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World Sustainability Forum 2014 – Conference Proceedings Abstract

Recovery of Sewer Waste Heat vs. Heat Pumps Using Borehole Geothermal Energy Storage for a Small Community Water Heating System: Comparison and Feasibility Analysis

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Abstract: The consumption of hot water represents a significant portion of national energy consumption and contributes to concerns associated with global climate change. Utilizing heat recovered from the sewer or stored in the ground via a borehole geothermal energy storage system are simple and effective ways of heating water for domestic purposes. Reclaiming heat from the waste warm water that is discharged to the sewer or stored heat in a borehole geothermal energy storage system can help reduce natural gas energy consumption as well as the associated energy costs and greenhouse gas emissions. In this paper, sewer waste heat recovery is compared with geothermal heat pump systems for a small community shared water heating system. It is found that the heat recovery from the sewer heat exchanger method demonstrates the lowest rate of return on investment for the selected community size. The findings also demonstrate a significant reduction in natural gas consumption and CO_2 gas emissions. The results are intended to allow energy technology suppliers to work with communities while accounting appropriately for economic issues and CO_2 emissions associated with these energy technologies.

Keywords: natural gas; shallow; borehole geothermal energy storage system; sewage waste water; sewage waste heat recovery; water heater heating; heat recovery; heat top-off; community; feasibility study.

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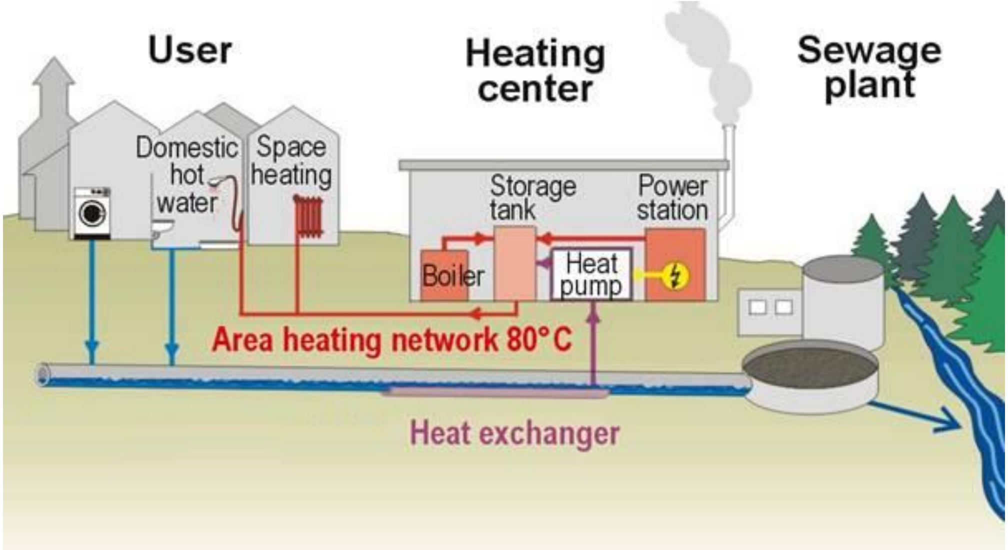
1. Introduction

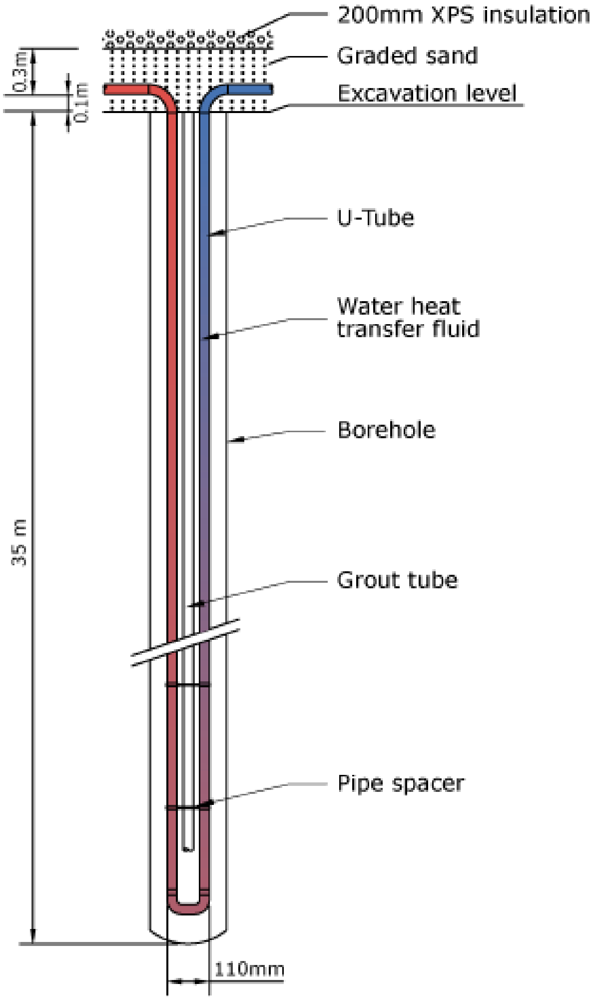
Space heating, cooling and domestic hot water supply represents the biggest share of energy in residential buildings [1]. There are a number of uses of hot water in buildings, including showers, sinks, dishwashers, clothes washers and others; the waste water retains a significant portion of its initial energy that could be recovered. By removing the waste heat it is possible to reduce the use of fossil fuels for heating water and subsequently reducing greenhouse gas emissions to the atmosphere as a result. The systems described in this section will be used for the analysis of heat recovery system. Figure 1 illustrates the process of the heat recovered and in combination with a heat pump to increase the temperature of the recovered heat for space heating and domestic hot water supply.

Figure 1: Heat recovery from sewage waste heat.



It is also possible to extract heat using a closed-loop ground couple heat pump system that relies on heat exchanges to reject or extract heat from the ground. This heat exchanger consists of a borehole in which a U-tube pipe is inserted. The borehole is usually filled with a grout to enhance heat transfer and protect underground aquifers as illustrated in Figure 2.

Figure 2: UOIT U-tube pipe layout in a borehole.

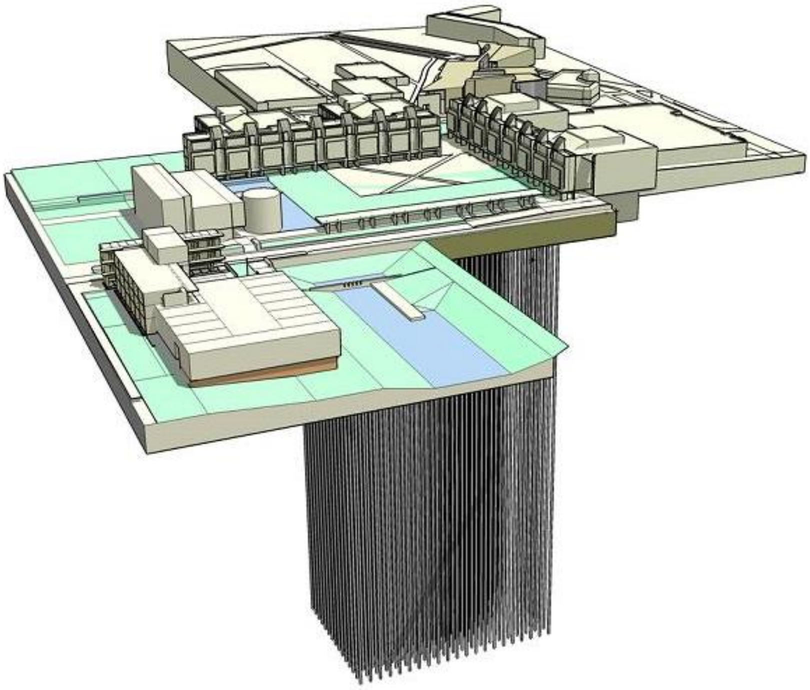


Alternatively, solar energy is an option for space heating and domestic water heater applications. Many studies have been performed in regards to the solar thermal energy collection as a stand-alone system or the combination of solar thermal energy and ground source heat pump system for domestic hot water heating purposes. In this paper the focus will be on economic and environmental benefits of heat recovery from sewage water in comparison to ground source heat pump systems.

In this paper the ground source heat pump system used is the underground Borehole Thermal Energy Storage (BTES) system that is installed at the University of Ontario Institute of Technology (UOIT) in Oshawa, Ontario, Canada. The BTES's are designed for heating and cooling applications, sometimes with renewable energy in order to minimize greenhouse gas emissions. For this paper the heating portion of this system is considered for the domestic water heater application.

The UOIT BTES system layout as shown in Figure 3 is unique in Canada in terms of the number of holes, capacity, surface area, technology, etc. Large-scale storage systems, comparable to the UOIT system, have been implemented at Stockton College in New Jersey, USA and in Sweden [2]. The conditions for heating the load water leaving the borehole that is 198 m deep to reach the approximate 52°C (126°F) temperature has a heat pump COP of about 3.5 [3]. The system is capable of producing nearly 1,386 MW of energy for heating [3].

Figure 3: UOIT BTES system layout.



The UOIT's BTES system is large and costly; however there is a smaller and less expensive type of ground heat source heat exchanger that is known as Shallow Geothermal Energy. The basic principle of a ground source heat pump is shown in Figure 4 and system layout in Figure 5 [4]. Heat can be extracted from the ground at a relatively at low temperatures, transferring the heat through the heat pump to increase the temperature to be useful for space heating [4]. The ground source heat pumps are typically 50 – 100 m deep and intended for closed-loop applications have heating COP ratings between 3.1 and 4.9 [5]. The typical Shallow Geothermal Energy at 100 m deep is capable of delivering a load water of approximately 35°C (95°F) using the heat pump [6].

Figure 4: Schematic of a ground source heat pump.

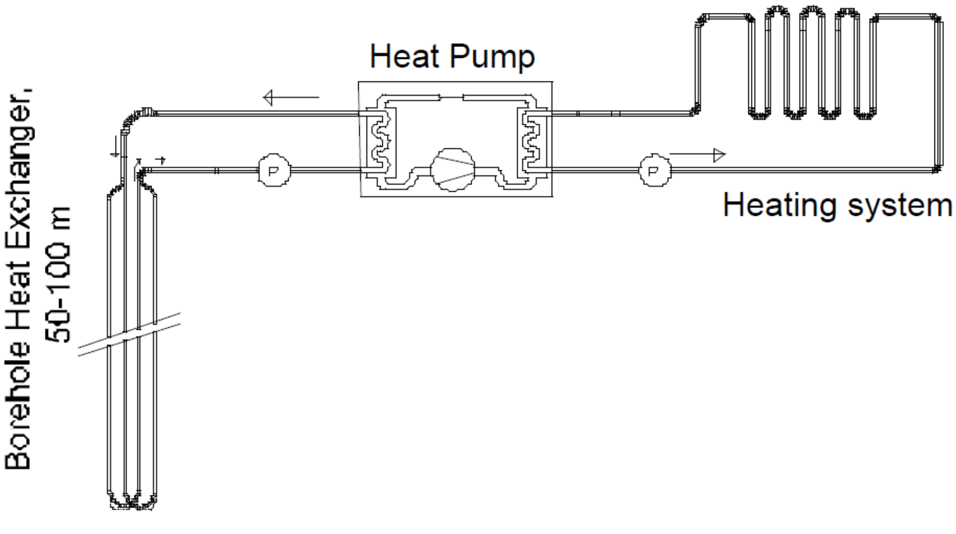
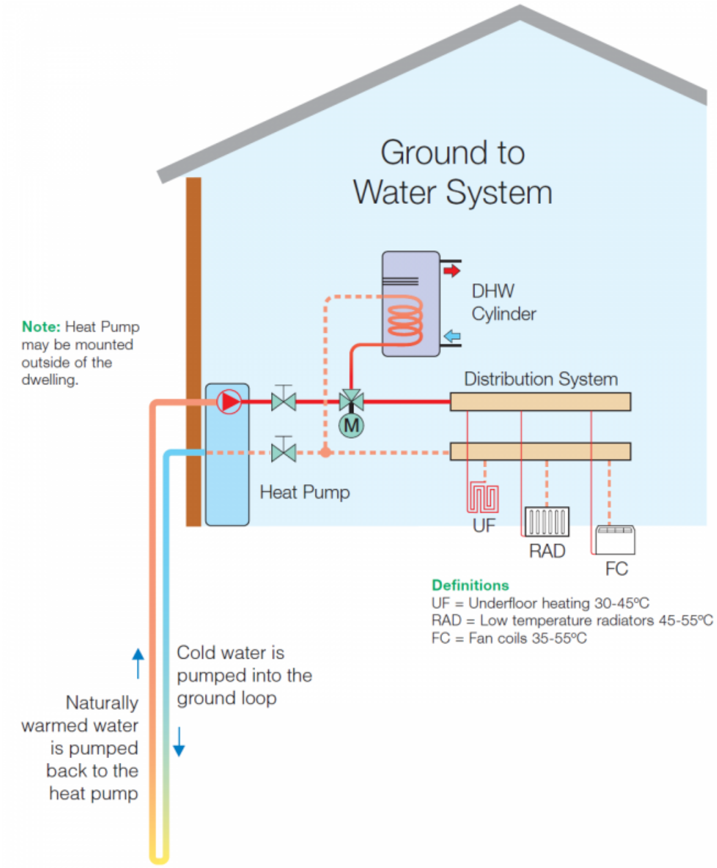
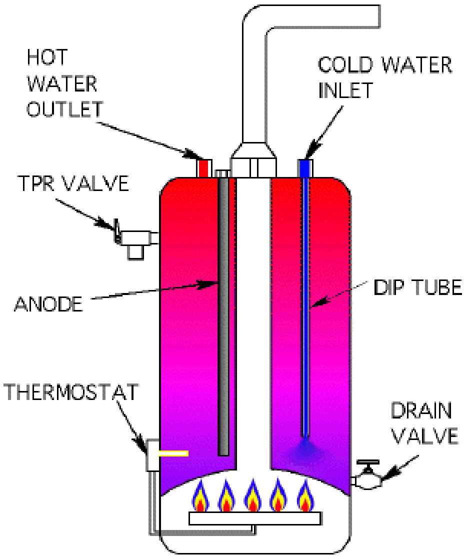


Figure 5: Shallow ground source borehole and heat pump system layout.



Conventional household natural gas powered storage tank water heaters as shown in Figure 6 operate at 67% – 69% efficiency [7] and water heater manufacturers recommend the maximum hot water temperature supplied to fixtures in residential occupancies shall not exceed 49°C (120°F) to help prevent from scalding and to save energy. The water heater manufacturers' recommendation is made as stated by the Ontario Building Code amended in September 2004 [8], however the requirement exempts dishwashers and clothes washers.

Figure 6: Typical household natural gas powered domestic water heater.

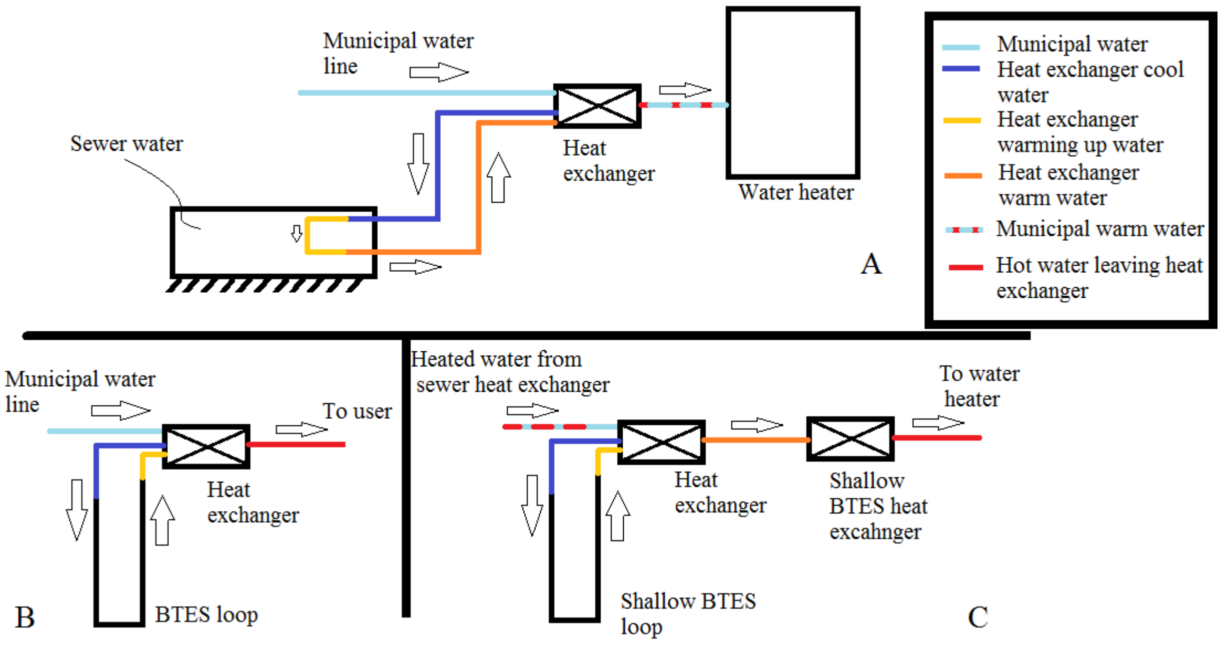


A BTES system similar to the UOIT BTES and shallow ground source BTES are compared simultaneously with the sewer heat exchange method. This is done to determine if using any of the domestic water heating systems, either stand-alone or in combination with other systems, has economic or environmental benefits for municipal water heating purposes. This study is performed in the pursuance of lowering the consumption of natural gas for municipal water heating purposes to reduce CO_2 emissions.

1.1. System Overview

There are several options to recover the heat embedded in waste water. These systems portrayed in Figures 1 to 5 shows the possibilities of creating systems for municipal water pre-heating. The heat content of waste water from households can be recovered within houses, this is considered as a small scale application, and may be costly. The heat content may also be recovered from the sewer, considered as medium scale application, or at waste water treatment plants for large scale applications [9]. In Figure 7, the schematic of these systems are outlined. Section A in Figure 7 shows the schematic of a sewage water heat recovery system. The heating water enters the sewer in a counter flow direction of the sewer water flow, absorbs heat and transfers the heat to municipal water line through a heat exchanger. This preheated municipal water then enters the domestic water heater and is heated to the desired temperature for the user. Section B of Figure 7, shows a typical BTES system. In this system, the heat exchanger water passes through the ground loop, absorbs heat and transfers the heat to the municipal water in the heat exchanger. Section C of Figure 7 shows the combination of sewer heat and BTES system for domestic water heating. In this system, the municipal water is preheated in two stages by flowing through a heat exchanger in connection with the sewer system and a second heat exchanger connected to the BTES. The preheated municipal water can then flow to the domestic water heater for additional heat top-off.

Figure 7: Schematic of heat recovery systems.



In this report, a simple counter flow heat exchanger with stainless steel tubing is considered. A counter flow heat exchanger is considered the ideal type among heat exchangers for the recovery of waste heat energy [10]. The performance of heat exchangers usually deteriorates over time as a result of accumulation of deposits on the tube surfaces. The layers of deposits represent additional resistance to heat transfer and decrease heat transfer rate. The most common fouling is the precipitation of solid deposits in a fluid on heat transfer surfaces. Stainless steel is used due to the limiting factors of fouling formation from the sewer sludge; it is less resistant compared to aluminium tubing [11]. The length of the tube in the counter flow heat exchanger can be evaluated using Equation 1.

$$A_s = \pi D L \tag{1}$$

where, D is the tube diameter and L is the tube length. For a typical stainless steel tube counter flow heat exchanger, a tube diameter of 5 cm is selected with a surface area of 5 m^2. The surface area is estimated for this case and the length is calculated to be 33 m.

2. Formulation

Usually, the modelling of waste water heat recovery presents several obstacles such as acquiring and generating appropriate input data based on highly variable water usage statistics. Since waste water heat has not been considered as a potential source of heat for domestic water heating applications, there are very few statistics available for waste water temperature data. In this study, data related to flow rate and temperature of the waste water in the sewer system of city of Oshawa, Ontario, has been considered. Similarly, the Borehole Thermal Energy Storage (BTES) from University of Ontario Institute of Technology has been considered for this analysis due to availability of information and the university size making it an ideal community size for such application. In some studies, the average sewer temperature considered for calculation is 18°C (64°F) [12]. Oshawa's Storm Sewer Use By-law 95-95, updated in 2013, indicates a 40°C (104°F) as the maximum temperature limit for storm sewer discharge [13].

The temperatures for waste water treatment range from 25°C (77°F) to 35°C (95°F) [14]. In general, biological treatment activity accelerates in warm temperatures and slows in cool temperatures but extreme hot or cold can stop treatment processes altogether. Thus, due to the variant temperature of the sewage water, a range of 18°C (64°F) to 26°C (79°F) is used for the calculations.

Multiple sources indicate the municipal water temperature is less than or equal to 15°C (59°F) [15, 16]. This temperature is adopted from the guidelines of Canadian drinking water [17]. The rational is that at temperatures above 15°C (59°F), the growth of nuisance organisms in the distribution system can lead to the development of unpleasant tastes and odors. Thus, the cold water temperature of 15°C is used for the analysis.

In this study, the heat transfer coefficient is 675 W/m^{2}K [18] for a common tubular counter flow heat exchanger with a double pipe shell and stainless steel tube construction. For this analysis, a small community such as UOIT has been considered that uses approximately 13,627 L (3,600 gallons) of water per day.

The energy input equation is shown below

$$\dot{Q}_{in} = \frac{\rho_W V_w C_p \Delta T_w}{\eta_{WH}} \tag{2}$$

where, $\dot{Q}_{in}$ is the daily energy input for heating municipal water, ρ_W is the water density at 15°C (59°F), V_w is the water tank volume, C_p is the specific heat capacity of the municipal water, ΔT_w is the temperature difference between the water entering the municipal water heater and user's desired temperature, and η_{WH} is the domestic water heater efficiency. When the municipal water is preheated before entering the tank, Equation 3 is used to calculate the additional heat required to heat the municipal water to the user's desired temperature (49°C in this study).

Table 1: Fixed variables used in the study.

Fixed variables	**Values**	**Units**
Tank size	13,627	L
Mass flow rate of cold municipal water (15°C) (59°F)	9.46	kg/s
Mass flow rate of warm water (25°C) (77°F)	163.91	kg/s
Cp	4.18	kJ/Kg°C
Water heater efficiency	68	%
Water density (ρwater)	0.99975	g/m^3
Energy to mass conversion (kJ to kJ/m^3)	35,435	kJ/m^3
Natural gas price	22	cents/m^3
Water exiting the water heater ($T_{c,out}$)	49	°C

This conversion rate is outlined in Table 1. The temperature of the municipal water exiting the heat exchanger preheating the water can be determined using the counter flow heat exchanger energy balance as shown in Equation 3. In this analysis, $T_{c,in}$ is the temperature of the cold water from municipal water pipeline and $T_{c,out}$ is the water temperature exiting the heat exchanger. The variable $T_{h,in}$ is the inlet warm water from the sewage, and $T_{h,out}$ is the outlet sewage warm water after it has passed through the heat exchanger [19].

$$Q_{max} = C_{min}(T_{h,in} - T_{c,in}) \tag{3}$$

where C_{min} is the minimum heat capacity value between the heat capacity of the cold water (C_c) and the heat capacity of the hot water (C_h),

$$C_c = m_c C_{p,c} \tag{4}$$

$$C_h = m_h C_{p,h} \tag{5}$$

The outlet temperatures after the heat transfer has taken place are determined by

$$Q_c = C_c(T_{c,out} - T_{c,in}) \quad (6)$$

$$Q_h = C_h(T_{h,in} - T_{h,out}) \quad (7)$$

where Q_c is the heat transferred to the cold water and Q_h is the heat transferred from the hot water.

Equations 6 and 7 can be rearranged to determine the $T_{c,out}$ as illustrated in Equation 8 and to understand how much heat can be transferred for other applications. If a combination system is considered that uses two heat exchangers, then it is possible to calculate the outlet temperature of the municipal water from the first heat exchanger using Equation 8 to calculate the heat transferred through the second heat exchanger. In addition, Equation 9 can be used to determine the heat content of the outlet heat exchanger water temperature and weather it can be reused to capture more heat.

$$T_{c,out} = T_{c,in} + \frac{Q_{max}}{C_c} \quad (8)$$

$$T_{h,out} = T_{h,in} + \frac{Q_{max}}{C_h} \quad (9)$$

A typical problem in the analysis of a heat exchanger is the performance calculation. Given the inlet conditions to evaluate how the exchanger performs, and determining the outlet temperatures. Using Equation 1, the solution may be reached only by trial-and-error. An alternate approach is the notion of heat exchanger effectiveness, *E*, as outlined in Equation 10.

For this study it is assumed a 100% heat transfer, making the effectiveness factor a value of one. This is done so to simplify the calculations and by varying the effectiveness value would require further analysis. The purpose of this study is to show the other available options of heating water to reduce the use of natural gas to heat water.

$$E = \frac{actual\ heat\ transfer}{maximum\ possible\ heat\ transfer} = \frac{T_{h,in} - T_{h,out}}{T_{h,in} - T_{c,in}} \quad (10)$$

3. Results and Discussion

In this paper, a set of fixed variables, identified in Table 1, are used to determine the outlet municipal water temperature as it passes through the conventional tank water heater using natural gas. The results in Table 2 show that approximately 2.85 GJ of energy, equivalent to about 80 m^3 of natural gas, is required to heat the 13,627 L (3,600 gallons) of water per day. This results in an annual natural gas cost of $6,567.

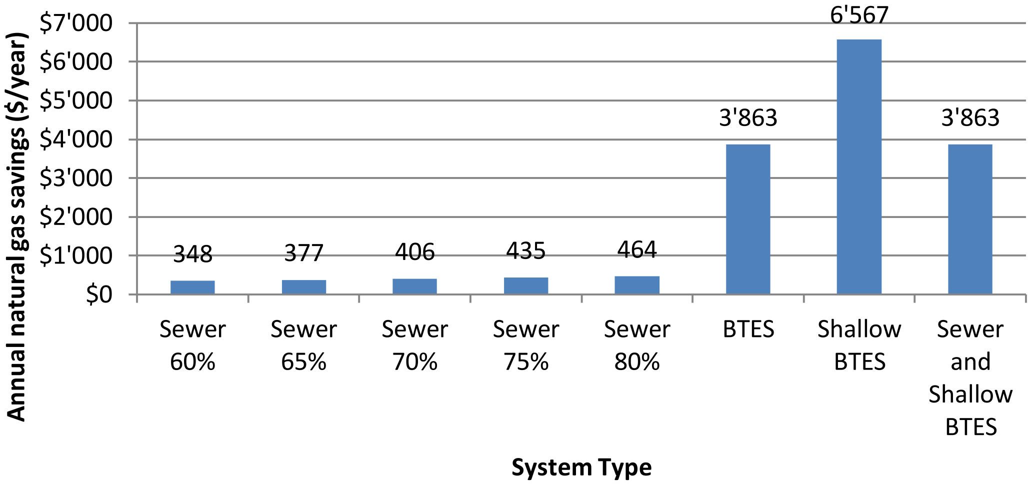
The results in Table 2 show the daily natural gas usage for the tank water heater. As it is expected, for cases where the water is preheated before entering the tank water heater, less natural gas is used to heat the water to the user’s required temperature (49°C). The annual natural gas cost is calculated based on the natural gas cost per cubic meter in southern Ontario. The following column shows the annual natural gas cost savings resulting from pre-heating the municipal water.

Table 2: Results from the analysis.

Description	Temperature range (°C)	Heat exchanger efficiency (%)	Water entering the water heater $T_{c,in}$ (°C)	ΔT (°C)	Daily energy usage $Q_{in\ eff}$ (GJ)	Natural gas mass equivalent (m^3)	Annual natural gas cost ($/year)	Annual natural gas cost savings ($/year)
Natural gas powered domestic hot water tank	15 - 49	0	15	34	2.85	80	$6,567	$0
Heat recovery from sewer waste water	15 - 18	80	17	32	2.56	75	$6,219	$348
Shallow borehole geothermal system	15 - 35	100	35	14	1.17	33	$2,704	$3,863
UOIT borehole geothermal system	15 - 49	100	NA	0	-	0	$0	$6,567
Combination of sewer waste water and shallow borehole	15 - 49	100	35	14	1.17	33	$2,704	$3,863

It is shown in Table 2 that the water coming out of the heat exchanger is calculated to be 17°C. The amount of saved energy using this method is approximately 0.29 GJ with annual savings of $348 in natural gas. The natural gas cost savings are outlined in Figure 8 for each system. It is notable that the shallow BTES system results in the highest annual natural gas savings. It is also noteworthy to observe the incremental savings in the different heat exchanger efficiencies for the sewer system.

Figure 8: Annual natural gas cost savings.



The cost of this simple sewage heat exchanger system is typically around $8,000 [20] and it is possible to calculate the rate of return on investment using a simple payback period method through the calculation of an Internal Rate of Return (IRR). IRR is a rate of return used in capital budgeting to measure and compare the profitability of investments. Accounting for the natural gas savings, the payback period is calculated to be approximately 17 years. However, this payback period decreases as the efficiency of the heat exchanger increases. The optimal point, when comparing heat exchanger efficiency and sewage water temperature in this study, is 80% heat exchanger efficiency and 26°C sewage water temperature. In this case, the simple payback period reduces from approximately 17 to 5 years.

Figure 9 displays the annual natural gas cost for heat exchanger efficiency that is between 60%-80% and various sewage water temperatures based on the maximum allowable discharge temperatures set by the municipalities. Figure 9 show the variation of the annual natural gas cost with heat exchanger efficiency. The higher heat exchanger efficiencies result in higher energy savings and lower natural gas consumption and CO_2 emissions. With higher heat exchanger efficiency, the water leaving the heat exchanger is at a higher temperature requiring less natural gas for the additional heat top-off. Similarly, as the sewer water temperature increases, more savings are observed. Figure 10 shows the daily natural gas energy required for heat top-off after the heat recovery for the sewage system. The heat top off is necessary as the municipal water temperature should reach 49 °C to meet the user needs and the sewer system alone is not capable of heating the water to this temperature.

Figure 9: Variation of annual natural gas cost with swage waste water temperature and sewer heat exchanger efficiency ranging from 60 - 80%.

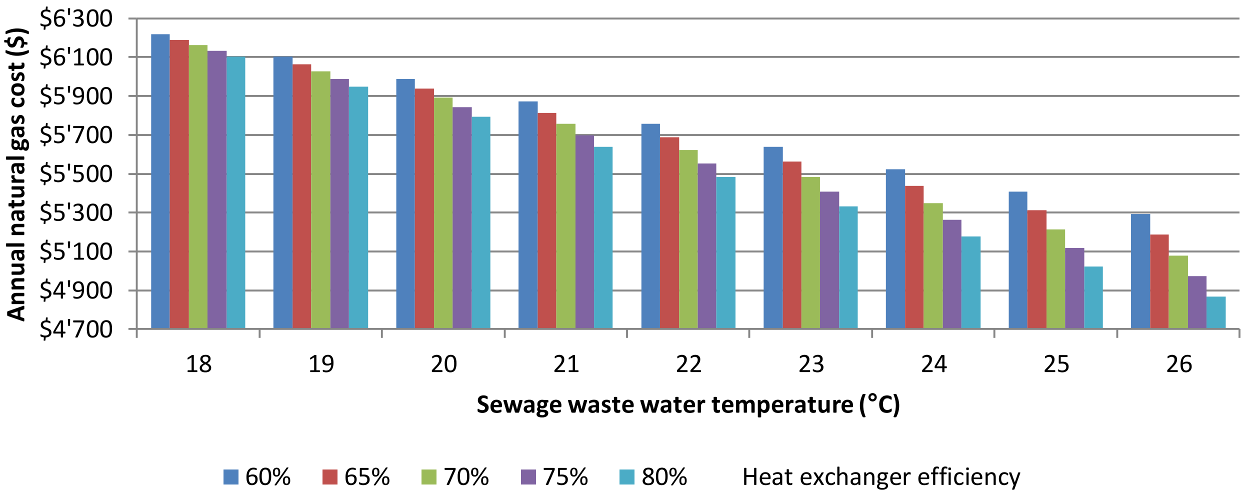


Figure 10: Sewer heat exchanger efficiency ranging from 60 - 80% and daily natural gas energy usage.

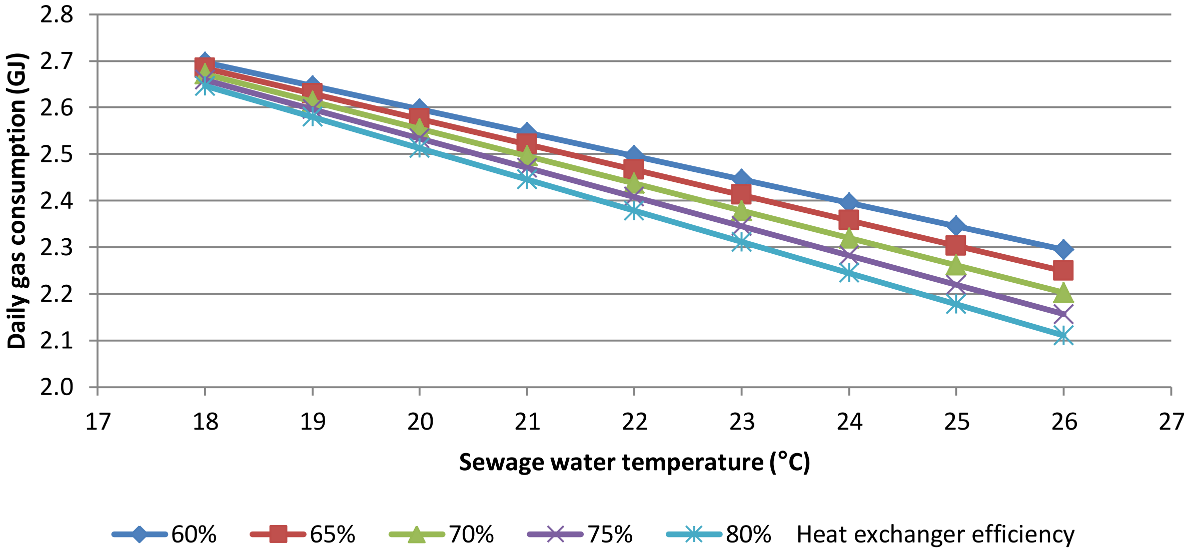


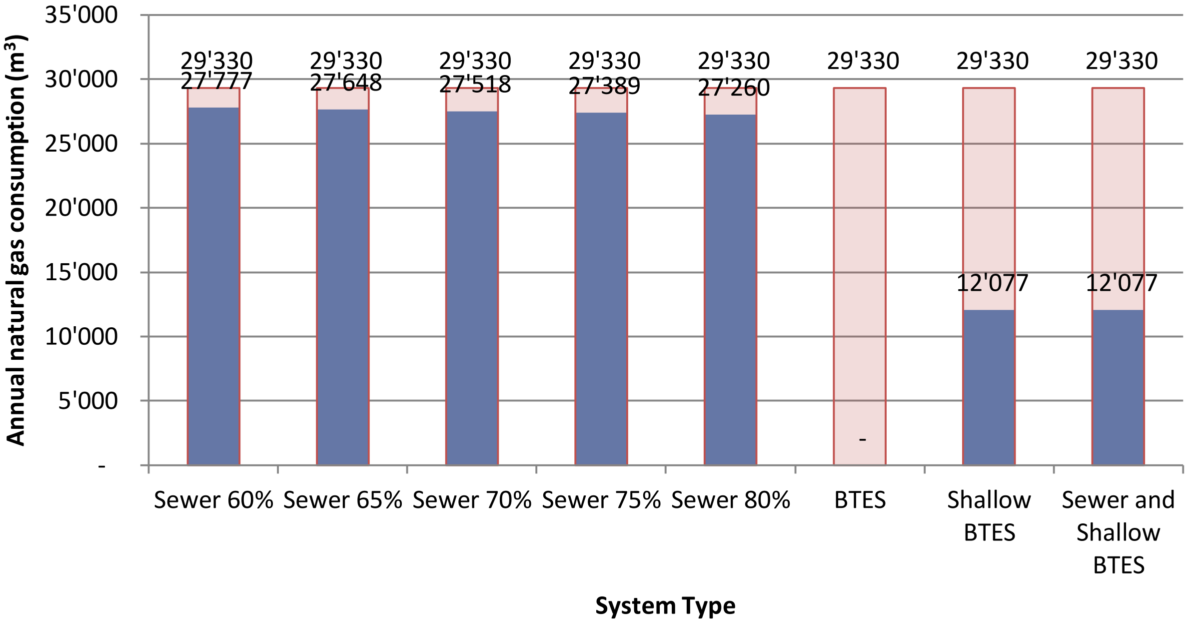
Table 2 also shows the results for the UOIT BTES system. As it is observed, no top-off heat is required, as the system is capable of producing enough heat to bring the municipal water temperature to the desired 49°C. Thus, an annual savings of $6,567 and prevention of 2.85 GJ/day energy of natural gas is achievable. Although this may appear to be an ideal system, the cost of this system is relatively higher as compared to the other systems and is approximately $7,000,000 [21] and would take approximately over 100 years to pay back initial cost based on only natural gas usage costs.

In Table 2, it is shown that the shallow ground source BTES system can increase the municipal water temperature to 35°C by recovering heat from the underground source using heat pumps. The annual Natural Gas cost is $2,704 and, for the 13,627 L (300 gallon) of water use per day application, the typical cost is approximately £11,000 to £15,000 ($20,000 – $27,500 CAD) [22] with a rate of return of approximately 6 years on this investment.

Lastly, in Table 2, natural gas cost/savings and temperatures of municipal water entering the heat exchanger are displayed for the combination of sewer heat exchanger with a shallow ground source BTES. It is shown that the annual natural gas cost for this system is similar to the shallow ground source BTES system at $2,704. The municipal water from the sewage heat exchanger enters the shallow BTES heat exchanger at 17 °C bringing the municipal water temperature up to the 35 °C before entering the water heater for additional heat top-off. It is notable that in this calculation, only the initial investment cost has been considered. This setup is a combination of both sewer heat exchanger and the shallow ground source BTES with a total investment cost of approximately $35,000. The payback period can be calculated to be approximately 8 years.

Figure 11 summarizes the annual natural gas usage as outlined by the blue bars, for each system and for the combination of the systems in comparison with the traditional domestic hot water system with no preheating system. The pink bars are the total natural gas usage for the traditional domestic hot water system. The difference is the savings in natural gas by using the municipal water preheating systems.

Figure 11: Annual natural gas usage per system compared to traditional natural gas domestic hot water method.



4. Conclusions

The benefits of utilizing waste heat and ground source heat as a means to improve the economic performance and to reduce CO_2 emissions has been analysed. Each system showed potential significant energy savings economically. Furthermore, energy savings would help prevent greenhouse gas emissions into the atmosphere. The energy recovery systems considered in this paper were the sewage warm water heat recovery, borehole thermal energy storage system and a shallow borehole thermal energy storage system. Each system was analysed and compared to the traditional natural gas powered water heating systems currently used in homes.

The costs of each system were obtained from various sources and, using only the natural gas savings from each system, a simple payback period had been calculated. The sewage system appeared more economical with higher heat exchanger efficiency and higher sewage water temperature. Although the combination system showed a faster rate of return on investment using the simple payback period method, it was also more costly as compared to the sewer heat exchanger system as an initial investment.

The borehole thermal energy storage system showed no natural gas usage, making it the most environmental beneficial when compared to the other systems in this analysis. When considering the economic factors only, the sewer system is considered as a sustainable and readily available system. This is due to readily available sewer in most areas where the heat exchanger unit can be installed with minimal labour and construction costs.

Acknowledgments

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Conflict of Interest

The authors declare no conflict of interest.

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