (A)	33,755.42

Outputs

	From Heat Equation j/y	GJ	From Energy Equation Joules	GJ	Heat Available from DC GJ	%
Q (Actual) J	**317,145,465,554,106.00**	**317,145.47**	**265,743,291,258,201.00**	**265,743.29**	**1,004,681.24**	31.57

Hourly Q Per Month

	Temperature ℃	joules from heat eq (24 hours)	joules from heat eq (months)	GJ	**Calc 1** joules from energy eq (24 hours)	**Calc 2** joules from energy eq (months)	GJ
January	-6.72	2,011,399,162,327.41	62353374032149.80	62,353.37	1,948,915,382,640.75	60,416,376,861,863.30	60,416.38
February	-7.27	2,077,540,613,608.65	64403759021868.10	64,403.76	1,985,107,663,377.82	56,079,291,490,423.50	56,079.29
March	-0.11	1,434,387,621,897.49	44466016278822.30	44,466.02	1,315,937,015,671.54	40,794,047,485,817.80	40,794.05
April	7.15	721,778,548,114.43	22375134991547.20	22,375.13	563,873,933,134.38	16,916,217,994,031.40	16,916.22
May	13.36	150,773,159,747.10	4673967952160.13	4,673.97	- 25,244,102,407.47	- 782,567,174,631.61	- 782.57
June	17.51	- 238,364,578,215.11	- 7,389,301,924,668.43	- 7,389.30	- 427,110,849,767.24	- 12,813,325,493,017.10	- 12,813.33
July	21.02	- 535,939,883,454.30	- 16,614,136,387,083.40	- 16,614.14	- 723,906,720,398.39	- 22,441,108,332,350.10	- 22,441.11
August	19.47	- 319,569,774,548.42	- 9,906,663,011,000.95	- 9,906.66	- 466,412,769,610.35	- 14,458,795,857,920.90	- 14,458.80
September	12.81	349,665,480,035.96	10839629881114.60	10,839.63	253,774,420,101.93	7,613,232,603,057.82	7,613.23
October	6.95	884,276,540,988.50	27412572770643.50	27,412.57	801,985,838,333.05	24,861,560,988,324.60	24,861.56
November	-1.16	1,627,909,853,828.51	50465205468683.90	50,465.21	1,572,096,226,619.36	47,162,886,798,580.70	47,162.89
December	-6.18	2,066,642,144,511.92	64065906479869.40	64,065.91	2,012,757,222,387.79	62,395,473,894,021.50	62,395.47

Days in Month

1	January	31
2	February	28.25
3	March	31
4	April	30
5	May	31
6	June	30
7	July	31
8	August	31
9	September	30
10	October	31
11	November	30
12	December	31

Yearly GJ	*Yearly kWh*	*Energy Cost*
317,145.47	**88,096,033.13**	**7,329,589.96**

APPENDIX I Greenhouse CO_2 Enrichment

Input Values

Volume	*m^3*	168,777.10
Area	*m^2*	33,755.42
Desired CO_2	*ppm*	1,400.00
Ambient CO_2	*ppm*	400.00
CO_2 level		0.001
CO_2	*kg/100 m^2*	0.6

CO_2 enrichment

Month		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of Days		31	32	33	34	35	36	37	38	39	40	41	31
Sunlight + Growlights (18)	*h*	558.00	576.00	594.00	612.00	630.00	648.00	666.00	684.00	702.00	720.00	738.00	558.00
CO_2	*kg*	56,506.57	58,329.37	60,152.16	61,974.95	63,797.74	65,620.54	67,443.33	69,266.12	71,088.91	72,911.71	74,734.50	56,506.57
	tonnes	56.51	58.33	60.15	61.97	63.80	65.62	67.44	69.27	71.09	72.91	74.73	56.51

Total CO_2	**tonnes**	**778.33**

APPENDIX J Greenhouse Cannabis Yield Estimations

Cannabis Yield

Greenhouse Area		**33,755.42**	359157.66
% canopy		66.67%	
% flowering		66.67%	
Canopy Area		15,002.41	
sq ft		161,485.93	
1.4 sq ft/plant		115,347	
$/g	$	7.62	

Yield Ranges

	low	high
plants per sq m	1	10
g/m2	50	250
seasons	3	6

Facility	Location	Size	Aurora Cannabis		Capacity	Status	License				
		sq. ft	*m2*	*acres*	*kg/y*		*Cultivation*	*Sale*	*g/sqft/yr*	*g/m2/y*	g/m2/harvest
Aurora Mountain	Mountain View, AB	55,200.00	5,128.25	1.27	4800	Operating since 2015	•	•	86.96	935.99	156.00
Aurora Vie	Pointe Claire, QC	40,000.00	3,716.12	0.92	4000	Operating since June 2018	•	•	100.00	1,076.39	179.40
Aurora Eau	Lachute, QC	48,000.00	4,459.34	1.10	4500	Full operation	•	•	93.75	1,009.12	168.19
Aurora Sky	Edmonton, AB	800,000.00	74,322.40	18.37	100000	Full operation	•	•	125.00	1,345.49	224.25
Aurora Sun	Medicine Hat, AB	1,620,000.00	150,502.86	37.19	230000	completed by 2020			141.98	1,528.21	254.70
Aurora Prairie	Saskatoon, SK	97,000.00	9,011.59	2.23	19000	operational since 2004	•	•	195.88	2,108.40	351.40
Aurora Ridge	Markham, ON	55,000.00	5,109.67	1.26	7000	operational since 2014	•	•	127.27	1,369.95	228.33
Aurora River	Bradford, ON	210,000.00	19,509.63	4.82	28000	full operation	•	•	133.33	1,435.19	239.20
Exeter	Exeter, ON	1,000,000.00	92,903.00	22.96	105000	land and building purchased			105.00	1,130.21	188.37
Whistler Alpha Lake	Whistler, BC	12,500.00	1,161.29	0.29	500	operating since 2014	•	•	40.00	430.56	71.76
Whistler Pemberton	Pemberton, BC	62,000.00	5,759.99	1.42	5000	phase 1 operational	•		80.65	868.06	144.68
Totals									111.80	1,203.41	200.57

Estimated Greenhouse Yield

From Yield Ranges

g/m^2		50	250
g			
	3	2,250,361.28	11,251,806.39
	6	4,500,722.56	22,503,612.78
Kg			
	3	2,250.36	11,251.81
	6	4,500.72	22,503.61
Value			
	3	**$ 17,147,752.94**	**$ 85,738,764.70**
	6	**$ 34,295,505.88**	**$ 171,477,529.40**

Averaged Aurora Yields

Averaged yearly yeild Aurora		111 g/sqft/yr	200.57 g/m^2
g			
	3	9,027,099.23	
	6	18,054,198.46	
Kg			
	3	9,027.10	
	6	18,054.20	
Value			
	3	**$ 68,786,496.14**	
	6	**$ 137,572,992.29**	

APPENDIX K Estimated Bitcoin Return

Inputs/Assumptions

Period	*days*	1
Initial mining difficulty		9.06416E+12
Base hash diff. change	*%/day*	0.0%
High hash diff. change	*%/day*	10.0%
Low hash diff. change	*%/day*	5.0%
Initial BTC value	*CAD*	$10,850
Miner cost	*$ USD*	$4,000
# of miners	*#*	4,752
Facility cost	*$*	$10,000,000
Hash rate	*TH/sec*	318,384
Power consumption	*MW/h*	31.9
Power cost	*$/kWh USD*	$0.03
Other opex	*$/day USD*	$0.00
Pool fees	*%*	2.0%
Hash rate scenario		**Base**

Output

Initial outlay *$MM* **$29.01**

		$10,850	**$3,500**	**$30,000**
Cum. CF	*$MM*	$34.98	$11.28	$96.72
Net Annual CF	*$MM*	$26.61	$2.91	$88.34
Payback	*months*	13.1	119.6	3.9

Power price	*$/kWh*	$0.03
Sale to grid rev	*$/day*	**$32,616**

Payback period

	BTC Price (USD)	$7,750	$8,250	$8,750	$9,250	$9,750	$10,250	**$10,750**	$11,250	$11,750	$12,250	$12,750	$13,250	$13,750
0% Difficulty Increase	**14.59**	20.95	19.10	17.55	16.23	15.10	14.11	**13.24**	12.48	11.80	11.19	10.63	10.14	9.68
2% Difficulty Increase	**19.97**	29.95	26.96	24.51	22.47	20.74	19.26	**17.98**	16.85	15.86	14.98	14.19	13.48	12.84
5% Difficulty Increase	**31.94**	53.04	46.25	41.00	36.82	33.42	30.59	**28.20**	26.16	24.39	22.85	21.49	20.28	19.20
10% Difficulty Increase	**74.27**	199.09	144.96	113.97	93.89	79.83	69.43	**61.43**	55.08	49.93	45.65	42.05	38.98	36.32