12/8/2023

Wastewater Energy Recovery

Final Report

CHENTONG SHEN
ANTHONY BURKE
JOSHUA MALONE
JAIMIN PATEL
JUSTIN SOBERMAN

FACULTY ADVISOR: DR. DARKO MATOVIC
COURSE INSTRUCTOR: PROFESSOR JAN SNEEP

Abstract
The primary goal of this project is to collect heat from wastewater in a sustainable way, that Utilities Kingston can then use to satisfy their client. To accomplish this, a wastewater heat recovery system has been designed that is compatible with pre-existing systems supplying Queen's university and several surrounding hospitals. The design uses a heat pump system to absorb thermal energy from wastewater and transfer it to clean lake water. This lake water is then used to raise the inlet water temperature being used at the central heating plant above its current ambient temperature. This in turn, increases the efficiency of the overall design and reduces the amount of greenhouse gases that the plant will emit. On top of reducing emissions, the design is expected to reduce energy consumption by up to 20% annually at the plant.

Contents

Abstract 2

1 Introduction 3

- 1.1 Background Information 3
- 1.2 Problem Definition 4
- 1.3 Project Scope 4
- 1.4 Design Benefits 4

2 Design Criteria & Functional Specifications 5

3 Alternative Designs Considered 6

- 3.1 Residential scale heat recovery 6
- 3.2 Commercial scale heat recovery 7
- 3.3 Smokestack heat recovery 8

4 Selection Methodology 9

- 4.1 Weighted Evaluation Matrix 9
- 4.2 SOD Risk Assessment 11
- 6.1 Overview 11

5 Technical Plan 12

6 Final Design 13

- 6.2 Schematic 13
  - Sensors and Controls 14
- 6.3 OpenFOAM Model 14
- 6.4 Thermodynamic Model 15
  - 6.4.1 Potential Energy in Wastewater 16
  - 6.4.2 Heat Pump Energy Requirements, Power Output, and the Efficiency 16

6.4.3 Energy Recovery vs Cost 17
7 Project Planning 19
7.1 Installation 19
7.2 Risk Management 19
7.3 Project Maintenance 21
8 Discussion and Overall Recommendation 21
9.Works Cited 22
10 Appendix 25
10.1 Photos of site 25
10.2 Extra Thermodynamic Modelling 26
10.3 Exhibition Poster 27
11 Faculty Advisor Sign-Off 28

1 Introduction

1.1 Background Information

Carbon footprint is a critical aspect of engineering that is becoming more and more important as the threat of climate change continues to grow. Carbon footprint is defined as the total amount of greenhouse gas emitted by human activities, effected by the efficiency of the system and the renewable energy usage [1]. The Canadian government established a plan to reach net-zero carbon emissions by

2050 [2]. This plan requires companies to have either zero carbon dioxide emissions or for them to offset the carbon dioxide emitted. On top of simply complying with this regulation there are financial benefits associated with lowering greenhouse gas emissions as well. The Canadian Government has imposed a carbon tax of 50 Canadian dollars per tonne of carbon dioxide emitted in 2022, with this amount increasing by $15 annually until the year 2030 [3].

For these reasons, it is important to find methods of heat generation that involve little to no greenhouse gas emissions. For this project, a wastewater heat recovery system is being investigated. The goal of a system like this is to absorb thermal energy from the wastewater to recover and be able to use elsewhere. In 2021, the Queen's Central Heating Plant emitted 27000 $MTCO_2e$ greenhouse gases, which makes up 83% of Queen's Scope 1 emission [4]. This plant provides heat to the Queen's main campus, west campus, Kingston General Hospital, Hotel Dieu Hospital, and St Mary's of the Lake Hospital. Currently the water enters the treatment plant, is heated by fossil fuels and then leaves the system with low heat. The inlet temperature of the water is around 21 degrees Celsius. If this starting temperature were to be increased, less fuel would need to be used, leading to less greenhouse gas emissions.

1.2 Problem Definition

The objective of this project was to sustainably collect heat from wastewater that Utilities Kingston can then use to service their client, Queen's University. More specifically, the team has designed a wastewater heat recovery system that is compatible with the existing heating infrastructure supplying Queen's University and surrounding areas. The aim for the design is to extract as much heat as efficiently as possible while remaining carbon neutral, or as close as possible.

1.3 Project Scope

In the interest of solving this problem, several deliverables have been provided. First, a schematic of the proposed design has been included. This schematic will serve as a proof of concept design and is simple to follow. A mathematical model has also been provided along with heat transfer simulations created in OpenFOAM. Additionally, an economic analysis has been conducted and projected manufacturing and installation costs, along with an estimated return on investment in the form of annual cost savings, has been provided. Finally, an estimate the reduction in energy consumption has been provided as well. More details on all of these deliverables can be found further in the report.

1.4 Design Benefits

Wastewater heat recovery would allow Utilities Kingston to extract excess heat from sewage water. Based on data surveys from the wastewater pumping station located beside Queen's, the average wastewater flow rate through the station is 23,000 cubic meters per day, at an average temperature of 16°C. This is significantly hotter than the average cold water supply temperature between September and April (7°C) [5] [6]. By using simple heat exchangers fitted to drainpipes, power could be saved at an approximate rate of 2.5 million Watts during the September-April time period. By using a powered heat pump to extract energy, up to 15.6 million Watts could be extracted. This report focuses on a heat pump requiring 2.2 million Watts of power input to extract 6.1 million Watts of energy.

2 Design Criteria & Functional Specifications

The main customers for the system are Queen's university and Utilities Kingston. Queen's will make use of the extra heat, and both customers may be involved in the device fabrication and maintenance. To develop the criteria, visits were made to the Utilities Kingston pump station, and the Queen's Central Heating Plant. Detailed design criteria are summarized below.

Table 1: Design criteria along with definitions.

Design Criteria	Definition
Low use of space	The system can fit into the available space at the chosen location
Low maintenance time	Maintenance should be fast, infrequent, and ideally does not require the whole system to be shut off.
Efficient heat exchange	The system should raise the temperature enough to be worth installing
Long lifetime	The system should be resistant to corrosion and its' lifetime should be comparable to the surrounding pipe infrastructure.
Automation	The system should not require constant operator input.
Low GHG emissions	Emissions should be minimized or eliminated if possible.
Low harm to surroundings	System should be nontoxic, low noise, and have low chemical pollution.
Low cost	Building, installation, and maintenance costs should all be minimized.
High detectivity	Malfunctions must be detected immediately.
Withstand pressure	The system must withstand expected water pressures.
Low pump power	The power requirements should be minimized

The engineering specifications provide quantitative targets for the system to achieve.

Table 2: Engineering specifications along with targets.

Engineering Specifications	Targets
Temperature/pressure sensors	Both values should be measured with uncertainty of 5% or lower.
Pipe cross sectional area	The system must fit the pipes at the central heating plant.
Pump power	The pump power must be less than the energy savings, so that the system produces net positive energy savings.
Heat retention	The system must retain 90% of heat energy or more.
Sediment deposit rate	Cleaning requirements should be at most annual.
Water flow rate	The system must function with flow rate of 1000 m^3 of water per hour.
Thermal conductivity	The minimum should be 200 W/mK, with an ideal target 400 W/mK.
Time to transfer heat	The system must transfer heat with zero decrease in water flow rate.
Cleaning time	Cleaning time should be one week per year or less.

Powder coating	Coating should be corrosion-resistant with a 10-year lifespan.
Surface area	Heat transfer surface area should be maximized within available space
Thermodynamic efficiency	Efficiency should be at least 70%.

3 Alternative Designs Considered

There are multiple methods for extracting energy from wastewater. Kinetic energy can power turbines, effluent can be converted into biofuel, and heat can be recirculated. Methods for wastewater heat extraction must also be compared with other energy-saving systems like solar panels. This ensures that wastewater heating is not only effective but is also worth the opportunity cost of investing in alternatives. The main benefit of wastewater heating over other green energy investments is the preexisting infrastructure near Queen's and the increased student population during the fall and winter terms. Wastewater heating can also be applied at different scales: the system can be applied individually at residence buildings or collect energy from a single location such as a pump station.

3.1 Residential scale heat recovery

The first alternative considered is a simple, residential heat recovery system. This model consists of a small-scale coil heat exchanger, the main line is connected to either individual hot water drains (shower, sink) or a mainline wastewater outtake. The coiled line is connected to the cold-water intake, pre-heating the hot water reservoir. For Queen's, this system would be put in place at individual residence buildings, libraries, or classrooms.

Figure 1: Small-scale residential heat recovery system fitted for individual drainage outtakes [1].

In this case, the main line of the small-scale heat exchanger is attached to the main drainage line, with the coiled line circulating into the hot water system, mixing with its own cold-water intake (pictured below in figure 2 as 'Heating Hot Water Return'). The main advantage of this design is the extremely low-cost per-unit relative to other proposed designs ($400-$1000, [7]).

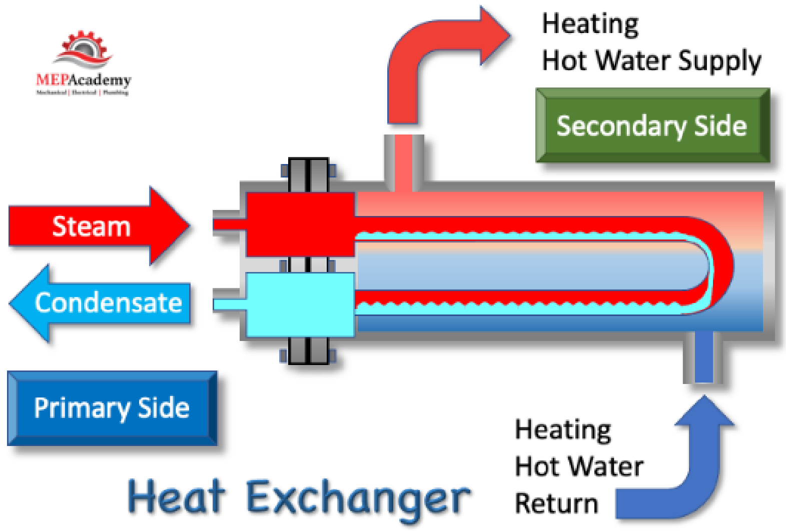


Figure 2: Example diagram of steam-based hot water generation [2].

3.2 Commercial scale heat recovery

The second alternative that was considered was applying a commercial-scale heat exchanger system directly to the centralized wastewater line at the Utilities Kingston wastewater pumping station. This model is similar to other large scale heat recovery projects such as the WET system at Toronto Western and the SHARC system, implanted at the Trico LivingWell Retirement community in Calgary (among others). These systems involve a solids pump attached to the wastewater line, leading into a macerator, volume filter and then ran through a large-scale heat exchanger that diverts the energy into the buildings heating system. These systems are proven and have examples in-place that are successful in reducing energy requirements for heating. In Toronto Western's case, the system is projected to account for up to 90% of the hospitals needs [8].

Figure 3: Toronto Western WET system [3].

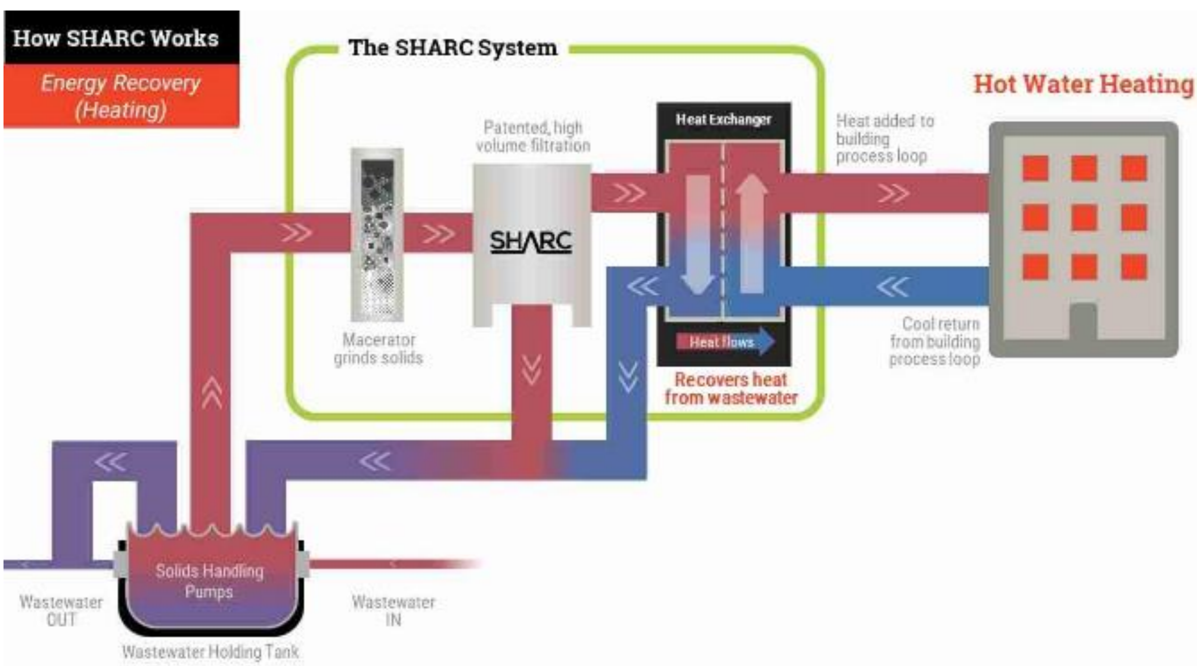


Figure 4: SHARC system schematic [4].

3.3 Smokestack heat recovery

The client, Queen's Central Heating Plant, reports an average stack temperature of around 265°F (≃ 130 °C, ≃ 400K). This excess heat is transported through the products of natural gas combustion exiting the steam boiler. Carbon dioxide makes up roughly 99% percent of the gas exiting the smokestack, travelling

25m vertically through the 1m diameter stack flue. Using these parameters, we can estimate the energy produced by transferring this heat to a steam-turbine apparatus, pictured below.

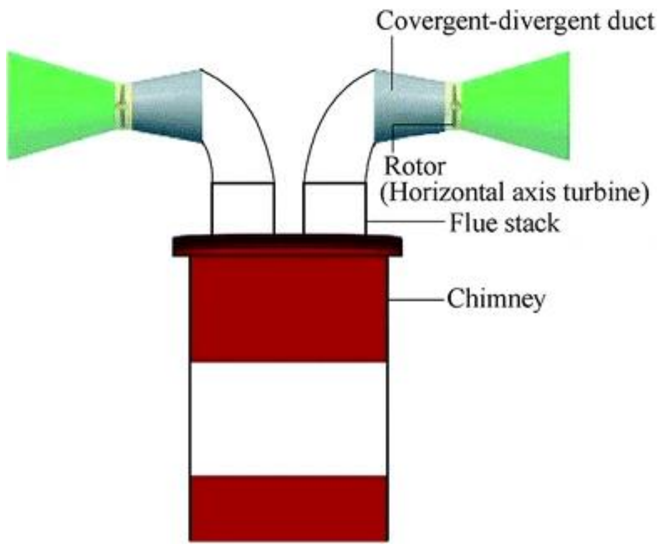


Figure 5: Diagram of smokestack heat recovery system [5].

$$W_{shaft} = Q_h - E_k = \dot{m}C_p\Delta T - \dot{m}\left(\frac{V^2}{2}\right) \tag{1}$$

Table 3: Smokestack energy estimation parameters.

Parameter	Value
C_p, Heat capacity coefficient for CO_2 at stack temp	≃ 37.35 (J/molK) [6]
V, Assuming velocity of flow through stack flue	≃ 10 m/s (Low end estimate)
D, Assumed diameter of stack outlet	≃ 1m
T_1, Average stack temperature	≃ 130 °C
T_2, Assumed final temperature at turbine outlet	≃ $T_{ambient}$ ≃ 20 °C (High end estimate)
Total Estimated Turbine Energy	≃ 220 kW

4 Selection Methodology

4.1 Weighted Evaluation Matrix

The QFD analysis below is derived from the full-size ‘House of Quality’ analysis provided in Appendix B. Design criteria are based on customer requirements for an effective design and were evaluated as a team. Importance is based on how much we valued each criterion within the scope of the project as well as their influence over a real-world implementation of the design. Designs were graded based on how well they meet each criterion. The final grade was determined through discussion and debate amongst all team members to ensure a well-rounded approach. The grades' assigned to criteria importance and each design's effectiveness range from 1 to 5 (5 pertaining to 'most' effective, 1 being 'least').

Table 1 4: Quality Function Deployment analysis of chosen design and two proposed alternatives.

			Design: Heat Pump Recovery to Queen's Central Heating Plant		Alternative 1: Residential Scale Heat Exchanger		Alternative 2: Commercial Scale Heat Exchanger	
Design Criteria	Importance Rating (1-5)	Weight (%)	Grade	Score	Grade	Score	Grade	Score
Exchange heat with high efficiency	5	13	3	39	2	26	4	53
Long Lifetime	2	5	3	16	4	21	3	16
Little or no harm to surroundings	4	11	4	42	5	53	3	32
Low cost	4	11	3	32	5	53	1	11
High detectivity	3	8	3	24	1	8	3	24
Automation	2	5	4	21	1	5	3	16
Low or no GHG emissions	5	13	5	66	5	66	5	66
Able to withhold high pressure	3	8	3	24	2	16	5	39
Low pump power	3	8	3	24	5	39	1	8
Low use of space	1	3	3	8	5	13	1	3
Low maintenance time	1	3	4	11	4	11	2	5
Feasibility	5	13	4	53	1	13	2	26
TOTAL		100		358		324		297

The first alternative design has the draw-back of requiring multiple units, due to the small scale. The volume of drain-water varies greatly from working to sleeping hours. For this design to be effective in supplying energy to a building's hot water system, several hundred units may need to be installed. This brings the feasibility of implementation way down and negates the advantage of its low-cost.

The second alternative may encounter a higher overall efficiency than the chosen design, as a passive heat exchanger does not require an additional energy input. The main reason for its ineffectiveness in relation to our project, is the client's use of high-grade steam for Queen's heating purposes. The heat pulled out of the 14°C - 16°C wastewater line will not be enough to significantly preheat the cold-water intake line at the Queen's central heating plant. Similar installations such as the Toronto WET system have costs upwards of $43 million which is a significant investment for uncertain energy returns [9].

4.2 SOD Risk Assessment

SOD Risk Assessment, also called an FMEA (failure mode & effect analysis), is a technique to transfer potential incidents to quantitative ratings, in dimensions including severity, occurrence, and detectivity [10]. The rating is between 1 to 10, in case 1 refers to few influence, hardly occurring, and easy to be monitored. Meanwhile, 10 refers to dramatical detrimental effects, happened in a regularly basis, and difficult to be found in inspection. The product of the ratings is calculated. In this design, if the rating of a potential incident of the system is below 50, it is defined as a risk that is well-solved. If the rating is between 50 to 150, the risk is defined as medium, which potentially requires further treatment, but it is acceptable in prototypes. In case the rating is higher than 150, the risk is unacceptable, and additional strategies and devices will be used to lower the risk.

6.1 Overview

The final design will extract thermal energy from the wastewater pumping station into refrigerant circulating through a heat pump. The Refrigerant will then transfer the energy into water at the Queen's Central Heating Plant.

At the wastewater pumping station, four pipes with 0.5m diameter carry the pump outflow wastewater. These pipes will be refitted with copper heat exchangers, treated for corrosion, that cover a 6m length along each pipe. The average flow velocity within the pipes is 1.06 m/s, and the average temperature is 16°C. The heat exchangers around the wastewater pipes will carry refrigerant cooled to -20°C. This heat exchanger will act as an evaporator for the heat pump, and the refrigerant will extract thermal energy from the wastewater at an estimated rate of 6.1 million Watts.

The refrigerant will then travel from the pump station to the heating plant through insulated pipes. At the heating plant, the refrigerant will pass through a compressor that powers the refrigerant flow and controls pressure changes. The compressor will require an average power input rate of 2.2 million Watts and will have variable capacity up to 3 million Watts for peak-use cases.

The refrigerant exiting the compressor will flow into a heat exchanger, where it will transfer heat into the water at the central heating plant. The heat exchanger will have a 0.4m diameter cylindrical shell for refrigerant flow, with 1.2 cm water flow tubes inside. The refrigerant temperature after exiting the compressor will be 60°C. The water temperature will vary based on season, with an estimate of 0-20°C entering the exchanger and 40-50° exiting.

5 Technical Plan

The goal of this heat pump design is to transfer heat to clean water extracted that is from Lake Ontario from a cold source. Heat will be extracted from the wastewater at the pump station, use a heat pump to increase the heat grade, then use the heat to preheat water entering the Central Heating Plant. The plant operators estimate that 16% of the water used for steam heating is sourced from the city, and has the potential to be preheated.

Starting the installation of a heat pump system for wastewater requires careful planning, which starts with a thorough site analysis. This first stage entails assessing the wastewater system's dynamic properties, such as the flow rates, temperature profiles, and accessibility logistics. Choosing a suitable heat pump is a crucial step in this process as there are various types of heat pumps used for wastewater applications. Assessing factors such as the Coefficient of Performance (COP) and the relationship between temperature variations and heating demands are crucial and to be considered when choosing the specific heat pump. The planning for installing the heat pump will require a balance between maximum heat transfer efficiency and a strong insulation design in order to reduce any heat loss. More details regarding installation, risk management, and project maintenance is discussed further in the report.

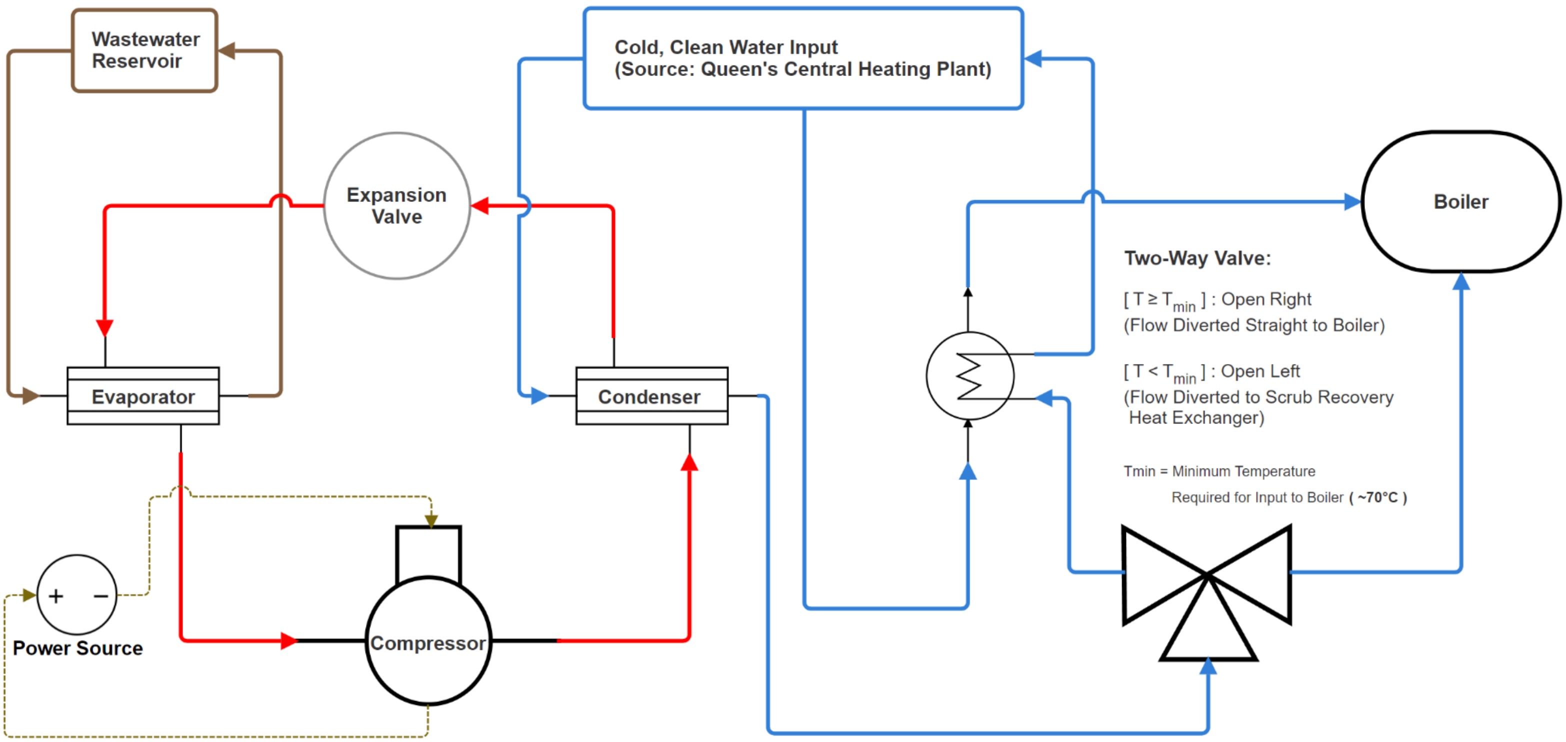
The process of integrating a heat pump system into the wastewater system starts with a thorough evaluation of its current situation. A crucial factor in system design, the pumping station's daily wastewater flow is measured to be about 23,000 m^3. This wastewater's average temperature of 16°C is a significant factor affecting its capability for total heat recovery. Understanding the system's surroundings will have a relatively low heat transfer rate, the focus shifted towards optimizing the energy transferred from the wastewater to reduce losses to the environment/surroundings. The wastewater in this system is intentionally cooled in order to achieve a 5 °C temperature drop during the heat transfer phase.

Examining the energy transmission inside the heat pump system forms the basis of the technical plan. Through analysis, it is projected that 15.6 MW of net power will be transferred from the wastewater to the system if the heat transfer system runs at maximum efficiency. The energy that is extracted from the wastewater is considered a useful resource when considering sustainable energy practices in a larger application. It's important to remember that not all of this energy is readily used right away as approximately 6.1 MW of this thermal energy will be directed towards the system's refrigerant, which is explained in more detail further in the report. This energy transfer junction reveals the complexities of heat pump functioning, as some thermal energy will be lost in this stage of the process and hence slightly lower the overall thermal efficiency. This is an expected occurrence due to heat transfer from the two sources, implementing a refrigerant and the various temperature variations involved in this heat recovery process.

The heat transport model is examined in detail, where factors such as temperature differentials, heat pump performance, and the particular properties of the refrigerant are considered to analyze the thermal dynamics at work during the heat transfer process. It explores in detail how the temperature of the wastewater drops by 5 °C while effectively transferring energy to the refrigerant. In addition to analyzing the dynamics of energy transfer, the model is essential for maximizing the overall system performance. For this, a detailed analysis was conducted to determine system variables including flow rates, compressor efficiency etc. More details on the heat pump schematic, how it will operate with respect to the sources of water and refrigerant, and the types of models considering constraints can be found further in the report.

6 Final Design

6.2 Schematic



The final proposed design includes the use of a heat pump to transfer and extrapolate energy collected from wastewater to then be input into the cold, clean water line that is used to feed the boiler at Queen's Central Heating Plant. Currently, the boiler input is preheated by a heat exchanger and flow diverted from weekly washout. A two-way valve is used to ensure the heated clean water is of a sufficient grade to make a difference in the vaporization process. If the output from the proposed system is not above the minimum boiler input temperature, then the valve and subsequent sensors will divert flow to the washout heat exchanger. Temperature sensors will also be located at the wastewater reservoir to ensure the system is inputting the correct amount of mechanical work to achieve the desired grade. This system ensures that there is zero contact between wastewater and clean water sources, as well as allows for the connection of multiple inputs (during summer, lake-water can be connected to take advantage of its higher grade).

Sensors and Controls

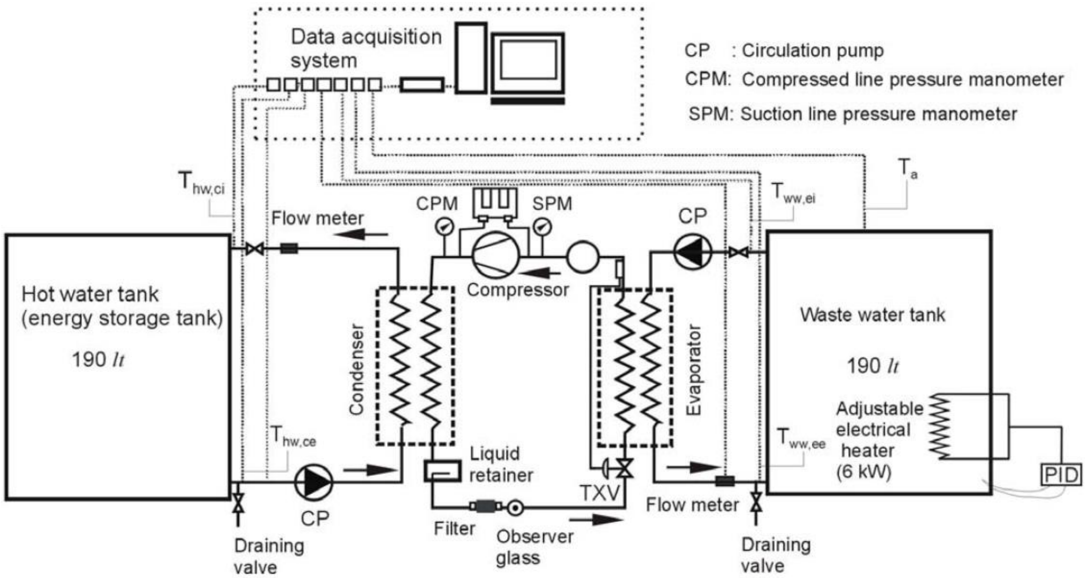


Figure 6: Example heat pump schematic [7].

6.3 OpenFOAM Model

The wastewater heat extraction and the heat pump compressor were modelled using OpenFOAM in order to confirm the manual calculations. These components were chosen because they are the main limits on the system's capacity. The heat exchanger used to extract heat from the wastewater is the main limit on how much energy can be extracted. This is because the wastewater pump station output pipes must maintain a constant flow rate and must be wide enough to prevent blockages due to solids/sediments in the wastewater. Therefore, the extraction heat exchanger was designed to fit around a 0.5 meter diameter, 6 meter in length copper pipe from the pump output. This design fits the existing wastewater pumps, is straightforward to construct, does not alter the wastewater flow rate, and is wide enough that solids will not block the pipe.

Figure 7: Paraview render of OpenFOAM simulation of a pump station output pipe. The wall boundary conditions simulate a 0.5cm copper pipe surrounded by refrigerant.

The fluid heat transfer simulation of the 6 meter pipe section with 1.06m/s water flow velocity, represents pump station outflow pipes. The pipe walls simulate -20°C refrigerant flow. The induced temperature drop is 5.5 degrees, which corresponds to 6.1 million Watts of heat extraction based on water flow rate. The system functions with the expected 1.06m/s flow velocity, but also works for higher velocities. At lower velocities, the system functions, but extracts less total heat.

The compressor was simulated as a rotating disc, one meter in diameter, with average pressure inside calculated for various speeds.

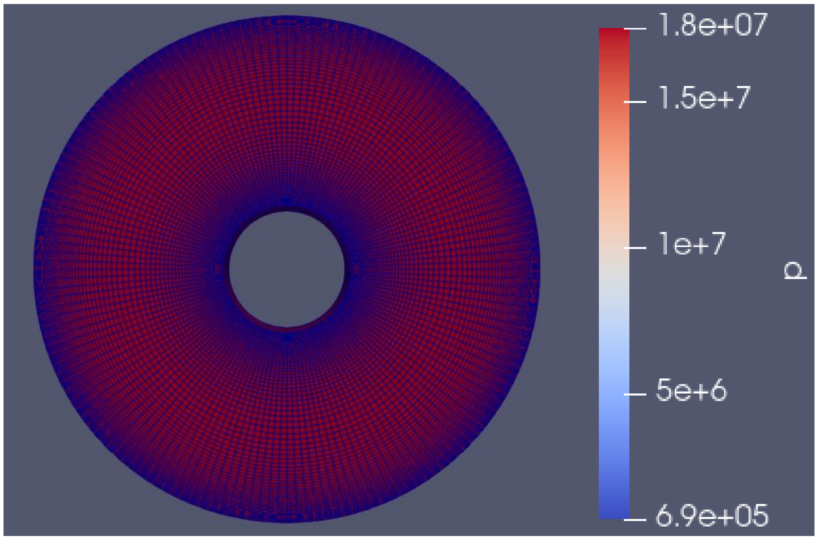


Figure 8: Paraview render of OpenFOAM simulation of heat pump compressor.

When the compressor is run at 1.5 Megawatts, it can generate pressures of up to 2.1 million Pascals. This ensures that the target pressure, 2 million Pascals or 20 bar, is achievable.

6.4 Thermodynamic Model

This design is aiming to transfer heat from a relatively cold source to clean water collected from Lake Ontario. Since the location of the pumping station and the central heating plant are close to Lake Ontario, and the distance between the two sites is relatively small, the energy used to pump water from the lake to the system, and pump water from the system to the central heating plant will be negligible. A heat pump system is designed to efficiently collect the energy from the relatively cold wastewater to clean water from Lake Ontario. The refrigerant in the heat pump system is specified as R-134a, which is legal in Canada. The heat pump system will have an indirect heat transfer from wastewater to the refrigerant in the evaporator, and one from refrigerant to clean water output in condenser. The inner pressure of the refrigerant is manipulated by a compressor and an expansion valve. The compressor is the only electrical device that requires power input to the system. The clean water output with a designed output temperature 60℃ will be pumped to the central heating plant, participating in the process that provides heat to the campus buildings.

A Carnot cycle in a T-S diagram will be used to describe the process. The pressure will be increased in a compressor, with a respective increase in temperature, followed by a decrease in entropy that results in a net decrease in the energy stored in the refrigerant by an indirect heat transfer to the . After that, the refrigerant will pass through the expansion valve as a relatively cold saturated liquid, and within another indirect heat transfer from wastewater, the entropy of the liquid will increase, and be prepared for passing the compressor.

Referring to **Error! Reference source not found.**, the shaded area is the Carnot cycle indicating the c hange of energy within the system in real-life situations. In theory, the entropy in the low-pressure conditions will be maximized, to get the literal maximum efficiency.

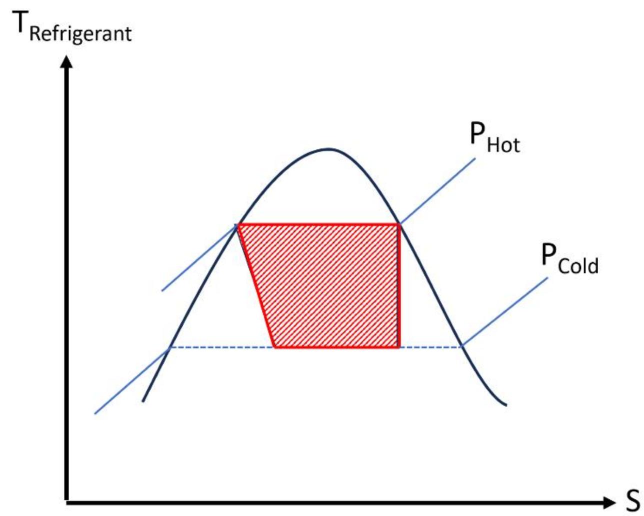


Figure 9: T-S diagram showing the heat pump process.

Based on Figure 9, when the pressure of R-134a can be manipulated to 1 bar in the expansion valve and compressed to 20 bar. The saturated temperature within such a pressure will be -27.53 ℃ and 67.43℃ respectively, satisfying the heat transfer.

6.4.1 Potential Energy in Wastewater

Based on the information given, the daily wastewater flow in the pumping station is approximately 23,000 m^3, with an average temperature around 16℃. In this case, provided that the heat transfer system can fully transfer the energy from the wastewater, since soil has a relatively low heat transfer rate there will be less energy transferred to the surroundings. The wastewater is designed to decrease the temperature by 5 ℃ in the heat transfer process. In this process, net power transferred from the wastewater will be approximately 15.6 MW, and the energy transferred to the refrigerant will be approximately 6.1 MW. This process will be investigated in-depth in the heat transfer model.

6.4.2 Heat Pump Energy Requirements, Power Output, and the Efficiency

The compressor is the only electrical device that requires a large amount of power to operate the system. The compressor is responsible for increasing the pressure of the refrigerant and keeping the refrigerant in the form of a saturated liquid. Referring to Petroskills [11], the efficiency of the compressor used is approximately 75%. Based on Equation 1, the work required can be calculated. Theoretically, the output temperature of the water will be 60 ℃, and the designed clean water flow has a mass flow rate 50 kg/s, which requires 10.5 MW output to fully heat the clean water collected from lake Ontario, with an average temperature of 10 ℃ referred to Figure 10.

$$W_{input} = \frac{\dot{Q}_H - \dot{Q}_c}{\mu}$$

Equation 1 The efficiency of the heat pump system

	Max Temp	Avg T	Min T
January	4.5	3	1.4
February	1.5	0.8	0.4
March	0.7	0.4	0.2
April	3.5	2.1	0.8
May	10.4	6.2	3.6
June	18.9	14	9.9
July	24.3	20.8	16.8
August	25	23.3	21.8
September	24.3	21.2	18.3
October	19	15.1	11.5
November	11.8	9.3	7.2
December	7.2	5.8	4.6

Figure 10 Average water temperature in lake Ontario [12]

Assuming all energy from refrigerants can be transferred to the clean water output, and no energy can be released to the surrounding environment in the process, Figure 11 is used to demonstrate the process. Based on Equation 1 and the assumed efficiency, the input power of the system from the compressor is around 5.9 MW.

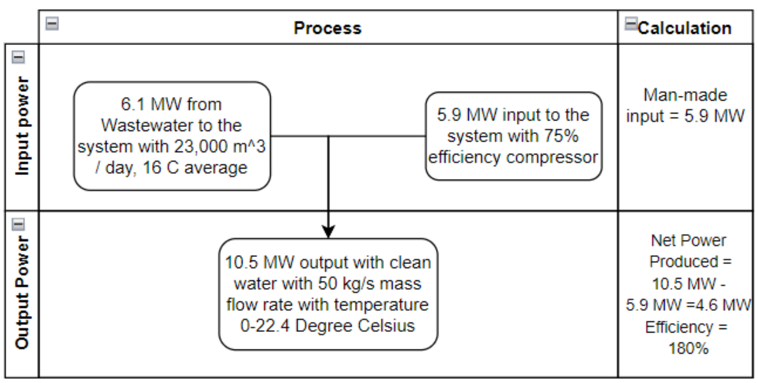


Figure 11 Flow chart of the power in and out the system

Referring to Equation 2, the efficiency of the system can be calculated, which is approximately 180%.

$$\mu_{system} = \dot{Q}_H / W$$

Equation 2 efficiency of the whole system

6.4.3 Energy Recovery vs Cost

Research was conducted looking through various types of heat pumps currently being used in commercial applications such as wastewater treatment plants. Heat pumps similar to this project’s functionality, amount of water being dealt, and similar volume of space available for installation were factors considered in choosing an appropriate cost. Thus, the heat pump for this project will have a cost (including installation and digging) of $300,000 to implement the system [8]. Inspection and maintenance will be done annually, looking at a couple times at most to ensure the system and the piping are operating correctly.

There are various amounts and types of heat pumps that are in use both commercially and residentially. Factors such as size/volume of space available, amount of heat energy conserved, and rate of water being dealt are considered when looking at pre-existing designs. An average of 23,000 m^3 /day of water is flowed and a potential to conserve 6.1 million Watts of heat energy is what the heat pump design will perform. Based on this information, an appropriate rate of $1400/kW for the heat pump is chosen to describe the operation of the design [13]. Considering 6100 kW of heat will be conserved, and costs of installation/construction, any maintenance is required, annual inspections, and piping modifications: a current budget of $13,287,00 is associated with the heat pump design. The table below outlines the main costs and total cost of the proposed heat pump design.

Table 5: Table showing all cost factors and total overall cost of proposed heat pump design.

Heat Pump Cost + Installation	$300,000
Inspection	$3,000
Maintenance	$4,000
Operating Cost	$1400/kW
Total Cost	$13,287,000

Currently Queen's University has an estimated yearly power consumption of 74 million Watts throughout the campus [4]. The budget corresponding to this power consumption is $18 million annually [4]. While implementing the proposed design, the budget would cost approximately $13,287,000, which is reduced by 37.3% from the Queen's University yearly electric budget of $18 million. In addition, Queen's University had an estimated power consumption of 74 million Watts, and with the heat pump implementation, the energy consumption reduces to 59.2 million Watts, a 20% reduction. Studies have showed implementing a heat pump in wastewater facilities can save 10-20% of energy consumption, which is what the proposed design can achieve [13]. The table below outlines the cost and energy savings while implementing the heat pump design.

Table 6: Table showing the annual cost and energy savings using the proposed heat pump design.

Cost Savings	**Percent Reduction in Electric Bill**	**Annual Energy Savings**	**Percent Reduction in Energy Consumption**
$4,714,000	26.1%	4,400,000 Watts	20%

7 Project Planning

7.1 Installation

The system is designed to be located underground, meaning digging work is required. Referring to CER [13], there are no interactive pipelines underground in the location chosen for the system, so there is no need to consider the effect on the preexisting pipelines. Referring to Utilities Kingston [14], a call to apply for the free location of municipal infrastructure is required before the installation of the heat recovery system. The pipes used will be connected by coupling and union fittings with tee fittings connected to a pressure gauge per 5-meter length of pipes. The coupling and union fittings will permanently connect the pipe sections. The selection between coupling and union fittings is hinged on the frequency of inspection because the union fittings can be removed by loosening the ring to disconnect the pipes, but it is potentially more expensive. The tee fittings with pressure gauges are used to monitor the inner pressure of the system. This can detect possible leakage and clogging in the pipe system, which should be monitored and recorded on a daily basis. There should also be a warehouse located next to the system.

7.2 Risk Management

Based on the research of an HVAC Company serving Delaware [15] and Supreme [16], the major risks and the respective problems are posted in Figure 12. In this figure, the severity, occurrence and detectivity of a potential risk of the heat recovery system is assessed with rating from 1 to 10. 1 means the safest and 10 is defined as the most dangerous. Final rating within 0 to 50 will be defined as a safe situation, which is marked in green, and rating within 50-150 will be defined as medium. This is acceptable but the inspection should be applied more regularly. Ratings larger than 150 will be unacceptable.

Based on the research of an HVAC Company serving Delaware [15] and Supreme [16], the major risks and the respective problems are posted in Figure 12. In this figure, the severity, occurrence and detectivity of a potential risk of the heat recovery system is assessed with rating from 1 to 10. 1 means the safest and 10 is defined as the most dangerous. Final rating within 0 to 50 will be defined as a safe situation, which is marked in green, and rating within 50-150 will be defined as medium. This is acceptable but the inspection should be applied more regularly. Ratings larger than 150 will be unacceptable.

Problem	Problem Description	Before Improvement			
		Severity	Occurrence	Detectivity	Overall
Unable to Turn On	It is possibly due to the lack of power, an inspection on its power source and circuit should be applied	7	5	3	105

Unusual Smell (musty or rotting)	Possibly microorganisms or animals in pipe	5	7	5	175
Unusual Smell (burning)	Possibly due to serious electrical issues	10	3	5	150
Piping system failure	It is possibly due to the high pressure of fluid in the pipe, the corrosion, and potential ground movement	10	5	3	150

Figure 12 The FMEA system assessing the risk of a potential heat pump heat recovery system based on possible accidents of heat pump systems and piping systems.

Referring to Figure 13, the problems have been considered in the design process, but some further improvements can be done. Based on the comments, the improved rating is estimated to be lower than the original ratings by additional inspections and extra monitoring devices.

Problem	Comments	After Improvement			
		Severity	Occurrence	Detectivity	Overall
Unable to Turn On	Reasonable but should be lower down, regular inspection on circuit should be taken to reduce the risk's occurrence, and a back-up circuit can be prepared to reduce the time influenced by the incident	5	3	3	45
Unusual Smell (musty or rotting)	Relatively high because it is quite usual to have bio foils on piping systems. To improve, anti-bacterial coatings such as black silicon can be applied, and the system should be isolated with external areas, and regularly inspection for piping system should be also applied.	5	3	3	45

Unusual Smell (burning)	Relatively high due to the high severity of the accident. However, it can be detected by inspections for electrical devices in the system. Fire extinguisher should be also prepared.	8	3	3	72
Piping system failure	Pressure gauge is already included in the design. To improve, the original wastewater piping system will be maintained, to make sure the wastewater can be pumped away from city when the heat recovery system does not work well.	7	5	3	105

Figure 13 Solutions and comments to optimize the ratings in the risk assessment.

7.3 Project Maintenance

As is mentioned, inspections on a regular basis are essential to detect the operation of the system. A daily inspection should be applied to the pressure gauge, monitoring the pressure in the piping system for wastewater, refrigerant, and clean water output. During the daily monitoring, the operator should also notice the smell of the surroundings of the system. When unusual smells are found, the operator should stop the system and have an in-depth inspection respective to the smell. The electrical circuits and devices should be inspected annually. In this period, the energy recovery system will be closed, and the wastewater will be pumped into the original pipelines. The inner part of the pipeline will also be inspected in this period, with cleaning and removing the bio foils on the wastewater pipeline inner surface due to the organic small particles in wastewater, and the potential dead animal bodies inside the pipeline. To face potential accidents, preparations should be done in advance. As mentioned, there will be a warehouse, for storing some back-up parts and tools. A separated bin will be prepared to store R134-a and other potential chemicals, such as acids to wash the bio foils. Epoxy Putty will be prepared in the warehouse as well, in order to prepare for unexpected leakage, and prepare for a temporary fixing solution.

8 Discussion and Overall Recommendation

Wastewater energy recovery would allow Utilities Kingston to harness unused energy in the Megawatt range, with a target average of 6.1 Megawatts for the fall and winter terms. The Queen's Central Heating Plant located directly beside the pump station would also benefit from using the extracted heat to improve efficiency.

Wastewater heat extraction at the pump station allows the system to scale easily. If wastewater flow in the region increases, it still all flows through the pump station. Even if a new building is built, it does not need any special modifications such as drainpipe heat exchangers. An increase in the flow of wastewater will increase energy recovery by providing more heat input. Using the existing pump station also allows the system to operate continuously with little maintenance, since the pump station has four pumps. The heat exchanger at each pump output can be maintained without altering flow at the other pumps.

Heat recovery is most effective during colder months, but this is not an issue because Queen's university has a full student population during the fall and winter terms. The most significant downside of wastewater heating is installing the heat exchanger and pipe system underground. The installation has a high upfront cost for excavation and assembly, and maintenance may require repeated excavation. The summer term, when the system sees less use, provides enough time for inspection/maintenance. However, potential failures during the school year cannot be fixed immediately. Since the heat pump is not the main source of heating for Queen's and is instead used to increase the efficiency of the heating plant, failure would not disrupt university operation. Overall, the heat pump system would be worth the construction cost and help make Utilities Kingston and Queen's more energy efficient.

9.Works Cited

[1] N. E. Selin, "Carbon Footprint," Encyclopedia Britannica, 23 September 2023. [Online]. Available: https://www.britannica.com/science/carbon-footprint.. [Accessed 16 October 2023].

[2] "Net-Zero Emissions by 2050," Government of Canada, 17 July 2023. [Online]. Available: https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.htm. [Accessed 16 October 2023].

[3] "The federal carbon price is going up. What does this mean for you?," CUPE, 19 March 2023. [Online]. Available: https://cupe.ca/federal-carbon-price-going-what-does-mean-you.. [Accessed 19 October 2023].

[4] "Queen's University Greenhouse Gas Inventory Report 2021," Queen's University, 2022. [Online]. [Accessed 16 October 2023].

[5] Utilities Kingston, "Annual Report on Drinking Water Quality," Kingston, 2020.

[6] "Lake Ontario Water Temperatuer," WATERTEMPERATURE.net, [Online]. Available: https://www.watertemperature.net/united-states/lake-ontario-water-temperature.html. [Accessed December 2023].

[7] "The Home Depot Canada," The Home Depot Canada, [Online]. Available: https://www.homedepot.ca/product/power-pipe-3-inch-diam-36-inch-long-price-includes-drain-connectors-/1000698163. [Accessed 18 October 2023].

[8] N. Energy, "The Toronto Western Hospital WET™ Project," Noventa Energy, [Online]. Available: https://www.noventaenergy.com/toronto-western-hospital. [Accessed 18 Oct 2023].

[9] "Toronto Western Hospital dives into $43 million WET project - constructconnect.com," Daily Commercial News, [Online]. Available: https://canada.constructconnect.com/dcn/news/infrastructure/2022/08/toronto-western-hospital-dives-into-43-million-wet-project. [Accessed 18 Oct 2023].

[10] "FAILURE MODE AND EFFECTS ANALYSIS (FMEA)," ASQ, [Online]. Available: https://asq.org/quality-resources/fmea. [Accessed 6 Dec 2023].

[11] "How to Estimate Compressor Efficiency?," Petroskills, [Online]. Available: https://www.jmcampbell.com/tip-of-the-month/2015/07/how-to-estimate-compressor-efficiency/. [Accessed 6 Dec 2023].

[12] "Lake Ontario Water Temperature," WATERTEMPERATURE.NET, 6 Dec 2020. [Online]. Available: https://www.watertemperature.net/united-states/lake-ontario-water-temperature.html. [Accessed 6 Dec 2023].

[13] "Canada Energy Regulator / Régie de l'énergie du Canada," CER, 14 Feb 2023. [Online]. Available: https://www.cer-rec.gc.ca/en/safety-environment/industry-performance/interactive-pipeline/. [Accessed 6 Dec 2023].

[14] "Utilities Kingston: All Your Utilities Under One Roof," Ultility Kingston, [Online]. Available: https://utilitieskingston.com/MultiUtility/Locates. [Accessed 6 Dec 2023].

[15] "4 Common Heat Pump Problems and What You Should Do: H & H," 02 May 2022. [Online]. Available: https://www.delcohvac.com/blog/4-common-heat-pump-problems-and-what-you-should-do/.

[16] "5 Causes of Pipe Failure," Supreme, 21 Jan 2021. [Online]. Available: https://supremepipe.com/blog/causes-pipe-failure/. [Accessed 06 Dec 2023].

[17] Micheal J Megan et.al, Fundamentals of Engineering Thermodynamics (2018, Wiley), wiley, 2018.

10 Appendix

10.1 Photos of site

Figure 14: Junction of pipes in Wastewater Pumping Station on Queen's University Campus

Figure 15: Various pipeline systems of wastewater in Wastewater Pumping Station

10.2 Extra Thermodynamic Modelling

TABLE A-10 Properties of Saturated Refrigerant 134a (Liquid–Vapor): Temperature Table

Pressure Conversions: 1 bar = 0.1 MPa = 10^2 kPa

Temp. °C	Press. bar	Specific Volume m^3/kg Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
−40	0.5164	0.7055	0.3569	−0.04	204.45	0.00	222.88	222.88	0.0000	0.9560	−40
−36	0.6332	0.7113	0.2947	4.68	206.73	4.73	220.67	225.40	0.0201	0.9506	−36
−32	0.7704	0.7172	0.2451	9.47	209.01	9.52	218.37	227.90	0.0401	0.9456	−32
−28	0.9305	0.7233	0.2052	14.31	211.29	14.37	216.01	230.38	0.0600	0.9411	−28
−26	1.0199	0.7265	0.1882	16.75	212.43	16.82	214.80	231.62	0.0699	0.9390	−26
−24	1.1160	0.7296	0.1728	19.21	213.57	19.29	213.57	232.85	0.0798	0.9370	−24
−22	1.2192	0.7328	0.1590	21.68	214.70	21.77	212.32	234.08	0.0897	0.9351	−22
−20	1.3299	0.7361	0.1464	24.17	215.84	24.26	211.05	235.31	0.0996	0.9332	−20
−18	1.4483	0.7395	0.1350	26.67	216.97	26.77	209.76	236.53	0.1094	0.9315	−18
−16	1.5748	0.7428	0.1247	29.18	218.10	29.30	208.45	237.74	0.1192	0.9298	−16
−12	1.8540	0.7498	0.1068	34.25	220.36	34.39	205.77	240.15	0.1388	0.9267	−12
−8	2.1704	0.7569	0.0919	39.38	222.60	39.54	203.00	242.54	0.1583	0.9239	−8
−4	2.5274	0.7644	0.0794	44.56	224.84	44.75	200.15	244.90	0.1777	0.9213	−4
0	2.9282	0.7721	0.0689	49.79	227.06	50.02	197.21	247.23	0.1970	0.9190	0
4	3.3765	0.7801	0.0600	55.08	229.27	55.35	194.19	249.53	0.2162	0.9169	4
8	3.8756	0.7884	0.0525	60.43	231.46	60.73	191.07	251.80	0.2354	0.9150	8
12	4.4294	0.7971	0.0460	65.83	233.63	66.18	187.85	254.03	0.2545	0.9132	12
16	5.0416	0.8062	0.0405	71.29	235.78	71.69	184.52	256.22	0.2735	0.9116	16
20	5.7160	0.8157	0.0358	76.80	237.91	77.26	181.09	258.36	0.2924	0.9102	20
24	6.4566	0.8257	0.0317	82.37	240.01	82.90	177.55	260.45	0.3113	0.9089	24
26	6.8530	0.8309	0.0298	85.18	241.05	85.75	175.73	261.48	0.3208	0.9082	26
28	7.2675	0.8362	0.0281	88.00	242.08	88.61	173.89	262.50	0.3302	0.9076	28
30	7.7006	0.8417	0.0265	90.84	243.10	91.49	172.00	263.50	0.3396	0.9070	30
32	8.1528	0.8473	0.0250	93.70	244.12	94.39	170.09	264.48	0.3490	0.9064	32
34	8.6247	0.8530	0.0236	96.58	245.12	97.31	168.14	265.45	0.3584	0.9058	34
36	9.1168	0.8590	0.0223	99.47	246.11	100.25	166.15	266.40	0.3678	0.9053	36
38	9.6298	0.8651	0.0210	102.38	247.09	103.21	164.12	267.33	0.3772	0.9047	38
40	10.164	0.8714	0.0199	105.30	248.06	106.19	162.05	268.24	0.3866	0.9041	40
42	10.720	0.8780	0.0188	108.25	249.02	109.19	159.94	269.14	0.3960	0.9035	42
44	11.299	0.8847	0.0177	111.22	249.96	112.22	157.79	270.01	0.4054	0.9030	44
48	12.526	0.8989	0.0159	117.22	251.79	118.35	153.33	271.68	0.4243	0.9017	48
52	13.851	0.9142	0.0142	123.31	253.55	124.58	148.66	273.24	0.4432	0.9004	52
56	15.278	0.9308	0.0127	129.51	255.23	130.93	143.75	274.68	0.4622	0.8990	56
60	16.813	0.9488	0.0114	135.82	256.81	137.42	138.57	275.99	0.4814	0.8973	60
70	21.162	1.0027	0.0086	152.22	260.15	154.34	124.08	278.43	0.5302	0.8918	70
80	26.324	1.0766	0.0064	169.88	262.14	172.71	106.41	279.12	0.5814	0.8827	80
90	32.435	1.1949	0.0046	189.82	261.34	193.69	82.63	276.32	0.6380	0.8655	90
100	39.742	1.5443	0.0027	218.60	248.49	224.74	34.40	259.13	0.7196	0.8117	100

v_f = (table value)/1000

Figure 16 Temperature Table of Properties of R134-a [17]

10.3 Exhibition Poster

MECH 460 Team Design 2023: Wastewater Heat Recovery

Chentong Shen, Jaimin Patel, Joshua Malone, Justin Soberman, Anthony Burke and Miodrag Matovic

ABSTRACT

The primary objective of this project is to sustainably collect heat from wastewater that Utilities Kingston can then use to service their client. To accomplish this, a wastewater heat recovery system has been designed that is compatible with existing heating infrastructure supplying Queen's university and the surrounding areas. The design uses a heat pump system to raise the inlet water temperature being used at the central heating plant above its current ambient temperature. This in turn, increases the efficiency of the overall design and reduces the amount of greenhouse gases that the plant will emit. On top of reducing emissions, the design is expected to reduce energy consumption by up to 20% annually at the plant.

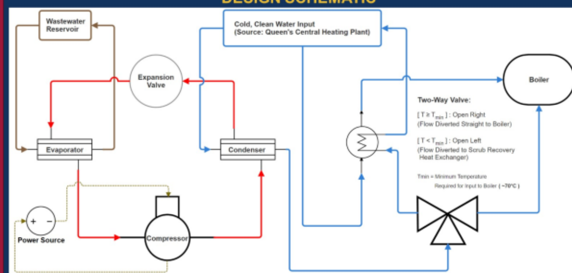
Background Information

Carbon footprint is a critical aspect of engineering and is defined as the total amount of greenhouse gas emitted by human activities, effected by the efficiency of the system and the renewable energy usage. This is becoming a growing concern and as such, the Canadian government is taking countermeasures. Currently the government has put forth regulations that require companies to have either zero carbon dioxide emissions, or to offset any carbon dioxide emitted, with the goal of reaching net zero carbon emissions by 2050. In addition to regulations, the government is also offering financial incentives as well.

For these reasons, finding methods of heat generation that involve low greenhouse gas emissions is massively important, and was a large focal point of the project. In this case, a wastewater heat recovery system, with the goal of collecting thermal energy to use elsewhere, is being investigated. The spot chosen for this is the Queen's Central Heating plant, which provides heat to the whole campus and several surrounding hospitals. However, the plant also emits 27000 $MTCO2e$ greenhouse gases, which makes up 83% of Queen's Scope 1 emissions. Currently the system operates using a low inlet temperature of about 21 degrees Celsius. The goal is to raise this temperature which will offset carbon emissions.

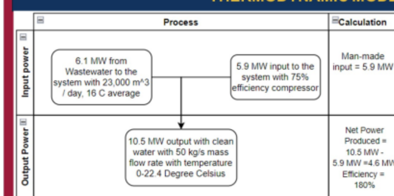
Department of Mechanical and Materials Engineering
Queen's University
Kingston, Ontario
K7L 3N6

DESIGN SCHEMATIC

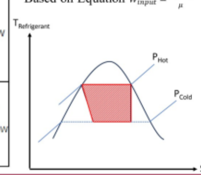


The design utilizes a heat pump to transfer and magnify heat collected from wastewater to then be transferred to the cold, clean water line feed line of the Queen's Central Heating Plant boiler. Currently, the boiler input is preheated by a heat exchanger capturing heat from weekly washout. A two-way valve is used to ensure the system's output is of a sufficient grade to be useful in the vaporization process. Temperature sensors will also be located at the wastewater reservoir to ensure the compressor operates at the desired frequency for heating. The system ensures zero contact between wastewater and clean water sources, as well as allows for the connection of multiple inputs (during summer, lake-water can be connected to take advantage of its higher grade).

THERMODYNAMIC MODEL



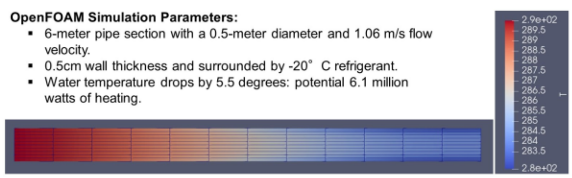
Based on Equation $W_{input} = \frac{\dot{Q}_H - \dot{Q}_c}{\mu}$



OPENFOAM FLOW MODEL

OpenFOAM Simulation Parameters:

- 6-meter pipe section with a 0.5-meter diameter and 1.06 m/s flow velocity.
- 0.5cm wall thickness and surrounded by -20° C refrigerant.
- Water temperature drops by 5.5 degrees: potential 6.1 million watts of heating.



Economic Analysis

An economic analysis for the proposed heat recovery design was conducted. A table summarizing the cost and energy consumption savings using the proposed design is shown in the table below.

Cost Savings	Electric Bill Percent Reduction	Annual Energy Savings	Energy Consumption Percent Reduction
$4,714,000	26.1%	4,400,000 Watts	44.76%

RECOMMENDATIONS

Maintenance and inspections: a pressure gauge is connected to the refrigerant system, monitoring possible leakages. Maintenance should include the removal of possible bio-foils from the wastewater line, as well as inspection of the coating on the pipe surface, particularly at unevenly protected connection points.

Seasonal modifications: a temperature sensor is connected to wastewater input to monitor weekly and seasonal changes. The wastewater temperature drops below that of Lake Ontario from June through September, during which Utilities Kingston is advised to connect the lake water as the input reservoir.

CONCLUSION

The heat pump design proposed by Team 31 will have met all the design criteria and engineering specifications required from the project proposal and formed from the team and Faculty Advisor. Analysis and simulations were conducted on the heat pump design and shows the system will be able to conserve heat energy of 6.1 million Watts to be used for various commercial and heating applications in Queen's University infrastructures and surrounding areas. The proposed design would cost approximately $13,287,000, reduced by 26.1% from the Queen's University yearly electric budget of $18,000,000. In addition, a 44.76% savings in energy consumption will be achieved through the use of the heat pump system.

Acknowledgements:
Dr. Matovic, Queen's University
Hugh McLaren, Utilities Kingston
David Gerrish, Queen's Facilities

11 Faculty Advisor Sign-Off

This sign-off was originally submitted to the "Team 31: Sign-off Sheet: Technical Work and Deliverables completion" dropbox due December 5th.

MECH 460: Completion of Technical Work and Deliverables Sign-off by Faculty Advisor

Team 31: Energy from Wastewater
Faculty Advisor: Professor Matovic

Following professional engineering practice, I bear the burden of proof for original work. I have read the Policy on Academic Integrity posted on the Faculty of Engineering and Applied Science web site engineering.queensu.ca/policy/Honesty and confirm that this work is in accordance with the Policy.

Anthony Burke ______________________ Date: Dec 4, 2023
Anthony Burke

C.S. ______________________ Date: Dec 4, 2023
Chentong Shen

Jaimin Patel ______________________ Date: Dec 4, 2023
Jaimin Patel

Josh Malone ______________________ Date: Dec 4,2023
Joshua Malone

JSoberman ______________________ Date: Dec 4, 2023
Justin Soberman

==

Based on the information provided to me by the Team, they have satisfactorily completed both the technical work and the deliverables for their project.

Matovic ______________________ Date: _____Dec 4, 2023_____
Professor Matovic