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A Step Towards A Lower Carbon Future: Integrating Closed Loop Geothermal Technology in District Cooling Applications

by

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ABSTRACT

This research will assess the technical, environmental, and economic feasibility of low-grade, closed loop geothermal heat extraction used for district cooling applications, specifically with the use of an Eavor-Loop™. This will be completed through literature review, interviews with subject matter experts, thermodynamic process simulations and optimization, and an economic analysis. As global warming, urbanization, and our dependency on digital storage increases, the world's cooling demands continue to rapidly grow with predictions showing that cooling demands will outweigh heating demands by 2060. Majority of current cooling systems utilize fossil fuels, emitting a great deal of greenhouse gases that have gone unchecked for decades. With the utilization of Eavor-Loop™ and absorption chiller technology, a 6,600 RT facility was designed for data center operations in California, USA with both environmental and economic benefits. This design aims to open up new, affordable possibilities with low-grade geothermal resources to meet the world's cooling demands.

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TABLE OF CONTENTS

APPROVAL PAGE .... **I**

ABSTRACT .... **II**

ACKNOWLEDGEMENTS .... **III**

DEDICATION .... **IV**

TABLE OF CONTENTS .... **V**

LIST OF TABLES .... **VII**

LIST OF FIGURES .... **VIII**

LIST OF EQUATIONS .... **IX**

LIST OF TERMS AND ABBREVIATIONS .... **X**

CHAPTER 1: INTRODUCTION **1**

1.1 Introduction *1*

1.2 Purpose of Research *2*

1.3 Research Objectives *3*

1.4 Eavor-Loop™ Technology *4*

1.5 Sustainability Pillars *5*

CHAPTER 2: BACKGROUND **7**

CHAPTER 3: METHODOLOGY **9**

3.1 Objective 1 .... *9*

3.2 Objective 2 .... *12*

3.3 Objective 3 .... *13*

CHAPTER 4: LITERATURE REVIEW **15**

4.1 Geothermal Energy in DCS *15*

4.2 Absorption Chillers *22*

4.2.1 Absorption Chiller Operation 24

4.2.2 Generic LiBr/H_2O Absorption Chiller Data 27

4.3 District Cooling 28

CHAPTER 5: RESULTS & ANALYSIS 33

5.1 Objective 1 Findings 33

5.1.1 Objective 1a – Literature Review 33

5.1.2 Objective 1b – Technical Specifications of Absorption Chillers 34

5.2 Objective 2 Findings 36

5.2.1 Objective 2a – Thermodynamic Process Simulation 37

5.2.2 Objective 2b – Economic Analysis 41

5.3 Objective 3 Findings 44

5.3.1 Objective 3a – Potential Applications 44

5.3.2 Objective 3b – Environmental Analysis 47

CHAPTER 6: DISCUSSION 49

CHAPTER 7: CONCLUSIONS & RECOMMENDATIONS 53

7.1 Conclusions 53

7.2 Limitations 53

7.3 Recommendations 55

7.4 Future Research 56

REFERENCES 58

APPENDIX A: HOT-WATER DRIVEN ABSORPTION CHILLER MODELS 63

APPENDIX B: YORK YHAU-CH DATASHEETS 64

APPENDIX C: ECONOMIC ANALYSIS 65

APPENDIX D: DATA CENTER PUE CALCULATION 67

LIST OF TABLES

Table 1: Four main methods used for cooling load production 16

Table 2: Various pairs of fluids used in cooling systems..17

Table 3: Common cooling methods...18

Table 4: Typical operation ranges of each cooling method...19

Table 5: Energy output vs. energy input...19

Table 6: Comparison of single-effect vapour absorption technology [absoprtion agent/ refrigeration agent] 23

Table 7: LiBr/H_2O absorption chiller performance characteristics 27

Table 8: LiBr/H_2O absorption chiller capital and O&M costs...28

Table 9: Optimized Eavor-Loop™ Performance characteristics..39

Table 10: Summary of main economic costs for both systems 41

Table 11: Results from the economic analysis 42

Table 12: Potential data center sizes...45

Table 13: Inputs for environmental analysis 47

Table 14: Yearly GHG emission savings 48

LIST OF FIGURES

Figure 1: Eavor-Loop™ Technology 5

Figure 2: Research Methodology..9

Figure 3: Load duration curve for Beijing and Abu Dhabi..18

Figure 4: LCOC variations for geothermal source temperature 20

Figure 5: Geothermal assisted air-conditioning system at the Sea Gaia Spring Hotel* 22

Figure 6: Simplified absorption cycle..25

Figure 7: In-depth depiction of absorption chiller process 25

Figure 8: Example of a district cooling system 29

Figure 9: Reduction in peak demand due to DC systems in the EU..30

Figure 10: Base and Peak Load energy supply (heat and cool) of the 67 reporting facilities.......31

Figure 11: Depiction of York absorption chiller with two-step evaporator-absorber process.....35

Figure 12: Regression model for change in temperature across allowable flow rates 38

Figure 13: PFD for integrated surface and subsurface design..39

Figure 14: Optimized absorption chiller layout..40

Figure 15: Sensitivity analysis of the LCOC with a varying cost of electricity 42

Figure 16: Tornado chart highlighting the main economic drivers 44

LIST OF EQUATIONS

Equation 1: Specific Heat Formula 37

Equation 2: Levelized Cost of Cooling 41

Equation 3: PUE Calculation 45

Equation 4: GHG savings equation 47

LIST OF TERMS AND ABBREVIATIONS

A/C:	Air conditioning
CAD:	Canadian dollars
CC:	Capital cost
CO_2:	Carbon dioxide
CO_{2eq}:	Carbon dioxide equivalent
COP:	Coefficient of performance
CRF:	Capital recovery factor
DC:	District cooling
DCS:	District cooling system
Eavor:	Eavor Technologies Inc.
Elec:	Electricity
ESG:	Environmental, social, and corporate governance
ETS:	Energy transfer station
EU:	European Union
FI:	Flow indicator
GHG:	Greenhouse gas
H_2O:	Water
HVAC:	Heating, ventilation, and air conditioning
ICT:	Information and Communications Technology
IRR:	Internal rate of return
IT:	Information technology, computer context
LCOC:	Levelized cost of cooling
LiBr:	Lithium Bromide
NA:	North America
NH_3:	Ammonia
NPV:	Net present value
O&M:	Operation and maintenance

PFD: Process flow diagram

PI: Pressure indicator

PIR: Profit investment ratio

PUE: Power usage effectiveness

TI: Temperature indicator

US: United States

UNITS

°C: Degrees Celsius, unit of temperature

kW: Kilowatt, unit of power

kWh: Kilowatt hour, unit of energy

kWth: Kilowatt thermal, unit of power

L/s: Liters per second, unit of flow

MM: Million multiplier

MPa: Megapascal, unit of pressure

MWth: Megawatt thermal, unit of power

Q: Heat energy

RT: Refrigeration ton, unit of power

TWh: Terawatt hour, unit of energy

W/mK: Watts per metre-kelvin, thermal conductivity, unit of energy

CHAPTER 1: INTRODUCTION

1.1 Introduction

It's no secret that when people think of energy, cooling applications are not the first thing to come to mind. However, it is predicted that by 2060, more energy will be spent on cooling than on heating (Henley, 2015). The majority of cooling applications currently utilize fossil fuels to fulfill the energy needs. Demand has been rapidly rising from a warming climate and urbanization of developing countries, many of these countries being located in warmer climates closer to the equator. The increased surge in the information and communications technology (ICT) sector adds to the problem. Data Center power consumption around the globe increased by 400% between 2007 and 2013, with predictions of doubling again by 2030 (Henley, 2015). As a global community we need to be more wary and thoughtful about the way we approach cooling systems. The proposed research will answer the following question: What is the technical, environmental, and economic feasibility of the Eavor-Loop™ when utilizing low-grade geothermal energy for district cooling applications?

District cooling (DC) could help to be a solution to the ever-growing problem. District cooling is a method that utilizes common infrastructure with a network of piping that can meet the demand of a whole network of buildings. There are many advantages to this when compared to individual cooling systems for each and every building. Some of these include increased control over building temperatures, lower maintenance, less space, reduced power consumption, lower fuel costs and eco-friendly refrigerants (Zafar, 2017). DC can be effectively applied to any region or industry that requires a high cooling load. This could be airports, office buildings, factories, warehouses, cities located in year-round hot climates, or data centers. For example, in Dubai, 70% of the electricity generated is put towards cooling needs (Fortune Business Insights, 2019).
In 2016, data centers worldwide used 416.2 terawatt hours (TWh) of electricity (~40% of this was used for cooling), 116.2 TWh more than total power consumption of the UK in that same year. Data center numbers are rapidly increasing, having totalled 500,000 centers in 2012 and an upwards of 8 million in 2019. With the expectations that these numbers will not slow down as

more people gain access to the internet and increased data storage needs are required, a sustainable outlook needs to be taken into account. To help combat emissions related with cooling, many big tech companies have looked towards renewable energy and increased efficiencies (Trueman, 2019).

1.2 Purpose of Research

The goal of this research is to assess the technical, environmental, and economic feasibility of low-grade, closed loop geothermal heat extraction for use in district cooling applications. Even though these systems have been investigated for their feasibility in high-grade, geothermal applications, the contribution of this research is investigating the feasibility of low-grade applications in a closed loop system, which is a new application with the potential to extend the use of the technology to geographic areas previously not explored. In terms of geothermal heat energy, there are two main categories; high-grade and low-grade (which often incorporates medium-grade). The term *low-grade* refers to heat energy below 149°C whereas *high-grade* refers to heat energy above 149°C (Helston, 2012). Majority of current cooling systems utilize fossil fuels for these needs, emitting a great deal of greenhouse gases that have gone unchecked within this sector for decades. It is the goal of the research to find an integrated subsurface and surface process that can provide clean, reliable, scalable, GHG emission free energy to markets that require a huge cooling load. This research will lay the groundwork for a solution that provides substantial social, environmental, and economic benefits for Canadians. These many benefits include dependable energy, reduced health risks due to improved air quality, reduced GHG emissions, minimal surface land footprint, reduced energy consumption through increased efficiencies, industrial diversification, job creation, reduced cooling costs, and affordable retrofitting of existing infrastructure. On a broader scale, this research is vastly applicable globally, further enhancing the benefits not only to Canadians but to the world. Given Canada's commitment to the Paris Agreement, this research could be a major stepping stone on the way to achieving that vision.

1.3 Research Objectives

The objectives to complete this research question are to:

[1] Develop and optimize a surface processing facility to provide efficient district cooling from the low-grade heat recovered using Eavor-Loop™ technology;

[2] Integrate the surface and subsurface processes to maximize cooling efficiency; and

[3] Determine the applicability of this new design within Canada and globally

Each of the three objectives has their own novelty that will help to bridge the gap between industry and academic research; however, given the time limits to complete this research, most of the research in this proposal falls under objectives [2] and [3].

[1] While this research aims to utilize existing district cooling technologies, the novelty comes from being able to integrate these with low-grade, clean, geothermal heat on commercial and industrial scales. Most existing district cooling systems use waste heat from the combustion of fossil fuels or local existing natural sources. Accordingly, the designs for these are well known and often have higher temperature ranges. Most closed loop, low-grade geothermal applications are used on a small, residential scale and do not have the capacity that the designed system will be able to achieve.

[2] The Eavor-Loop™ itself is a novel technology. This will be the first time that an analysis will be completed on the potential for integration with district cooling technology. The Eavor-Loop™ can extract heat over a wide range of operating conditions with varying efficiency. Optimizing the overall process takes a holistic view of the subsurface (Eavor-Loop™) and surface (district cooling facility) dynamics and how they interact with each other.

[3] Traditional geothermal energy is restricted to well-known hot spots around the globe that have both a large heat gradient and high permeability. The Eavor-Loop™ does not require either of these. Extending the applicability of geothermal energy offers global communities with high

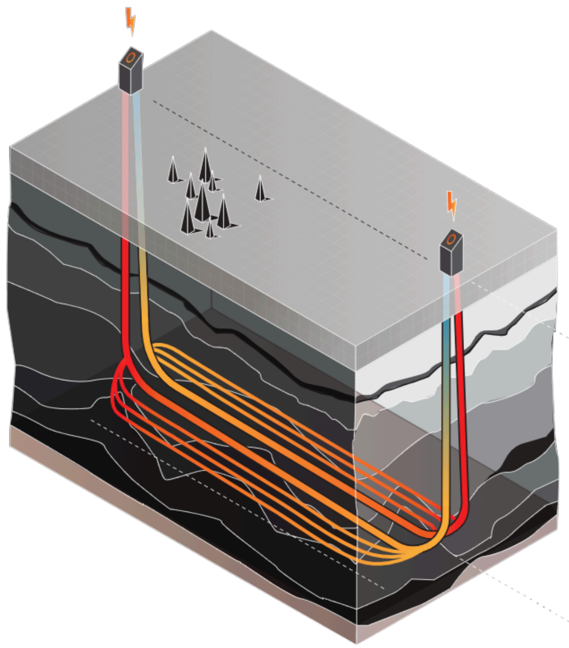
cooling demands a clean, renewable solution. High cooling demands are not limited to hot climates and include data centres, industrial buildings, airports, universities, and densely populated metropolitan areas.

Current research, while limited, has shown some success with using geothermal energy for cooling applications. However, these have all been implemented in locations with higher grade geothermal potential. With all of this in mind, the research will identify if Eavor-Loop™ technology can be feasible when combined with district cooling systems to meet demand, and the applicability of this new design.

1.4 Eavor-Loop™ Technology

Eavor Technologies Inc. is a new, geothermal company that comes from Calgary, AB and leverages the skills of the oil and gas industry, particularly drilling, in developing a novel approach to geothermal technology. Different from traditional geothermal, the Eavor-Loop™ (Figure 1) is a closed loop system that acts like a radiator within the subsurface without the need to extract a heated brine. A working fluid is run through the system, absorbing the natural heat from within the formation solely via conduction. At the surface, this thermal energy can be used as heat or converted to power and cooling potential. The Eavor-Loop™ presents resilience and sustainability as it operates without the need of fuel and is emission free. Additionally, the Eavor-Loop™ allows for utilization of both low- and medium-grade heat, a source that is often not considered viable with traditional methods due to cost. The thermosiphon effect allows the fluid to circulate without the need of a pump, removing the parasitic load and making the overall process more efficient. The technology is both scalable and available to provide baseload power. The Eavor-Loop™ requires a very small physical footprint on surface and could repurpose inactive well sites and industrial facilities. The technology utilizes multilaterals and Rock-Pipe completions technology, ensuring that fluids are contained within the system. The spread section helps to maximize efficiency and all the multilaterals are precisely drilled into each other at an intersection point.

Figure 1: Eavor-Loop™ Technology



Source: (Eavor Technologies Inc., n.d.)

1.5 Sustainability Pillars

This feasibility study is multi-disciplinary and will be anchored in energy, environment, and economics.

Energy: The final project itself is directly associated with the energy industry through the production of clean energy. The combined system and its associated technologies will be an alternative, renewable solution to current cooling methods. As mentioned, the energy demands required for cooling needs are quite high with projections showing rapid increases. Companies that have large energy consumption needs are looking to renewables to help minimize their carbon footprint. This project could prove to be a valuable addition and game-changer in the energy industry.

Environment: Given the renewable and clean nature of the Eavor-Loop™ technology, this research will look to displace current fossil fuel utilization within district cooling applications, lowering global greenhouse gases (GHG's) and the carbon footprint associated with these energy demands. The implementation of a district cooling network alone would provide environmental benefits, but when combined with energy production from a clean source, these benefits increase by a great deal. The research will compare GHG emissions of current cooling methods with the newly designed Eavor Cooling System. A fuel reduction analysis will be calculated as well. The project hopes to aid society in taking a step towards a lower carbon future through reliable, clean energy and decrease the dependency on fossil fuels.

Economics: The project will require an economic model in order to determine the feasibility of the proposed Eavor Cooling System. Costs of the new system will be calculated, and sensitivity analyses will be completed to determine important drivers that can help to make the project more favourable. This will be dependent upon market assessments, geographic location, energy demands, fuel prices (historic and projected), and the value that a company puts on its ESG policies. If potential clients are willing to provide information on the costs of their current systems, a cost-benefit analysis can be completed to show what the economics would like if they were to switch systems. This will help to provide a comprehensive view of the proposed solution, especially when compared to other projects. This will be a very important pillar due to the nature of markets and the knowledge required to bring a project to execution.

CHAPTER 2: BACKGROUND

While there is a lot of information readily available for integrating renewables such as geothermal and solar thermal into district heating applications, there is very little outlining a reliable solution solely for the purposes of cooling that can be applied to any geographic location. According to Inayat and Raza (2019), renewable energy such as biomass, solar thermal, solar PV, traditional geothermal, deep surface water, and waste heat are all 'suitable' to integrate with a district cooling system (DCS). It is commonly known that renewable energy like wind and solar face intermittency problems and cannot be considered a reliable, year-round source. Other forms of renewable energy such as traditional geothermal energy require very specific subsurface requirements to be effective and deep surface water energy requires the operation to be next to a coastline. The findings of the article outline five different notable literary contributions to the use of geothermal energy in DCS with four of those only being documented in the last seven years. These included the following:

(1) the use of NH_3-H_20 as a working fluid in an absorption refrigeration system (Tugcu & Arslan, 2017);

(2) a single-stage 10 kW LiBr water absorption chiller in Poland that was considered successful enough to take it a step further and create an advanced chiller design (Rogowska, 2003);

(3) an absorption heat pump used for space cooling and the influencing factors surrounding this technology (Jóhannesson & Chatenay, 2014);

(4) a simulated single stage absorption chiller implemented in Izmir, Turkey. Both a thermodynamic and economic analysis was completed (Yilmaz, 2017);

(5) an air conditioning system in the Jinshan District, Taiwan utilizing 90 to 100°C water resulting in a 26% electrical efficiency (Tsaia, Wua, & Chang, 2014);

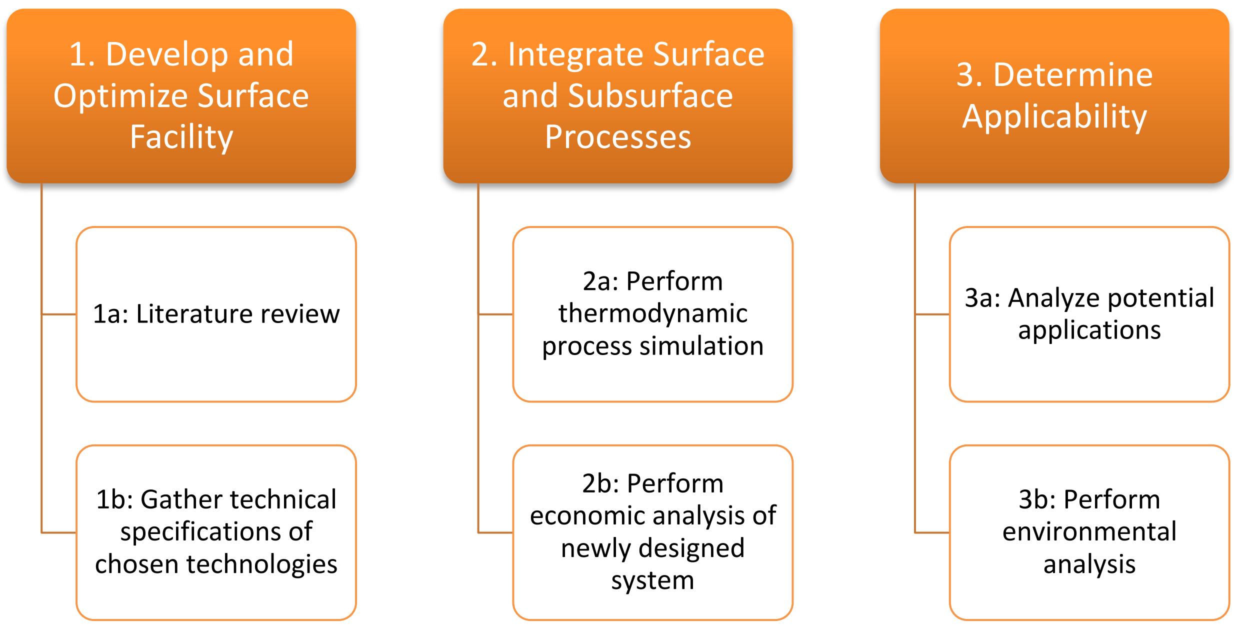
It is important to note that all of the papers discussed technologies that were put to use in known areas with an increased level of geothermal activity. In conclusion, it was found that energy used for cooling was contributing to global greenhouse gases and causing harm to our environment. With increasing knowledge and concern from citizens around the globe, it is more important than ever to start truly analyzing how we can utilize clean, renewable energy into DC systems. Inayat & Raza (2019) showed that all six highlighted renewable energies have high potential to replace fossil fuels in terms of technology, costs, and reduced environmental harm, allowing for an increased transition into clean, alternative energies.

As presented, there is no previous literature that addresses the proposed research topic. With the use of the Eavor-Loop™ to produce reliable, scalable, non-traditional geothermal energy, the geographic zones for application and uses have vastly increased. Additionally, it will not draw water from a deep hot zone causing waste, reducing the total amount of water, an important natural resource, that is used in operation. This project will show the potential that an Eavor Cooling System can have in a growing energy dimension to mitigate risks we are only currently becoming more aware of. This research will provide the world with a truly scalable, reliable form of energy that can be implemented in regions that were not thought of to have a valuable geothermal energy source.

CHAPTER 3: METHODOLOGY

The following methodologies were employed to meet each objective as seen above in section 1.3 and illustrated in Figure 2.

Figure 2: Research Methodology



Source: (Author, 2020)

3.1 Objective 1

***[1]** Develop and optimize a surface processing facility to provide efficient district cooling from the low-grade heat recovered using Eavor-Loop™ technology.*

(1a-i) Investigate current uses of renewable energy within district cooling applications.

A literature review was completed to find any existing research or work that has been done on incorporating the use of renewables in district cooling applications, with an emphasis on geothermal energy. Given that the Eavor-Loop™ is new, proprietary technology, there will be no research that has been done on this unique scenario. The literature review highlights any other technologies that have been utilized and any interesting information on what worked well or didn't. The literature review provided insight on important aspects of district cooling applications and provided the background required to have when talking with technology developers or potential users of the proposed solution.

(1a-ii) Identify and compare current technologies used in district cooling applications to determine a technological fit with the Eavor-Loop™ .

Investigation of district cooling technologies was completed through the use of a literature review. The literature review identified what technologies exist, the technical requirements of each, their primary source of fuel, the environmental impact of each, and how they vary globally. Information on the Eavor-Loop™ , how it works, and expected outputs and costs was provided by Eavor Technologies.

The information obtained in 1a led to the development of the following questions for interviews.

Questions developed for technology developers/ vendors included:

- What models do you have to offer in terms of hot water chillers?
- Are they fairly common within the industry?
- What are the absorption/ refrigerant agents used?
- What is the operating envelope? (Flow rate, temperature range, pressure)
- What are the parasitic losses of the chiller?
- What is the coefficient of performance? How does this change with inlet conditions?
- What would capital and operating costs range?
- What does maintenance look like?
- Can multiple units be used in sequence?
- What could be done if the hot water coming out is still useful?

Questions developed for university professors included:

- Can you tell me about some of your work regarding district cooling or geothermal applications?
- How do you see the industry moving forward?

- Do you find people seem to not think about cooling demands?
- In your experience, what energy is used for cooling and what sort of technology?
- What challenges have you come across with the use of geothermal?
- Where do you find the biggest setbacks in a practical application?
- Looking at district cooling applications, do you think there will be more success in implementing systems within the design of cities and architecture or will be people be willing to change infrastructure for a higher efficiency and decreased energy usage?
- Do you see developers and companies shifting towards looking to renewables to play these energy roles?
- Where do you think the ICT sector will go and how will it play a role?
- What will the effects of Covid-19, if any, be on the use of renewables in these applications?

(1b) Gather technical specifications of currently available, compatible technologies from subject matter experts to provide greater understanding of strengths and weaknesses of each technological variation as identified in 1a-ii.

Once compatible technologies were determined, interviews were conducted with subject matter experts in the field of cooling technologies. This was done through email, video chat and phone calls. The data collected from these subject matter experts outlined how various technologies work, confirming compatibility with the Eavor-Loop™ . Additionally, any strengths or weaknesses in the different technologies were identified. Eavor-Loop™ compatibility was assessed based on cooling efficiency given process conditions (location dependent), required maintenance, and what the costs associated with it would be, both capital (CC) and operating/maintenance (O&M). The data was collected, analyzed, and summarized in a chart so that multiple technologies could be compared. Potential subject matter experts identified include technology developers and university professors conducting research within the field of renewables and/or district cooling technologies. Promising technologies were used to create potential designs for the Eavor Cooling System which was run through a thermodynamic process simulator as outlined in 2a.

3.2 Objective 2

[2] *Integrate the surface and subsurface processes to maximize cooling efficiency.*

(2a) Perform thermodynamic process simulation work based on knowledge gained in objective [1] using Microsoft Excel software to do preliminary process definition on potential designs provided with Eavor-Loop™ process conditions.

Process simulations were completed for each potential design utilising a Microsoft Excel model provided by Eavor. Eavor provided access to the program as well as human resources, their subject matter expert on process simulations. Utilizing both of these resources, process simulations were run for all potential designs over a range of variables for both the Eavor-Loop™ and the applied technology. These variables included inlet temperature, available working pressure, and flowrate, as well as geological conditions provided by Eavor for the case study location. The data collected highlights the total thermal output, cooling output, efficiency of the system, parasitic loads, and sizing of equipment which was the necessary data used to optimize the design and calculate capital and variable operating costs. Uncertainty analysis was performed using individual and multivariable perturbations within the model. Data coming from the simulation highlights the value of these variables going into and out of each process unit as identified in the process flow diagram (PFD). Each cooling process has its own unique PFD, based on literature review and information gained from subject matter experts in objective [1] modified for integration with the Eavor-Loop™ .

(2b) Perform economic analysis of the new, full Eavor Cooling System; determine drivers which could make the economics more favourable (ex. Geography, output levels, cooling demands, ESG policies of potential users, etc.). This is critical as proof of technical feasibility is not sufficient for widespread implementation. In order to realize the benefits of the research, the proposed solution must be economically, as well as technically, feasible.

An economic assessment was conducted on the chosen, optimized design. The economic assessment includes a levelized cost of cooling (LCOC) calculation as well as standard project economics (NPV, IRR, PIR, and simple payback). Data from Eavor was provided for any Eavor-

Loop™ related costs (CC and O&M) in order to create an accurate economic model. Additionally, information collected from cooling subject matter experts in objective [1] was used for the analysis. From the economic assessment, a sensitivity analysis was completed to help determine important drivers that can make the financials more favourable. These drivers can include geography, output levels, cooling demands, electricity prices, population density, government regulations, and ESG policies of potential users. The program 'Crystal Ball' from the developer Oracle was utilized to perform the sensitivity analyses, providing a tornado chart. This chart can be a very useful tool when looking where a technology would have a better chance at being implemented or where Eavor could focus their efforts on reducing cost.

3.3 Objective 3

[3] *Determine the applicability of this new design within Canada and globally.*

(3a) Analyze potential applications of Eavor Cooling System; examine existing applications and perform a comparative analysis on various technological characteristics including cost, energy usage and fuel type (if applicable). This will shed light on the magnitude of applicability given new geological boundaries and create a case for why the Eavor system could be a competitive green solution compared to current methods.

Using the information obtained from objectives [1] and [2], a list of potential users was created. Data was gathered through emails or phone calls on what systems are currently employed for cooling, how much and what fuel is used, and how much this system costs. Additionally, publicly available data was used to understand the needs of each applicable user, find any public data for fuel use and emissions, and determine if there are any ESG initiatives that the Eavor Cooling System innovation could benefit. Using all of this information and the economic assessment from objective [2b], a competitive case for Eavor as an alternative, green solution was made. Some of the major factors that came into play are the drivers determined from the sensitivity analysis in objective [2b]. Potential users identified include businesses in need of reduction in GHG emissions that also face high cooling demands, building managers and developers, telecommunication companies, universities, industrial facilities, food storage warehouses, as well as governments (all levels). Methods used to find the right person to contact include reaching out to my professional network, LinkedIn, company/ government/ university websites, etc. In addition, the size of the district network or data center that the design could support was calculated.

(3b) Perform environmental analysis; Compare the GHG emissions of current cooling methods with the newly designed Eavor Cooling System. This will include the environmental footprint of the different systems and the amount of fuel reductions if a switch to the Eavor design was made. Research was conducted on current cooling methods to determine the GHG emissions, amount of fuel used, and environmental footprint of each. This data came from a combination of literature review and any information obtained in the interviews. A comparison of current cooling methods against the Eavor Cooling System was completed with the help and guidance from Eavor employees. Any lifetime emissions from the construction of the Eavor-Loop™ were taken into account.

CHAPTER 4: LITERATURE REVIEW

In order to truly understand what was required for the surface facility in the design, an in-depth literature review was completed on current uses of geothermal energy within district cooling systems. This chapter will detail the key findings from each current practice, and the technologies that were employed in order to aid with the final decision for the design.

4.1 Geothermal Energy in DCS

The first real world application comes from research from Tugcu and Arslan (2017). A single-stage absorption refrigeration system (aka an absorption chiller) utilizing a working fluid of NH_3-H_2O was optimized for below 0°C food preservation cooling needs within the Simav region of Turkey. Traditional geothermal resources found in the Simav geothermal field was modelled as the hot water source for the refrigeration unit. The fluid was tested at different concentrations of NH_3 and H_2O with an input temperature of 110°C and outputs consisting of cooling effect coefficient, exergy efficiency, and net present value. The run time for this unit was determined to be 4500 hours based on local data. Depending upon the specifics required for different food products (grapes, apples, and quince), payback periods were calculated to be 7, 13, and 18 years with an NPV ranging of 27.183, 6.328, and 1.778 million (US$) respectively. In this geographic region, the design for the food preservation unit was worth investing in as noted by the positive NPV. No environmental analysis was completed.

The second real world application comes from research from Rogowska (2003) on the use of an absorption cooling system for the city of Stargard Szczecinski, Poland. Exploration confirmed that Poland has extensive low-enthalpy waters (~60% of the region) ranging from 30 to 130°C at accessible depths of 1 to 4 km. Flow rates of the reservoir ranged from a few L/s up to 150 L/s, adding to the suitability of the low-enthalpy water. Additionally, cooling needs within Poland is increasing such that some buildings require air conditioning year-round. In order to meet these needs, fossil fuels are employed in order to cover peak loads as well as the production of the electricity. In order to run these A/C systems, a great deal of electricity consumption is required.

As these cooling needs grow, Poland will require a greater deal of electricity, which means the increased use of fossil fuels and with that CO_2 emissions. Given the time that this academic paper was written, approximately 5 years after the Kyoto protocol, many nations were looking to utilize renewable energy sources in order to limit GHG emissions. Rogowska saw this an opportunity to look for a renewable energy solution to the growing cooling demands of Poland. The biggest issue outlined with current cooling practices was the use of the mechanical vapour compression cycle, a process that requires a great deal of electrical input. Rogowska (2003) highlighted four main methods for cooling load production as seen in Table 1.

Table 1: Four main methods used for cooling load production

	Compression chiller	**Absorptive chiller**	**Adsorptive chiller**	**DEC**[1]
Physical cooling -effect	Vaporisation of refrigerant			Evaporation of refrigerant
Kind of compression	Mechanical compression	Thermal, absorption loop	Thermal adsorption of water steam	Sorptive drying
Power source	Electrical energy	Heat energy 85-180°C	Heat energy 55-95°C	Heat energy 50-100°C
Refrigerant agent	Chlorinated CHC or chlor free hydrocarbons	Water with LiBr or NH_3 as absorption agent	Water with solid as adsorption agent (Silica-Gel)	Water
Coefficient of performance[2]	1.3-1.65	0.6-1.0	0.4-0.6	0.3

[1] Desiccative and evaporative cooling;
[2] Coefficient of performance = Ratio of received cooling load to employed heating load, 0.6-1.0 by absorptive chillers means that 1 kWh heat provides 0.6-1.0 kWh cold.

Source: (BHKW Infozentrum Rastatt, 2003, as cited in Rogowska, 2003)

The working absorption and refrigerant agents that are used within thermal compression systems can vary. These pairs are seen in Table 2.

Table 2: Various pairs of fluids used in cooling systems

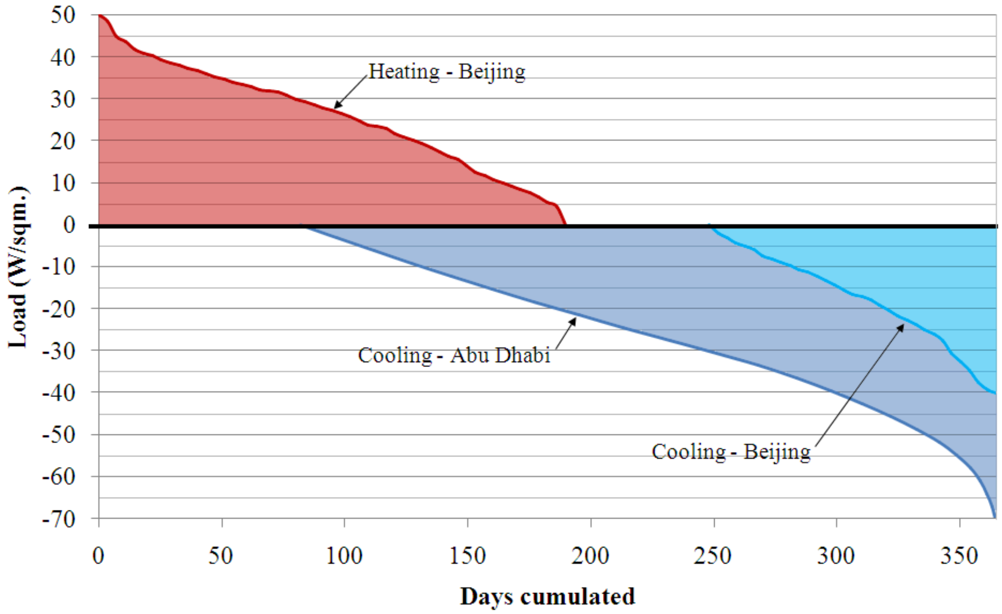
	Absorption agent	Refrigeration agent
Liquid working fluids	Lithium bromide (LiBr) Water (H_2O) LiCl	Water (H_2O) Ammonia (NH_3) Water (H_2O)
Soild adsorbents	$CaCl_2$ Active coal Zeolites, silica-gel	Ammonia (NH_3) Ammonia (NH_3) Water (H_2O)

Source: (Rogowska, 2003)

The system suggested for the city needs included a 500 kW LiBr-water absorption chiller that utilized the low-enthalpy water and provided an overall COP of 0.71 for the chiller. An optimization of the internal components of the chiller was taken into account when designing the system.

The third application comes from research conducted by Jóhannesson and Chatenay (2014) out of Reykjavik, Iceland. The main purpose of this academic research was to discuss the parameters surrounding geothermal space cooling and make a competitive case for widespread implementation. The use of geothermal heat pumps is very common in Europe and can be used for both heating and cooling applications. Once again, for cooling, the heat source is used as the driving force, removing the need for extensive electricity required to run a compressor. With increasing costs for electricity and a global drive towards decarbonisation, geothermal driven absorption chillers are becoming more popular. A system needs to be designed with regards for building characteristics, local weather, and load requirements in mind. Depending where you are, the needs can vary greatly. For example, the load duration curves for both Abu Dhabi and Beijing can be seen below in Figure 3. You will notice that Beijing requires both heating and cooling while Abu Dhabi's cooling needs are much greater.

Figure 3: Load duration curve for Beijing and Abu Dhabi



Source: (Jóhannesson & Chatenay, 2014)

Jóhannesson and Chatenay (2014) identify the main cooling methods used in today's society as a mechanical run compression chiller and thermal absorption chiller. The characteristics of these can be seen in Table 3.

Table 3: Common cooling methods

Chiller type	**Compression**	**Absorption**
Compression type	Mechanical	Thermal absorption loop
Energy source	Electric power	Heat energy 85°C–150°C
Refrigerant agent	Halons, chlorinated CHC, Chlorine free hydrocarbons	Water with lithium bromide as an absorption agent
COP	4-6	0.6–1.0

Source: (Jóhannesson & Chatenay, 2014)

The typical operation ranges for each of these methods can be seen below in Table 4.

Table 4: Typical operation ranges of each cooling method

Chiller Type	Compression	Absorption
Energy Source	Electricity	Hot water (85 -150°C)
Cooling Water Temp (°C)	27/35 (from cooling tower)	27/35 (from cooling tower)
Chilled Water Temp (°C)	16/6 (space cooling)	16/6 (space cooling)
COP	4-6	0.7 single stage; 1.2 double stage
Cost	----	20 – 50% more than standard compression machine

Source: Data collected from (Jóhannesson & Chatenay, 2014)

Although the compression chiller has a higher COP, the choice of technologies should take into account the entire process, including the production of electricity. For example, if you were to look at a geothermal heat source, there would be two options. You could convert it into electricity in order to run a compression driven chiller or use the heat energy directly with the lower COP absorption chiller. The results of this analysis, using the average COP for both technologies can be seen below in Table 5 (Jóhannesson & Chatenay, 2014). When the source of energy is coming from geothermal, it will actually take 2 kWh heat to produce 1 kWh of cooling load through the compression driven chiller versus 1 kWh heat to produce 1kWh of cooling load through the absorption chiller. Site specific energy sources are dependent upon location and availability.

Table 5: Energy output vs. energy input

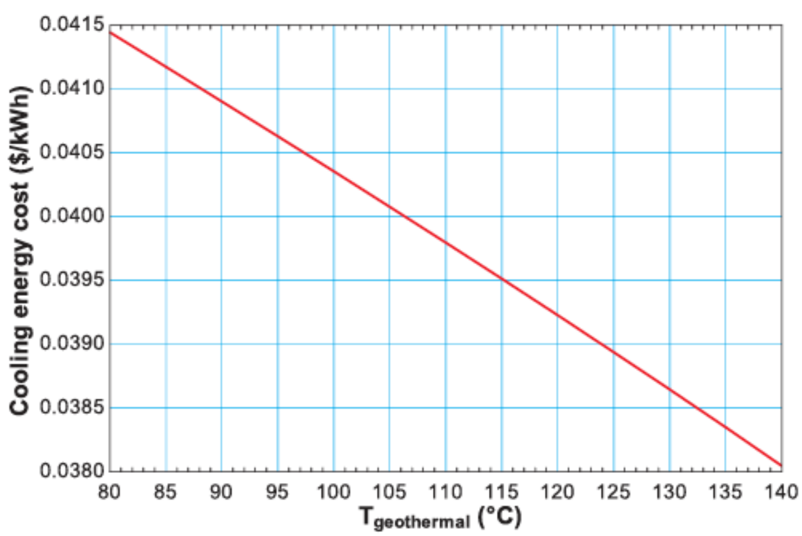
Machine	COP	Energy source	Initial energy input at the chiller	Output
Compressor driven chiller	5	Electricity	0,2 kWh to deliver 1 kWh chiller effect	1 kWh
Absorption chiller	1	Geothermal hot water, 120°C	1 kWh heat to deliver 1 kWh at the chiller. No losses are expected to occur between the well and the chiller	1 kWh
Electricity		Geothermal hot water, 120°C	2 kWh heat from geothermal used to produce 0.2 kWh electricity (10% thermal efficiency)	0.2 kWh

Source: (Jóhannesson & Chatenay, 2014)

Ultimately, Jóhannesson and Chatenay (2014) determined that geothermal space cooling can be a viable, dependable, commercially competitive solution with its main advantages being the reduction of GHG emissions and increased national energy sufficiency.

The fourth application comes from research conducted by Yilmaz (2017) on a geothermal powered absorption cooling system for buildings within Izmir City, Turkey. Turkey has great potential for the use of geothermal energy with many of the current applications utilizing the primary energy source for heating needs. At the time of publication, Turkey had 17 geothermal district heating systems. The hot water characteristics considered for the modelling was 100°C with a flow rate of 100 kg/s. The absorption chiller chosen used a working fluid of ammonia-water with a COP rating of 0.441. Generally, for the absorption chiller, the COP will decrease as the source temperature lowers from standard ratings. The peak cooling load of the system considered was 3713 kW. A levelized cost of cooling (LCOC) was completed. This can be seen in relation to source temperature for the region in Figure 4.

Figure 4: LCOC variations for geothermal source temperature

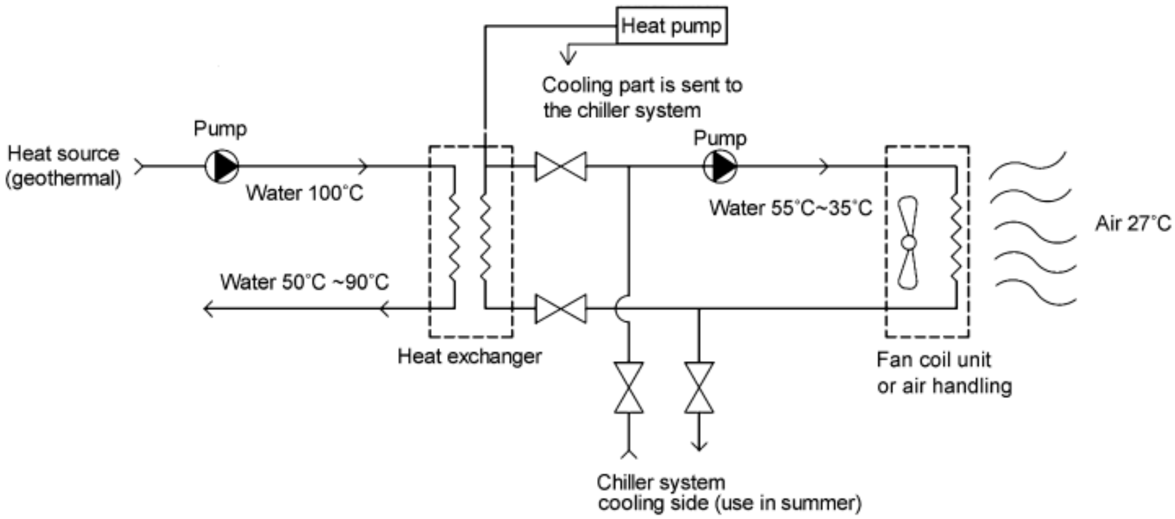


Source: (Yilmaz, 2017)

After the use of thermodynamic and economic modelling, it was determined that the system had a payback period between 5 and 9 years with a positive return on investment. Existing systems were given feedback of high satisfaction (Yilmaz, 2017). It does not appear that an absorption chiller with a working fluid of LiBr/water was considered for the application. This could just be a limitation as the authors were looking to compare to similar systems within the region.

The fifth real world application comes from research by Tsai et al. (2014) at the Sea Gaia Spring Hotel in Taiwan. The hotel used low-grade geothermal water to assist the air-conditioning systems (heating and cooling) in an effort in an effort to reduce harmful pollutants from a diesel-fuelled boiler and lower electrical costs. Climate change has had a noticeable effect on Taiwan, changing the local climate to dry, hot summers and wet, cold winters from that of a humid, subtropical one. Because of these changes, there was a demand increase for the use of these systems, increasing energy consumption. Thanks to the proximity to the Tatun Volcano Distribution, shallow geothermal deposits were present. Before the use of this new system, the hotel depended upon electrical run appliances with the addition of a diesel-fuelled boiler for early deployment of heating. The geothermal assisted air-conditioning system can be seen in Figure 5.

*Figure 5: Geothermal assisted air-conditioning system at the Sea Gaia Spring Hotel**



Source: (Tsaia et al., 2014)

*Note: The temperature of the incoming hot water is ~100°C and the system has both heating and cooling components.

The geothermal assisted system greatly reduced both water and electricity expenses and emissions. The payback period for the unit when compared to the diesel-fuelled boiler was 4-5 years with annual fuel savings from the diesel. Overall, the electricity consumed was reduced by 26% for the hotel with the geothermal assisted unit. It was recommended that the hotel work towards implementing a fully dependable geothermal unit to reduce electricity and emissions in the long term (Tsaia et al., 2014).

4.2 Absorption Chillers

Based on the real-world applications, it became very evident that absorption chillers were the most common technology utilized when dealing with a geothermal source due to the flexibility of the units and no need for mechanical compression. This next section will go into more depth on the technology and how it operates.

Absorption chillers have been around for over 75 years and work off of a few main basic principles. These principles include (Dixit, 2018b; LG, 2018; Rogowska, 2003):

- the use of a heat source to evaporate pressurized refrigerant from a solution;
- the affinity between the absorption agent and refrigerant agent; and
- within vacuum conditions, water will boil, and flash cool itself.

Commercially, absorption chillers have two main pairs of working fluids. The characteristics of the these can be seen in Table 6. The LiBr/H_2O pair is more commonly used for air conditioning of buildings whereas the H_2O/NH_3 pair is used for industrial refrigeration and ice production (Rogowska, 2003).

Table 6: Comparison of single-effect vapour absorption technology [absoprtion agent/ refrigeration agent]

	LiBr/H_2O	**H_2O/NH_3**
Heat source oper. temp. (˚C)	80-110	120-150
Cooling operat. temp. (˚C)	5-10	<0
Cooling capacity (ton)	10-100	3-25
COP	0.5-0.7	0.5
Current status	Large water chiller	Commercial
Remarks	1. Simplest and widely used; 2. Using water as refrigerant, cooling temperature is > 0˚C; 3. Negative system pressure; 4. Water cooled absorber is required to prevent crystallization at high concentration.	1. Rectification of refrigerant is required; 2. Working solution is environmentally friendly; 3. Operating pressure is high; 4. Suitable for using as heat pump due to wide operating range.

Source: (Srikhirin et al, 2001, as cited in Rogowska, 2003)

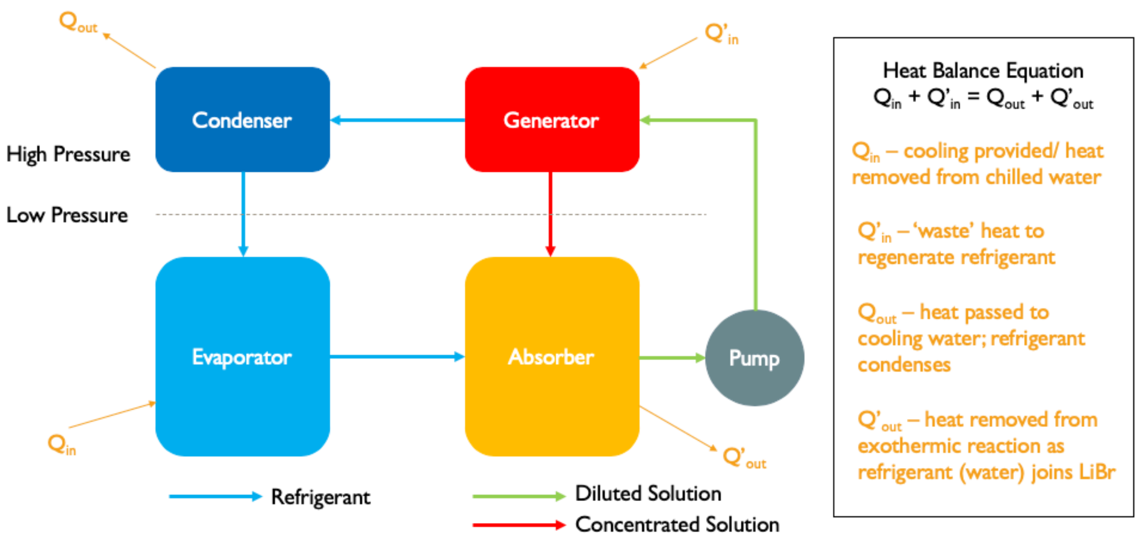
The absorption chillers themselves can come in a single-stage or double-stage operational design. The double-stage design can only operate at higher temperatures, often that above 140°C, requiring either high pressure steam or exhaust heat from a fossil fuel source (US Department of Energy, 2017). As seen in Table 4, the COP for a single-stage was 0.7, whereas double-stage was higher at 1.2. Although this may seem like a positive for the double-stage chiller, the source heat is often harder to produce, maintenance costs increase due to complexity, and the units themselves are often much more expensive (US Department of Energy, 2017). Technological advances and the increased presence of absorption chillers on the market has led to COP improvements, more specifically for the low- to medium-grade hot water energy sources. A single-stage absorption chiller can have a COP as high as 0.84 (Santini & Dwyer, 2016). Like any other technology, different developers will have unique components within the chiller that can provide a better efficiency, increase heat transfer, reduce space requirements, reduce required maintenance, and overall lower the costs of the units. No two units are the same. The sizing of the unit and the temperature of the incoming heat source can affect the ability for the chiller to remove the heat, and the required pressure drop to maintain operation. With facilities looking for a clean, cost-effective solution to their cooling needs, absorption chillers could become much more mainstream at an exponential rate (Dixit, 2018a)

Overall, absorption chillers can provide quiet, reliable, and cheap cooling, which is especially important for regions where electricity is expensive. Other advantages of absorption chillers when compared to traditional vapour compression units include the use of heat energy for the generator (waste heat or renewable source), reduced electrical requirements, reliability due to reduced moving parts, low-noise and vibration free, longer life, reduced operating costs, and environmentally friendly working fluids (Rogowska, 2003).

4.2.1 Absorption Chiller Operation

The process itself is very similar to that of the vapour compression cycle. However, the absorption chiller uses a chemical cycle as opposed to that of a mechanical one (Santini & Dwyer, 2016; US Department of Energy, 2017). A generator, absorber, and solution pump replace the electric motor and compressor (US Department of Energy, 2017). A simplified cycle of the process can be seen below in Figure 6. In the simplified diagram, the waste heat would be the energy source, whether it be from geothermal energy, or byproducts of combustion.

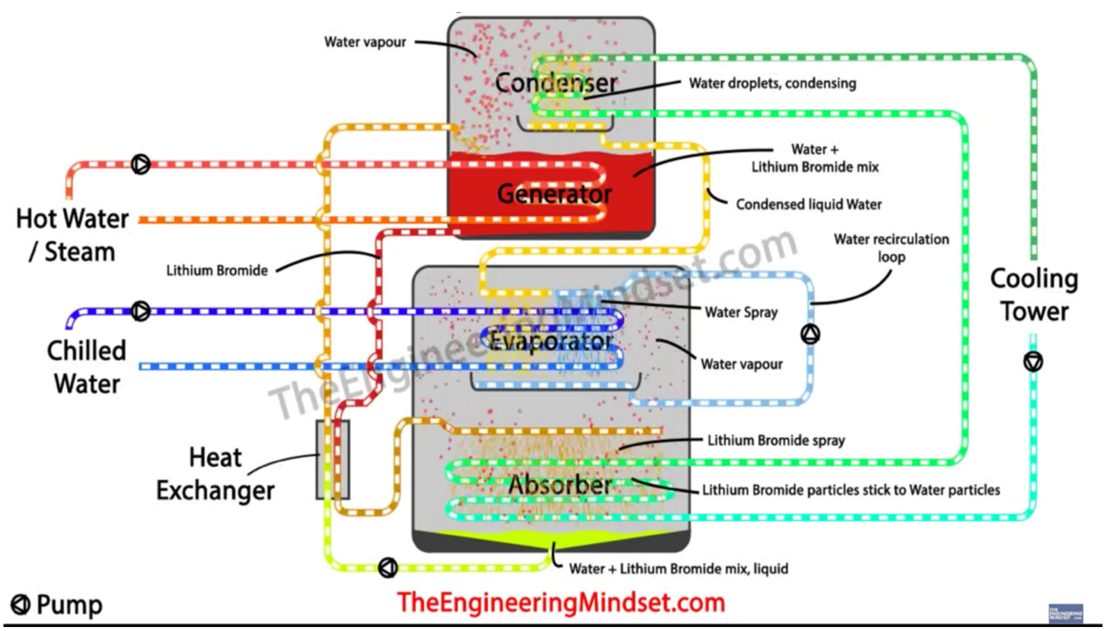
Figure 6: Simplified absorption cycle



Source: Adapted by (Author, 2020) from (Santini & Dwyer, 2016)

A more in depth look at the technology can be seen in Figure 7 below.

Figure 7: In-depth depiction of absorption chiller process



Source: (Evans, 2017)

It is important to note that there are three separate closed loop systems required to operate the chiller. There is one for the heat source, one for the chilled water moving throughout the buildings, and one for the water moving through the cooling tower. The separate systems are necessary in order to keep the fluid characteristics of each controlled and within allowable ranges, while eliminating the possibility of the different fluids to mix. Evans (2017) has outlined the step-by step, continually operating process (for a LiBr/ Water chiller) as the following:

1. Water and LiBr solution are pumped from the absorber to the generator to form a reservoir for the solution, passing through a heat exchanger
2. A heat energy source (hot water or steam) is piped through the reservoir in the generator, causing the water to evaporate out, and separating the LiBr and water.
3. The concentrated LiBr (heavier than the solution), sinks to the bottom, and is piped through the heat exchanger into the absorber to be sprayed. This is where the LiBr will be reunited with water molecules (which they have an affinity for) and rejoin into a solution.
4. Meanwhile, the water vapour rises into the condenser, where it is turned back into liquid form as the heat energy is removed by water being piped through from the cooling tower. This condensed liquid water flows down to the evaporator through a pipe.
5. Once in the evaporator, the condensed liquid is sprayed over the chilled water circulation loop. Since the evaporator is kept at a very low pressure, it acts like a vacuum*. In this scenario, liquids will boil at low temperatures. The condensed liquid will flash (evaporate into steam), taking with it the excess heat energy from the chilled water. The chilled water will leave the evaporator at a cooler temperature than it came in and go out to the customer to cool down buildings.
6. Any liquid water that was not evaporated is collected and recirculated through the evaporator.
7. The water vapour (or steam) that is produced within the evaporator is strongly attracted to the LiBr spray that is occurring within the absorber. The LiBr and water particles join together, forming the mixture, and beginning the journey all over again.

*The vacuum in the evaporator is created by the strong attraction between the LiBr and water particles.

8. Any remaining heat within the absorber is removed by the cooling tower loop.

4.2.2 Generic LiBr/H_2O Absorption Chiller Data

As mentioned previously, no two chillers are the exact same. The following tables outline some generic metrics for both performance (Table 7)and costs (Table 8) for a LiBr/H_2O chiller. Costs are in US$.

Table 7: LiBr/H_2O absorption chiller performance characteristics

Description	System						
	1	2	3	4	5	6	7
Design	Single stage			Two stage			
Heat Source	Hot Water		Steam (low pressure)	Steam (high pressure)		Exhaust Fired	
Nominal Cooling Capacity (tons)	50	440	1,320	330	1,320	330	1,000
Thermal Energy Input							
Hot Water Inlet Temp (°F)	190	208	n/a	n/a	n/a	n/a	n/a
Hot Water Outlet Temp (°F)	181	190	n/a	n/a	n/a	n/a	n/a
Steam Pressure (psig)	n/a	n/a	14.5	116	116	n/a	n/a
Exhaust Gas Temperature (°F)	n/a	n/a	n/a	n/a	n/a	530	850
Heat Required (MMBtu/hr)[2]	0.85	7.1	20.1	2.8	11.2	2.9	8.7
Energy Output (chilled water)							
Inlet Temperature (°F)	54						
Outlet Temperature (°F)	44						
Cooling COP (full load)	0.70	0.74	0.79	1.42	1.42	1.35	1.38

Note: Performance characteristics are based on multiple sources, including vendor data and discussions with industry experts. The characteristics are intended to illustrate typical absorption chillers, and are not intended to represent performance of specific products.

Source: (US Department of Energy, 2017)

Table 8: LiBr/H_2O absorption chiller capital and O&M costs

Description	System						
	1	2	3	4	5	6	7
Design	Single stage			Two stage			
Heat Source	Hot Water		Steam (low pressure)	Steam (high pressure)		Exhaust Fired	
Nominal Cooling Capacity (tons)	50	440	1,320	330	1,320	330	1,000
Equipment Cost ($/ton)	$2,010	$930	$820	$1,190	$1,000	$1,330	$930
Construction and Installation ($/ton)	$3,990	$1,370	$980	$1,810	$1,200	$1,970	$1,070
Installed Cost ($/ton)	$6,000	$2,300	$1,800	$3,000	$2,200	$3,300	$2,000
O&M Costs (¢ / ton-hr)	0.6	0.2	0.1	0.3	0.1	0.3	0.1

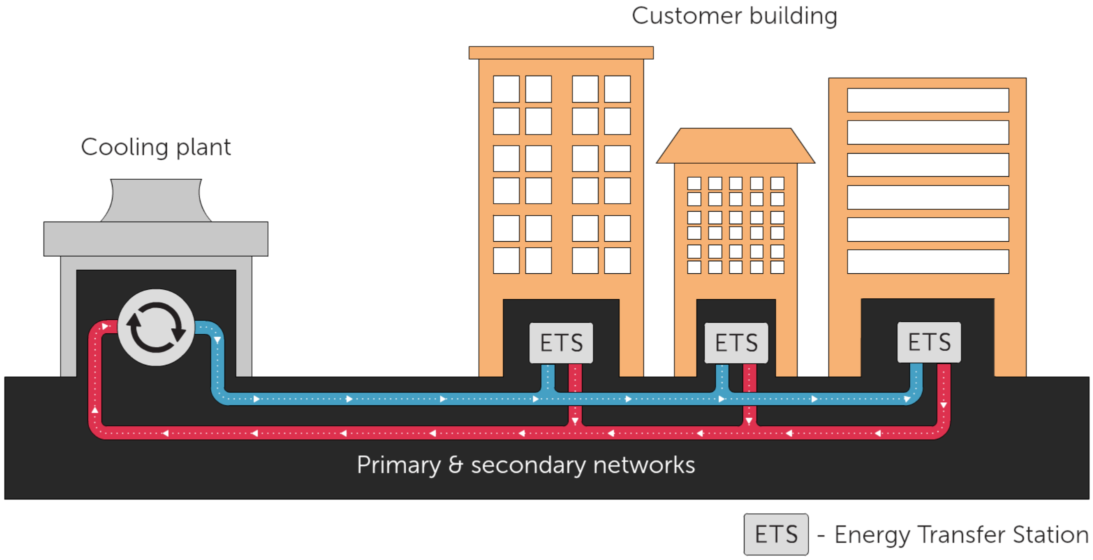
Note: Costs are based on multiple sources, including vendor data and discussions with industry experts. The values shown are composite results, and are not intended to represent a specific product.

Source: (US Department of Energy, 2017)

4.3 District Cooling

District cooling operates off the same principles of a district energy network. A single, centralized cooling plant will produce chilled water that can be distributed through underground, insulated pipes to meet the demands of a network of buildings (IDEA, n.d.). Customers can include residential, commercial, or industrial applications (Rogowska, 2003). Each individual building will have its own energy transfer station (ETS), which collects heat from the building and sends it back to the main cooling plant through a closed loop system. The building, with heat removed, can now recirculate chilled water throughout its space in order to maintain a cooling effect (IDEA, n.d.). Typically, one centralized plant will take care of a few dozen buildings, however this is dependent upon the energy demands of the buildings within the system. With increasing temperature, the use of more equipment like computers, lighting, and passive heating, cooling demands can exist year-round. District cooling systems can be found in Japan, the USA, Korea, and Europe (Rogowska, 2003). This depiction can be seen in Figure 8 below.

Figure 8: Example of a district cooling system



Source: (Salih, 2019)

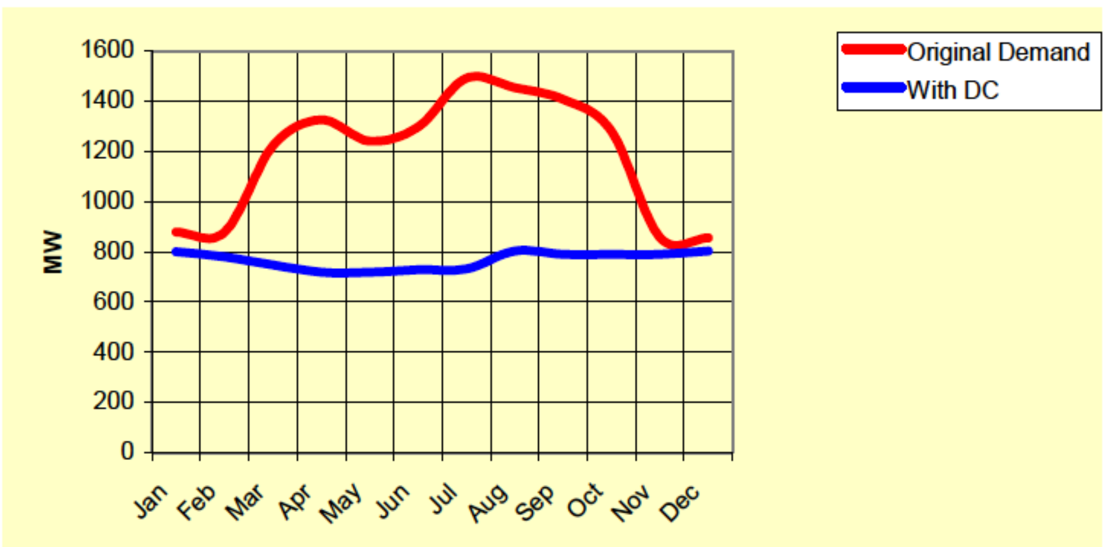
When compared to building-specific systems, district cooling is more cost-effective and environmentally friendly (Rogowska, 2003). This is often due to the use of industrial-grade equipment (highly-efficient), economies of scale (cheaper costs per tonnage of capability), and the ability to use natural, renewable sources or 'waste' heat from combustion that would otherwise go unutilized (IDEA, n.d.). One of the biggest benefits from a district cooling system is the reduced strain on electrical grid. Given that many traditional systems employ electricity as its source of energy, air conditioning demands can account for 50 – 70% of peak electricity demand (IDEA, n.d.).

The many benefits of district cooling systems include (Dalin & Rubenhag, 2006; Jóhannesson & Chatenay, 2014):

- Cost-competitive when compared to traditional systems;
- Energy performance is better (higher efficiencies);
- Investment costs for users reduced;
- Saved space which can be allocated to other uses as opposed to large equipment;

- Reduction in sound pollution;
- Reduction in GHG emissions when utilizing renewable vs. fossil fuels;
- Reduction in peak electricity demand (Figure 9);
- Flexibility and efficiency of cooling production technology; and
- Increased energy security and reliability.

Figure 9: Reduction in peak demand due to DC systems in the EU



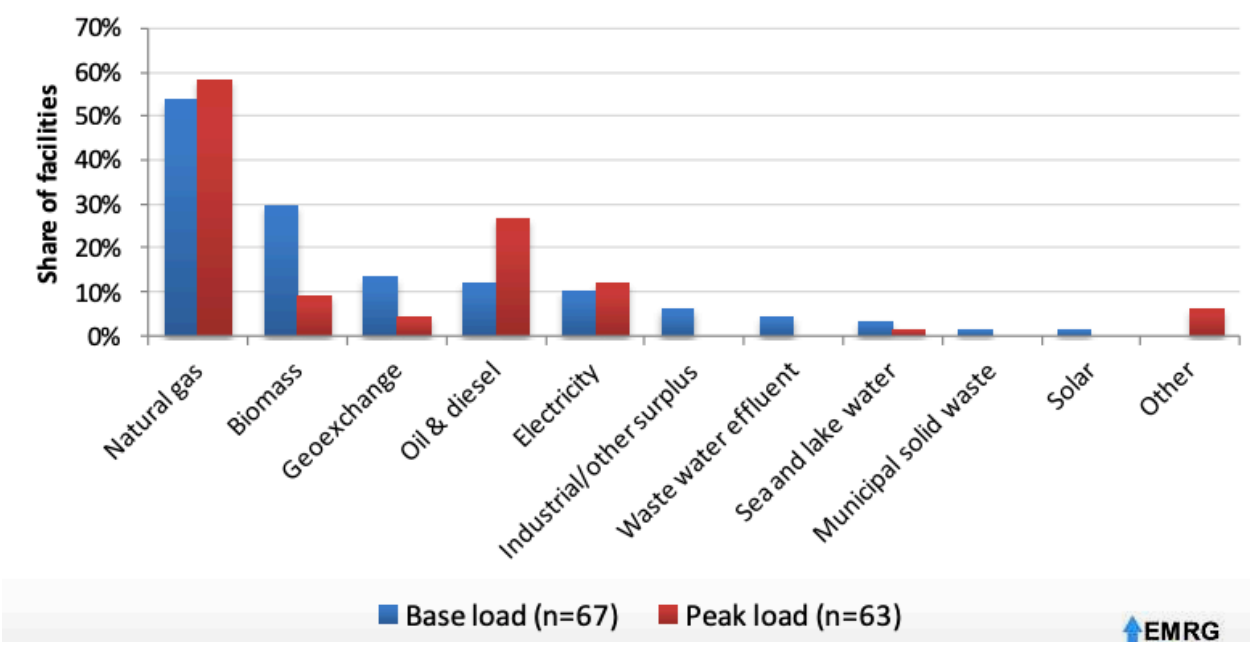
Source: (Dalin & Rubenhag, 2006)

District cooling networks are quite common within the EU; with Sweden, Germany, Italy, France, and Spain leading the way. They are generally operated by energy utility companies and used within heavily populated areas (Dalin & Rubenhag, 2006). Regulations put in place by the European Commission regarding the energy performance of new buildings and the renovation of existing buildings have helped to play a part in this (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019).

These sorts of networks are not as popular in North America. However, this is increasing due to climate change concerns, the increased popularity in clean energy technology, and energy resiliency. Buildings have been identified as the third largest GHG emitter, behind oil and gas and transportation. Approximately 2/3 of energy consumption within Canadian buildings is associated with heating and cooling needs. Some of the networks in Canada are specifically for cooling demands, while a few address both heating and cooling. The majority of district energy networks in Canada are for heating needs due to the geographical location and climate of the region. Some of the locations of these networks include Vancouver, Toronto, and smaller communities within the Yukon and Manitoba (Chung, 2019).

Canada has over 100 facilities that are used for district energy with over half of them located in Ontario and BC. 50% of these facilities were put into operation between 2000 and 2012 and have expansions planned for the future. Based off of the reporting facilities (67 of them), each facility served an average of 39 buildings, with the largest serving 302 buildings, and majority served more than one building type. Natural gas and biomass were the two leaders for base energy supply. This can be seen in Figure 10. A large portion of these facilities still use fossil fuels or electricity to run their operations (Nyboer, 2014).

Figure 10: Base and Peak Load energy supply (heat and cool) of the 67 reporting facilities



Source: (Nyboer, 2014)

District energy network applications are going to increase globally as the proven benefits become mainstream knowledge and clean energy technology becomes more viable through technology improvements and reduced capital costs from industry learning. They will play an important role in meeting emission targets, decarbonizing energy production, and increasing national resiliency.

CHAPTER 5: RESULTS & ANALYSIS

This section details the major findings of the project, as broken down into each objective and sub-objective that was presented in the methodology. Given the design of the project, information gathered at each stage was critical in the ultimate design with many iterations happening as new information was gathered.

5.1 Objective 1 Findings

Objective 1 focuses on the development of the surface facility, specifically the technology that will be used in order to provide an effective cooling load in the district cooling application.

5.1.1 Objective 1a – Literature Review

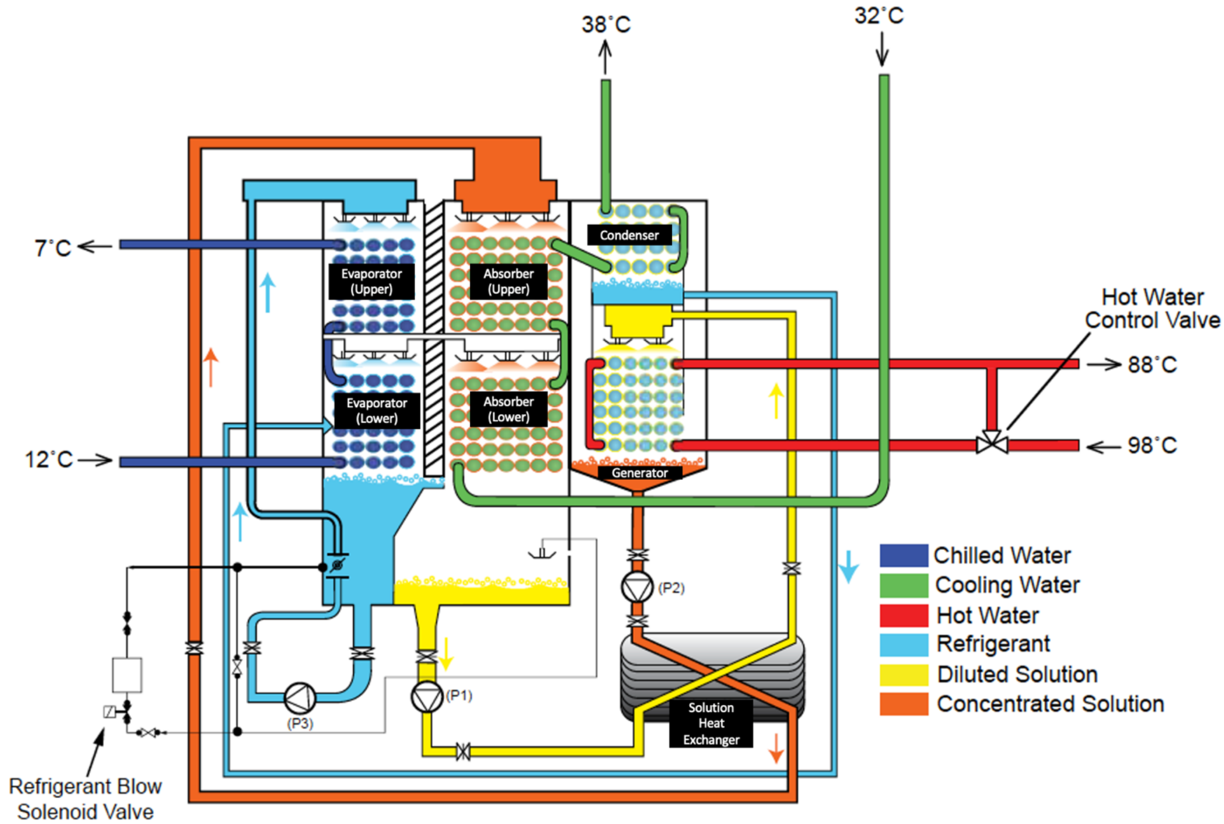
Geothermal energy is not as common in cooling applications as it is in heating applications. There were only a handful of academic papers highlighting some of these real-world examples. The papers mentioned all came from areas of known geothermal activity and none were in regard to North American application. Absorption chillers tended to be the technology of choice. The main reasons that these systems had been looked at were done so in an effort to reduce GHG emissions and the demand upon the electrical grid. Between the 1997 Kyoto Protocol and the 2015 Paris Agreement, nations are beginning to look for alternative solutions to meet their energy demands that are much more environmentally friendly. Through the use of district networks integrated with renewable energy, this can be achieved.

It became very obvious that absorption chillers were the most common and simplistic solution that could convert the primary heat energy directly into a cooling load. Table 1 highlighted the four main methods for cooling production. Mechanical compression was eliminated due to the large electrical needs and the inability to directly use primary thermal energy. Adsorption chillers were eliminated due to the low COP and small range of incoming temperatures. Desiccative and evaporative cooling was eliminated due to its low COP, requirement of hot, drier climates, varying effectiveness dependent upon the ambient air, and lack of industrial applications with a geothermal energy source. Ultimately, the absorption chiller was chosen. In addition to its commonality and simplicity, the range of temperatures acceptable at the inlet was quite large, the fluids used (LiBr/H_2O) were environmentally friendly, and the technology itself has been increasing with new developers finding ways to make them even better at converting the thermal energy. The Eavor-Loop™ itself can provide a range of characteristics due to the ability to control the working fluid within the system to achieve desired temperature and pressure ranges.

5.1.2 Objective 1b – Technical Specifications of Absorption Chillers

There were many different models and designs of absorption chillers available on the market. The four main developers of the technology included LG, York, Trane, and Thermax. The different models (and their various properties) that were looked at as being potentially compatible with Eavor-Loop™ technology can be seen in Appendix A. COP's ranged from 0.6 to 0.81 for a single-stage design with compatible source temperatures ranging from 70 to 160°C. There was one double-stage model from Trane that could obtain a COP of 0.9 to 1.2, but source temperatures would need to be closer to 188°C. Although these high temperatures could be possible in the right geologic zone, a double-stage absorption chiller would not be utilizing low- or medium-grade geothermal resources. Interviews were conducted with Johnson Controls, a certified supplier for the York absorption chillers and information from Thermax was also personally received. Both suppliers utilized an advanced, two-step evaporator-absorber process within the chiller. These components are identifiable by the dark blue and green depiction of piping in Figure 11 below. Essentially, by dividing each component into two sections, they operate at different temperatures and pressures, improving the efficiency of the process, lowering the required incoming thermal energy, and decreasing overall LiBr concentration within the process (Johnson Controls, 2019).

Figure 11: Depiction of York absorption chiller with two-step evaporator-absorber process



Source: (Johnson Controls, 2019)

*Note: the two-step process reduces required energy by 10% and the overall LiBr concentration from the conventional 60 – 57% to 58 – 54%. The concentration of the LiBr is important as you don't want crystallization, and any reduction will minimize this.

Johnson Controls (personal communication, June 24, 2020) was able to confirm that the Eavor-Loop™ would indeed be compatible with absorption chiller technology, and that any additional valves or components could be added to ensure optimized compatibility. While the chillers were not a popular sell in Canada, due to limited applications of geothermal energy in cooling, the York YHAU-CH Model (incoming hot water temperature range of 100 - 160°C) was available. The alternative model, the York YHAU-CL is designed for lower temperatures of 70 – 99°C. Johnson Controls was able to run scenarios based on an incoming heat source (given a specific temperature and flow rate), in order to determine what the required pressure would be, the change in temperature of both the incoming hot water and the chilled water, the COP, and any electrical requirements for operation. An example of these data sheets can be seen in Appendix B.

A professor out of the University of Manitoba, Eric Bibeau (personal communication, June 19, 2020) identified that the issue regarding the use of renewables like geothermal in cooling applications isn't the lack of technology, more so getting communities onboard with these higher upfront costs for district networks and specialized technology and getting around any blockages coming from the municipalities or utilities. North America seems to have this aversion with piping heat. It's cheaper, primary energy, that should be used for heating and cooling as opposed to electricity. Electricity should be saved for sectors where it will be critical in the coming years, such as transportation. Additionally, the water molecule has the highest heat capacity of any known fluid, and thus should be utilized in these applications. In order to get district cooling networks in the ground, the right play needs to be made with a willing community. Once the benefits are proven and seen, widespread implementation will follow as more communities and governments get on board.

5.2 Objective 2 Findings

Objective 2 focused on the integration of the chosen technology (absorption chillers) with the Eavor-Loop™ in order to maximize the cooling load that can be provided. Technical and economic feasibility was assessed in this section. In order to select the appropriate absorption chiller model, a case study location was chosen to run the design simulation. A data center in California was selected for the case study. There were many factors that played into this decision. These included:

- High, stable, year-round cooling demands needed within data centers (which are most often met with the needs with a large amount of electricity);
- Volume of data centers within the state, with lots of technology companies that are looking to decarbonize and 'go green';

- Suitability of the area for high geothermal temperatures due to the igneous rock play type (rock thermal conductivity of 2.5 W/mK);
- Location of the igneous rock within 3 to 5 km from the surface;
- Availability of subsurface data and model (Eavor-Loop™ process conditions provided by Eavor);
- Well known, high electricity prices;
- An electrical grid with natural gas as its main electrical producer; and
- Electrical grid issues plagued by blackouts and the inability to meet demand (lack of reliability);

*Please note: It was assumed that the designed cooling load would be required 100% of the year in order to meet the stable demands.

Because of time constraints, one supplier of absorption chillers was chosen as the priority unit for modelling. The York YHAU-CH model (with a cooling capacity of 1000 Refrigeration Tons [RT]), supplied by Johnson Controls was chosen for its two-step design, incoming temperature range of 100 - 160°C, availability in both Canada and the US, high COP of 0.78, and large cooling capacities (ranging up to 1,600 RT or 6,100 kW). Additionally, Johnson Controls was the most receptive to the initial request; willing to put in effort to aid in the research and help with understanding how the two technologies could be put together.

5.2.1 Objective 2a – Thermodynamic Process Simulation

Using basic thermodynamic principles, the maximum amount of heat energy that you can have in a fluid can be calculated using Equation 1.

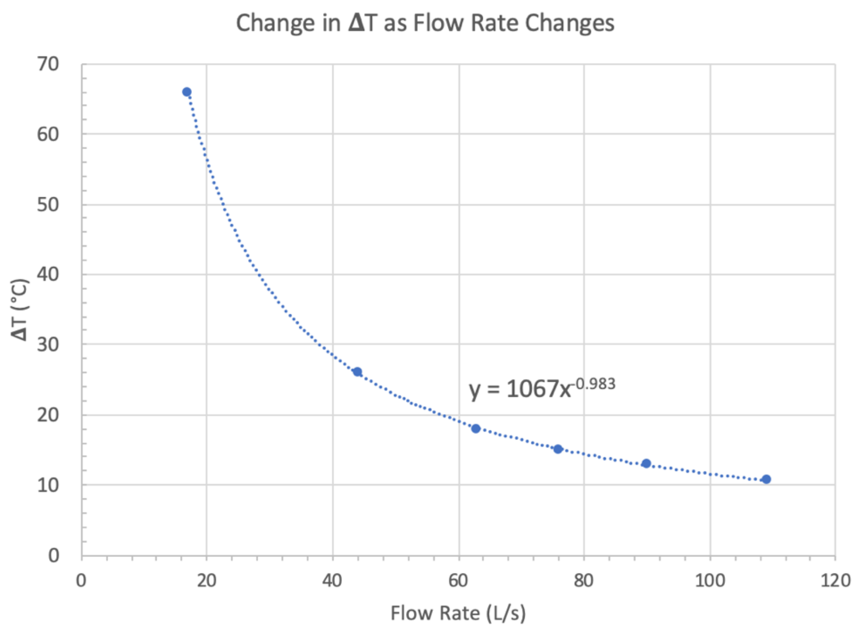
Equation 1: Specific Heat Formula

$$Q = m * C_p * \Delta T$$

Where: Q is heat energy; m is flow rate; C_p is specific heat capacity; and ΔT is the change in temperature

Within the absorption chiller, the change in temperature is a critical piece of information required to complete the design. The slower the flow rate, the more time the chiller has to remove heat energy from the hot water. Using data sheets (like the one seen in Appendix B) provided by Johnson Controls (personal communication, June 2020) for the YHAU-CH model, a regression model, seen in Figure 12, was completed to determine the relationship that ΔT had when compared against the incoming flow rate.

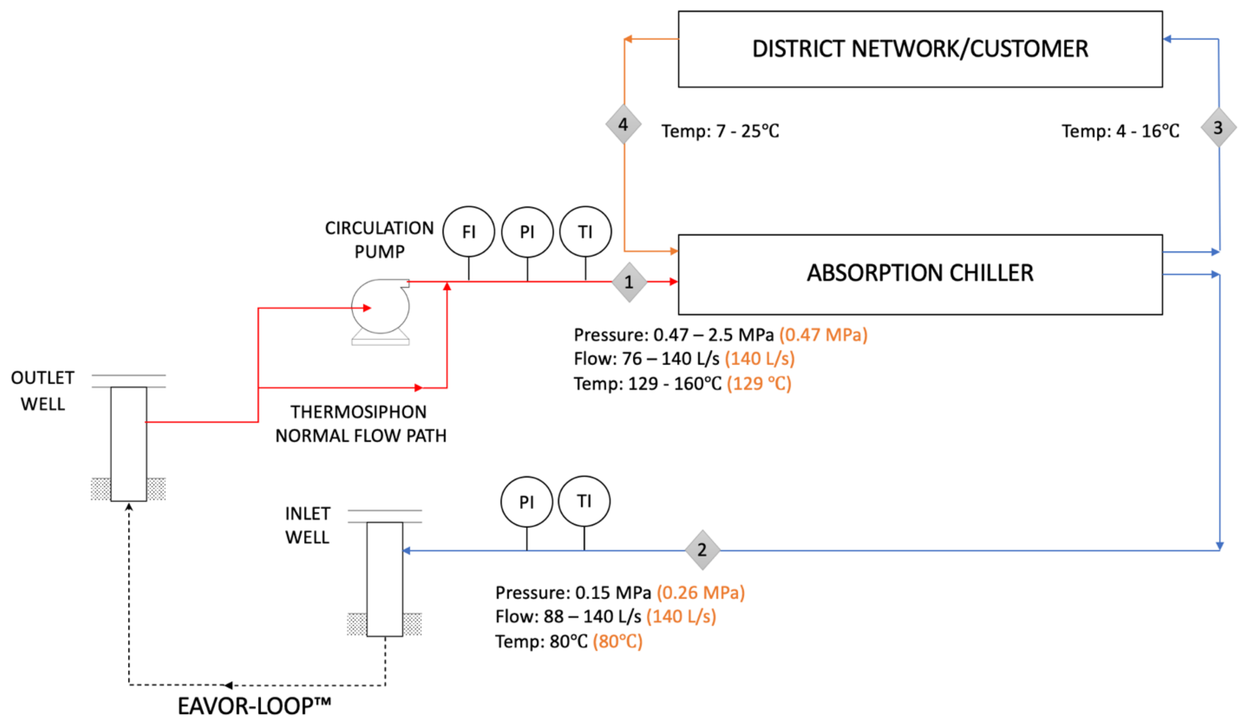
Figure 12: Regression model for change in temperature across allowable flow rates



*The equation obtained indicated that $\Delta T = 1067m^{-0.983}$

Using a Microsoft Excel model for the thermodynamic process simulation (provided by Eavor), optimization of the Eavor-Loop™ was completed. Variables that were adjusted included flow rates and pressure drops through the system. Through these simulations, the temperature of the working fluid coming out of the Eavor-Loop™ and the available pressure within the system changed. Each individual simulation provided a different thermal output. The goal of the optimization was to provide the highest thermal capacity, all while trying to get the working fluid back to a low temperature (so that it can recirculate, maximizing the availability to collect more heat energy) and maintaining acceptable input conditions for the chiller model itself. The process flow diagram (PFD) for the case study can be seen in Figure 13. The orange text indicates the optimized values. The absorption chiller and district network/ customer box seen in the PFD are there to symbolize the existence of each. In order to know what the inside of these boxes look like; performance characteristics are required.

Figure 13: PFD for integrated surface and subsurface design



The results of the optimized Eavor-Loop™ can be seen in Table 9.

Table 9: Optimized Eavor-Loop™ Performance characteristics

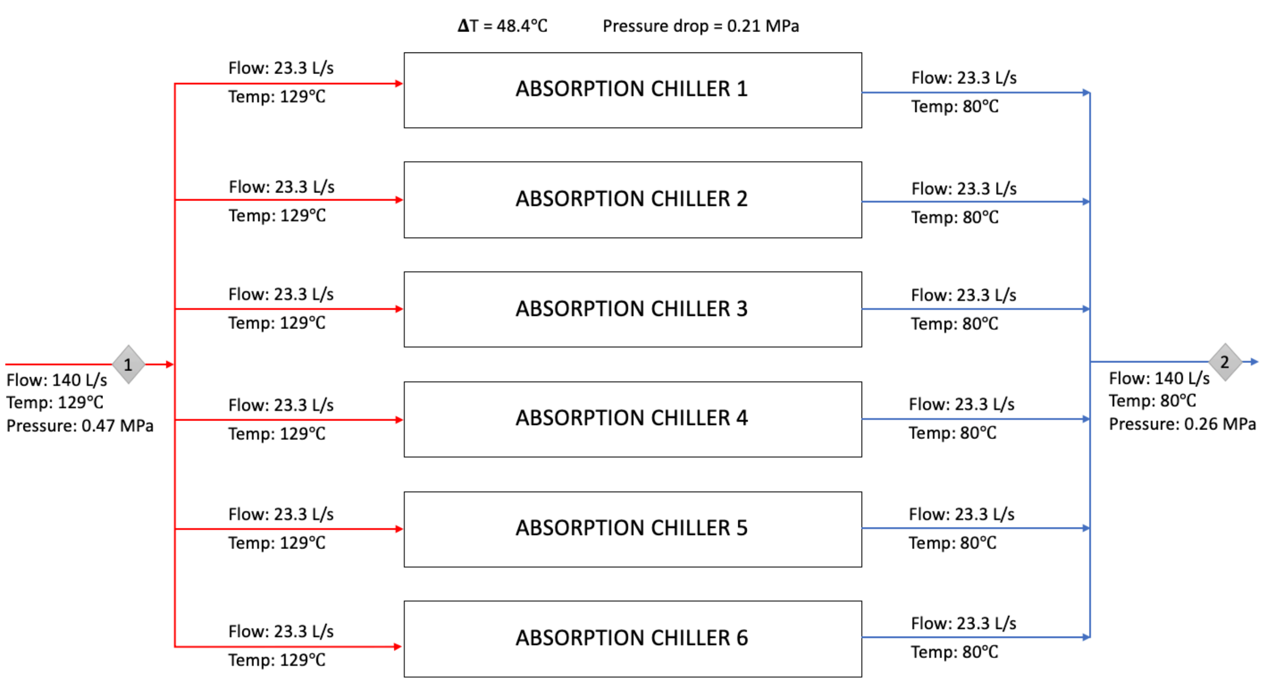
Value	*Performance*	*Units*
Total Thermal Output	30,101	kWth
COP of Chiller (*)	0.77	
Cooling Output	23,178	kWth
Cooling Output	6,590	RT
# of Chillers (*)	6.6	Chillers

**Model Specific: YHAU-CH1400EXW4S (1000 RT capacity)*

Source [COP of chiller]: (J. Controls, personal communication, July 2020)

Given the performance results, the designed Eavor-Loop™ can support 6,590 RT, meaning ~6.6, 1000 RT capacity chillers. Since, there cannot be .6 of a chiller, the design will support six of the chosen units. In order to meet all the requirements of the absorption chiller, the six units will be positioned in parallel, as seen in Figure 14. The specific details of the fluid as it moves through the chiller are directly on the figure. With the units in parallel, the fluid is reduced to a very low flow, maximizing the time the water is within the chiller, allowing more heat to be removed. Additionally, the fluid only has to go through one pressure drop. Once going through the chiller, the water will rejoin with the other streams, and circulate through to the inlet well of the Eavor-Loop™ . The parasitic load (electrical) for one absorption chiller was determined to be 19.9 kW, which is very low when compared to mechanical compression.

Figure 14: Optimized absorption chiller layout



This would be the magnified view of the absorption chiller 'box' seen in the PFD in Figure 13.

5.2.2 Objective 2b – Economic Analysis

In order for a project of this magnitude to be considered, it must show that it is economically feasible. To do this, a stage 1 economic assessment was completed. It also must show that it can have long-term benefits and savings when compared to current production methods. In order to do this, an economic analysis on electrically generated cooling was also completed. The results from this analysis will help to show which system would be preferred within the case study region (California) for any new data center or district network designs. All prices displayed in this section are in US$. At the moment of publication, 1 CAD$ is equivalent to 0.75 US$. Economics were run assuming full utilization of the available cooling capacity from the Eavor-Loop™. An LCOC was completed over the lifetime of each project in addition to the NPV, IRR, PIR, and simple payback. The summary of the main economic values used can be seen in Table 10. The results of the analysis can be seen in Table 11. Detailed assumptions and values for this analysis can be found in Appendix C. The calculation used for the LCOC can be seen in Equation 2.

Equation 2: Levelized Cost of Cooling

$$LCOC = \frac{Fixed\ Costs}{Annual\ production} + Variable\ Costs$$

$$= \frac{(Capital\ Cost * Capital\ Recovery\ Factor) +\ Fixed\ O\&M}{Annual\ production} + Variable\ Costs$$

*Note – a more detailed breakdown is available in Appendix C

Table 10: Summary of main economic costs for both systems

	Electric Cooling	*Eavor-Loop™ & Absorption Chiller Design*
Capital Cost ($)	2,636,054	20,235,867
Fixed O&M Cost ($/year)*	52,721	408,471
Electricity Usage (kWh/year)	49,520,709	1,148,818

** Cost of electricity is not included*

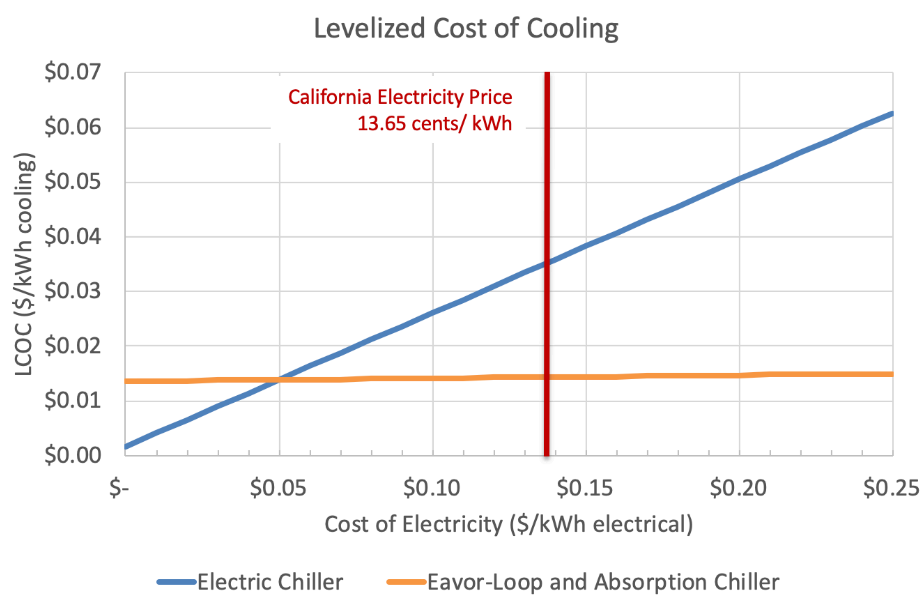
Table 11: Results from the economic analysis

	Electric Cooling	*Eavor-Loop™ & Absorption Chiller Design*
LCOC (cents/kWh cooling)	3.56	1.44
NPV ($)	0	40, 210,348
IRR (%)	10	33
PIR	N/A	1.99
Simple Payback (years)	9	3

From the results, the Eavor-Loop™ & absorption chiller design appears to be the much better option (in this particular case study location). It has a lower cost per kWh of cooling load, a positive NPV, high return on investment, and short payback period.

Since the electricity cost is really high in California (13.65 cents/kWh), a sensitivity analysis was completed to determine at what rate, the two systems would provide the same LCOC. The analysis will also highlight how each system is affected by the cost of electricity. The analysis can be seen in Figure 15. The red line identifies the current cost of electricity for an industrial consumer in California (for the month of May 2020).

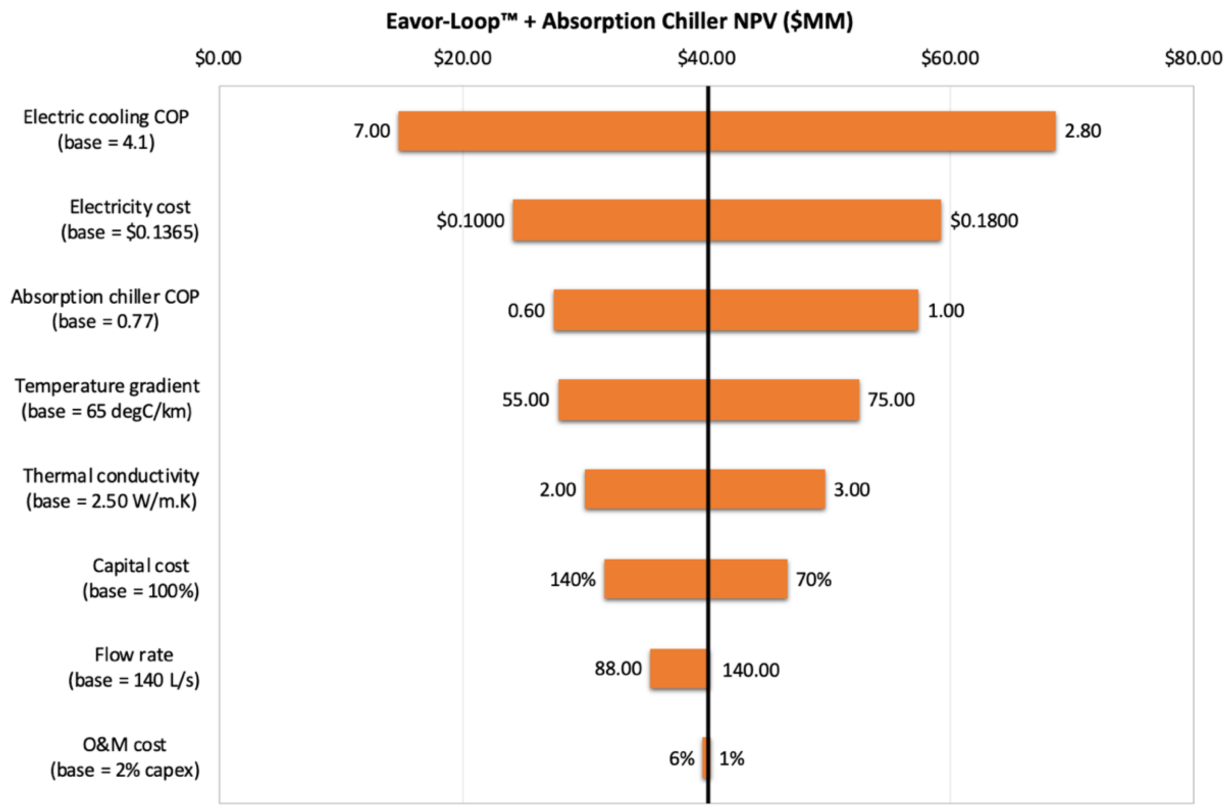
Figure 15: Sensitivity analysis of the LCOC with a varying cost of electricity



The results from the sensitivity analysis show an intersection at an electricity cost of ~5 cents/kWh. It is at this point that the LCOC for both systems will be the same. The LCOC of the electric chiller is drastically affected by the cost of electricity, whereas the Eavor-Loop™ and absorption chiller hovers around a consistent LCOC, with minimal affect by the electricity cost.

A second sensitivity analysis, a tornado diagram, was completed on the main economic indicators that were used in the analysis. This can be seen in Figure 16. The top indicators listed by level of importance include the electric chiller COP, cost of electricity, absorption chiller COP, subsurface temperature gradient, thermal conductivity of the igneous rock, capital cost, flow rate, and O&M costs. A comparison was made to traditional electric cooling. The black line represents the base case with the values for these shown on the left hand side. The prices at the top show the NPV in millions for the new system. Each indicator has a level of uncertainty which correlates to changes in the economics. It can be seen that even considering an electric cooler with a higher rated COP, the NPV is still positive, indicating that the Eavor-Loop™ and absorption chiller design would still be the better choice in this scenario.

Figure 16: Tornado chart highlighting the main economic drivers



5.3 Objective 3 Findings

Objective 3 focuses on the applicability of the new design and the environmental benefits that can be gained from its implementation. This included the sizing of a district network and different efficiency rated data centers. An environmental analysis was completed to show the GHG emission savings from using the Eavor-Loop™ and Absorption Chiller within the case study location as opposed to electricity, which has a main producer of fossil fuels.

5.3.1 Objective 3a – Potential Applications

In order to determine the size of the data center the new integrated design could satisfy, power usage effectiveness (PUE) must be briefly discussed. PUE is the ratio of the total amount of energy that is required to operate a data center to the energy to run specifically IT equipment. This can be expressed as the follows (Equation 3):

Equation 3: PUE Calculation

$$Power\ Usage\ Effectiveness\ (PUE) = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power} = 1 + \frac{Non{-}IT\ Facility\ Power}{IT\ Equipment\ Power}$$

IT equipment in this equation refers to the energy directly used for computing equipment. Non-IT energy would include the cooling/HVAC, electrical equipment, lighting, and anything else that might require energy. The lowest possible value that PUE could equal is 1. If a PUE value is equal to 1.67, this means that 67% of the energy required is for overhead. Dependent upon the efficiencies of the systems and the equipment installed, a PUE can anywhere from 1 to 3 (Avgerinou, Bertoldi, & Castellazzi, 2017). Table 12 shows the results for different data center power ratings that the integrated design could satisfy based on a certain PUE.

Table 12: Potential data center sizes

PUE	Data Center Power Rating (MW)
1.25	144
1.5	86
1.67*	72
1.75	67
2	58

*Average PUE is 1.67 or 67% overhead (Avgerinou et al., 2017)

Assumptions:

- Cooling load (23 MW) accounts for 80% of non-IT Power
- Non-IT Power is ~29 MW

For further granularity on this calculation, please see Appendix D.

Alternatively, a district cooling network that had a peak cooling demand of 6000 RT could be satisfied with this design, dependent upon the level of redundancy and how many additional units would be required. In order for this to work, there would have to be a similar demand in a cluster of closely located buildings with a dense population. With the required infrastructure for a district cooling network, the underground piping would have to be pre-existing or it would have to be a new development for it to become a feasible solution. It would be very difficult to convert a densely populated zone with individually run HVAC systems into a district network. However, as mentioned in the literature review, Canada currently has district networks that are set up with natural gas. This could be a prime location to implement the new low-grade geothermal design as the underground infrastructure is already existing. It would not be that difficult to construct a new surface facility or change out the equipment in the existing one. Even if the Eavor-Loop™ cannot be drilled at the site of the central plant, the hot water could always be transferred through a pipeline to the location with very minimal losses in the thermal energy. This adaptability is one of the great features of the Eavor-Loop™. However, with the small surface footprint, there is generally a location that can be found nearby.

Jason Baker (personal communication, August 7, 2020), a Senior Project Manager at a Canadian Telecommunication company, was able to provide insights on where in Canada an application of this magnitude could be of real value. While hot-water driven absorption chillers are not currently in use at any facilities, the increase in demand and the need for new buildings could be an opportunity for an implementation of this kind. As a telecommunications provider, demand has only been growing, especially with Covid-19 and an increased digital presence. Sometime soon, Canadian telecommunication companies will be looking to develop buildings that are closer to resembling data centers as opposed to the buildings that they have been operating out of for many decades. Being one of the main providers of fibre optic, there is a lot more electronic equipment that needs to be housed for it to work smoothly. Not only that, but it's no longer "a guy in a room moving wires". There is now an increased amount of stronger equipment that requires more energy, which means more heat and power. The increased volume and automation of equipment requires HVAC systems that can provide stable, constant temperature and humidity conditions. Cooling solutions are definitely going to be a necessity in the coming decades as technology improves. One of the key points mentioned was the importance of redundancy and being able to provide a solution that can offer a tier 4, fully redundant system. If the cooling system were to fail without adequate redundancy, the electronic equipment would overheat very quickly, causing unwanted and costly downtime. Having the ability to provide a fully redundant energy system to a telecommunications provider that uses clean energy and reduces electrical consumption is definitely going to be a market advantage.

5.3.2 Objective 3b – Environmental Analysis

An environmental assessment was completed on the implementation of the new design in place of an electric chiller. Data from Table 13 and Equation 4 was used for this analysis.

Table 13: Inputs for environmental analysis

Inputs	Values	Source
Cooling Output (kWth)	23,178	
Electric Chiller Efficiency	4.1	
US Electric Average Grid Efficiency	0.37	(Metcalfe, 2017)
US Electric Average Emissions (kg/GJ)	168.8	(Supple, 2007)
Coal-Fired Grid Efficiency	0.3	
Coal-Fired Emissions (tonnes CO_2/ MWh)	0.953	(Supple, 2007)
New Design Emissions (tonnes CO_{2eq}/year)*	501	(Eavor, personal communication, July 2020)

Source: Varying – see column on the far right

*Note: The new design emissions account for 100% utilization of the technology. These emissions are practically negligible, coming in at under 0.5% of conventional baseline emission intensity.

Equation 4: GHG savings equation

$$Emissions\ Savings\ (tonnes\ {}^{CO_2}/_{year}) =$$

$$= \left[\left(\frac{\left(\frac{Cooling\ Output}{Electric\ Chiller\ Efficiency}\right)}{Grid\ Efficiency}\right) * fuel\ source\ emissions\right] - New\ Design\ Emissions$$

*Note: The fuel source emissions are multiplied out by the appropriate unit conversions to ensure units come out to tonnes CO_2/year

The results from the analysis can be seen in Table 14. The average US electric grid accounts for nationwide generation efficiencies, whereas coal-fired represents 100% utilization of coal for electricity generation. The environmental analysis provides clear benefits to a potential user and could provide a positive impact on any GHG strategy or alignment with current sustainability policies.

Table 14: Yearly GHG emission savings

Grid Fuel Source	Emissions Savings (tonnes CO_2/year)
US Electric Average	90,689
Coal-Fired	156,879

CHAPTER 6: DISCUSSION

The project case study location and building of choice was wisely chosen for the initial development of this design. Not only is California burdened with heavy electricity prices, but much of the electricity that is used to run mechanical compressors comes from the energy source of natural gas. It is also home to Silicon Valley, a hotspot to many successful technology start-ups, as well as many other large technology companies. Thanks to this, data center industrial areas are common within these regions. Many of the big-name companies like Google and Amazon are always promoting their positive ESG policies and looking for ways to improve their associated ratings. There would definitely be interest in this region of the world for the Eavor-Loop™/ absorption chiller integration as the new design would provide many benefits to these customers. However, while a project may be technically feasible and more environmentally friendly, unless it can provide economic benefits, the demand for the solution may not be there for actual investments. But this is not the case in this scenario. Data centers require a large amount of energy to operate and many of these buildings still utilize electric-driven HVAC equipment. The design presented throughout this research has cut yearly electrical requirements from 7,514,371 kWh/unit to 174,324 kWh/unit. That is almost a 98% reduction in electricity consumption for the cooling unit alone. While the absorption chiller may have a lower COP than the electric chiller, the absorption chiller does not require a compressor. Absorption chillers can also utilize 'waste' and low-grade heat sources, which can often come at a very cheap price. On a global scale, humans need to make more of an effort to utilize waste sources of energy. We also need to make an effort to use primary sources of energy for heating and cooling needs as opposed to using electricity for something that potentially doesn't require it. We need to start thinking of how everything goes together. Electricity should be used for lighting and the transition to electric vehicles, not to heat or cool our buildings. As a whole, we need to be more wary about our impacts in this world and how we are using the energy around us. Throughout the different discussions that I have had with others in regard to HVAC needs, people seem to stick to what they know, avoid high initial capital costs, and look for redundancy, especially the latter for data centers. The worldwide applications that utilize geothermal energy for cooling on a large scale are few and far between even though technologies like absorption chillers have been around for over 75 years. In the last 20 years or so, absorption chillers have begun to gain more popularity due to the simplicity of their design, and low maintenance. As is with any technology, as investments increase, it brings in new developers who come up with innovative ways to improve the technology. The real benefits of the absorption chillers mentioned in this report is the wide range of incoming temperatures in which they can operate, the ease of operation, and the cooling capacity that they can provide.

The optimization of the two technologies was difficult as each technology on its own has ideal operating conditions. For example, the higher a flow rate that can be pushed through the Eavor-Loop™ while maintaining enough operational pressure for the thermosiphon effect to work will result in a higher thermal output than if you run the Eavor-Loop™ at a lower flow rate. Even though the water has more time to pick up heat, a higher volume of lower – temperature water will produce more energy. This was opposite the conditions of the absorption chiller. As noted by Figure 12, the change in temperature was the greatest with a lower flow rate. In the absorption chiller, the more time the machine has to extract heat from the fluid, the better. The optimization of these two processes involved looking at what capacities the Eavor-Loop™ could provide at different flow rates and pressure drops in order to determine if the number of supported units could make an arrangement that was still within the allowable ranges of the chiller. Ultimately, the chosen process conditions included an Eavor-Loop™ flow rate of 140L/s carrying water in at a temperature of 129°C. This flow rate was then split into 6 parallel units where the temperature remained the same, but the new flow rate going into each absorption chiller was 23.3 L/s (just above the minimum 17 L/s that was required). Other benefits of arranging the six chillers in parallel as opposed to a series or a combination of trains is during failure and maintenance as well as the pressure that the water needs to hold. If one machine in parallel fails, only one goes down, whereas in the other arrangements, at least 2 machines would be down unless you had piping that could bypass an offline machine. Additionally, the water only flowing through one machine means one pressure drop, as opposed to 2 or 3. Ideally, in a scenario like the one described in this report there would be a certain amount of backup chillers installed in order to provide a certain level of redundancy, a failsafe in case something was to go wrong. Often, operations requiring these high cooling loads need to operate seamlessly. For example, if the chiller chosen had been the ammonia/water working solution and was being used for food refrigeration, a failure would mean that all of that food would go to waste and there would be lost product. The importance of redundancy and reduced electrical consumption is key for these designs and major selling points to those that would be looking to utilize it. The Eavor-Loop™ fits in very well with this as it is a form of renewable energy that can provide baseload power and could be scaled up or down depending on the energy requirements. It was obvious from the beginning of this research that the use of an Eavor-Loop™ to provide a dominantly fossil fuel generated source of energy would provide massive environmental benefits. This combined with the potential use of connecting to a district energy network is an added bonus.

The tornado analysis (Figure 16) was a bit surprising. I had expected the electricity cost to be the largest economic driver and at the top of the results. However, the electric chiller COP was actually more of an uncertainty when it came to calculate the NPV. While the economics stayed positive for all scenarios analysed with the tornado, the electric chiller COP, electricity cost, and absorption COP were the biggest economic drivers. Based on the Tornado analysis, regions where you could implement a similar design with an improved NPV would require regions with similar subsurface geological characteristics, higher electricity rates then California, and electric chillers with a lower COP than that of the average 4.1. It would also be worthwhile to look at regions that already utilize a district network (ideally one run off of fossil fuels and not renewables). With infrastructure already in place, the only updating that would be required of the existing facility would be to switch to hot water driven absorption chiller. The costs to drill and implement the Eavor-Loop™ would still exist, but one large hurdle would already be passed.

It was also interesting to see how Europe was so far ahead of North America (NA) in terms of the amount of district energy networks. Based on the research that I have come across; I believe there are a few main reasons for this. The first reason is the in-depth land planning that the cities have to go through. In Europe, everything is much more condensed, people live closer together, and there is not space for cities to just spread like they do in North America. When a city spreads in NA, a municipality may decide to get another power plant erected to meet up with demand. European cities seem to plan ahead better for growth and put these district networks in as communities develop, understanding that it will be easier to deal with peak demand and consumption when the energy system is run this way. The second reason is the energy directives and energy efficiency policies that are put in place to incentivize the use of these networks (Hoos, 2019). In some cases, it appears that to meet the required energy efficiency, a district energy network must be put in place as opposed to individual units for different buildings. The 'New Renewable Energy Directive 2018/2001/EU' actually allows consumers to disconnect from inefficient networks and allow third party access to any supplier that is providing renewables or waste heat/cold. It would definitely be beneficial to look more in depth at these European district networks in order to learn more about what successful implementation would look like.

CHAPTER 7: CONCLUSIONS & RECOMMENDATIONS

7.1 Conclusions

The findings of this feasibility study proved that it was possible to combine the Eavor-Loop™ technology with cooling technologies, specifically absorption chillers for low- to medium-grade geothermal energy. Using a case study of constant, data center cooling demand in California, USA, a 6,590 RT cooling facility was designed. The integrated facility was able to provide an LCOC of 1.44 cents/kWh compared to that of an electrically run facility of 3.56 cents/kWh. A project NPV of $40,210,348 was obtained with a simple payback of 3 years, an IRR of 33% and PIR of 1.99. In addition, the newly designed cooling facility was able to displace ~91,000 tonnes CO_2/ year. Overall, the project was technically, environmentally, and economically feasible. One of the many advantages of the system included a stable LCOC regardless of external electricity costs whereas the electrically driven chiller LCOC was dominated by the external market cost. California was chosen as the case study location due to its geothermal potential, expensive electricity costs, and unreliable electrical grid. California is also home to many technology companies that require large buildings to store servers and IT equipment that happen to create a lot of heat and require a very precise temperature. The design itself has global applications with the best chances of implementation in areas with high electricity costs, high cooling demands, subsurface geothermal source, and pre-existing district energy networks. The biggest uncertainty, as determined by a tornado analysis is the COP of the compared electric chiller. However, even with an electric chiller with a highly rated performance, the Eavor-Loop™ and absorption chiller design still came out on top with a positive NPV. Integrating the Eavor-Loop™ with absorption chiller technology opens up new and broader areas for utilization of low- and medium-grade geothermal resources to help meet the worlds growing cooling demands.

7.2 Limitations

There were three main limitations throughout the scope of this project. These included the lack of responses from technology developers and suppliers, availability of data to model multiple locations, and the granularity of the economic analysis.

While I was able to find information on absorption chillers from the four main developers publicly, I was not able to get in personal contact with half of them. Hours were spent cold calling customer support lines trying to get connected to someone who could provide a little more insight into the technology. In most instances, efforts to set up a meeting with someone from the company were failed attempts. Because of this, certain absorption chillers were not modelled as the detailed information required to understand how they work and integrate with the Eavor-Loop™ could not be obtained. Ideally, there would have been three absorption chillers modelled (in addition to the York model, a Trane and LG model), all with their own economic analysis. This would have been able to provide the study with a wider range of values and a better understanding of the factors that affect the feasibility. It also seemed as if the suppliers in Canada did not know the technology as it is not widely used. This caused delays in communications as a third party would have to become involved in order to provide accurate data.

The second limitation is partially due to time and partially due to the lack of available data for geographic locations of interest. It would have been very interesting to compare the California data center scenario with an Ontario or European district energy network. Something of this nature would have made the scope of the project too large to complete in the given timeline. Additionally, without the subsurface data, there is no way to accurately model the thermodynamic processes acting in the system. Unfortunately, there was not enough conclusive factors or data points to allow for a Canadian scenario.

The third limitation is in relation to the granularity of the economic analysis. While the economic assessment had a very positive result, it was definitely a stage 1 assessment and a high-level overview of the financials. The lack of available data on certain aspects meant assumptions had to be made. Having clear prices for aspects surrounding the absorption chiller and electric chiller would have proved to be useful. The only real "rough" cost that I was able to obtain from the supplier of the absorption chiller was the capital cast of a unit (without installation and construction). For this reason, I believe that if the information was readily available, there is a chance that the project NPV would decrease due to these additional items. However, some of these items were taken care of with the tornado sensitivity analysis. By doing this, I was able to analyze what the NPV would look like if my capital costs were to increase due to installation. Additionally, the economic data from Eavor that was used in the analysis was for the year 2023. The values used for drilling costs were definitely a bit more aggressive when compared to 2020 as an expected learning curve and decrease in costs is expected as more Eavor-Loop™ implementations are completed. Given the size of the project and all the factors that would need to align to have the new design implemented any faster than 2023 does not seem like a reasonable timeline. Even though the costs cannot be confirmed at this time, this was a valid assumption to use. Also, depending upon the geographic location, certain services may cost more or less than expected.

7.3 Recommendations

The first recommendation is to advance this project to a stage 2 assessment. The research had very promising potential, with many global applications. Although many of these applications aren't as close to home, we as humans are in charge of this one planet. The Eavor-Loop™ combined with the absorption chiller is an excellent way to use primary thermal energy for a direct use in cooling. There are definitely more advantages to using primary thermal energy as opposed to converting to electricity for a secondary use. It is important that thermal energy is put to good use as the world has a great deal of low-grade geothermal energy. Being able to tap into this resource opens up a wide web of practical applications. A huge advantage of the Eavor-Loop™ over traditional geothermal energy is the fact that you are not pumping up a brine from the subsurface which will require treatment. The Eavor-Loop™ uses very little water in comparison as the same fluid recirculates. With cooling demands increasing every year and a push towards renewable energy, this could be a very important application for Eavor, and it is definitely worth seriously looking at.

The second recommendation is to begin to find a community, university, or small municipality that wants to work with Eavor in an effort to “go green”. Finding a community with like-minded ambitions and goals will help to speed up and processes and decrease the large hurdle that is people themselves. The cooling design that this research looked at could be completed on a smaller scale in order to have enough thermal energy for heating and cooling combined, or even the possibility of trigeneration aspects (heating, power, and cooling). These different components could be integrated into a single surface facility with the same subsurface design. A smaller cooling project like one of this nature would also allow for technology learning and give Eavor the option to try different models in different locations. The range of characteristics across the absorption chillers highlighted in this research allow for practical applications of all sizes.

The third and final recommendation is to work as close as possible with governments in an effort to gain access to important policy makers. This can help to bridge any legislation gaps and lead to the implementations of district networks in new communities/ districts. From a sustainability standpoint, governments, especially Canadian, are going to need to be looking towards alternative solutions in an effort to meet Paris Agreement targets that were set out in 2015. In many cases, Europe leads the way in sustainable practices. Europe also has a great deal of district energy networks. The technology that Eavor has designed has far reaching implications and would work very well integrated with these district energy networks. There is no denying that district networks are beneficial in many ways. Technology like the Eavor-Loop™ could provide the evidence of a clean, stable, scalable, energy system that is needed to change a policy makers mind. Having a good relationship with government could also help to break down barriers that is making low-grade geothermal technology tough in Canadian applications. One of these being the low electricity costs, specifically in Alberta, that make it hard to compete with current practices.

7.4 Future Research

With everything that has already been said, I will end this research with a few final thoughts on where I believe future research should be focused. Even though traditional Canadian geothermal resources (hydrothermal) are not as good as in other parts of the world, Canadian locations should be explored further as geothermal opportunities still exist with the application of emerging closed loop technologies; specifically, integrating the Eavor-Loop™ with currently existing district energy networks. Additionally, the results of this research should be integrated into the development of trigeneration capabilities as this could be a great way to get larger customers who are looking for a truly renewable company who can do it all. In my previous professional experiences, being able to provide multiple solutions that a client would have to look for 2 or 3 providers for is a major advantage. Clients are willing to pay a premium for simplicity and logistical ease. Lastly, in the coming decades, developing nations, which are often located in the hottest part of the world, are going to be in demand of cooling services. There is definitely market and subsurface potential in these regions, and it is worth looking into. From a sustainability standpoint, removing the length of time that it takes for these developing nations to switch over from coal or other fossil fuels to renewables will reap large environmental benefits.

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APPENDIX A: HOT-WATER DRIVEN ABSORPTION CHILLER MODELS

Table A1: Varying characteristics of hot-water driven absorption chillers on the market

Developer/ Supplier	Model #	Name/ Type	COP (@ideal conditions)	Hot Water Temp (°C)	Chilled Water Temp (°C)	Cooling Water Temp (°C)	Cooling Capacity Range (kW)	Cooling Capacity Range (RT)	Hot Water Temp Range (°C)	Notes (all use LiBr/water as working fluid)	Source
LG	WCMW	Hot water Single-Effect (W Series)	0.72	95 to 80	12 to 7 or 13 to 8	31 to 36.5	98 to 3,587	28 to 1,020	85 to 130	Steady best selling model; Up to 2000 RT upon request	(LG, 2015)
LG	WC2H	Hot-water Single-effect (double-lift, low temp)	0.74	95 to 55	12 to 7 or 13 to 8	31 to 36.5	258 to 4,745	73 to 1,350	85 to 130	low-temperature outlet; Up to 2000 RT upon request	(LG, 2015)
LG	WCMH	Hot-water Single-effect (H Series)	0.80	95 to 72	13 to 8	31 to 36.5	98 to 3,587	28 to 1,020	85 to 130	world class high efficiency; Up to 2000 RT upon request	(LG, 2015)
York/ Johnson Controls	YHAU-CL	Hot water single-effect (double-lift)	0.78	90 to 72 (as low as 60)	12 to 6 (as low as 4)	27 to 32 (as high as 37)	105 to 6,153	30 to 1,621	70 to 99	2 step evaporator and absorber (saves 10% energy consumption); Not available in Canada	(Johnson Controls, 2017) (Johnson Controls, 2019)
York/ Johnson Controls	YHAU-CH	Hot water single-effect (double-lift)	0.78	132 to 95* (as low as 80)	12 to 6 (as low as 4)	27 to 32 (as high as 37)	105 to 6,153	30 to 1,621	100 to 160	2 step evaporator and absorber (saves 10% energy consumption); Available in Canada	(Johnson Controls, 2019) * (J. Controls, personal communication, July 27, 2020)
Trane	ABTF-XX	Double-stage hot water	0.9 to 1.2	188	15.6 to 4.4 10 to 4 (ideal)	24 to 35	1,336 - 5,803	380 to 1650	up to 188	water temp is most likely too high for normal applications; XX refers to capacity	(Trane, 2005b)
Trane	XX	Single-stage hot water	0.6 to 0.8	132	15.6 to 4.4 10 to 4 (ideal)	24 to 35	393 - 1,635	112 to 465	up to 132	capacity seems low compared to others; XX refers to capacity	(Trane, 2005a)
Thermax	Cogenie	Vapour absorption chiller	0.65 to 0.72	90 to 85	12 to 6 (as low as 3.3)	30 (inlet)	70 - 738	20 -210	70 to 110	compact, small capacity	(Thermax Ltd., 2008)
Thermax	Prochill	Twin Design Vapour absorption chiller	0.75 to 0.8	90 to 85	12 to 6 (as low as 3.3)	30 (inlet)	844 - 4,044	240 - 1150	70 to 110	2 step evaporator and absorber (one high pressure, and the other low)	(Thermax Ltd., 2008)
Thermax	TAC L5 XX	Twin Type Low temperature hot water driven absorption chiller	0.81	95 to 85	12 to 6 (as low as 1)	30 to 38	700 - 5,765	200 - 1640	75 to 120	2 step evaporator and absorber (one high pressure, and the other low); XX refers to capacity	(Thermax Ltd., n.d.)

Source: Varying – see column on the far right

APPENDIX B: YORK YHAU-CH DATASHEETS

Figure B1: Design conditions datasheet provided by Johnson Controls

YORK

Design Conditions Datasheet

Unit Tag	Qty	Model No	Cooling Capacity (ton.R)	Nominal Voltage	Working Fluid
CH-1	2	YHAU-CH1400EXW4S	1000.0	460-3-60.0	LiBr - H_2O

PIN:								
YHAUCHXX01	400EXW4XXS	WXAXRXXXXX	XXXVXXS030	204XXXXXGA	MLCCXAD222	XSMSXSSSX1	X232XLXXXS	XXXXXCSXBX
....5...10	....5...20	....5...30	....5...40	....5...50	....5...60	....5...70	....5...80	....5...90

Evaporator Data		Absorber / Condenser Data	
Fluid Volume (ft^3)	92	Fluid Volume (ft^3)	153
Evaporator Passes	3	Absorber / Condenser Passes	2
Fluid Pipe Diameter (Inlet / Outlet) (mm (in))	250 (10) / 250 (10)	Fluid Pipe Diameter (Inlet / Outlet) (mm (in))	400 (16) / 400 (16)
Max. Working Pressure (PSIG)	150 or less	Max. Working Pressure (PSIG)	150 or less
Entering Fluid Temperature (°F)	54	Entering Fluid Temperature (°F)	85
Leaving Fluid Temperature (°F)	44	Leaving Fluid Temperature (°F)	95
Flow (USGPM)	2399.6	Flow (USGPM)	5510.2
Pressure Drop (ft H_2O)	36.8	Pressure Drop (ft H_2O)	18.7
Fluid	Water	Fluid	Water
Fouling Factor ($h.ft^2.F/Btu$)	0.0001	Fouling Factor ($h.ft^2.F/Btu$)	0.00025
COP Cooling	0.77	Amount of Heat (MBH)	27587.2

Driving Heat Source Data	
Source	Hot Water
Fluid Volume (ft^3)	74
Amount of Heat (MBH)	15585
Entering Fluid Temperature (°F)	194
Leaving Fluid Temperature (°F)	162
Flow (USGPM)	1000
Pressure Drop (ft H_2O)	15.7
Fluid	Water
Fouling Factor ($h.ft^2.F/Btu$)	0.0001
Driving Heat Source Passes	4
Capacity Control Range (%)	20 - 100
Fluid Pipe Diameter (Inlet / Outlet) (in)	300 (12) / 300 (12)
Max. Working Pressure (PSIG)	150 or less

Electrical Data	
Total Electrical Consumption (kW)	19.9
Total Electrical Input (kVA)	24.8
Solution Circulation Pump kW + Solution Spray Pump kW	7.5+3.7
Refrigerant Pump kW	1.5
Vacuum Pump kW	0.8
Physical Data (Approximate)	
Shipping Weight (lb)	96122
Operating Weight (lb)	115522
Emergency Weight (lb)	190039
Overall Length (in)	322.8
Overall Width (in)	129.9
Overall Height (in)	153.5
Flange Type (Evaporator)	ANSI 150#
Flange Type (Absorber/Condenser)	ANSI 150#
Flange Type (Driving Heat Source)	ANSI 150#
Insulation Area Cold (ft^2)	527
Insulation Area Hot (ft^2)	527
Tube Extracting Space (in)	275.6

Notes:
Rating is in general accordance with AHRI standard 560.
This equipment shall be manufactured based on GB standard, CE(MAD, EMC and PED, as applicable).
Evaporator tube material: Copper, Absorber/Condenser tube material: Copper, Generator tube type: , Generator tube material: SS22053
Reported physical data is approximate. Contact Johnson Controls for confirmed physical data associated with specific chiller configurations.

Source: (Johnson Controls, personal communication, June 2020)

APPENDIX C: ECONOMIC ANALYSIS

This section provides a detailed breakdown of the LCOC calculation, key values, and assumptions used within the analysis.

LCOC Calculation

$$LCOC = \frac{Fixed\ Costs}{Annual\ production} + Variable\ Costs$$

$$= \frac{(Capital\ Cost * Capital\ Recovery\ Factor) +\ Fixed\ O\&M}{Annual\ production} + Variable\ Costs$$

$$= \frac{CC * CRF + Fixed\ O\&M + Elec\ Consumption * Elec\ Cost}{Utilization * Cooling\ Load * 8760\ hr/year} + Variable\ O\&M$$

Key Values

Table C1: Common Terms (Apply to both Electric Cooling and Eavor-Loop™ and Absorption Chiller)

Common Terms Between Systems	***Value***	***Assumptions/ Source***
Capacity Utilization (%)	100	operational all year at full capacity
Project Life (years)	25	Lifetime of an energy project
Discount Rate (%)	10	Provided by Eavor
Capital Recovery Factor	0.11	Calculated with project life and discount rate
Variable cost – fuel – electricity ($/kWh)	0.1365	May 2020 – California industrial electrical cost (US Energy Information Administration, 2020, p. 138)
# of units	6.6	Assuming 1000 RT modules for both
Cooling Load (kW/unit)	3517	1000 RT = 3517 kW

Source: Varying – see column on the far right

Table C2: Unique terms to the electric chiller

Electric Chiller Terms	***Value***	***Assumptions/ Source***
Capital Cost ($/unit)	400,000	Average $400/RT (FPL, 2019)
Fixed O&M ($/year-unit)	8,000	Assumed 2% of capital cost for absorption chiller
Variable O&M ($/kWh)	0.0006	Assumed to be the same as an absorption chiller
Generation Efficiency (COP)	4.1	Average value calculated from multiple sources (Evans, 2018; Lizardos, n.d., p. 13)
Electricity Consumption (kWh/year-unit)	7,514,371	Calculated using 100% utilization

Source: Varying – see column on the far right

Table C3: Unique terms to the Eavor-Loop™ and absorption chiller

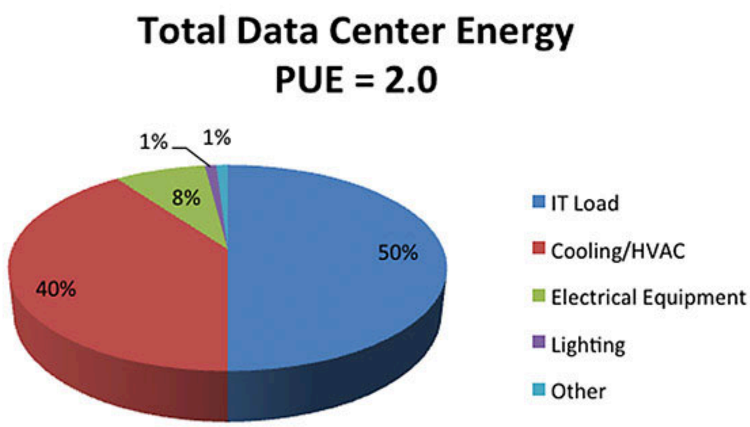
Eavor-Loop™ and Absorption Chiller Terms	***Value***	***Assumptions/ Source***
Capital Cost Eavor-Loop™ ($)	17,312,317	Costs provided by Eavor (2023 development year)
Capital Cost Absorption Chiller ($/unit)	443,625	Costs provided by Johnson Controls
Fixed O&M Eavor-Loop™ ($/year)	350,000	Costs provided by Eavor (2023 development year)
Fixed O&M Absorption Chiller ($/year-unit)	8,873	Assumed 2% of capital cost for absorption chiller
Variable O&M ($/kWh)	0.0006	Assumed 0.2 cents/RT-hour (US Department of Energy, 2017)
Generation Efficiency (COP)	0.77	York Data Sheet (J. Controls, personal communication, July 2020)
Electricity Consumption (kWh/year-unit)	174,324	Calculated using 100% utilization and electrical requirements
Electrical Requirements of chiller (kW/unit)	19.9	York Data Sheet (J. Controls, personal communication, July 2020)

Source: Varying – see column on the far right

APPENDIX D: DATA CENTER PUE CALCULATION

In order to calculate the data center size at each PUE value in Table 12, some assumptions were made. Figure D1 shows the energy usage of a data center with a PUE of 2. At this PUE, the IT Load is 50% and the Cooling/HVAC load is 40%. We can assume then that the cooling load is 40/50%, meaning cooling accounts for approximately 80% of the non-IT load.

Figure D1: Data center energy use at a PUE of 2



Source: (Evanuik, 2015)

The Eavor-Loop™ and absorption chiller design can supply 23 MW of cooling load. If the 23 MW accounts for 80% of non-IT, the non-IT load would be equal to ~29 MW.

$$PUE \ = \frac{Total\ Facility\ Power}{IT\ Equipment\ Power} = 1 + \frac{NonIT\ Facility\ Power}{IT\ Equipment\ Power}$$

$$PUE = 1 + \frac{NonIT\ Facility\ Power}{IT\ Equipment\ Power} = 1 + \frac{29\ MW}{43\ MW} = 1.67$$

Where IT is 43 MW, and Non-IT is 29 MW, meaning total power rating is 72 MW (29 +43MW)