ACHIEVING ENERGY EFFICIENCY VIA HEAT RECOVERY FROM BUILDING SCALE WATER RECYCLING SYSTEMS

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ABSTRACT

With rising populations, challenges arise to meet water and energy demands. Reducing both water and energy consumption is possible to achieve on a building-scale through graywater or wastewater reuse and heat recovery with heat exchangers. The purpose of this study is to understand the energy use involved to apply wastewater reuse within a multi-residential scale building, with a particular focus on the impact of heat recovery from wastewater on the total energy requirements. This was done by analyzing the energy requirements for treating and supplying municipal water (including energy to treat wastewater) and treating graywater or wastewater on-site under different scenarios of heat recovery. Graywater was found to have lower energy requirements in a multi-residential building compared to conventional water supply, while wastewater reuse had higher energy requirements. Pairing water reuse with heat recovery showed energy savings for all graywater and wastewater scenarios evaluated.

INTRODUCTION

The treatment and supply of fresh water and the collection and treatment of wastewater are energy intensive processes. Water and energy are closely interrelated, and this realization has only grown in importance. Efforts are underway to include water and energy in research as outlined by the Department of Energy's Energy-Water Nexus (Bauer, 2014). One of the research areas identified is reuse of wastewater including recovering heat from wastewater. This can be done from the building to municipal scale, and little work has been done to determine the most appropriate scale.

There is a potential to conserve both water and energy by treating and reusing graywater or wastewater (GW or WW) at the site of a building. GW excludes blackwater, i.e. wastewater from toilets and kitchens, but can be collected from showers, baths, bathroom sinks, and laundry (Boyjoo, 2013). GW can also be divided into light and heavy GW, where light GW contains fewer contaminants, and includes bathroom GW (Boyjoo, 2013).WW encompasses all water leaving a building, including GW and blackwater. When building scale water recycling systems are coupled with heat recovery, there is potential to reduce building energy use. Water has a high specific heat capacity and density, and as a result has a high potential of energy to be used, or exergy (Meggers and Leibundgut, 2011).

Reusing wastewater is beneficial in reducing the consumption of freshwater and treated wastewater can be used to meet non-potable demands (e.g. toilet flushing and irrigation). This reduces the amount of freshwater supplied to a building and subsequently discharged to wastewater treatment. This practice has the potential to reduce energy for utility companies because about 80% of the costs of a utility company to supply and treat water are from using electricity (Bauer, 2014). Reusing wastewater has potential to be cost effective within a building as well and requires less infrastructure than municipal scale water reuse. Studies have looked at the effectiveness of different onsite GW and WW treatment and reuse systems. A study done by Xue et al. (2016) compared the conventional systems to different GW and blackwater diversion or reuse systems and their impacts on energy, greenhouse gases, and eutrophication by using Life Cycle Assessment.

GW and WW both have heat embedded within them, particularly when collected at the building scale and both are common water sources for on-site reuse. In this study, the energy embedded within the treatment, reuse, and heat recovery processes on-site will be compared to energy that would be required to supply water and treat resulting wastewater via conventional, centralized approaches. The objective of this study was to assess energy from the following wastewater systems: Building scale with conventional municipal treatment without wastewater reuse, building scale with bathroom graywater and wastewater reuse, and building scale with bathroom graywater and wastewater reuse and heat recovery. We hypothesized that when building wastewater is collected and reused on-site in systems where heat from the wastewater is recovered, building scale water recycling systems offer energy savings compared to conventional water delivery and wastewater treatment. Additionally, scale of heat recovery from wastewater has an impact on the temperature of water collected and the efficiency of heat recovery and reuse systems and there exists an optimal scale to achieve energy efficiency.

MATERIALS AND METHODS

Graywater and Wastewater Reuse

This study looked at GW/WW reuse at the multi-residential scale. The selected scales for a multi-residential building were 100 and 200 unit building(s) with the assumption of 2.5 residents per unit. Water usage was assumed to be 58.6 gallons per day (gpd) (DeOreo et al., 2016). It was also assumed that water consumption would not change as a response to GW/WW reuse. Consumptive water use, where water is not returned to the system, was considered negligible. The treated and reused water would be applied to toilets. The percentage of water used to flush toilets in an average household is 24% (DeOreo et al., 2016), which was used to calculate the amount of water that could be reused. For the 200 unit buildings, the volume of water reused is 7000 gpd, and for the 100 unit buildings this amount is 3500 gpd. The values for energy of water supply/wastewater treatment were used to calculate total energy required at the multi-residential building because even with GW/WW reuse, there is still a need to supply freshwater and treat outgoing wastewater that is not reused. The scenarios evaluated were 100 unit building with water supply energy compared to that of an average WWTP, 100 unit building with energy compared to that of a large WWTP, 200 unit building with average WWTP, and 200 unit building with large WWTP. In each of these four scenarios, the different water reuse scenarios were conventional (no reuse), GW reuse, and WW reuse.

To estimate potable water supply energy, both pumping and treatment had to be considered. The values for energy used for the calculation were from the report by Arzbaecher et al. (2013). The values for the WWTP were assuming medium (on a low, medium, high scale) pumping efficiency (Arzbaecher 2013). In Table 1, the energy estimations for municipal water supply and wastewater treatment are listed.

Table 1. Energy Values for Water Treatment

Type of Water Treatment	**Treatment System Capacity**	**Energy Required (kWh/th gal)**
Water Supply[1]	Low capacity, higher energy	1.9[a]
	High capacity, lower energy	1.4[b]
WWTP	50 MGD	1.78[2]
	130 MGD	1.6[3]
GW –sand filtration, UV disinfection[4]	1000 gpd	3.4
WW – membrane bioreactor[5]	30000 gpd	6.0

[1]Table 4.5 Arzbaecher 2013. [a]Average without CA Energy Commission Report [b]1996 EPRI Report [2]Table 5.3, Arzbaecher 2013:Average of 80 and 20 MGD [3]Table 5.1 Arzbaecher 2013: Energy Use from Average flow of 101-330 MGD [4]Hodgson 2012. [5]Horvath personal communication, 2016

Energy from graywater treatment and reuse was calculated by using data from Hodgson (2012). The scale used by Hodgson was a 1000 gpd system, which is smaller than the scale used for this model. The value of 3.4 kWh/ th gal was still used, although this is a conservative assumption. Generally, with increasing scale, the energy per volume treated either decreases or stays the same, due to the economy of scale (Arzbaecher, 2013) With more advanced treatment systems that include biological or membrane treatment, there would likely be a greater amount of energy needed to treat GW. Energy for on-site wastewater treatment was calculated by obtaining a best fit average energy requirement by using a small membrane bioreactor from many different scales ranging from 1000 gpd -30000 gpd (Horvath personal communication, 2016).

Heat Recovery

Given the temperatures of the wastewater and the municipal inflow, which were taken from literature, we can estimate the potential for heat recovery using the formula from Lienhard and Lienhard's textbook:

$$Q = \dot{m}C_p(T_{out} - T_{in})$$

where:

Q = rate of heat transfer (J/s)
m = mass flow rate (g/s)
C_p = heat capacity of water (J/gK)
T_{out} = temperature of gray/wastewater (K)
T_{in} = temperature of influent freshwater (K)

This equation was used first to find the rate of heat transfer for wastewater. The temperature of the municipal water varies in Denver throughout the year, but is estimated to be about 10˚C average. The final temperature the wastewater was cooled down to in the model was 12˚C. This value was chosen because it was close to, but still above the municipal water temperature, so there is still heat potential in the wastewater at that temperature. The rate of heat transfer was then used to find the final temperature of the freshwater with the heat transfer. With the input and output temperatures for both the wastewater and freshwater, we used the temperatures to find the Log Mean Temperature Difference.

The Logarithmic Mean Temperature Difference is given by the formula from Lienhard and Lienhard's textbook:

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

where:

ΔT_1 = T Hot In – T Cold Out
ΔT_2 = T Hot Out – T Cold In

Ultimately, to find the heat transfer rate between the wastewater and freshwater, we would need to use the formula for the overall heat transfer coefficient (Lienhard and Lienhard 2012):

$$\dot{Q} = UA\Delta T_m$$

where:

Q = heat transfer rate (Watts)
U = overall heat transfer coefficient (W/m^2K)
A = heat exchanger area (m^2)
ΔT_m = Logarithmic Mean Temperature Difference (Kelvin)

The A value was $1.2ft^2$, which was given by a tube from Standard Xchange. Standard U values were obtained from Engineering Toolbox (http://www.engineeringtoolbox.com/heat-transfer-coefficients-exchangers-d_450.html). The lowest and highest U values in the range from Engineering Toolbox were used for a shell and tube heat exchanger with liquids on the inside and outside of the tubes. The final Q value was in Watts, and was converted first to kW, then multiplied by 24 to get kWh for the energy savings per day.

The heat recovery scenarios analyzed were recovering heat from bathroom GW (showers, bath, sink) from the whole building, and WW from the building. Bathroom GW was selected because it had the high temperatures and highest flow per day. Kitchen WW and Laundry GW had higher temperatures, but significantly less flow per day. The average temperature for bathroom GW was used (26.9˚C) (The National Academies, 2015), and the average temperature for WW was calculated (22.1˚C) (Natural Systems Utilities, 2014).

RESULTS

Graywater and Wastewater Reuse

The energy to treat and reuse GW and WW at the 200 unit multi-residential building is shown in Figure 1 below. With the conventional system, no water is reused, but there is also no energy expended for on-site treatment. The smaller water supply and WWTP require more energy to treat water.

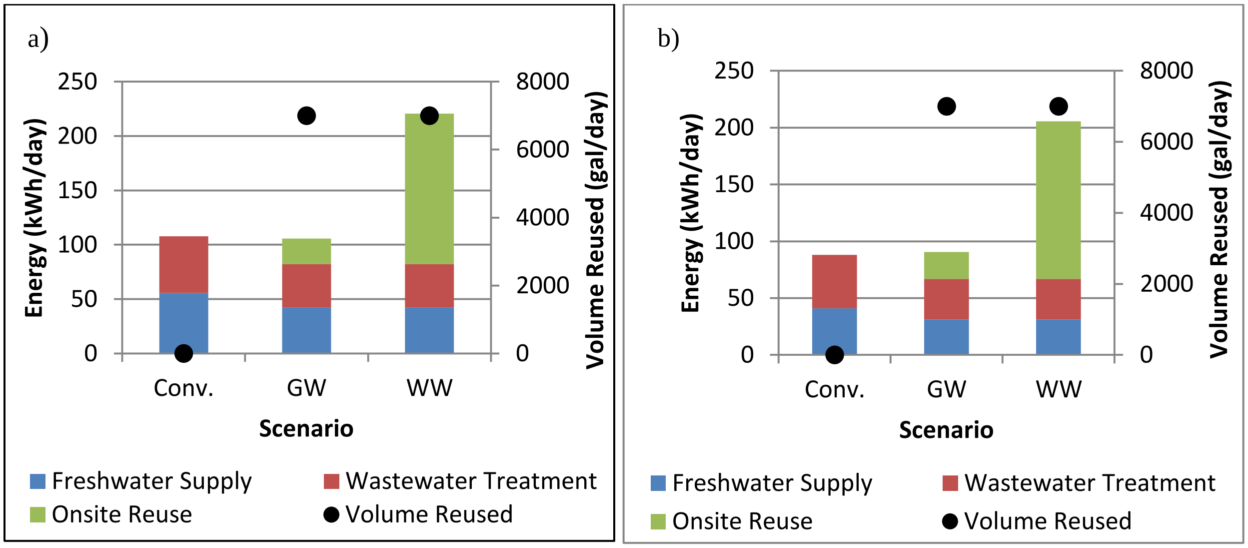

Figure 1. GW and WW reuse in a 200 unit multi-residential building a) Comparing GW and WW reuse energies to average water supply energy and 50 MGD WWTP and b) Comparing GW and WW reuse energies to low estimate water supply energy and 130 MGD WWTP.

Approximately 7000 gpd is required for flushing toilets at this scale, so the amount of GW/WW possible to reuse is 7000 gpd for this model. Reusing GW on-site requires less energy as conventional water systems for a medium sized WWTP.A large WWTP, for example the size of the one in Denver, is more energy efficient than reusing on-site because it treats a large quantity of water per day and it takes less energy to treat on per gal basis compared to a smaller facility. A 100 unit complex gives similar comparative energies and is shown in Figure 2 below.

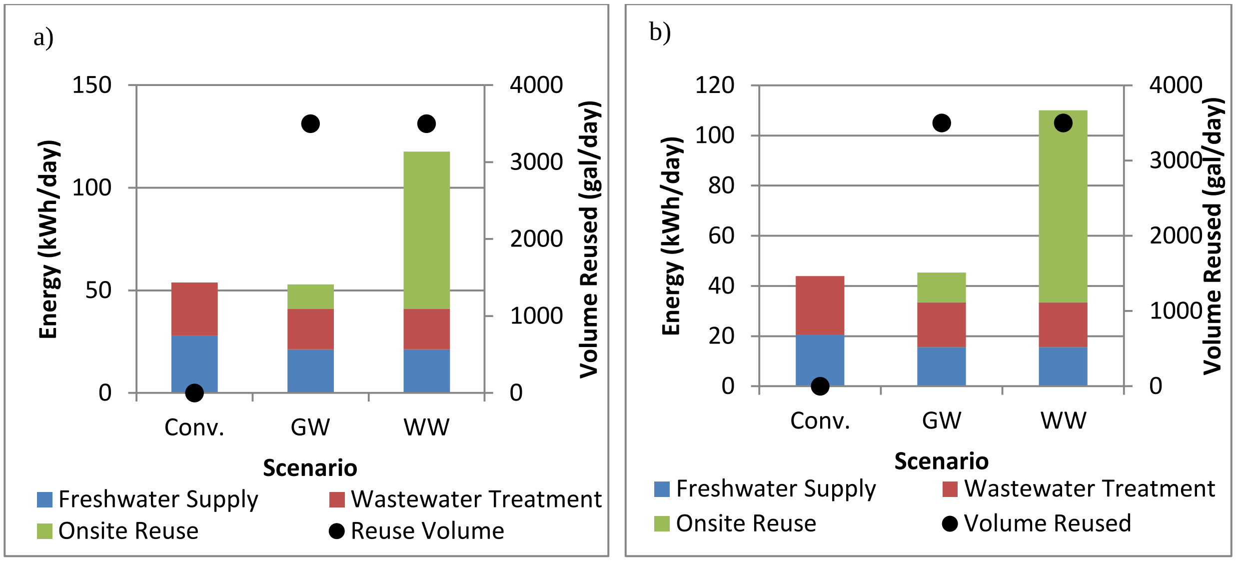

Figure 2. GW and WW reuse in a 100 unit multiresidential building a) Comparing GW and WW reuse energies to average water supply energy and 50 MGD WWTP and b) Comparing GW and WW reuse energies to low estimate water supply energy and 130 MGD WWTP.

The multi-residential unit with 100 units requires less energy overall for supply. Like the 200 unit complex, it takes slightly less energy to reuse GW when the WWTP is smaller. The amount of water reused is half that of the 200 unit building.

Heat Recovery

The heat recovery scenarios considered were recovering bathroom GW (shower and sink) from the entire multi-residential building and WW from the entire multi-residential building. The 200 unit scale multi-residential building was considered because there is a greater potential for heat recovery in the 200 unit building because of the higher volume. The energy savings in Figure 3 below are from a heat exchanger with high U (overall heat transfer coefficient) value estimation.

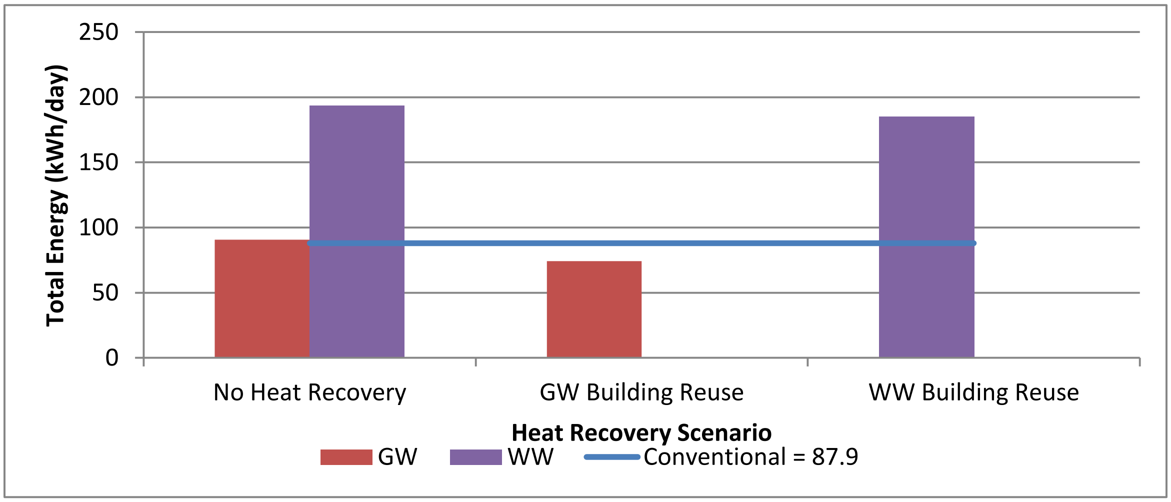

Figure 3. Comparison of Energy requirements with and without heat recovery.

The line is the energy for conventional water systems (no reuse) and without heat recovery. There is a decrease in the overall energies needed for each scenario when heat recovery is applied. The low energy estimation of GW reuse is the only scenario that would require less energy than conventional water treatment systems. Of note is that this study assumed a simple, low energy treatment system for graywater treatment. A higher U (overall heat transfer coefficient) in the heat exchanger translated into greater energy savings (8-23 kWh/day) for heat recovery of GW. The graph shows the highest possible energy savings of 23 kWh/day for GW and 9 kWh/day for WW.

DISCUSSION

These results suggest energy savings potential particularly in GW reuse and heat recovery. GW reuse has the potential to save energy with an average sized WWTP (50 MGD) compared to the larger WWTP (130 MGD). The higher energy demand of the smaller WWTP makes reusing GW on-site more favorable. The 100 unit multi-residential building requires less energy for water supply and wastewater treatment overall because of the smaller water demands. However, the energy savings by using GW (low energy estimate) are about 1 and 2 kWh in the 100 and 200 unit multi-residential building respectively. These energy savings may not be convincing enough to consider GW reuse unless water conservation is a strong driver in addition to energy conservation.

Wastewater reuse was found to be a more energy intensive process than graywater reuse. Treating blackwater to levels where it is safe for reuse, particularly with toilet flushing, requires extensive treatment because of the proximity to humans when it is reused. Membrane bioreactors are not the only WW treatment systems, so more studies on the energy requirements for other WW treatment systems, as well as membrane bioreactors would be beneficial in understanding WW treatment overall.

Graywater is likely a better option for heat recovery because it has a higher temperature on average. The bathroom GW (shower, sink, bath) which was used in the scenario was assumed to have an average temperature of 26.9˚C compared to the average WW temperature, assumed to be 22.1˚C. The higher temperature allows for a greater amount of heat to be exchanged. Graywater reuse was found to be promising for reducing energy consumption in the study by Xue et al (2016). In the study, the graywater was reused for irrigation and washing, and was combined with blackwater biogas electricity generation. These were the most energy efficient methods compared to conventional water treatment and GW/blackwater septic system scenarios (Xue et al., 2016). The graywater treatment system assumed for this study was a low energy system, and if another filtration and treatment method is used, it could potentially have higher energy requirements which could make conventional water treatment systems have the lowest energy. To make stronger conclusions, more research is needed. There are many different methods for filtration and disinfection of graywater, and the intensity of treatment depends on the source and the application of reuse. Only light GW was considered in this study, and only for toilet reuse. Less energy may be required to apply this GW to drip irrigation. Laundry GW, though having high concentration of detergent, could potentially be directly applied to irrigation.

The hypothesis evaluated for this study was supported. There is energy savings potential for implementing heat recovery in building scale water reuse systems. The use of heat exchangers in the model showed energy savings from the heat in GW/WW. The high volume of water from the building also has a greater amount of heat that can be recovered (Meggers and Leibundgut, 2011). Other studies have shown similar results. One study found that colder incoming freshwater requires more energy from water heaters, and implementing heat recovery would have a greater margin of savings compared to warmer incoming freshwater. This is because using heat exchangers to preheat cold, incoming freshwater results in less energy needed to heat the water the rest of the way by the water heater (Eslami-nejad and Bernier 2009). There is a study that was done by Michigan State on shower heat exchangers where water from the drain preheats the water to the shower head (Barthkowiak et al., 2009). This can be an effective method because it requires less energy from the water heater and negates the need to pump hot water to the shower. When fouling and other application problems improve, this may be a viable method of energy savings within a building.

For this model, a low energy GW system was used, and the amount of water that was reused was conservative. More GW/WW could be treated and reused and applied to irrigation as well to save more water. Despite the promising results of water conservation and heat recovery, more research is needed. GW/WW reuse systems are not widely implemented, and they have their limitations due to cost, regulatory barriers for on-site GW/WW reuse, and public view of these non-conventional systems. As these systems are implemented, it is necessary to report the energy requirements so communities can make more informed decisions if energy and water savings is imperative.

ACKNOWLEDGEMENTS

I would like to thank the National Science Foundation and the Urban Water Innovation Network for the opportunity and the funding for this research from the grant CBET-1444758. I would like to thank the graduate students of my mentors, Brock Hodgson and Hongshan Guo for helping in the research process.

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