Final Report
MECH 460 Energy from Wastewater

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MECH 460
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Executive Summary

Wastewater heat recovery (WWHR) systems capture the thermal energy within wastewater and transfer it to a useful system for heating, cooling, and other useful work. Kingston Utilities and Queen's University have appointed a group of Queen's Engineering students to design a WWHR system that can be used towards Queen's goal of carbon neutrality by the year 2040.

A location of interest for this project is the waterfront pumphouse. This site sees 22,678 m^3 of wastewater per day at an average temperature of $16℃$. Directly west of the pumphouse is the Queen's University Central Heating Plant (QUCHP). This site uses natural gas boilers to create steam for Queen's University. This steam is transported to heating systems across campus and to the Kingston General Hospital (KGH). The QUCHP is conveniently situated directly west of the pumphouse. Any solution combining these two sites will make for an interruption-free install as no buildings or roads in the area will warrant a closure. Making a design within these two buildings is more favorable in the perspective of installation.

Within the QUCHP there is a system that cleans the boilers called blowdown. Blowdown will remove a portion of the water from the steam system to control the concentration of minerals and impurities in the make-up water. This process also heats the incoming water prior to the natural gas boiler. The temperature of the make-up water before and after the blowdown process is $12℃$ and $20℃$, respectively. Since the QUCHP is operated primarily on high grade heat, the blowdown process is an opportunity to leverage low grade heat from the wastewater.

The proposed design will take thermal energy from Kingston's wastewater to heat the make-up water prior to the boiler. To achieve this, the design is a heat pump cycle between the waste and make-up water. A specialized wastewater heat exchanger will be plumbed into the pumphouse and will transfer the wastewater's heat to the refrigerant. The refrigerant will then increase its pressure and temperature after passing through the compressor. The refrigerant will run through a second heat exchanger where domestic water will absorb the heat from the refrigerant. The heated domestic water will then be sent to the QUCHP where it will be integrated to the make-up water system and eventually transferred to steam. The domestic water is now at a higher temperature than before and requires less natural gas per kilogram to convert into steam.

This process will prevent 3.3 kT of greenhouse gas (GHG) emissions per year from being released into the environment. This will be a 16% reduction in CO_2 released from the QUCHP. Following a detailed cost analysis, the upfront cost of the project has been estimated to be $ $685,220 and a 40-year project will generate energy for Kingston Utilities at a profit.

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Introduction

Queen's Facilities is responsible for the construction, operation, renovation, and maintenance of virtually everything on campus. Their scope includes all buildings, grounds, and infrastructure necessary to operate all functions of the university. Queen's Facilities provide maintenance to all building systems, provide ample housekeeping, conduct emergency repairs, and look for opportunities to become a more environmentally friendly campus. For the duration of the project, Queen's Facilities will provide technical support and be the beneficiary of the results.

Kingston Utilities is a multi-utility provider for the Kingston area, providing gas, water, and electricity to over 40,000 homes. Additionally, they process any waste from the utilities they provide, in this case, wastewater. Kingston Utilities has infrastructure to handle, treat, and transport wastewater from various industrial sites, hospitals, and residential buildings. Kingston Utilities is the second client for this project as the final design will include a system that will integrate with their current infrastructure.

The goal of this project is to harvest energy from Kingston Utilities' wastewater for use within Queen's University. WWHR systems capture thermal energy within wastewater and transfer it to a useful system for heating and/or cooling. A location of interest for this project is Kingston Utilities' waterfront pumphouse at 74 King St W, Kingston. This site processes 22,678 m^3 of wastewater per day at an average temperature of $16°C$. The pumphouse features a wet well and four submersible pumps that transport the wastewater to a treatment facility east of downtown Kingston (Ravensview). Directly west of the pumphouse is the Queen's University Central Heating Plant (QUCHP). This site uses natural gas boilers to generate steam. This steam is then distributed across campus to heat the buildings, produce domestic hot water, and for steam sterilization.

Problem Definition

Kingston Utilities and Queen's University have appointed a group of engineering students to design a WWHR system that can be used towards Queen's goal of carbon neutrality. A solution to this problem would generate carbon-neutral energy, thereby reducing Queen's University's carbon emissions. The main stakeholders for this project are Queen's University and Kingston Utilities.

Scope

The scope of this project is to determine a system that will recover energy from Kingston's wastewater and deliver it to Queen's University. A viable solution should be carbon neutral, energy efficient, and economically viable for the clients. Showing each step along the way, making rational decisions, and asking the right questions will give direction towards a solution. Project deliverables include calculating the tonnes of CO_2 reduction, an estimated project cost, an economic analysis, and a parts list.

Pending the availability of energy in the system, an alternative deliverable could be a counter argument. For instance, evidence for why a WWHR system will not be viable is a valid deliverable for the client. If a system were to be implemented, installation and maintenance procedures would be kept to Kingston Utilities' standards. For example, all safety considerations would be discussed with the project manager before any work is done on the system. Any solution must not be an architectural addition to the footprint of the building. This is because strict waterfront regulations will prohibit additions to the building to preserve Kingston's waterfront.

Final Design

Design Process

The design process started with understanding the project constraints and clients' requirements. With this information in hand, the team employed the Quality Function Deployment technique to connect engineering specifications with the clients' requirements. Throughout this process, the team considered the connections between different engineering specifications to assess potential trade-offs. This part of the design process is illustrated in the House of Quality displayed in Appendix A – Project House of Quality.

Next, the team brainstormed many potential solutions to the problem and shortlisted the options to the best four solutions. These solutions were about using the wastewater heat to:

1. Assist the Future Install of a Residential Air Heat Pump in the Pumphouse.
2. Reheat the QUCHP Condensate Prior to Re-Boil.
3. Heat the QUCHP Make-up Water Pre-Blowdown.
4. Assist with Heating a Nearby Queen's University Building – Waldron Tower.

Using the Weighted Evaluation Matrix (WEM) displayed in Appendix B – Weighted Evaluation Matrix, the four design alternatives were compared to quantitatively determine which design satisfied the client requirements the best. The results from this comparison are displayed in Appendix C – Results from Design Alternative Comparison and indicate that the third design alternative was the best design. After being selected, this design was iterated to improve its performance and eventually led to the proposed final design which is discussed in the next section.

Proposed Final Design

The proposed final design will use a WWHR system to transfer heat to the make-up water blowdown process in the QUCHP. The favourable difference in temperature is the driving reason for this design. As seen in Figure 1, the design will feature a refrigerant fluid between the wastewater heat extraction point and the recovery blowdown system. R134a will be used as the refrigeration fluid to transfer heat between the two locations. A wastewater loop will be installed downstream of the submersible pumps in the pumphouse to capture maximum flow through the heat exchanger. Refer to Figure 2 to view where the team plans to install the heat exchanger in the pumphouse.

A compressor will be utilized to heat and pressurize the refrigerant as it flows from the heat exchanger to the condenser. The condenser will transfer the heat from the high temperature refrigerant to the make-up water. An expansion valve will be used to de-pressurize the refrigerant before it re-enters the wastewater heat exchanger. This process will increase the temperature of the make-up water before it enters the blowdown process so there is less dependence on gas powered boilers to heat the water. The costs and GHG emissions that result from heating using the gas boilers will decrease due to this solution. A more detailed explanation on how the heat pump cycle works can be found in Appendix D – Brief Explanation of Heat Pump Cycle.

To model the system, a computational thermodynamic analysis was conducted using Python coding software. Python offers many thermal energy system analysis tools, including the TESPY module which allows for the creation and iterative analysis of thermal energy systems [1]. Within TESPY, the system shown in Figure 1 was constructed for iterative analysis through multi-parameter variation. The software works by first defining the primary components, which have designated thermodynamic equations associated with their specific functions. These components are then connected to each other in proper sequence, creating a system of equations that are interdependent. Initial properties can then be set to components and connections, and variable parameters can be assigned to allow for design optimization. The system can then be solved, optimizing the system's theoretical performance. A further description on how the model was used to determine functional requirements for the WWHR system can be found in the Use of Engineering Tools section.

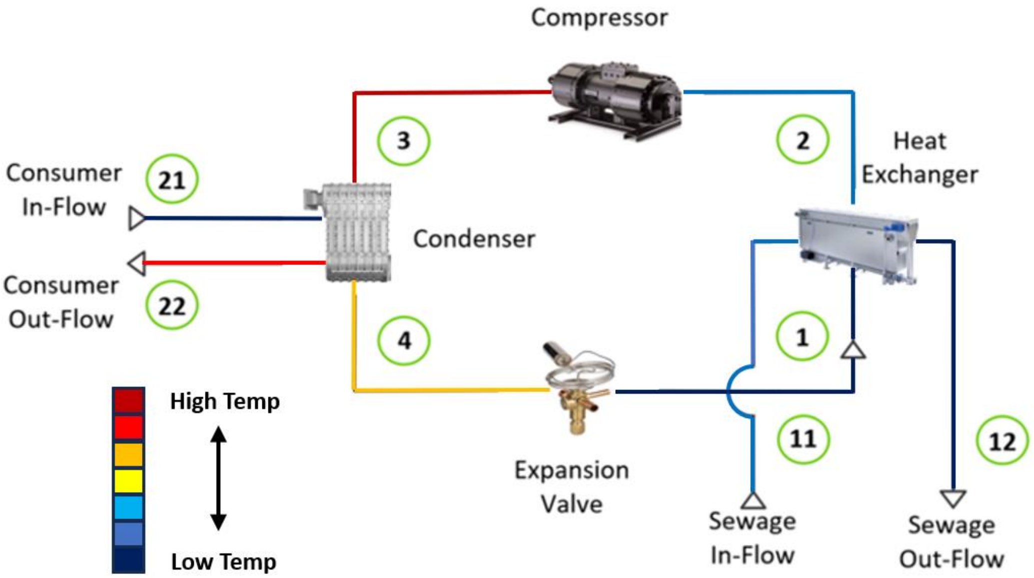

FIGURE 1: FLOW DIAGRAM OF PROPOSED DESIGN.

FIGURE 2: DISPLAYS WHERE THE TEAM PLANS TO INSTALL THE HEAT EXCHANGERS IN THE PUMPHOUSE.

Specification and Performance Requirements

The model was used to determine specific constraints and performance requirements for the components in the WWHR system. The working pressure of the refrigerant will range from 3.2 – 11.95 bar. All systems must have a maximum operational pressure limit of 18 bar to allow for a safety factor of 1.5. Moreover, the model helped the group determine that the compressor needs to have a power capacity of 713 kW while running at 85% efficiency. Additionally, the power of the heat energy entering the sewage heat exchanger is 4.109 MW and 3.713 MW of this power will be collected (73% efficiency). This heat exchanger must be able to withstand 262 $\frac{kg}{s}$ of wastewater flow at temperatures around 16℃. The make-up water heat exchanger will have flow rates up to 1.07 $\frac{kg}{s}$ and there will be a 55℃ to 45.38℃ temperature drop across the system. Additionally, 3.713 MW of heat power will be delivered to this heat exchanger and 2.710 MW is transferred to the make-up water (73% efficiency). The flow rate of the R134a refrigerant between the two heat exchangers is 0.022 $\frac{kg}{s}$.

Component Determination

Specific components were selected for the refrigerant cycle to satisfy the determined performance requirements. Copeland will supply their thermostatic expansion valve and their oil-free centrifugal compressor. Both components are compatible with R134a, and they meet the specified pressure requirements. The compressor has a frictionless design so there is no need for any lubricant or oil. The frictionless design and the low quantity of parts in the compressor make it a highly reliable option that will require minimal maintenance [2].

The Huber Rowin was selected for the wastewater heat exchanger. This system is designed specifically for wastewater heat energy extraction purposes. Additionally, it has been used in similar projects, including the Toronto Western Hospital Wet project. The Huber Rowin can handle temperatures up to 30℃ which will still be over 10℃ warmer than the temperature of the wastewater in the summer seasons [3]. Huber's 80% efficiency meets the specified requirement of 73% [3]. Also, the heat exchanger has fully automatic operations and resistance to floating or coarse materials that are contained in the water. Large particles floating in the wastewater and any biofilms that form on the heat exchanger are cleaned or removed. These factors reduce the wear on the component and increase the heat exchanger's longevity [3].

The Bekaert AluPower heat exchanger will be used for heating the make-up water. It has a small physical footprint which will allow it to be easily integrated within the pumphouse where space is limited. The model predicts a 55 ℃ maximum flow temperature and a 9.6 ℃ temperature drop across the heat exchange. This heat exchanger allows for flow temperatures up to 90℃ and 50℃ temperature drops [4]. Therefore, this component's specifications are well within what is necessary for this project.

R134a was selected as the working fluid since it is a standard refrigerant that is compatible with most heat pump components. R134a has desirable heat transfer properties, and it is more environmentally friendly than other commonly used refrigerants such as R22, R12, and R500 [5]. The boiling temperature for R134a is -14.9℃ which is sufficient for the design since the refrigerant loop will not be exposed to and sub-freezing temperatures [5].

Rules and Regulations

The American Society of Heating, and Air-Conditioning Engineers (ASHRAE) is a committee that has several codes, guidelines, and rules in place to govern the installation of refrigeration systems. Several aspects of the design have had to be altered to comply with industry standards. ASHRAE 15:8.10.1 and 15:8.10.2 contains regulations that restrict refrigerant piping in several locations such as elevators, near moving objects, or near stairways. Additionally, the pipe cannot penetrate floors, ceilings, or roofs and crossings must be greater than 7.25 feet above the floor [6]. To follow ASHRAE standards, the refrigerant pipe will be directed to the roof between the heat exchanger and the compressor as there will be a walkway between these two components. The rest of the piping can be run directly in between the other components as there are no walkways or moving components between these parts.

Section 1109.9 of ASHRAE contains rules to protect occupants, equipment, and electronics from any damage that may occur from pipe condensation. Since the piping is in a heated building, condensation is not a main concern now. A third party will be hired to conduct more research to thoroughly understand the risks and possible harm from refrigeration condensation in the pumphouse. Protective equipment such as troughs will be utilized if deemed necessary [6].

The Ontario Provincial Standard Drawings (OPSD) and the Ontario Provincial Standard Specification (OPSS) have codes and regulations for installing PVC water piping underground. OPSD 1109.011 contains standards for placing sacrificial anodes onto metallic fittings so that the material does not corrode. This includes that the anode is to be placed 1.0 m away from the watermain and that thermite welds need protective coatings. Additionally, all connecting wire is to be wrapped and then knotted around pipes and fittings [7]. These regulations for anode placement will be used for all fittings (elbows) that are needed to run the water pipe between the two buildings.

When a 90-degree elbow is used to change the direction of flow, a concrete thrust block must be placed on the vertical (outer side) of the fitting to withstand the flow forces at the bend [7]. This means that the water main loop that is between the two buildings will require 4 thrust blocks. They will be located below each of the buildings where the pipe is changed from vertical to horizontal (as the pipe is brought in/out of the building).

OPSD 1109.030 includes standards for insulating buried watermains. This includes that the insulation material is to be extruded polystyrene according to OPSS 1605. The minimum insulation thickness is 50 mm and multiple sheets of insulation shall be applied at the location of joints. The insulation sheets are to be placed 150 mm above and 150 mm beside the water pipes as seen in Figure 3 [7].

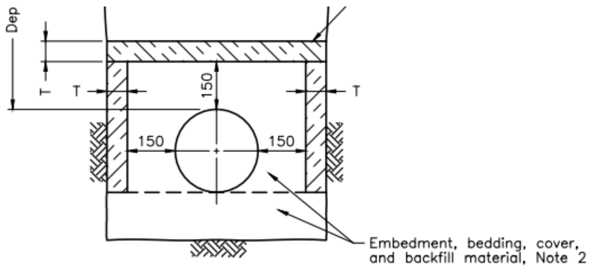

FIGURE 3: OPSD 1109.030 SPECIFICATION ON INSTALLING POLYSTYRENE INSULATION SHEETS [7].

Problem Analysis

Some problems that were critical to achieving the design include figuring out how much CO_2 can be reduced by the proposed design, the amount of energy that can be yielded, and the costs associated with the final design. CO_2 reduction can be solved by determining the reduction of natural gas consumption from using the boilers in the QUCHP. The results from this analysis are quite accurate because the pre-installation scenario acts as a control datapoint, and the post-installation scenario represents the change in CO_2 emissions due to the implementation of the final design.

To determine the energy that can be yielded, the lumped capacitance model can be employed to analyze thermal energy systems, such as the proposed heat pump design. This will consider the wastewater temperature, power consumption of the compressor, and heat exchanger efficiencies. The results from the energy output analysis are a valid approximation of the total energy output of the real-life system. Some approximations were made throughout the analysis that reduce the result's accuracy. For example, energy losses within the system are unaccounted for. The results are a valid preliminary analysis, and the complete modelling process and results are described in more detail in the Use of Engineering Tools section.

To accurately predict the cost per unit of energy generated by the final design, a discounted cash flow method will be used. This economic analysis will consider the time value of money over the 40-year life of the project. To determine the value of each cost, both research and obtaining quotes from vendors proved to be a valuable method. Like the energy output analysis, the economic analysis is a great preliminary approximation of the cost associated with the project. To improve the results, official quotes for installation and each heat pump component must be retrieved from contractors and manufacturers respectively.

A key design challenge was determining where to situate each component of the heat pump to eliminate refrigerant traveling underground. In consultation with Professor Mechefske and Professor Sneep, the team determined that housing all heat pump components within the pumphouse was the best design choice. Although this means some rerouting of the make-up water supply pipe, it eliminates any environmental risk of putting R134a pipes underground.

Use of Engineering Tools

To realize the design of a WWHR system, it was determined that a lumped capacitance model would be the most efficient method. A lumped capacitance model works by splitting a system into discrete sections, with the properties of each section remaining uniform. This method of analysis is typically utilized for applications where utilizing a system of differential equations would be too complex and therefore must be simplified. In the case of the WWHR system, the connections between the main components of the system were made into discrete sections with each section possessing unique variables for thermodynamic and fluid properties. To integrate these sections into a system, the components are simplified into the basic thermodynamic equations that govern their intended functions.

With the model now in place, a sufficient method of analyzing the model was needed. The necessary system optimization would require numerous iterations of calculations, making analysis 'by-hand' heavily time-consuming and inefficient. Software tools such as Python, MATLAB, and Microsoft Excel would allow for repeated calculations to be made, but it was determined that Python possessed the most applicable built-in methods to realize the design.

TESPy, a library within Python, utilizes pre-programmed lumped capacitance methods specific to the analysis of thermal energy systems. A model of the WWHR system was created within this software and known data about the wastewater and make-up water systems were assigned to the appropriate fixed variables. With the system modelled and known data assigned to the parameters in question, optimization of the system could commence. For any system there are tolerances and constraints by which the optimization is bounded. In the case of this WWHR system, these bounds for optimization are governed by the allowable temperature gradients of the waste-water heat exchanger, the capacity of the working-fluid, and existing infrastructure.

These bounds were then integrated into the model's optimization and key output parameters were assigned to the optimization process. This process would start out with initial values within the bounds and repeatedly adjust variables, searching to maximize the heat output of the system while minimizing the amount of required work input. Once the system was optimized, the final variable parameters and heat parameters could then be translated into a simple thermodynamic analysis of the boiler system to estimate the reduction in GHG emission that the WWHR would provide. These final parameters were also used to dictate the real-world components that would be used to construct the system. A full breakdown of the final computational analysis can be seen in Appendix E – Computational Thermodynamic Modelling.

Installation Procedure

A 2 m deep trench will be excavated in between the pumphouse and the QUCHP for the water line to be placed underground. Unfortunately, road access to the Kingston General Hospital helicopter pad runs in between the two buildings. Before excavating, a temporary road will be constructed on the east side of the pumphouse, as shown in Figure 4. Additionally, 3 test pits will be vacuum excavated to check for limestone and bedrock depth. If the bedrock depth is less than 2 m deep and the water line needs to be raised, extra insulation will be added to the piping to minimize energy loss during the winter seasons. After installing the water line, the trench will be refilled with the native material that was previously excavated. The backfill is to be compacted with a diesel plate or roller every 0.8 m. The compaction of the excavated area must be approved by a City of Kingston inspector before it is re-paved. The wastewater heat exchanger and compressor will be installed inside the pumphouse where the wastewater main is leaving towards Ravensview. Further information on the equipment and subcontractors required for installation can be found in the installation costs section. Figure 4 below shows a satellite image of the area where both the pumphouse and QUCHP is located. All details can be seen below on the map.

FIGURE 4: SATELLITE MAP OF PROJECT LAYOUT, CONSTRUCTION ZONE AND ACCESS PLAN

Economic Analysis

Due to the dual-client nature of this project, the financial analysis incorporates both Kingston Utilities and Queen's University. Based on new information from the clients, Kingston Utilities has agreed to fund all costs associated with the project because they will own the WWHR system. In return, Queen's University has agreed to buy all the energy that is produced by the WWHR system. This arrangement provides Kingston Utilities with a guaranteed revenue stream. According to the average electricity prices published by the Ontario Electricity Board, energy would be sold for about $\frac{\$0.109}{kWh}$ [8].

The cost per unit of energy ($/kWh) is an important metric that will determine the financial viability of the project. If the WWHR system can generate energy at a cost lower than the market price, then Kingston Utilities can sell the energy for a profit. Hence, the following criteria describes the economic viability of the WWHR system:

1. If the cost per unit of energy is less than the market price per unit of energy, then the project is economically viable.
2. If the cost per unit of energy is greater than the market price per unit of energy, then the project is not economically viable.

Initial Costs

The project requires an initial investment which will include the cost of procuring each component and the cost of installation. Each of these costs will be calculated individually in their own subsection below, and then the initial cost will be calculated by summing them.

Procurement

The Final Design section details all the components that will need to be purchased. Table 1 below displays the cost of each component and the total procurement cost.

TABLE 1: PARTS LIST AND BREAKDOWN OF TOTAL PROCUREMENT COST BY COMPONENT

Component	Cost [$]	Reference
Copeland Oil-free Centrifugal Compressor	15,000	Phone call with sales associate [9]
Copeland Expansion Valve	300	Phone call with sales associate [10]
Huber RoWin Heat Exchanger	600,000	Phone call with sales associate [11]
Bekaert Alu Power Heat Exchanger	5,000	Phone call with sales associate [12]
Copper and PVC Piping	750	[13] [14]
Refrigerant – Type R134a	4,250	[15]
Total Procurement Cost	625,200	Sum of all the previous rows

Installation Costs

An initial cost for all project aspects should be considered for a fair assessment of the project finances. This section will cover an estimate of all costs associated with the installation portion of the project. To accommodate a hot water line going from the pumphouse to the QUCHP, an excavation crew will need to be sourced. The excavation crew will be comprised of a foreman, two operators, and two laborers. Equipment and associated costs for excavation are outlined below in Table 2.

TABLE 2: PEOPLE AND EQUIPMENT COSTS ASSOCIATED WITH EXCAVATION

People		Rate $ / hour	Quantity	Hours		Sub Total [$]
	Foreman	150	1	12	x	1800
	Operator	80	2	12	x	1920
	Labourer	60	2	12	x	1440
Equipment						
	Cut Off Saw	30	1	12	x	360
	Excavator	160	1	12	x	1920
	Water pump	20	1	12	x	240
	Skid steer	80	1	12	x	960
	Dump truck	180	1	12	x	2160
	Total	$10 800				

To install and plumb all the components inside the pumphouse, a team of industrial plumbers and pipefitters should be sourced. A 60-hour period was allocated to complete this aspect of the project. This crew will be one foreman, three pipefitters and two journeymen. Equipment and associated costs for plumbing are outlined below in Table 3.

TABLE 3: PEOPLE AND EQUIPMENT COSTS ASSOCIATED WITH INDUSTRIAL PLUMBING

People		Rate $ / hour	Quantity	Hours		Sub Total [$]
	Foreman	150	1	60	x	9000
	Pipe Fitter	80	3	60	x	14400
	Journeyman	60	2	60	x	7200
Equipment						
	Materials	10000	1	1	x	10000
	Preliminary planning	2000	1	1	x	2000
	Safety	3000	1	1	x	3000
	Zoom-Boom	100	1	3	x	300

Total	$45 900

A paving crew should be scheduled onsite when exterior work is completed to repave the areas that were used for the trench. This will also allow regular access to the KGH helicopter pad. A paving crew for this small area will need one foreman, two operators and two laborers. Equipment and associated costs for paving are outlined below in Table 4.

TABLE 4: PEOPLE AND EQUIPMENT COSTS ASSOCIATED WITH PAVING PROCESS

People		Rate $ / hour	Quantity	Hours		Sub Total [$]
	Foreman	150	1	4	x	600
	Operator	80	2	4	x	640
	Labourer	60	2	4	x	480
Equipment						
	Dump truck	180	1	4	x	720
	Skid steer	80	1	4	x	320
	Spreader	90	1	4	x	360
	Steam Roller	50	1	4	x	200

Total	$3 320

The provided hourly rates and quantities serve solely as estimates based on past project experience and should be considered indicative. This estimation excludes general and subcontractor fees, administrative charges, as well as taxes. Table 5 below summarizes all installation costs.

TABLE 5: SUMMATION OF ALL INSTALLATION COSTS

Excavation	Pipefitting	Paving	Total
$10 800	$45 900	$3 320	$60 020

Initial Cost

The initial cost is calculated by adding the total procurement cost to the total installation cost as seen below.

$$\text{Initial Cost } = C_{Initial} = C_{Proc} + C_{Install} = \$625{,}200 + \$60{,}020 = \$685{,}220$$

Annually Recurring Cost

In addition to the initial cost, the project requires annually recurring costs. The annually recurring cost of the WWHR system is composed of maintenance and operational costs. Each of these costs will be calculated individually in their own subsection below, and then the annually recurring cost will be calculated by summing them.

Maintenance

The annual maintenance cost is composed of the cost of materials and labour cost. The cost of materials was approximated to be $31,260 because that is 5% of the procurement cost. The cost of material calculation is displayed below.

$$Material\ Cost = C_{Mat} = C_{Proc} \times 5\% = \frac{\$31{,}260}{year}$$

The labour cost was calculated with the assumption that Kingston Utilities workers make $40 an hour and a maintenance team consist of three workers. The labour cost is calculated based on the number of visits a maintenance team needs to perform each calendar year. The labour cost calculation is displayed below.

$$Labour\ Cost = C_{Lab} = \frac{\$40}{hour} \times \frac{3\ workers}{team} \times \frac{8\ hour}{shift} \times \frac{2\ shifts}{month} \times \frac{12\ months}{year} = \frac{\$23{,}040}{year}$$

The annual maintenance cost is calculated by adding the material cost to the labour cost. This calculation is shown below.

$$Maintenance\ Cost = C_{Maint} = C_{Mat} + C_{Lab} = \$54{,}300$$

Operational

The annual operational cost is composed of the electricity cost required to run the WWHR system. Specifically, the compressor needs electricity to function, and it is assumed that the compressor will be always running. The cost of energy is based on the average electricity prices published by the Ontario Electricity Board, $\frac{\$0.109}{kWh}$. As described in the Final Design section, the compressor's power specification is 713 kW [8] [9]. The calculation for operational cost is displayed below.

$$Operational\ Cost = C_{Oper} = 713kW \times \frac{24\ hours}{day} \times \frac{365\ days}{year} \times \frac{\$0.109}{kWh} = \frac{\$680{,}800}{year}$$

Annually Recurring Cost

The annually recurring cost is calculated by adding the annual maintenance cost to the annual operational cost as seen below.

$$\text{Annually Recurring Cost} = C_{AR} = C_{Maint} + C_{Oper} = \$54{,}300 + \$680{,}800 = \frac{\$735{,}100}{year}$$

Cost Per Unit of Energy

The cash flow diagram illustrated in Figure 5 incorporates the initial cost and the annually recurring cost. Using the concept of time value of money, the initial cost is amortized over the 40-year lifespan of the project to calculate the total annual cost of the WWHR system. The resultant cash flow diagram displayed in Figure 6 indicates that the total annual cost (C_{Annual}) is $818,220 per annum.

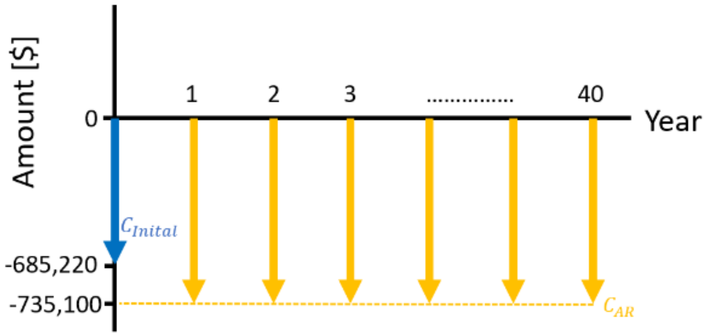

FIGURE 5: CASH FLOW DIAGRAM OF INITIAL AND ANNUALLY RECURRING COST

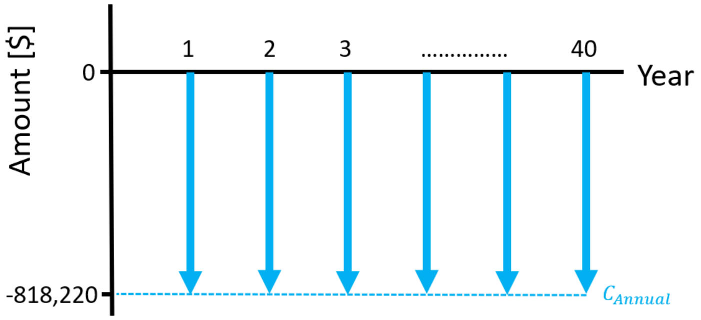

FIGURE 6: CASH FLOW DIAGRAM OF THE TOTAL ANNUAL COST

Using the WWHR system's estimated energy output described in the Use of Engineering Tools section, the total energy generated in a year can be calculated. This calculation is displayed below.

$$\text{Annual Energy Output} \ = E_{Annual} = 2710\ kW \times \frac{24\ hours}{day} \times \frac{365\ days}{year} = 23{,}740{,}000\ \frac{kWh}{year}$$

To calculate the cost per unit of energy, the total annual cost must be divided by the annual energy output as seen below.

$$\text{Cost Per Unit of Energy} \ = C_{PUOE} = \frac{C_{Annual}}{E_{Annual}} = \frac{\frac{\$818{,}220}{year}}{23{,}740{,}000\ \frac{kWh}{year}} = \frac{\$0.03447}{kWh}$$

The cost per unit of energy ($\frac{\$0.03447}{kWh}$) is less than the market price of energy ($\frac{\$0.109}{kWh}$). According to the success criteria described at the beginning of this section, this means that the WWHR system is profitable and economically viable.

Impact of Engineering

The final design solution must be evaluated for its technical, societal, environmental, and enterprise impact. Additionally, sustainability of the design must be evaluated because both clients have indicated that they value sustainable solutions. The following five subsections evaluate each of the topics discussed above.

Technical Impact

The final design has a substantial technical impact on Kingston Utilities because they will own and operate the WWHR system. The WWHR system will have to be carefully installed to integrate seamlessly with Kingston Utilities' existing infrastructure. Additionally, regular maintenance crews will have to be trained and scheduled to work on the WWHR system to ensure that the system is upkept well.

Societal Impact

This project has a large societal impact on the Canadian university landscape because every university is looking for ways to lower their carbon emissions. If Queen's University were to implement a WWHR system, it would be the first of its kind. This means other universities would learn from Queen's WWHR project when implementing their own system, thereby making Queen's University a leader of the Canadian university energy transformation.

Environmental Impact

Climate change has caused institutions across the globe to look for ways to generate carbon neutral energy. A WWHR system would generate carbon neutral energy, which thereby reduces the carbon emissions emitted by Queen's University. Therefore, the WWHR will help Queen's University reduce their environmental impact. Additionally, most of the WWHR system components are sourced from Canadian companies, which eliminates unnecessary carbon emissions associated with international shipping.

Sustainability

Sustainability is an important factor that impacts the success of the final design. The WWHR system uses R134a for the heat pump. This is not sustainable because R134a is proven to have direct global warming potential [16]. The team considered R134a's environmental impact when selecting a refrigerant, but R134a's unparalleled heat transfer properties are needed because the WWHR system is transferring low-grade heat. Scientists are currently trying to produce sustainable refrigerants that have similar heat transfer properties to traditional refrigerants. Once a high performance and sustainable refrigerant is developed, the team recommends that Kingston Utilities replace R134a with the environmentally friendly refrigerant to improve the sustainability of the design.

Enterprise Impact

Both clients have invested interest in this project for their enterprises. Queen's University has developed a goal to achieve carbon neutrality by 2040, and they need solutions like WWHR to get them closer to this goal [17]. One of Kingston Utilities' biggest customers is Queen's University; therefore, Kingston Utilities has an enterprise interest in this project. If Kingston Utilities helps Queen's University achieve their goal, they will be strengthening their relationship with their most important customer. Additionally, the implementation of a successful WWHR system will generate more energy for Kingston Utilities. This diversifies Kingston Utilities' energy portfolio while generating more revenue for the organization.

Conclusions

The transition to environmentally friendly heat sources has encouraged Kingston Utilities and Queen's Facilities to seek reductions in carbon emissions through WWHR systems. After conducting research of existing systems and current infrastructure, a heat-pump system was selected to transfer heat from the town’s wastewater to the QUCHP’s water make-up system.

The system will consist of a Huber RoWin heat exchanger, transporting heat from the wastewater to the R134a refrigerant which will then flow into a Copeland compressor. The 713 kW of work done by the compressor will increase the energy within the R134a fluid which is then transferred to the make-up water through the Bekaert heat exchanger. The R134a will then pass through a Copeland expansion valve, where it will then repeat its cycle through the system. The entire system is to be contained within the pump-house and connected to the make-up water system through an extended underground waterline. This, in conjunction with the current blow-down heating system, will increase boiler efficiency and reduce Queen’s Heating Station’s GHG emissions by an estimated 16%.

The entire system is expected to initially cost $685,220 with an additional $735,100 per year over its 40-year lifespan. Based on the annual worth of this project, the cost per unit of energy supplied by the heat pump system is expected to be approximately one-third of the current market price. Therefore, Kingston Utilities can sell the energy profitably. Overall, the system will provide a sustainable source of energy at an affordable price and aid in the reduction of GHG emissions for Queen’s University and the municipality of Kingston.

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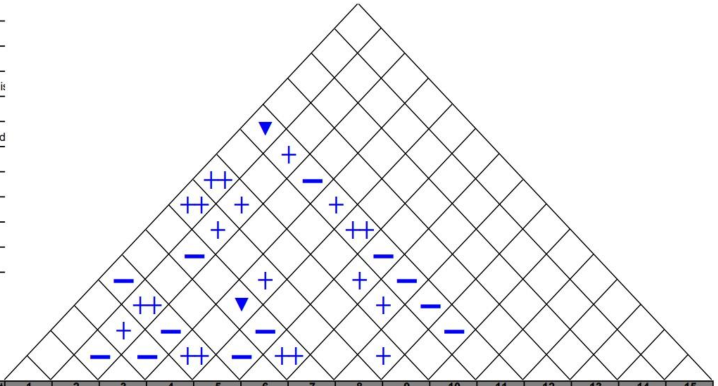
Appendix A – Project House of Quality

Title: Queen's Facilites Energy from Wastewater
Author: Team 30
Date: Sept 28th 2023
Notes: The team has two customers in this project. Queen's University i
the main stakeholder because they will be the end user of the
energy. However, the wastewater heat recovery system will need
be integrated with Kingston Utilities current infastructure.
Therefore, Kingston Utilities is a relevent customer to consider
as well.



Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitive Analysis (0=Worst, 5=Best)				
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▼	▼	▼	▼	▲	▲	▲	▼	▲	▼									
				Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Project lifetime	Frequency of maintance tasks /visits	Exhaust /filteration system (limit ppm)	Physical size of system	Parts and systems required	Tonnes of CO2 saved - Tonnes of CO2 Generated	Energy output	Strength of material	Corrosiveness of material	Thermal conductivity of material	Cost					Leurkerbad Wastewater Energy Recovery	False Creek Neighborhood Energy Unit	Sandvika Norway's Dual Pump System	Toronto Westeern Hospital WET Project	Wintower Wastewater Energy Recovery
1	9	17.9	5.0	Durability and Longevity	Θ	O		▲	O			Θ	Θ							3	3	4	4	3
2	9	14.3	4.0	Low Maintenance	Θ	Θ	▲		Θ		▲	▲	O		▲					5	4	5	5	5
3	9	3.6	1.0	Limited odour			Θ													5	3	3	5	5
4	9	7.1	2.0	Limited space required				Θ	O		▲									4	4	5	2	4
5	9	10.7	3.0	Easy to assemble and integrate (cannot stop Kingston Utilities operations)			▲	O	Θ		▲				▲					4	2	3	3	4
6	9	17.9	5.0	Carbon neutral			▲	▲		Θ	▲									3	3	4	5	4
7	9	17.9	5.0	Energy is generated	▲	▲		O		O	Θ			Θ						2	4	2	5	3
8	9	10.7	3.0	Affordability	O	Θ		O			O	O		O	Θ					4	2	2	2	4
9																								
10																								
				Target or Limit Value	50 Years	4 visits/month	1000ppm	2 cubic meters	20 parts	1000 MTCO2	500 kW	240 MPa Yield Strength	0.001 mm/year	200 W/mK	$ 250 000									
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	6	4	2	7	7	6	7	4	4	4	8									
				Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9									
				Weight / Importance	339.3	296.4	75.0	217.9	300.0	214.3	242.9	207.1	203.6	192.9	121.4									
				Relative Weight	14.1	12.3	3.1	9.0	12.4	8.9	10.1	8.6	8.4	8.0	5.0									

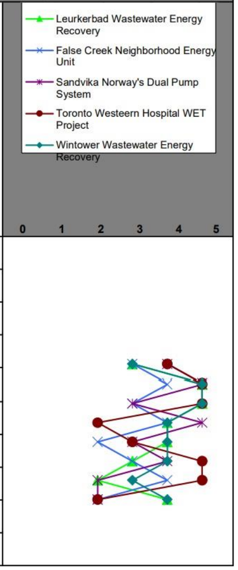


Figure 7: The house of quality based on the QFD analysis for the Kingston Utilities Wastewater Energy Recovery Project.

Appendix B – Weighted Evaluation Matrix

TABLE 6: WEIGHTED EVALUATION MATRIX RUBRIC THAT WAS USED TO COMPARE THE DESIGN SOLUTIONS.

	Weight	**Outstanding / Above Expectations (9-10)**	**Meets Expectations (7-8)**	**Approaching Expectations (5-6)**	**Minimal Consideration (3-4)**	**Completely Disregarded (1-2)**
Affordability (Labour and materials)	3	Extremely affordable to install and maintain (less than $150,00 throughout its lifecycle).	An affordable system to construct and integrate ($150,000 to $300,000 over its lifecycle).	Costs for installation, operating, and maintenance for the lifecycle: $300,000-500,000.	High costs of installation and operation ($500,000 to $1 million dollars over its lifecycle).	Will cost more than $1 million to install, operate, and maintain the system over its lifecycle.
Limited space required	1	<2 m^2.	2-6 m^2.	6-10 m^2.	10-20 m^2.	20+ m^2.
Carbon neutral: CO_2 saved – CO_2 produced	5	300+ tonnes/year.	150-300 tonnes/year.	25-150 tonnes/year.	0-25 tonnes/year.	More $C0_2$ produced than saved.
Energy is produced: Energy produced – energy used	4	2 MW+	1-2MW	500kW-1MW	0-500kW	More energy is used than produced.
Durability and longevity	3	Materials used have great resistance to creep, heat, pressure, crack propagation, and corrosion. No major parts (i.e., compressor, pump, heat exchanger) are expected to need replacement. Life expectancy of 50+ years.	Materials used have great resistance to creep, heat, pressure, crack propagation, and corrosion. However, 1 to 3 major parts of the design (i.e., compressor, pump, heat exchanger) will need replaced before the system is retired. Life expectancy of 50+ years.	Still a life expectancy of 50+ years. However, the design is based of replacing parts (pumps, valves, compressors, pipes) multiple times throughout the lifecycle.	Designed for a shorter lifecycle (25-50 years). This could be from expected creep, corrosion, or fatigue failure. 1 or more of the parts/machines will be unable to use and replace.	The Lifecycle for the system is less than 25 years. The parts and machines have a small fatigue lifecycle, poor creep resistance and/or experiences corrosion.
Low maintenance	2	Self ran system (no operator). Only requires (on average) less than 2 hours of maintenance per week. All parts of the system are easy to access and perform maintenance on.	Does not require an operator to run. Needs less than 2 hours of maintenance a week (on average). All parts are easy to access for maintenance. However, out-of-company sub trades are required to perform the maintenance.	Self ran (without an operator). Needs 2-5 hours of maintenance a week. Re-occurring scheduled maintenance and/or uneasy access to parts may cause the increase in needed maintenance time.	Requires daily input from the operator to run the system. Less than 10 hours a week spent on operating and maintaining the system.	Requires more than 10 hours a week to operate and maintain the system. Requires re-occurring maintenance.
Easy to assemble and integrate	2	Installation does not disrupt Kingston Utilities operations. As well, the project is accepted/liked by Kingston residents. No other existing systems will need to be shut down for installation. Can easily be integrated with current heat/energy transportation systems in Kingston.	Installation is accepted by Kingston residents. It can easily be implemented with existing Kingston Utilities system. However, 1 or more system (i.e. pump, boiler, or water/sewer main) must be shutdown/re-routed for instillation. However, the shutdown will not affect heat or wastewater transportation throughout Kingston.	The design does not raise any concern with Kingston residents. However, shutdown of 1 or more systems (i.e. pump, boiler, or water/sewer main) must be shutdown. This shutdown will cause a temporary (less than 12 hours) disruption to heat and/or wastewater transportation throughout Kingston.	Either heat or wastewater delivery throughout Kingston will be temporarily disturbed. Or the design must be implemented in a residential area and the sound will disrupt residents.	The design must be implemented in a residential area and the sound will disrupt residents. Also there will be a temporary disruption to Kingston heat and/or wastewater delivery.

Appendix C – Results from Design Alternative Comparison

TABLE 7: SUMMARY OF THE RESULTS FROM THE WEM FOR EACH OF THE DESIGN SOLUTIONS.

Design Outcomes	**Weight**	Assist the Future Heat Pump in the Pumphouse	Reheat the QUCHP Condensate Prior to Re-Boil	Heat the QUCHP Make-up Water Pre-Blowdown	Assist Heating a Nearby Queen's University Building
Affordability (labour and materials)	3	9	8	8	2
Limited space required	1	8	9	10	3
Carbon neutral: CO2 saved – CO2 produced.	5	4	6	7	7
Energy is generated: Energy produced – energy used	4	2	4	9	8
Durability and Longevity	3	7	8	8	6
Low maintenance	2	7	5	6	5
Easy to assemble and integrate	2	6	5	8	1
Total Score		110	123	159	106

Appendix D – Brief Explanation of Heat Pump Cycle

The heat pump is a device that simply moves heat from one place to another using small amounts of input work. The heat pump cycle works off the principles of thermodynamics and heat transfer. From heat transfer, without external work, heat will always flow from hot to cold. According to the 2nd law of thermodynamics, entropy shall increase over time. A good example would be that of the ice cube melting whilst it sits at room temperature. As the water transitions from solid to liquid, its entropy, or degree of randomness, increases. However, by applying external work, heat can go from cold to hot, via input work.

Within a heat pump there are a few components to explain how heat can be extracted from wastewater to higher temperature applications such as the QUCHP. The main components are as follows: the heat exchanger, compressor, condenser, and expansion valve as seen in Figure 8.

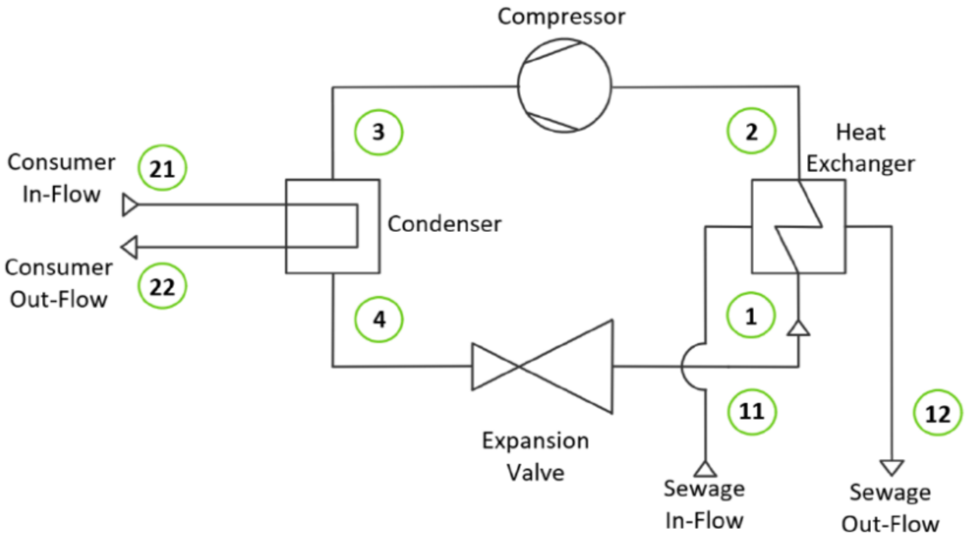


FIGURE 8: SIMPLE DIAGRAM OF HEAT PUMP DESIGN

The heat exchanger, as the name implies, simply exchanges heat between two sources. In the case of wastewater heat recovery, the wastewater itself would act as one of the fluids and the working fluid within the heat pump would be the other. The heat exchanger extracts heat from the wastewater and rejects it to the refrigerant. This process is highlighted in Figure 9, going from step 4 to 1. The ideal working fluid in this heat pump would have to be compressible, so that the temperature of the working fluid can be controlled from its pressure alone. This leads to the next component of the process, the compressor.

The compressor compresses the working fluid. This means that external work is being applied to the working fluid, increasing its pressure. Hence, most of the work and energy required for this design is attributed to compressing the working fluid. By compressing the working fluid, the temperature will increase because its molecules will collide with each other with a much higher frequency. This process can be seen in Figure 9 under compression, moving from step 1 to 2. A good example of compression would be a pressure cooker. Water in a pressure cooker is pressurized so that water can easily boil and reach higher temperatures without the input of heat. This is necessary for the next step of the process involving the condenser.

The condenser is simply another heat exchanger, but it exchanges the heat from the high temperature working fluid to the consumer fluid. The working fluid is at a higher temperature than the consumer's fluid due to the compressor, so heat from the working fluid will reject to the consumer fluid. This is seen in Figure 9, going from step 2 to 3. This is how heat from the wastewater can be delivered to the make-up water for the QUCHP. Finally, the expansion valve relieves the pressure in the working fluid to its initial pressure. This is seen in Figure 9 going from step 3 to 4. After this final step, the cycle repeats itself.

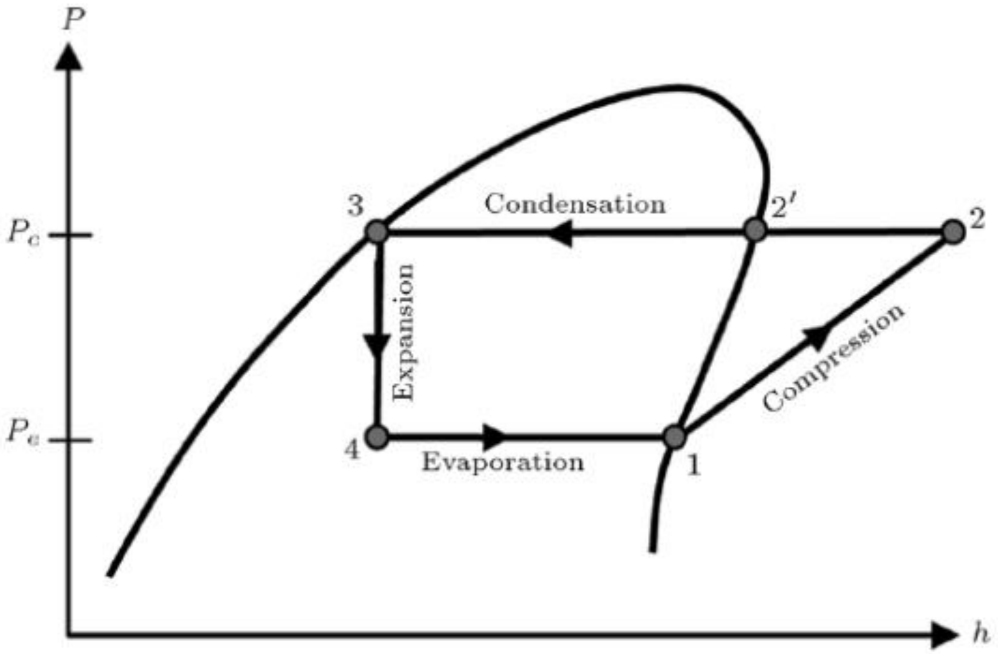
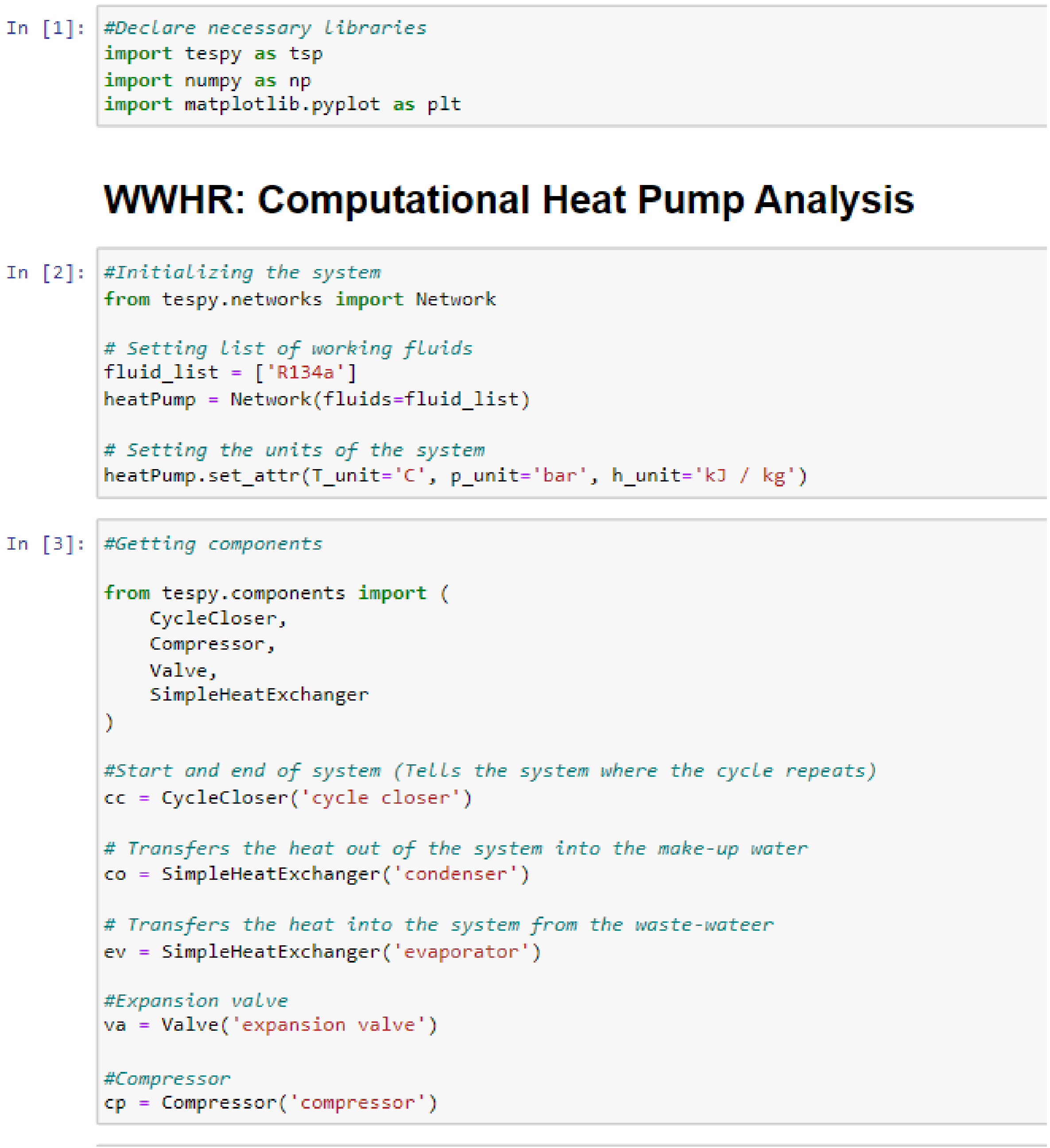


FIGURE 9: A PRESSURE-ENTHALPY GRAPH THAT DEMONSTRATES THE HEAT PUMP CYCLE.

Appendix E – Computational Thermodynamic Modelling

This section displays the code used for the computational analysis of the final design, including the analysis of GHG emission reductions for the steam plant. Figure 10 displays the start of the analysis, where all necessary libraries are imported, and the system is initialized as a network. This network will act as a container for which information can be stored. The units in which the system will operate are declared, the working fluid is set, and all necessary components are added to the system.



In [1]:

```python
#Declare necessary libraries
import tespy as tsp
import numpy as np
import matplotlib.pyplot as plt
```

WWHR: Computational Heat Pump Analysis

In [2]:

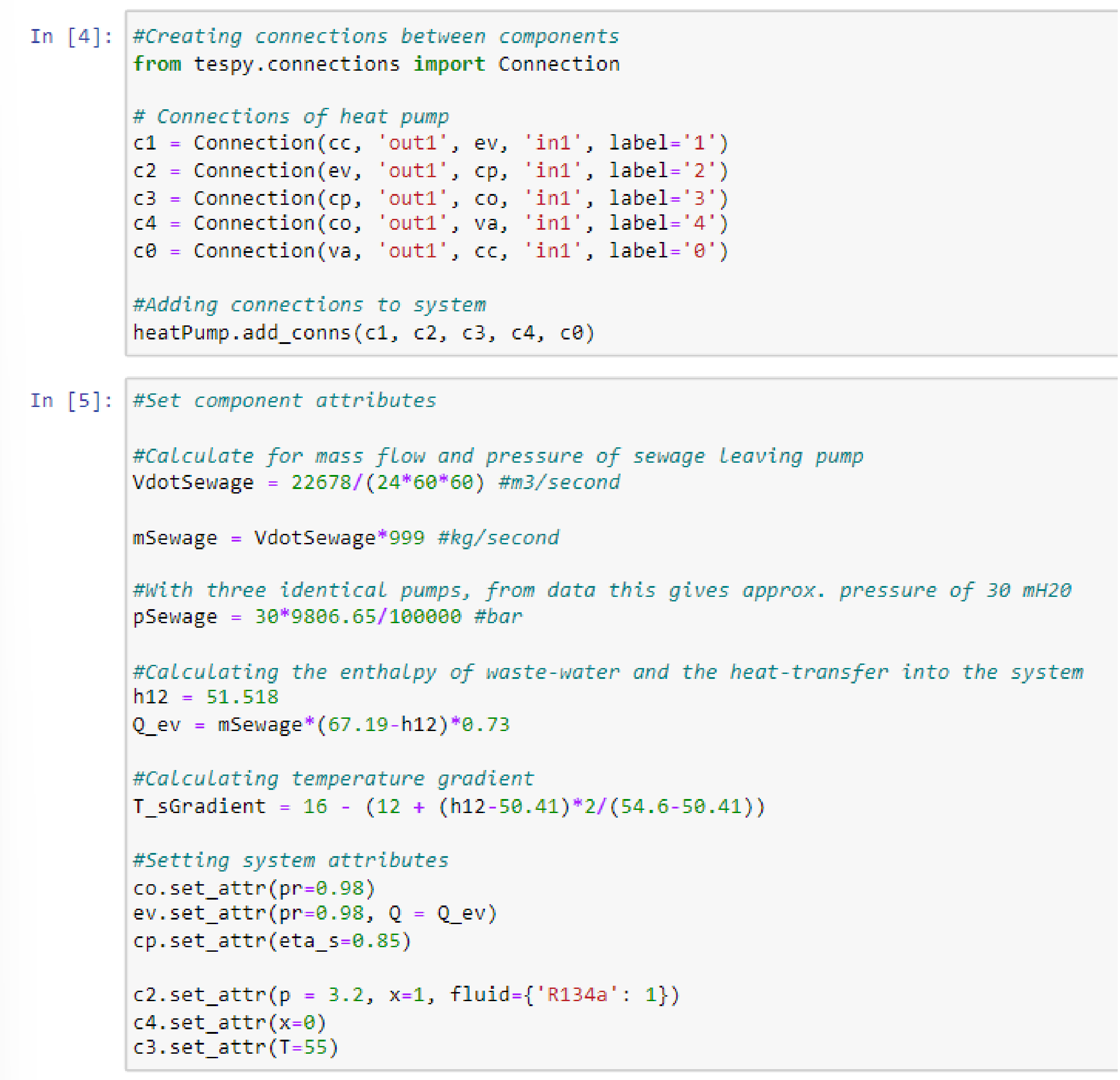
```python
#Initializing the system
from tespy.networks import Network

# Setting list of working fluids
fluid_list = ['R134a']
heatPump = Network(fluids=fluid_list)

# Setting the units of the system
heatPump.set_attr(T_unit='C', p_unit='bar', h_unit='kJ / kg')
```

In [3]:

```python
#Getting components

from tespy.components import (
    CycleCloser,
    Compressor,
    Valve,
    SimpleHeatExchanger
)

#Start and end of system (Tells the system where the cycle repeats)
cc = CycleCloser('cycle closer')

# Transfers the heat out of the system into the make-up water
co = SimpleHeatExchanger('condenser')

# Transfers the heat into the system from the waste-wateer
ev = SimpleHeatExchanger('evaporator')

#Expansion valve
va = Valve('expansion valve')

#Compressor
cp = Compressor('compressor')
```

FIGURE 10: THE CODE CELLS CONTAINING THE INITIALIZATION OF THE LUMPED CAPACITANCE MODEL OF THE HEAT PUMP SYSTEM WITHIN PYTHON.

From this initial set-up, connections are added to formulate the system of equations that will act as the main structure of the system, as shown in Figure 11. Calculations for fluid flow within the wastewater are made and the total heat transfer is calculated based on changes in enthalpy of the condensed water. The temperature gradient across the wastewater side of the heat exchanger is then calculated using interpolation and stored. The component and connection attributes of the system are then declared, allowing the system to solve for key parameters.



In [4]:

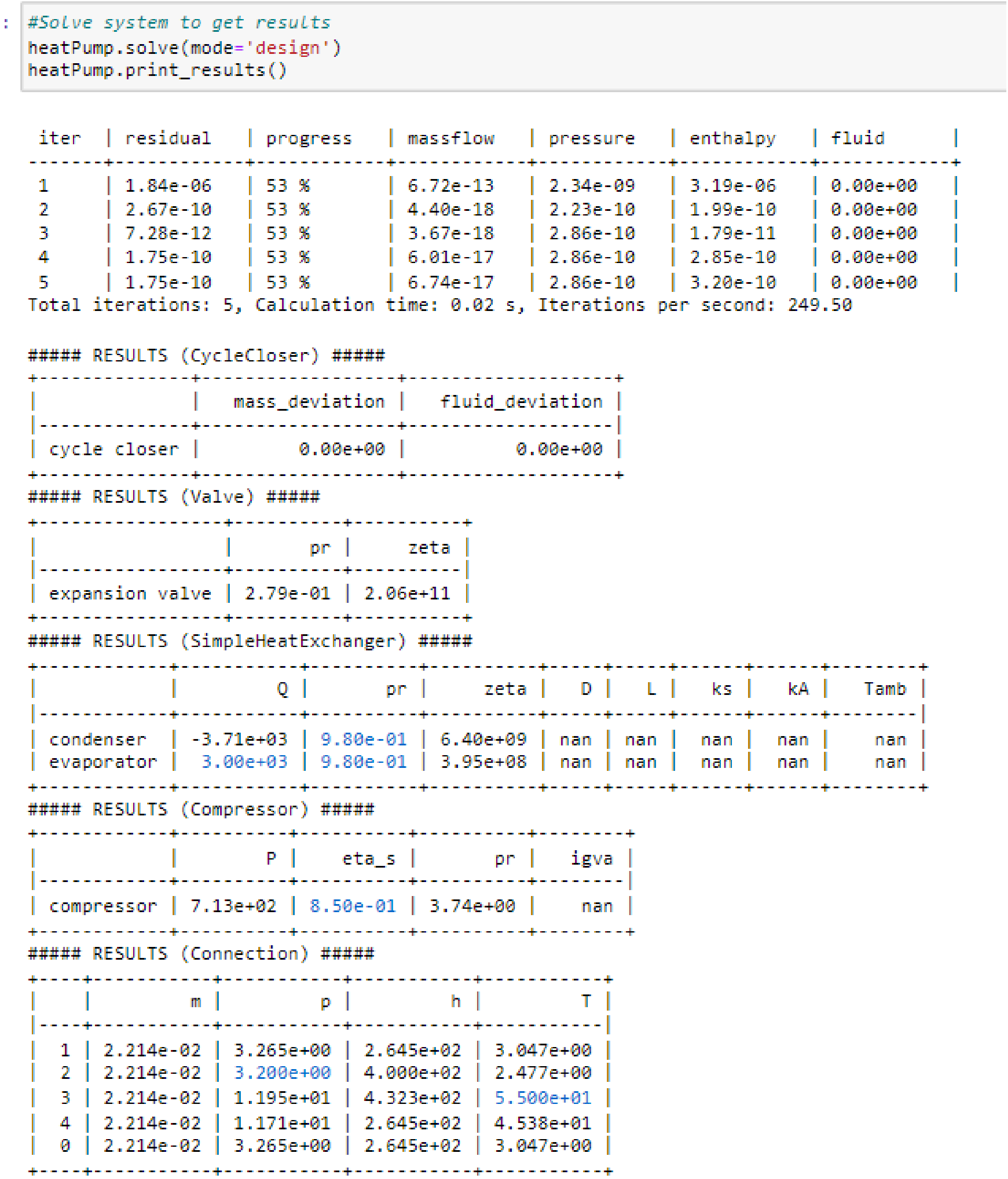
```
#Creating connections between components
from tespy.connections import Connection

# Connections of heat pump
c1 = Connection(cc, 'out1', ev, 'in1', label='1')
c2 = Connection(ev, 'out1', cp, 'in1', label='2')
c3 = Connection(cp, 'out1', co, 'in1', label='3')
c4 = Connection(co, 'out1', va, 'in1', label='4')
c0 = Connection(va, 'out1', cc, 'in1', label='0')

#Adding connections to system
heatPump.add_conns(c1, c2, c3, c4, c0)
```

In [5]:

```
#Set component attributes

#Calculate for mass flow and pressure of sewage leaving pump
VdotSewage = 22678/(24*60*60) #m3/second

mSewage = VdotSewage*999 #kg/second

#With three identical pumps, from data this gives approx. pressure of 30 mH20
pSewage = 30*9806.65/100000 #bar

#Calculating the enthalpy of waste-water and the heat-transfer into the system
h12 = 51.518
Q_ev = mSewage*(67.19-h12)*0.73

#Calculating temperature gradient
T_sGradient = 16 - (12 + (h12-50.41)*2/(54.6-50.41))

#Setting system attributes
co.set_attr(pr=0.98)
ev.set_attr(pr=0.98, Q = Q_ev)
cp.set_attr(eta_s=0.85)

c2.set_attr(p = 3.2, x=1, fluid={'R134a': 1})
c4.set_attr(x=0)
c3.set_attr(T=55)
```

FIGURE 11: THE CODE CELLS CONTAINING INITIAL CALCULATIONS AND VARIABLE DECLARATION FOR THE SYSTEM.

Once all the necessary variables within the system of equations are set, the system can then be solved, as shown in Figure 12. The solution is obtained by solving the steady state conditions of the system, until residual errors approach zero. Once this is complete, key parameter values can be obtained and used for further analysis.

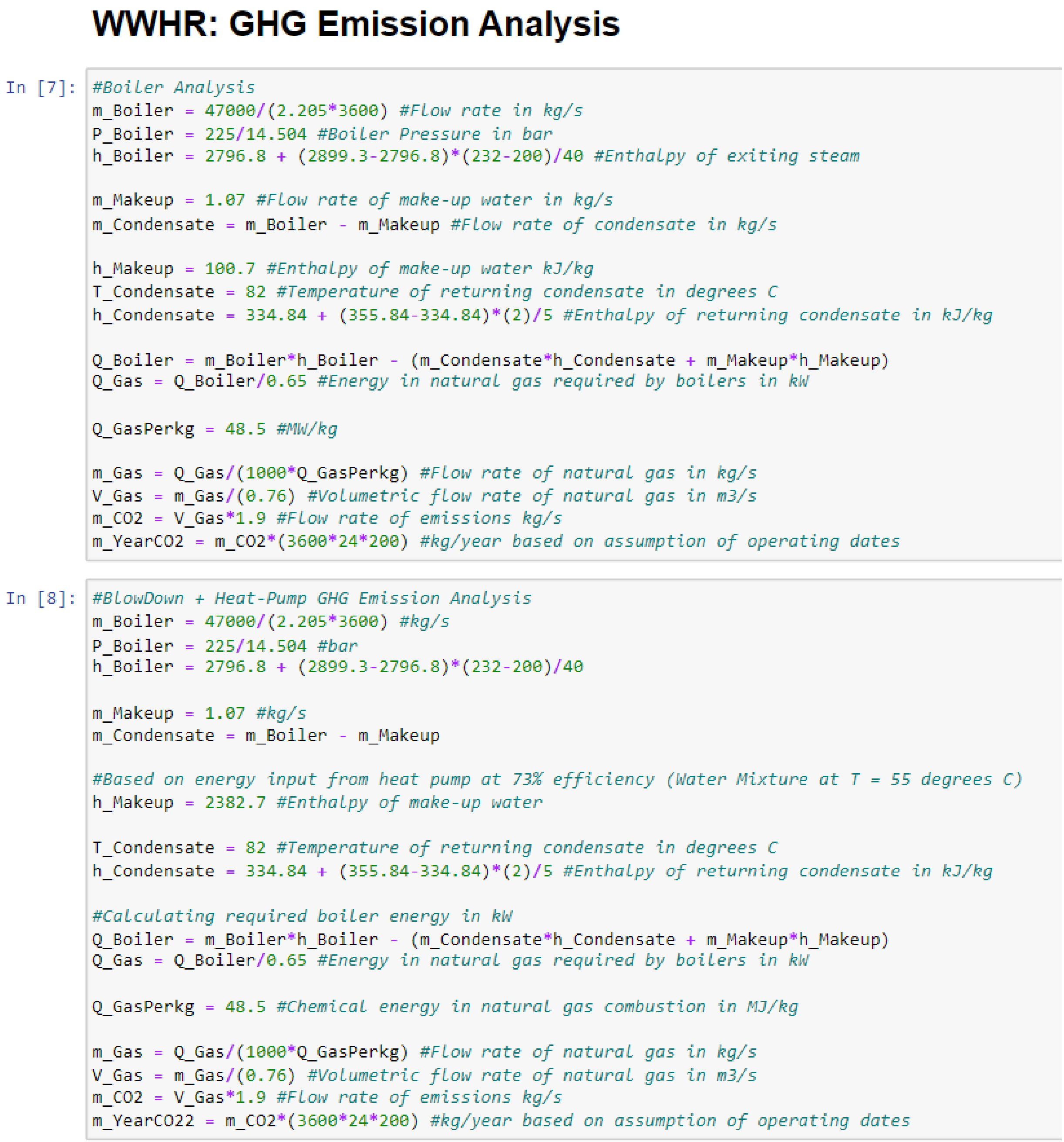


```
#Solve system to get results
heatPump.solve(mode='design')
heatPump.print_results()
```

```
 iter  | residual   | progress   | massflow   | pressure   | enthalpy   | fluid      |
-------+------------+------------+------------+------------+------------+------------+
 1     | 1.84e-06   | 53 %       | 6.72e-13   | 2.34e-09   | 3.19e-06   | 0.00e+00   |
 2     | 2.67e-10   | 53 %       | 4.40e-18   | 2.23e-10   | 1.99e-10   | 0.00e+00   |
 3     | 7.28e-12   | 53 %       | 3.67e-18   | 2.86e-10   | 1.79e-11   | 0.00e+00   |
 4     | 1.75e-10   | 53 %       | 6.01e-17   | 2.86e-10   | 2.85e-10   | 0.00e+00   |
 5     | 1.75e-10   | 53 %       | 6.74e-17   | 2.86e-10   | 3.20e-10   | 0.00e+00   |
Total iterations: 5, Calculation time: 0.02 s, Iterations per second: 249.50

##### RESULTS (CycleCloser) #####
+--------------+------------------+------------------+
|              |   mass_deviation |   fluid_deviation |
|--------------+------------------+------------------|
| cycle closer |         0.00e+00 |          0.00e+00 |
+--------------+------------------+------------------+
##### RESULTS (Valve) #####
+-----------------+----------+----------+
|                 |       pr |     zeta |
|-----------------+----------+----------|
| expansion valve | 2.79e-01 | 2.06e+11 |
+-----------------+----------+----------+
##### RESULTS (SimpleHeatExchanger) #####
+------------+-----------+----------+----------+-----+-----+------+------+--------+
|            |         Q |       pr |     zeta |   D |   L |   ks |   kA |   Tamb |
|------------+-----------+----------+----------+-----+-----+------+------+--------|
| condenser  | -3.71e+03 | 9.80e-01 | 6.40e+09 | nan | nan |  nan |  nan |    nan |
| evaporator |  3.00e+03 | 9.80e-01 | 3.95e+08 | nan | nan |  nan |  nan |    nan |
+------------+-----------+----------+----------+-----+-----+------+------+--------+
##### RESULTS (Compressor) #####
+------------+----------+----------+----------+--------+
|            |        P |    eta_s |       pr |   igva |
|------------+----------+----------+----------+--------|
| compressor | 7.13e+02 | 8.50e-01 | 3.74e+00 |    nan |
+------------+----------+----------+----------+--------+
##### RESULTS (Connection) #####
+----+-----------+-----------+-----------+-----------+
|    |         m |         p |         h |         T |
|----+-----------+-----------+-----------+-----------|
|  1 | 2.214e-02 | 3.265e+00 | 2.645e+02 | 3.047e+00 |
|  2 | 2.214e-02 | 3.200e+00 | 4.000e+02 | 2.477e+00 |
|  3 | 2.214e-02 | 1.195e+01 | 4.323e+02 | 5.500e+01 |
|  4 | 2.214e-02 | 1.171e+01 | 2.645e+02 | 4.538e+01 |
|  0 | 2.214e-02 | 3.265e+00 | 2.645e+02 | 3.047e+00 |
+----+-----------+-----------+-----------+-----------+
```

FIGURE 12 : THE CODE CELL UTILIZED TO SOLVE THE SYSTEM AND THE CORRESPONDING OUTPUT.

Using these key parameters, a comparative analysis of the GHG emissions of the Queen's Heating Plant can be conducted, as shown in Figure 13. This comparative analysis is based off the rate of superheated steam produced by the plant and the states of the water entering the boiler. This allows the total amount of energy required to operate the plant to be calculated, which in turn is translated into the amount of natural gas required. From the amount of natural gas, a direct relation to carbon-dioxide emissions is made.



WWHR: GHG Emission Analysis

In [7]:

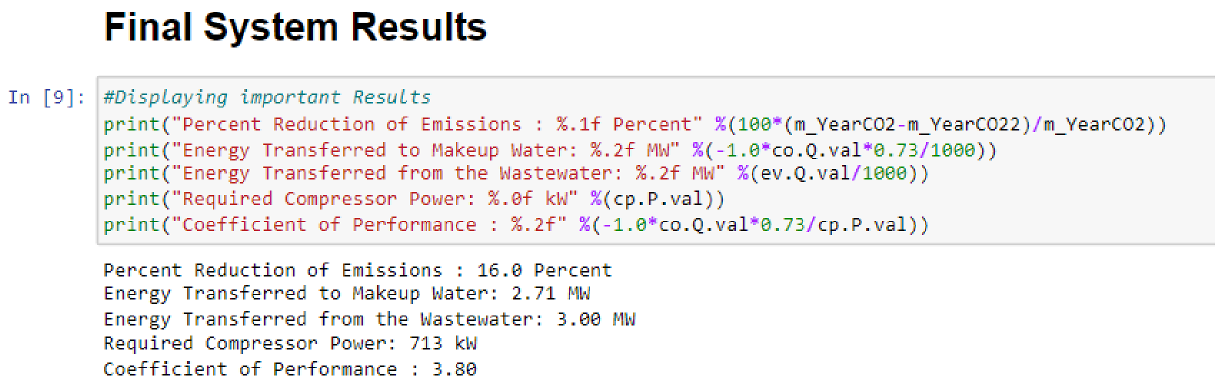
```
#Boiler Analysis
m_Boiler = 47000/(2.205*3600) #Flow rate in kg/s
P_Boiler = 225/14.504 #Boiler Pressure in bar
h_Boiler = 2796.8 + (2899.3-2796.8)*(232-200)/40 #Enthalpy of exiting steam

m_Makeup = 1.07 #Flow rate of make-up water in kg/s
m_Condensate = m_Boiler - m_Makeup #Flow rate of condensate in kg/s

h_Makeup = 100.7 #Enthalpy of make-up water kJ/kg
T_Condensate = 82 #Temperature of returning condensate in degrees C
h_Condensate = 334.84 + (355.84-334.84)*(2)/5 #Enthalpy of returning condensate in kJ/kg

Q_Boiler = m_Boiler*h_Boiler - (m_Condensate*h_Condensate + m_Makeup*h_Makeup)
Q_Gas = Q_Boiler/0.65 #Energy in natural gas required by boilers in kW

Q_GasPerkg = 48.5 #MW/kg

m_Gas = Q_Gas/(1000*Q_GasPerkg) #Flow rate of natural gas in kg/s
V_Gas = m_Gas/(0.76) #Volumetric flow rate of natural gas in m3/s
m_CO2 = V_Gas*1.9 #Flow rate of emissions kg/s
m_YearCO2 = m_CO2*(3600*24*200) #kg/year based on assumption of operating dates
```

In [8]:

```
#BlowDown + Heat-Pump GHG Emission Analysis
m_Boiler = 47000/(2.205*3600) #kg/s
P_Boiler = 225/14.504 #bar
h_Boiler = 2796.8 + (2899.3-2796.8)*(232-200)/40

m_Makeup = 1.07 #kg/s
m_Condensate = m_Boiler - m_Makeup

#Based on energy input from heat pump at 73% efficiency (Water Mixture at T = 55 degrees C)
h_Makeup = 2382.7 #Enthalpy of make-up water

T_Condensate = 82 #Temperature of returning condensate in degrees C
h_Condensate = 334.84 + (355.84-334.84)*(2)/5 #Enthalpy of returning condensate in kJ/kg

#Calculating required boiler energy in kW
Q_Boiler = m_Boiler*h_Boiler - (m_Condensate*h_Condensate + m_Makeup*h_Makeup)
Q_Gas = Q_Boiler/0.65 #Energy in natural gas required by boilers in kW

Q_GasPerkg = 48.5 #Chemical energy in natural gas combustion in MJ/kg

m_Gas = Q_Gas/(1000*Q_GasPerkg) #Flow rate of natural gas in kg/s
V_Gas = m_Gas/(0.76) #Volumetric flow rate of natural gas in m3/s
m_CO2 = V_Gas*1.9 #Flow rate of emissions kg/s
m_YearCO22 = m_CO2*(3600*24*200) #kg/year based on assumption of operating dates
```

FIGURE 13: THE CODE CELLS CONTAINING THE COMPARATIVE GHG EMISSIONS ANALYSIS FOR THE STEAM PLANT.

Finally, the key results of these analyses are displayed, displaying the performance of the system for key design metrics, as seen in Figure 14.



Final System Results

```
In [9]: #Displaying important Results
        print("Percent Reduction of Emissions : %.1f Percent" %(100*(m_YearCO2-m_YearCO22)/m_YearCO2))
        print("Energy Transferred to Makeup Water: %.2f MW" %(-1.0*co.Q.val*0.73/1000))
        print("Energy Transferred from the Wastewater: %.2f MW" %(ev.Q.val/1000))
        print("Required Compressor Power: %.0f kW" %(cp.P.val))
        print("Coefficient of Performance : %.2f" %(-1.0*co.Q.val*0.73/cp.P.val))
```

```
Percent Reduction of Emissions : 16.0 Percent
Energy Transferred to Makeup Water: 2.71 MW
Energy Transferred from the Wastewater: 3.00 MW
Required Compressor Power: 713 kW
Coefficient of Performance : 3.80
```

FIGURE 14: THE FINAL CODE CELL USED TO DISPLAY KEY RESULTS OF THE CUMULATIVE ANALYSIS.

Appendix F – Faculty Advisor Sign Off

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

Team 30: 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.

Date: November 29, 2023
Adam Barkas

Date: November 29, 2023
Ashwin Sharma

Date: November 29, 2023
Joel Gallagher

Riley Betson
Date: November 29, 2023
Riley Betson

Date: November 29, 2023
Steven Ma

==

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

Date: December 5, 2023
Professor Matovic