Techno-economic feasibility of Sewage Wastewater Heat Recovery (WWHR) based Community Energy Network (CEN) in a cold climate - a case study of Ryerson University, Toronto, Canada

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Abstract. Wastewater is an underutilized and readily available source of carbon free thermal energy. The energy derived from wastewater can be augmented using heat pumps to supply thermal energy to buildings. Due to favorable temperatures, wastewater sourced heat pumps are able to operate more efficiently than air and ground sourced heat pumps. This paper evaluates the potential of using wastewater heat recovery (WWHR) to provide heating and cooling to a mid-sized university campus located in the urban center of Toronto, Canada.

1. Introduction
The energy sector is one of the largest contributors to greenhouse gas (GHG) emissions, specifically heating and cooling of buildings. In Canadian residential buildings, 62% of energy is used for space heating, and an additional 19% is used for domestic hot water (DHW) [1]. Much of this heating is performed through fossil fuels, leading to large GHG emissions.

The average household in Toronto consumes 790 L/day of water [2]. Across all of Canada, this number escalates to 3.2 billion m³ of water annually [3]. In addition, it is estimated that up to 90% of the energy used to heat water is lost down the drain [4]. The recovery of a portion of this heat represents a large carbon-free source of energy that could drastically reduce GHG emissions and help pave the way to a sustainable future.

WWHR is severely underutilized and has largely been limited to small installations. This paper will look to evaluate WWHR performance when implemented in the context of a district energy system. Installation on this scale would require higher sewer flow rate, and this model uses years of sewer data to generate a sewer flow profile in order to evaluate how sewer flows will affect the WWHR system. In addition, real operating costs will be used to evaluate the potential savings. Lastly, the WWHR will be used to balance the system. Since there is a substantial year-round simultaneous heating and cooling demands, the system will investigate recovering rejected heat from the chilled water system to supply heating to the hot water loop. If either the heating or cooling demand drops, then the WWHS will be used to supplement the required energy using the wastewater. This would also be applicable to other heat pump-based systems, not just WWHR.

2. Background
2.1 Wastewater Flow and Temperature
The energy present in a sewer cannot be quantified without extensive knowledge of the temperature and flow profile of the wastewater stream over an entire year. Both parameters are vital when gauging the potential of a WWHR system for a specific site – the COP of the system is a direct function of the wastewater temperature, and the flowrates dictate the availability of the energy source and size of the overall system. The first step in designing a WWHR system for the Ryerson Campus was to evaluate the amount of energy that could potentially be recovered. Through the assistance of Toronto Water, the municipal entity responsible for water supply and wastewater management in Toronto, it was determined that a mid-sized combined interceptor sewer running through the main campus would exhibit flows large enough for the ideally sized WWHR system.

Toronto Water was able to provide approximately three years’ worth of flowrate data for the interceptor sewer running along Church Street. Temperature data for the Church Street interceptor sewer was not available. The temperature profile for three similarly sized sewers in close proximity to the campus were used as a substitute instead. All three sites exhibited an average annual temperature of approximately 24°C, with an average daily variation of 1°C. Flowrate data for the Church Street sewer from 2015 to 2018 is shown in Figure 1. The data was recorded on a 5-minute interval and was aggregated on an hourly resolution.

As is evident from Figure 1, the flow rate consistently remains well above about 600 L/s throughout the year. Each heat exchanger requires a shell side (wastewater side) flowrate of 32.6 L/s to operate at optimal conditions. The abundance of wastewater flow in the sewer allows the system to be adequately sized, and also allows room for expansion should the possibility be considered in the future. Numerous peaks can be seen in the graph. These spikes represent the run off from rainwater. A larger cluster of such spikes can be seen in the spring, which on top of rain, would also likely be attributed to snow melt.

2.2 Ryerson University Campus

Ryerson University (RU) is mid-sized public university located in downtown Toronto, Canada. The entire campus spans a total 281,020 m² consisting of 18 major buildings. The campus contains two central cooling plants with capacities of 3100 tons and 530 tons, respectively. The larger, 3100-ton plant serves approximately 66% of the Campus’ cooling requirements, whereas the smaller plant covers 11% [5]. On top of the two central plants, Ryerson also uses deep lake water cooling (DLWC) for 9% of the campus. The Ryerson campus supplies the majority of its space heating, DHW, and heat for absorption chillers using district heat (steam) supplied by the Enwave Energy Corporation.
In order to accurately model the performance of the WWHR system, the hourly performance of the system in conjunction with the thermal demand of the Ryerson campus buildings must be taken into consideration. The hourly thermal loads of buildings are dependent on a plethora of complex variables such as building envelope, ambient air temperature, wind, solar gains, occupancy and internal gains. These parameters must be considered when attempting to model the heating and cooling loads on an hourly resolution. An extensive energy audit of Ryerson University, conducted by [5], included simulating 86% of the total campus conditioned area. The energy audit provided essential information on Ryerson’s HVAC system, overall energy requirements, and building envelope. The building models and information obtained from the audit were used to run simulations for 16 major buildings, using 2018 weather data, to determine Ryerson’s hourly heating and cooling demand. The results of these simulations are summarized in the Table 1.

### Table 1. Ryerson Building Summary

| Number | Building Name | Annual Heating Demand (mmBTU) | Annual Cooling Demand (mmBTU) | Floor Area (m²) |
|--------|---------------|--------------------------------|------------------------------|----------------|
| 1      | CED           | 633                            | 706                          | 4 180          |
| 2      | IMA           | 2 907                          | 2 089                        | 9 345          |
| 3      | VIC           | 2 318                          | 2 684                        | 12 708         |
| 4      | JOR           | 1 380                          | 3 690                        | 10 964         |
| 5      | LIB           | 797                            | 5 907                        | 18 487         |
| 6      | POD           | 2 001                          | 4 302                        | 21 730         |
| 7      | ENG           | 5 961                          | 6 483                        | 22 350         |
| 8 & 9  | EPH & SHE     | 1 876                          | 5 069                        | 21 019         |
| 10     | SID           | 327                            | 563                          | 4 373          |
| 11     | SCC           | 654                            | 681                          | 4 180          |
| 12     | HEI           | 548                            | 545                          | 2 985          |
| 13A    | KNE           | 4 711                          | 1 478                        | 52 409         |
| 13B    | KNW           | 5 990                          | 1 273                        |                |
| 13C    | KSE           | 16 218                         | 5 067                        |                |
| 13D    | KSW           | 6 845                          | 4 313                        |                |
| 14     | RCC           | 1 108                          | 2 850                        | 13 100         |
| 15     | PIT           | 502                            | 652                          | 17 866         |
| 16     | RBB           | 4 522                          | 6 326                        | 24 378         |
| TOTAL  |               | 59 306                         | 54 685                       | 240 074        |

To validate the accuracy of the simulations, the annual energy demand from the simulations was compared to the heating consumption documented in current RU utility bills obtained from Campus Facilities. The amount of steam consumed annually was averaged out over a 3-year span and converted from pounds of steam to thermal energy. Enwave supplies saturated steam at 250 psi and it is returned as a saturated liquid. Therefore, the energy content of the steam is equivalent to the heat of vaporization at 250 psi. Since Ryerson has absorption chillers to provide cooling, the steam consumed during the summer months was ignored. Lastly, not every building in the campus was simulated due to their small sizes and/or having their own HVAC systems, so the percentage of floor area considered in the simulation was determined, and the total steam consumption from the bills during the heating season was compared. This confirmed the accuracy of the simulations.

### 3. WWHR System Configuration

The WWHR system is comprised of 3 main components: a wastewater collector, a heat exchanger, and a heat pump. The wastewater flows from the sewer into the wastewater collector where the solids and particles are screened out. This screened brown water is then pumped to a heat exchanger where heat transfer occurs with an intermediary fluid. Despite the initial screening, the brown water still contains...
impurities that would accumulate and foul up the heat transfer surface area, which would greatly reduce the rate of heat transfer. To prevent this, the heat exchanger modelled in this analysis has a built-in cleaning system to remove and prevent fouling.

The heat pump is used to achieve the required supply temperatures and draws or rejects heat from the intermediary fluid. This intermediary fluid flows between the heat exchanger and heat pump and allows for thermal energy to be carried between the brown water on the shell-side of the heat exchanger and the heat pump.

With most larger sewers there is enough flow to allow the WWHR system to supply the entire thermal demand of the building(s). However due to the higher capital costs of WWHRS compared to conventional boilers, chillers and cooling towers, most WWHRS only serve to provide the base demands. This hybridized system is the most economically viable solution as it allows the high capital, low operating cost WWHR to provide the majority of the thermal demand, and allows the lower capital cost, but higher operating cost conventional equipment be used for peaking. The analysis carried out in this paper considers such a hybridized WWHRS.

Lastly, since Ryerson University has substantial simultaneous heating and cooling demands for large parts of the year, heat pumps will be used to recirculate thermal energy within the campus. Heat pumps providing cooling will be distributed through the chilled water loop, and the heat rejected by the heat pumps will be supplied as low-grade heat. This low-grade heat can be used to preheat outdoor air in the winter and/or DHW. In this study, heat pumps operating in such a manner will be referred to as heat-reclaim heat pumps. This will reduce the overall energy consumption of the campus by recycling low-grade thermal energy. In this study, heat pump operating in this manner will be referred to a heat-reclaim heat pumps. If the rejected heat from the heat pumps is higher than the low-grade thermal demands then excess heat will be rejected to the sewer via the heat exchangers.

4. Model Overview
A model was developed in Excel to calculate and analyze the operation of the hybridized WWHR system on an hourly basis. The model determines the operating performance of the hybridized WWHR system in comparison to a conventional system.

4.1 Building Demands
The aggregated RU campus loads were used for the analysis. As per discussion with RU facilities management, a base cooling load of 400 tons was added into the profile.

All heating at Ryerson is performed by the steam system, which operates at temperatures far greater than what heat pumps can supply. Therefore, rather than targeting these high supply temperatures, the WWHR system will provide low grade heating at 40 °C, which will be used to perform preheating of outdoor ventilation air. This allows for the heat pump based WWHR system to provide heating/preheating, thus reducing the demand on the steam system, but the lower supply temperature allow the heat pumps to perform at much higher COPs. Though not considered in this analysis, it may also be used to provide preheating for domestic hot water.

The majority of the buildings at Ryerson do not have a heat recovery unit to reclaim thermal energy from air being exhausted out of the buildings. Therefore, there would be a large thermal demand to heat outdoor ventilation air in the winter. Based on ASHRAE 62.1-2010, the suggested outdoor ventilation requirement for a lecture hall is 0.06 CFM/ft² [6]. Assuming this ventilation requirement for the 2,584,135 ft² of simulated floor area provides a requirement of approximately 155,048 CFM of outdoor air. The model will calculate the outdoor air heating demand as:

\[
Q_{\text{air preheat}} = V \cdot \rho \cdot C_p \cdot (T_{\text{supply}} - T_{\text{outdoor}})
\]

Where \(Q_{\text{air preheat}}\) is the amount of heating required in kW, \(V\) is the volumetric flowrate of outdoor air, \(\rho\) is the density of outdoor air in kg/m³, \(C_p\) is the specific heat of air in kJ/kg-K, \(T_{\text{supply}}\) is the temperature at which air is to be supplied, and \(T_{\text{outdoor}}\) is the outdoor air temperature. For this analysis the heat pumps
will provide heating at approximately 40 °C, and a target air supply temperature of 35 °C. A restriction was imposed in the model that the heating demand of the outdoor air cannot exceed the building demand obtained from the building simulations for any given hour.

4.2 Conventional Equipment

The WWHR system will be compared to a conventional system using boilers, chillers and cooling towers. For this analysis a boiler efficiency of 75 %, and an electric chiller COP of 4.0 were assumed as seasonal efficiencies, based on typical performance. The cooling tower evaporation rate was 8.3 L/T-hr, and consumed an additional 0.05 kW/ton for the fan. The average water cost used was $3.45/m³, and a chemical treatment cost $0.60/m³ of water. To prevent freezing of the water in the cooling tower during the winter, a heater element was used when free cooling was activated and draws an additional 0.1 kW/ton. Free cooling was employed when outdoor air temperatures fell below 5 °C. During free cooling the electric chillers were turned off.

4.3 Heat Exchanger Parameters

The shell and tube heat exchanger used in the analysis has a built-in cleaning system to prevent fouling and ensure optimal performance. The shell side fluid is screened wastewater at a flow rate of 32.6 L/s, as per manufacturer recommendations. On the tube side is an intermediary fluid that flows between the heat exchanger and the heat pump. The maximum flow rate for the tube side fluid is 16 L/s, as per manufacturer specifications. In the analysis, the tube side flow rate is adjusted based on the building demand. This is to ensure a large portion of the buildings thermal demand can be met, and to have the return temperature of the intermediary fluid be more favorable to the heat pump, allowing it to operate at higher COPs. An effectiveness curve is shown in Figure 2 that depicts the effectiveness of the heat exchanger as a function of tube side flow rates.

\[ \eta_{\text{HX}} = \frac{T_{\text{exit}} - T_{\text{in}}}{T_{\text{exit}} - T_{\text{in}}} \]  

4.4 Heat Transfer Equations

The amount of heat being transferred across the heat exchanger is calculated as:

\[ Q_{\text{HX}} = \dot{m}_{\text{TS}} \cdot C_p \cdot (T_{\text{sewer}} - T_{\text{evap.exit}}) \cdot \eta_{\text{HX}} \]  

Where \( Q_{\text{HX}} \) is the amount of heat transferred in kW, \( M_{\text{TS}} \) is the tube side flow rate in kg/s, \( C_p \) is the specific heat in kJ/kg-K, \( T_{\text{sewer}} \) is the temperature of the sewage in K, \( T_{\text{evap.exit}} \) is the temperature of the intermediary fluid leaving the evaporator of the heat pump in K, and \( \eta_{\text{HX}} \) is the effectiveness of the heat exchanger. The temperature of the intermediary fluid leaving the heat exchanger to the heat pump is calculate as:

\[ T_{t_{\text{to HP}}} = T_{t_{\text{from HP}}} + \dot{Q}_{\text{HX}} \cdot \dot{m}_{\text{TS}} \cdot C_p \]  

Figure 2. Heat Exchanger Effectiveness vs Tube-side Flow Rate
Where $T_{\text{fromHP}}$ is the temperature of the intermediary fluid leaving the heat pump going to the heat exchanger in °C.

### 4.5 Heat Pump Parameters

Heat pump operating data was obtained from a reputable manufacturer. For the heat pumps operating in conjunction with the heat exchangers, COP curves were obtained for the heating and cooling supply temperatures. The heating COP curve was obtained as a function of the entering evaporator temperature. The cooling COP curve was obtained as a function of the condenser exit temperature. Both COP curves can be seen in Figure 3.

![Figure 3. COP Curve for 40 °C Heating Supply and 5 °C Cooling Supply Temperature](image)

Heat pumps operating in heat-reclaim mode will be assumed to operate under steady entering and exiting temperatures for the evaporator and condenser. Therefore, their performance is modelled after specification sheets obtained from the manufacturer.

### 4.6 Auxiliary Power Draw

In addition to the heat pumps, the WWHR system auxiliary equipment draws electricity for the controls, cleaning system, sewage supply pump, and mixer. A reputable controls manufacturer was consulted and stated that the WWHR system controls could be integrated with the heat pump controls, with minimal additional power draw. Therefore, the controls were assumed to draw 140W per heat exchanger. As per specifications obtained from the heat exchanger manufacturer, the cleaning system consumes approximately 1 kWh of electricity per day. A mixer is installed within the heat exchanger to create turbulence in the shell side fluid, and as per manufacturer specifications, consumes 1.26 kW of electricity when heat transfer is occurring. The sewage supply pump must supply 32.6 L/s of screened sewage to each heat exchanger. For this analysis, the pump head was set to 10 m, with an efficiency of 88%.

### 4.7 Utility Rates

For the analysis Ryerson’s current electricity rate, Class B, was used to calculate the operating costs of all electrical components. The HOEP rate (Hourly Ontario Energy Price) from 2018 was used and charged by consumption at a rate that changes each hour. Ontario’s Class B global adjustment rate was charged per kWh consumed at a rate that changes each month. For the analysis, the global adjustment rate used for a given month was the average price for that month over the past 3 years. The local electrical utilities, Toronto Hydro, transmission and distribution rates were used and for the analysis, and for the analysis were charged per maximum kW consumption for a given month. It should be noted that the transmission and distribution charges would be charged on the aggregated electrical consumption for the entire campus. However, for this analysis only the HVAC equipment is considered, not other electrical consumption such as lighting or plug loads.
Ryerson’s current natural gas rate, rate 100, was used for the analysis using Enbridge’s, the local natural gas utility, pricing structure. Included in this pricing are tier consumption charges, contract demands, transportation charges, rate rider C, system sales supply gas charge, and sales service.

5. Techno-Economic Analysis

The following capital costs were used in the financial analysis:

| Equipment               | Cost                        |
|-------------------------|-----------------------------|
| Heat Exchanger          | $ 175,000 each              |
| Wet Well                | $ 400,000                   |
| WW Supply Pump          | $ 3,000 /heat exchanger     |
| Heat Pump               | $ 180,000 /heat exchanger   |
| WW Screen/Filter        | $25,000 /heat exchanger     |
| Construction and permits| 30% of equipment cost       |

The base load was covered using the heat-reclaim HPs. Additional heating in the winter and cooling in the summer was provided through the WWHR system. The final design will provide annual energy cost savings of $396,000 compared to the conventional system, with a capital cost of $4,047,000. This would provide a simple payback of 10.2 years. The WWHR system has a peak heating and cooling capacity of 3.7 MW and 3.4 MW, respectively, and is able to provide 10,900 MWh of heating and 14,500 MWh of cooling annually. In addition, the reduced load on the cooling tower would save 34,700 m³ of water annually that would not be evaporated through the cooling towers. Lastly, the 1,378,000 m³ of natural gas offset would result in a CO₂ reduction of 2,600 tonnes per year, using an emissions factor of 1.89 kg/m³ of natural gas [7], and 36 g/kWh for electricity [8]. Graphs of the performance of the WWHR system can be seen in Figures 4 and 5.

![Figure 4. Annual Heating Provided by WWHRS](image)
6. Conclusion
The viability of installing a heat pump based WWHR system was modeled and analyzed for a university campus. The WWHR system was able to reduce the total energy consumption of the campus by 13,800 MWh system would cost approximately $4.05 million and provide annual savings of approximately $396,000 for a simple payback period of 10.2 years. In addition, the WWHR system would reduce 2,600 tonnes of CO₂ annually.

Acknowledgements
The authors would like to acknowledge Ryerson University and MITACS for their continued financial support. The authors would also like to extend their gratitude to Noventa Energy Partners, specifically Steve Condie and Dennis Fotinos for their insight and support.

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