



Modelling of Wastewater Heat Recovery Heat Pump Systems

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Cite as: Smith, N. R., Henze, G. P., Modelling of Wastewater Heat Recovery Heat Pump Systems, J. sustain. dev. energy water environ. syst., 9(1), 1080330, 2021, DOI: <https://doi.org/10.13044/j.sdewes.d8.0330>

ABSTRACT

Wastewater heat recovery is currently an underutilized technology that could be part of solving the climate crisis. A large portion of the heat that leaves a building in the form of wastewater is potentially recoverable for pre-heating domestic hot water or other service water systems. While there are several different approaches to wastewater heat recovery, this project focused on creating detailed, integrated building models for wastewater heat recovery heat pump systems. EnergyPlus models were developed featuring inputs and assumptions corresponding to manufacturers' specifications, performance lab test data and feedback from engineering consultants. EnergyPlus's supervisory control Energy Management System objects were heavily relied upon to overcome modelling challenges. The developed EnergyPlus model was integrated into U.S. Department of Energy New Construction Reference Building models for various climate zones and building types to assess potential energy use, energy cost and greenhouse gas emission reductions.

KEYWORDS

Wastewater heat recovery, Heat pump, Modelling, EnergyPlus.

INTRODUCTION

In October of 2018, the Intergovernmental Panel on Climate Change (IPCC) issued a dire warning to the world. If global warming is not limited to 1.5 °C relative to pre-Industrial Revolution levels, the effects to human and natural systems could be "irreversible" [1]. The IPCC report details that preventing global temperature increases above 1.5 °C will require "rapid and far-reaching" transitions in energy, industry, buildings and cities [1]. For this reason, engineers, scientists and policy makers are researching and analysing a plethora of solutions to reduce Greenhouse Gas (GHG) emissions.

One technology that is vastly underutilized in the building sector is Wastewater Heat Recovery (WWHR). WWHR has been the subject of a great deal of enthusiasm and study over the past several years. The River Network, a Colorado based environmental advocacy organization, estimated that 383 GWh of energy were used for water heating in

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the United States in 2005. It was also estimated that 204.9 million metric tons of carbon emissions were released associated with water heating [2].

Similarly, the U.S. Department of Energy (DOE) estimates that 350 GWh of hot water is lost to drains annually in the United States [3]. To put this last estimate in perspective, 350 billion kWh is roughly the amount of energy required to heat 7,088,000 Olympic-sized swimming pools from 10 °C to 27 °C. A large portion of the heat that leaves a building in the form of wastewater is potentially recoverable for pre-heating Domestic Hot Water (DHW) or other service water systems. While several drain water heat recovery technologies exist, this project focused on a wastewater heat recovery heat pump (WWHR-HP) system developed by a Canadian company. This WWHR-HP unit operates at the building level and is typically installed in facilities with large DHW usage rates, such as apartment buildings and hotels.

There were two main objectives for this research project. The first was to create a high-fidelity model of a WWHR-HP system using EnergyPlus (E+). Model fidelity is a measure of a computer models' ability to replicate reality. One potential factor in the current underutilization of this technology is the difficulty that stakeholders have in accurately predicting potential energy and energy cost savings for customers and/or financiers. By developing and demonstrating the value of high-fidelity WWHR models, practitioners will be more likely to include WWHR in early design sustainability charrettes. The second objective was to assess building types and climates that might be conducive to WWHR for DHW heating. The Department of Energy EnergyPlus Reference Building Model library was used to conduct feasibility assessments and allowed for heuristics to be developed as to what inputs are most critical to the economic and environmental viability of WWHR systems.

Prior to this project, no detailed, integrated building EnergyPlus model of a WWHR-HP system was known to exist. This conclusion was drawn following a literature review. It was hypothesized that a high-fidelity integrated building model could be developed and used to identify the potential climates and building types most well suited for WWHR from an economic and environmental perspective.

Literature review

In order to better understand the current state of the industry and establish the present gaps in academic knowledge, a literature review was conducted. Specifically, publications sought for review were those focusing on WWHR systems using heat pumps, raw sewage, EnergyPlus and operating at the building level rather than at the district level. Ultimately, a great deal of insight was gained from the wide variety of publications reviewed.

Ni *et al.* [4] investigated a novel residential grey water energy-recovery system using heat pumps and EnergyPlus. However, the heat pump studied was an air source heat pump and EnergyPlus was used exclusively to estimate building heating and cooling loads. A numerical model was used to estimate energy impacts in various residential home settings. This study did not feature a water source heat pump fully integrated into the building model like that proposed for this project.

Hepbasli *et al.* [5] provided a comprehensive review of wastewater heat pump system publications from across the globe as recent as 2014. The authors reviewed 33+ publications and summarized each source's methods, analysis types (energy, exergy, economic, environmental) and main conclusions. Only one of the 33+ studies explicitly used EnergyPlus for modelling. That study was the previously mentioned residential grey water energy-recovery system authored by Ni *et al.* [4].

Kahraman and Alaeddin [6] used an experimental setup like the one analysed in this study. The experimental data obtained from their measurements showed a mean uncertainty value of $\pm 2.47\%$ for the measurement parameters. The authors reported that

the heating Coefficient of Performance (COP) values were 3.36, 3.43 and 3.69 at the wastewater temperatures of 20 °C, 30 °C and 40 °C, respectively. It was also found that the maximum temperature in the energy storage tank was 50.6 °C. These insights served as good benchmarks for the computational models created for this project. It should be reiterated that while the wastewater heat pump setup was similar, no holistic building energy model was created that could be used in energy simulations.

Chao *et al.* [7] analysed the field performance of a WWHR-HP installed at a spa in Shenzhen, China. The authors pointed out that the volume, temperature and cleanliness of bath water captured at the building level is very different from wastewater at the district treatment plant level. The system evaluated by the author is very similar to the system that was analysed for this project, except for the type of heat pump heat exchanger and the cleanliness of the heat source water. The data collected found that higher wastewater temperatures correlated to higher COPs. Higher wastewater temperatures led to higher refrigerant temperatures at the evaporator inlet (17.9 °C, 16.6 °C, 14.8 °C) and led to COPs of 3.38, 3.01, 2.87, respectively.

Culha *et al.* [8] conducted a review of many wastewater heat pump/heat exchanger publications. Swiss researchers reported that more than 15% of the thermal energy supplied to buildings was lost through the sewer system. The review separated systems and equipment studied into broad classifications. According to these classifications, the WWHR-HP system investigated for this project is a “monovalent, domestic usage system with a shell-tube wastewater heat exchanger.” Of the 27+ papers that were reviewed, none were categorized as a shell-tube wastewater heat exchanger used in a domestic setting and none explicitly were noted as having created integrated holistic building models using EnergyPlus.

The 2017 publication by Zhang *et al.* [9] investigated the performance of an installed sewage source heat pump system in China. Located within a 15,000 m² hotel, the average COP of the heat pump was found to be 6.0 and the average COP of the overall heat pump system was found to be 3.9. The heat pump was used sewer water as a heat source and sink in order to meet both building heating and cooling loads. The payback period of the system was found to be 4.7 years. Two-thirds of the power consumed by the system was used by the heat pump, while the remaining one-third was used by the system pumps. This led to the recommendation that variable frequency drive pumps should be used to adjust to varying load conditions, resulting in energy and maintenance savings. The sewage inlet temperature correlated nearly linearly and was directly proportional to the COP of the heat pump.

Spriet and Henrick [10] investigated WWHR using heat pumps and sewer integrated heat exchangers in downtown Brussels, Belgium. The heat pumps used in the study featured a COP between 3.7 and 5.0 and the sewer wastewater temperature fluctuated between 8 °C and 16 °C when measured between December and April. Monte Carlo simulations were used to predict the levelized cost of energy and total equivalent warming impact. The WWHR-HP system reduced the total equivalent warming impact by 49% compared to a natural gas water heater, but also had a greater levelized cost of energy, except for high heating demand buildings.

In the publications reviewed, none of the research involved constructing a building integrated EnergyPlus model for a WWHR-HP system. Thus, the opportunity was available to test the hypothesis that such a model could be constructed.

Wastewater Heat Recovery Heat Pump background

Because WWHR using heat pumps is relatively new and with few installed instances at the onset of this project, a deeper dive into the physical components of the WWHR-HP and overall DHW production system is provided. The Canadian manufacturer of the

WWHR system that was analysed describes it as a self-contained thermal energy recovery system that is designed to produce DHW at high efficiencies [11]. The system heating capacity is available in several different sizes including 35,170 W (10 refrigeration tons, i.e., the T-10 unit), which was the unit used during lab performance testing. Table 1 displays greater detail about the T-10 unit.

Table 1. WWHR-HP T-10 specifications

Cabinet volume [m ³]	Approximate mass [kg]	Wastewater content [L]	Refrigeration type [-]	Refrigerant charge [kg]	Domestic water flow rate [L/s]
2.26	517	1,303	R134a	9.1	1.51

Lab test performance data

The T-10 unit manufacturer contracted an independent 3rd party to conduct performance testing on the WWHR-HP [12]. The testing involved supplying a constant wastewater temperature to the evaporator side of the heat pump and measuring the condenser side water heat transfer. The condenser and evaporator water flow rates were held constant. Five different constant wastewater temperatures were tested: 18 °C, 21 °C, 24 °C, 27 °C, 30 °C. The condenser water temperature was free to increase during testing. This water was circulated between the plate-frame condenser and a nearby tank. The heat pump COP was calculated as seen in eq. (1) [12]:

$$COP = \frac{\text{Condenser water heat transfer rate [W]}}{\text{Heat pump power [W]}} \tag{1}$$

Figure 1 displays the results from the five performance tests. As the difference between the wastewater temperature and the condenser water temperature increased, more work was required by the heat pump, which led to a decay in the heat pump COP.

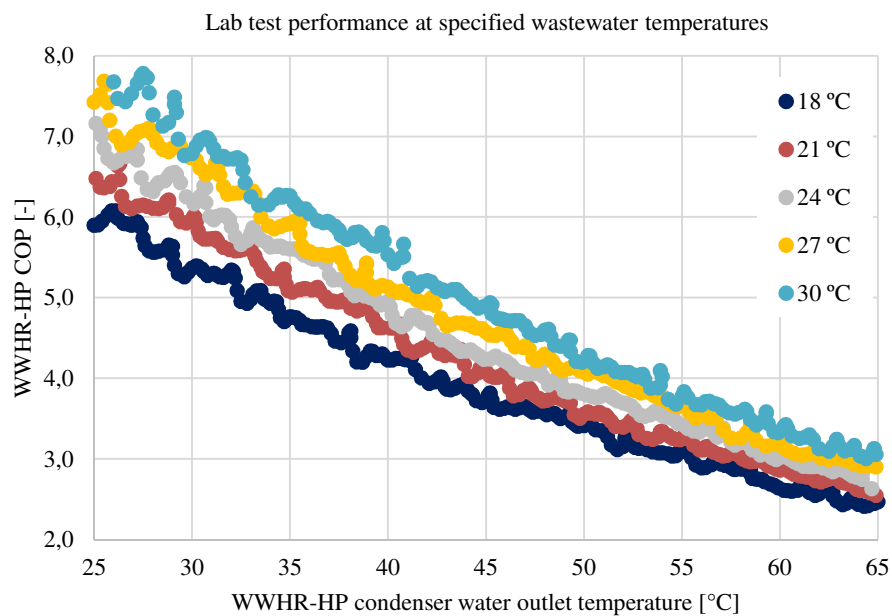


Figure 1. WWHR-HP lab test results

Typical Domestic Hot Water production system

The WWHR-HP unit is one of five components found in a typical DHW production system. The other components are: Domestic Pre-heated Water (DPW tank) storage tanks,

Wastewater storage tank (WW tank), Top-Off storage tanks (Top-Off tank) and Top-Off boilers. Figure 2 shows how a typical system might be connected.

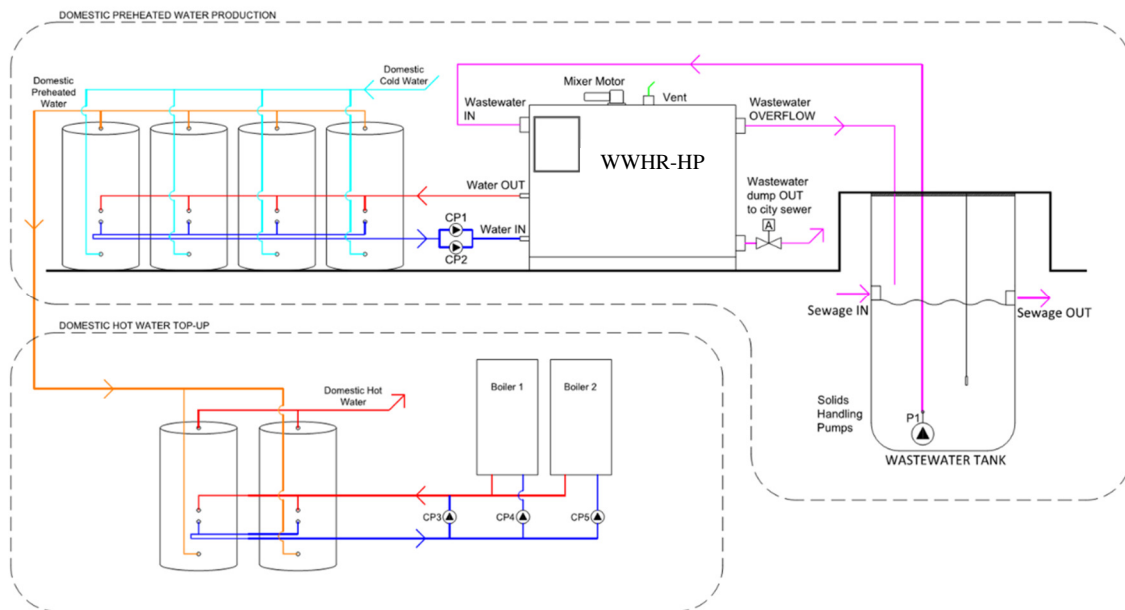


Figure 2. Typical setup of a WWHR-HP DHW system

Domestic pre-heated water tanks. The first stop for domestic water entering the system is the DPW tanks. Cold water from a well or city water main enters the bottom of the tank(s) and rises as it is heated. The EnergyPlus models assumed the tank(s) were fully mixed. This is likely a conservative assumption since most designs prefer water tank stratification so that the warmest water (closest to setpoint) can be drawn from the top of the tank. Water from the top of the DPW tanks then travels to the Top-Off tanks. Water is also circulated between the tanks and the WWHR-HP unit in order to heat the water.

Wastewater storage tank. According to the manufacturer, it is recommended that a 3,785 L tank be installed in conjunction with the T-10 unit. This storage tank (WW tank) receives wastewater from the building and holds it until it is drawn to the WWHR-HP unit or it overflows to the main sewer. The WW tank is sized large enough to fill the WWHR-HP internal heat exchanger tank and still have reserve wastewater available, as well as provide a large enough heat reservoir for the system. A solids-handling pump is installed at the bottom of the collection pit and uses float valves to control wastewater flow to the WWHR-HP.

Top-off tanks. The Top-Off tanks receive water from the DPW tanks and are connected to boilers to heat the water to a desired setpoint temperature. Similar to the DPW tanks, the tanks are assumed to be fully mixed. Building flow fixtures draw water from the tanks as it is demanded.

Boilers. The purpose of the boilers is to ensure that the DHW supplied to fixtures meets the temperature setpoint. While the WWHR-HP unit is capable of meeting a majority of a building's water heating load, varying wastewater temperatures, water consumption rates and other conditions require a supplemental heating system. Typically, the boilers are natural gas fired and heat the water to a minimum of 60 °C in commercial buildings in order to prevent water-borne diseases.

METHODS

All models were simulated using EnergyPlus version 8.8. EnergyPlus is an open source, holistic building simulation tool that features hundreds of pre-defined objects that can be used in sub-hourly energy calculations. The Input Data File (IDF) is where a user adds, deletes and connects the pre-defined objects. Development of E+ began in 1997 and over USD 80 million has been invested to date to make EnergyPlus as accurate, flexible and robust as possible for its approximately 43,000+ users [13]. E+ is an integrated simulation engine that solves thermodynamic state equations simultaneously rather than sequentially as with legacy software such as DOE-2 [14] (p 25). When a simulation is run, E+ calls upon modules to do calculations and pass outputs to other parts of the program. Branches, nodes and loops are used in energy and mass balance calculations.

Model inputs were based upon manufacturer provided drawings, references and other materials. E+ default input values were used when available and reasonable. Additional inputs were determined by consulting licensed engineering professionals at several design firms. The E+ heat pump object was calibrated using WWHR-HP manufacturer lab testing data and a publicly available EnergyPlus auxiliary calibration spreadsheet tool. As with any computer model, several key assumptions were made to simplify model formulation. These assumptions were made with high regard as to their possible impacts on model fidelity. These assumptions included the following:

- All pipes were modelled as adiabatic;
- Wastewater was modelled as pure water (i.e., no solids);
- Constant heat pump source (evaporator) water flow;
- Frictionless pipes;
- Linear water pump curves.

The DOE Reference Building feasibility case models were created by deleting the original DHW heating objects and replacing them with the T-10 unit model objects via a text editor. The original and modified model simulated energy use, energy cost and GHG emissions were used to determine if WWHR would be feasible in the given building type and climate.

EnergyPlus model description

Plant loops were created to best mimic the real-life behaviour of the WWHR-HP system. The formulation of this model was based upon the typical hot water production setup like that in Figure 2. In total, five plant loops were required to model the system. The plant loops were the: DHW loop, DPW loop, Top-Off loop, WW-HP loop, and WW-Water loop. The branch connection diagram for all five of these loops is seen in Figure 3.

Each plant loop can be broken into a supply and demand side. The supply side contains equipment that meets the heating or cooling load created by equipment on the demand side. The E+ Plant Manager simulates the demand half-loops simultaneously and then all the supply half-loops simultaneously and uses a series of complex integral functions and predictor/corrector equations to converge on a solution for each simulated timestep. Several of the most important governing equations are listed below. One should refer to the EnergyPlus Engineering Reference and EnergyPlus Input-Output Reference for more detailed information.

Loops. Heating or cooling demand that the supply half-loop serves (LoopDemand) is determined via eq. (2), where LoopSetPoint is the supply half-loop leaving water temperature setpoint, LoopTempIn is the supply loop entering water temperature, \dot{m} is the water mass flow rate and c_p is the specific heat of the loop water [14] (p 467):

$$\text{LoopDemand} = \dot{m} \times c_p \times (\text{LoopSetPoint} - \text{LoopTempIn}) \quad (2)$$

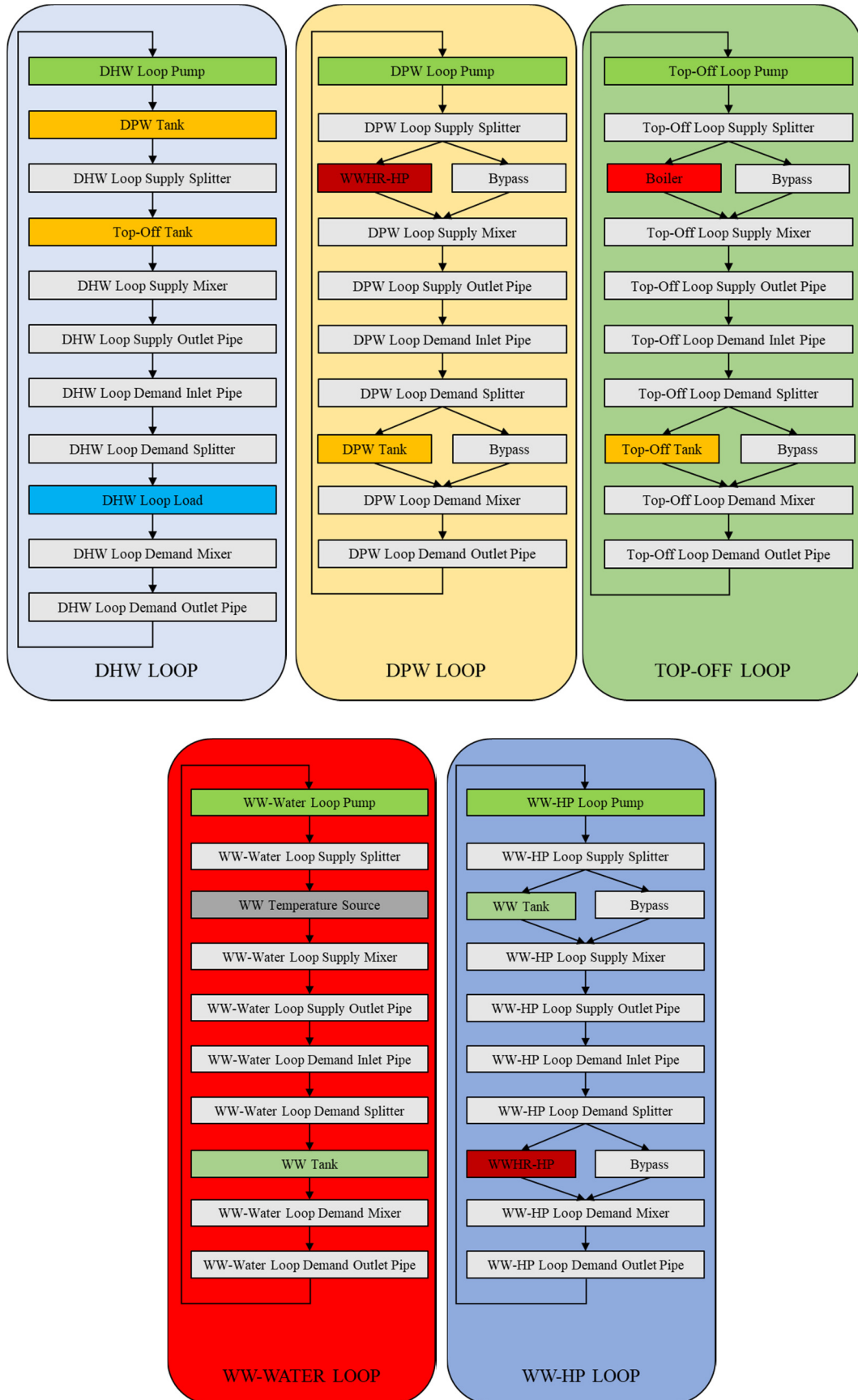


Figure 3. EnergyPlus model loop branch connection diagrams

Pumps. Each plant loop contains a circulation pump that was modelled as a variable speed pump. The pump is governed by eqs. (3-6) found in section 18.4.3 of the

EnergyPlus Engineering Reference [14] (p 1275). Each pump was modelled with $A_1 = A_3 = A_4 = 0$ and $A_2 = 1$ in order to produce a linear pump curve:

$$\text{FracFullLoadPower} = A_1 + A_2 \times \text{PLR}_p + A_3 \times \text{PLR}_p^2 + A_4 \times \text{PLR}_p^3 \quad (3)$$

The part load ratio (PLR_p), is the volumetric flow rate at a given timestep (VolFlowRate), divided by the E+ autosized maximum pump volumetric flow rate (NomVolFlowRate):

$$\text{PLR}_p = \frac{\text{VolFlowRate}}{\text{NomVolFlowRate}} \quad (4)$$

The loop water volumetric flow rate (VolFlowRate), is equal to the loop mass flow rate (PumpMassFlowRate), divided by the loop water density (LoopDensity). The LoopDensity is determined by E+ during the simulation via interpolating internal program fluid property tables:

$$\text{VolFlowRate} = \frac{\text{PumpMassFlowRate}}{\text{LoopDensity}} \quad (5)$$

The electric power consumed by the pump is a function of pump curve value (FracFullLoadPower), multiplied by the pump maximum power (NomPowerUse):

$$\text{PumpPower} = \text{FracFullLoadPower} \times \text{NomPowerUse} \quad (6)$$

Boiler. The natural gas fuelled boiler found in the Top-Off loop is governed by eqs. (7-9) [14] (p 718). The amount of natural gas consumed by the boiler (FuelUsed), is the heating demand calculated via eq. (2) (BoilerLoad), divided by the user-input thermal efficiency ($\text{NominalThermalEfficiency}$), and the boiler efficiency performance curve value ($\text{BoilerEfficiencyCurveOutput}$):

$$\text{FuelUsed} = \frac{\text{BoilerLoad}}{\text{NominalThermalEfficiency} \times \text{BoilerEfficiencyCurveOutput}} \quad (7)$$

The boiler efficiency curve is a biquadratic function with six coefficients. T_{water} is the boiler operating temperature:

$$\text{BoilerEfficiencyCurve} = B_1 + B_2 \times \text{PLR}_b + B_3 \times \text{PLR}_b^2 + B_4 \times T_{\text{water}} + B_5 \times T_{\text{water}}^2 + B_6 \times T_{\text{water}} \times \text{PLR}_b \quad (8)$$

The boiler part load ratio (PLR_b) is the boiler heating load (BoilerLoad), divided by the E+ autosized heating capacity (BoilerNomCapacity):

$$\text{PLR}_b = \frac{\text{BoilerLoad}}{\text{BoilerNomCapacity}} \quad (9)$$

Mixed thermal water tanks. The water tanks used in the model loops, including the WW tank, DPW and Top-Off tanks are thermodynamically governed by eqs. (10-14) as featured in section 20.3.1 of the EnergyPlus Engineering Reference [14] (p 1481). The tank energy balance is governed by the differential equation in eq. (10) with the tank water net heat transfer rate (q_{net}), being equal to the product of: the density of the tank water (ρ), the tank volume (V), the specific heat of water (c_p), and temperature variation with respect to time (dT/dt):

$$q_{\text{net}} = \rho \times V \times c_p \times \frac{dT}{dt} \quad (10)$$

The tank water net heat transfer is the sum of three components: the water entering the tank, the water leaving the tank, and the losses to the ambient environment. Eq. (11) is a simplification of the full E+ equation, which allows for the tanks to function as water heaters:

$$q_{\text{net}} = q_{\text{use}} + q_{\text{source}} + q_{\text{offcycloss}} \quad (11)$$

Eq. (12) and eq. (13) use the specific heat of water (c_p), the heat exchanger effectiveness (ε), mass flow rate of the water (\dot{m}), temperature of the entering water ($T_{\text{use}}/T_{\text{source}}$), and temperature of the tank water (T). The heat exchanger effectiveness was input as 1 for all tank use and source sides. The use-side water is the water entering the tank and the source-side water is the water leaving the tank:

$$q_{\text{use}} = \varepsilon_{\text{use}} \times \dot{m}_{\text{use}} \times c_p \times (T_{\text{use}} - T) \quad (12)$$

$$q_{\text{source}} = \varepsilon_{\text{source}} \times \dot{m}_{\text{source}} \times c_p \times (T_{\text{source}} - T) \quad (13)$$

The standby losses to the environment ($q_{\text{offcycloss}}$), are defined in eq. (14) and are equal to the product of the off cycle loss coefficient (UA), and the difference between the environment ambient temperature (T_{amb}), and the tank water temperature (T):

$$q_{\text{offcycloss}} = UA \times (T_{\text{amb}} - T) \quad (14)$$

Heat pump. The keystone object in the EnergyPlus model is the heat pump. Eqs. (15-18) are the heat pump object governing performance equations for each timestep of a simulation. These equations can be found in the EnergyPlus Engineering Reference guide [14] (p 1128). T_{ref} is specified to be 283.15 Kelvin per the EnergyPlus Engineering Reference guide equations. The heat pump model was developed by the University of Oklahoma State and is discussed in a 2005 master's thesis by Tang [15]. The heat pump equations and their inputs are elaborated on in the next section of this report:

$$\frac{Q_h}{Q_{h,\text{ref}}} = C1 + C2 \times \left(\frac{T_{L,\text{in}}}{T_{\text{ref}}}\right) + C3 \times \left(\frac{T_{S,\text{in}}}{T_{\text{ref}}}\right) + C4 \times \left(\frac{\dot{V}_L}{\dot{V}_{L,\text{ref}}}\right) + C5 \times \left(\frac{\dot{V}_S}{\dot{V}_{S,\text{ref}}}\right) \quad (15)$$

$$\frac{\text{Power}_h}{\text{Power}_{h,\text{ref}}} = D1 + D2 \times \left(\frac{T_{L,\text{in}}}{T_{\text{ref}}}\right) + D3 \times \left(\frac{T_{S,\text{in}}}{T_{\text{ref}}}\right) + D4 \times \left(\frac{\dot{V}_L}{\dot{V}_{L,\text{ref}}}\right) + D5 \times \left(\frac{\dot{V}_S}{\dot{V}_{S,\text{ref}}}\right) \quad (16)$$

$$Q_{\text{source},h} = Q_h - \text{Power}_h \quad (17)$$

$$\text{COP}_h = \frac{Q_h}{\text{Power}_h} \quad (18)$$

Heat pump coefficient estimation

The lab testing data provided by the T-10 unit manufacturer was used in conjunction with an EnergyPlus auxiliary program to estimate the values for coefficients C1-D5 [16]. The auxiliary program uses ordinary least squares and the Nelder-Mead optimization algorithm to determine the coefficients. These methods are based on research conducted at the University of Oklahoma State [15]. Coefficients C1-C5 and D1-D5 in eqs. (15-18) were calculated using all 1,080 observations obtained from the lab testing mentioned in the Introduction and seen in Figure 1. These are the initial coefficients values seen in Table 2 and Table 3.

Table 2. EnergyPlus heat pump coefficients for eq. (15)

	C1	C2	C3	C4	C5
Initial	1.51439831	-0.491629991	4.62356048	0	-5.2734375
Adjusted	-3.50792302	-0.491629991	4.62356048	0	0

Table 3. EnergyPlus heat pump coefficients for eq. (16)

	D1	D2	D3	D4	D5
Initial	0.43647803	3.89611258	0.64400684	-0.00781250	-5
Adjusted	-4.33286711	3.89611258	0.64400684	0	0

The $Q_{h,ref}$ and $Power_{h,ref}$ quantities in eq. (15) and eq. (16), respectively, were taken to be the largest condenser heat transfer rate (43,890 W) and compressor power draw (12,625 W) found in the lab testing data. These values were input into the auxiliary program and model as such. $\dot{V}_{L,ref}$ was taken to be the constant lab test data condenser flow rate, 0.00166 m³/s and $\dot{V}_{S,ref}$ was taken to be 0.00662 m³/s, the typical recommended T-10 wastewater solids handling pump flow rate.

As mentioned in the Lab Test Performance Data section of this manuscript, the condenser and evaporator side flow rates were held constant during testing. It was therefore deemed inappropriate to calibrate the heat pump object based on constant flow conditions to then simulate with potentially varying flow rates. To correct this inconsistency, the initial values of C4 and C5 were combined with C1. Coefficients C4 and C5 were then set to zero. This was repeated for the D coefficients. The adjusted coefficients can be seen in Table 2 and Table 3. Figure 4 displays the EnergyPlus heat pump performance using eqs. (15-18) with the adjusted coefficients overlaid on the original lab test data. The graph shows that the model's heat pump object is well calibrated to mimic the actual performance of the T-10 unit.

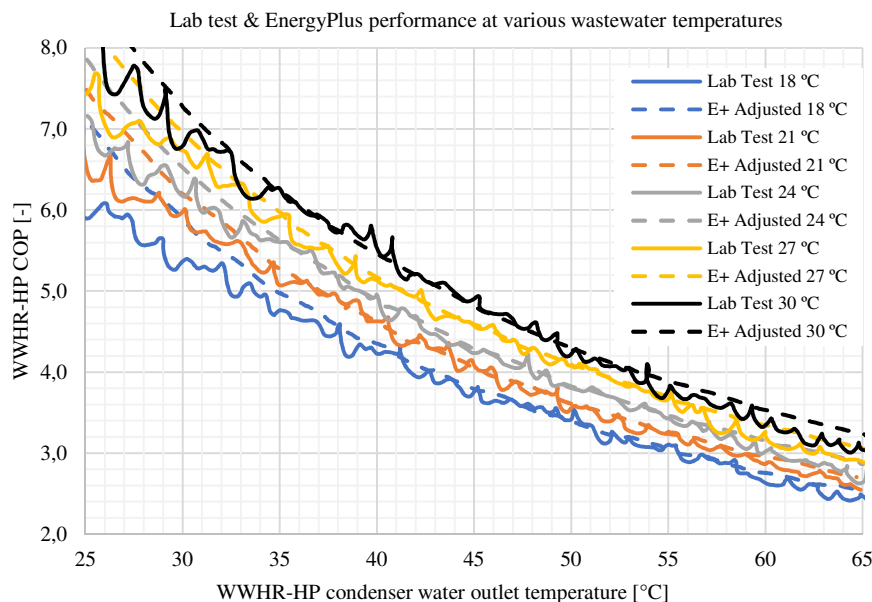


Figure 4. Original lab test data and adjusted EnergyPlus heat pump performance

Energy Management System

The Energy Management System (EMS) is a ‘high level, supervisory control’ feature of EnergyPlus [17]. EMS involves creating customized programs using the EnergyPlus

Runtime Language. For this model, EMS was used to transmit virtual wastewater from the DHW loop to the WW-Water loop. This EMS work around is required because the domestic water connections object is an open loop and E+ does not allow for open loop water to be easily incorporated into a closed plant loop. EnergyPlus calculates the demanded flow rates for both hot and cold water, as well as the resultant wastewater temperature. Figure 5 is a diagram of a generalized domestic water connections object from the EnergyPlus Input-Output Reference [18] (p 2200). The built-in WWHR feature seen in Figure 5 attempts to capture the effects of a drain pipe wrap gravity film heat exchanger coil and is not flexible enough to model a heat pump system properly. The built-in heat recovery feature can only recover heat for pre-heating water at the fixture. If this feature was used in the model, it would not properly capture the temperature and mass flow rate profiles seen by the T-10 heat pump. Thus, EMS was used.

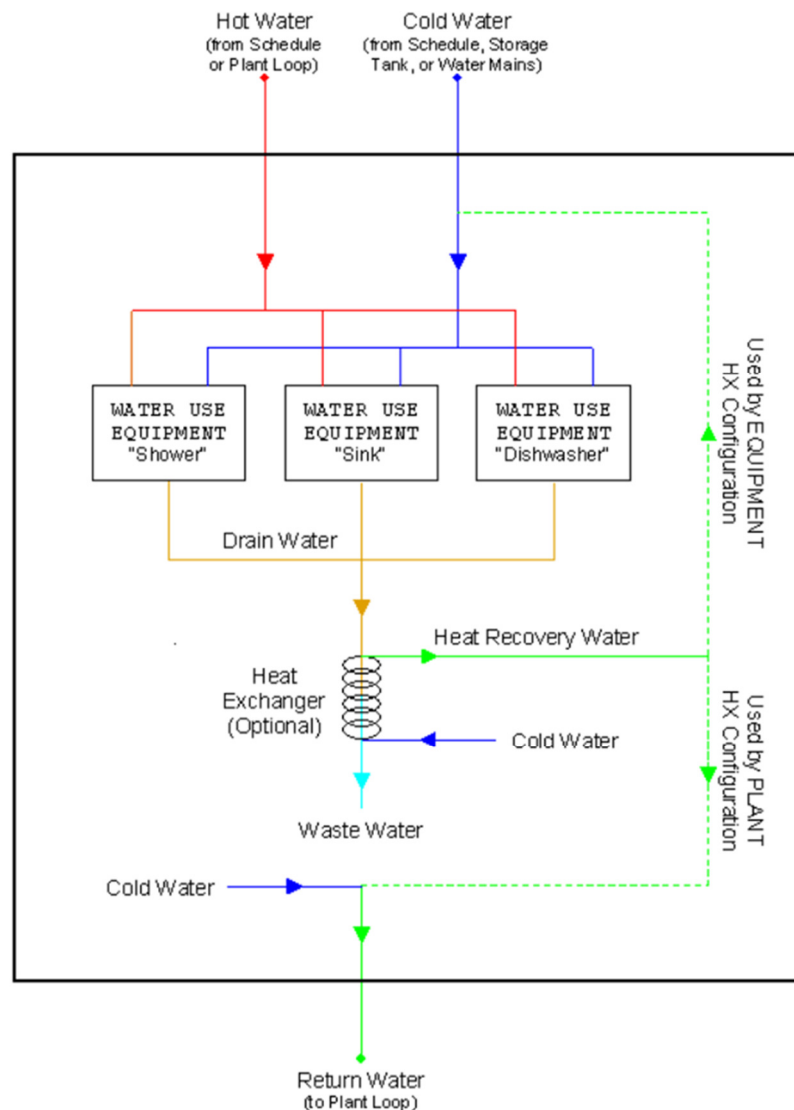


Figure 5. EnergyPlus WaterUse: Connections diagram [14] (p 1510)

An EMS program was written to use the wastewater outlet temperature and drain water mass flow rate to control the flow of water to the WW-Water plant loop (Figure 6). This loop connects the WW tank to a temperature source object. The temperature source object outputs water at a scheduled temperature without using any virtual fuel resources [18] (p 832). Not using any virtual fuel resources allows for accurate accounting of

energy transfers during simulations since, in reality, no resources are required to generate the warm wastewater in the storage tank. EMS resets the scheduled output temperature and mass flow rate of the temperature source object to match the calculated drain water temperature from the domestic water end uses at each timestep. The result is that the WW-Water loop demand side, which contains the WW tank, sees water with the same temperature and mass flow rate as actual wastewater entering the tank.

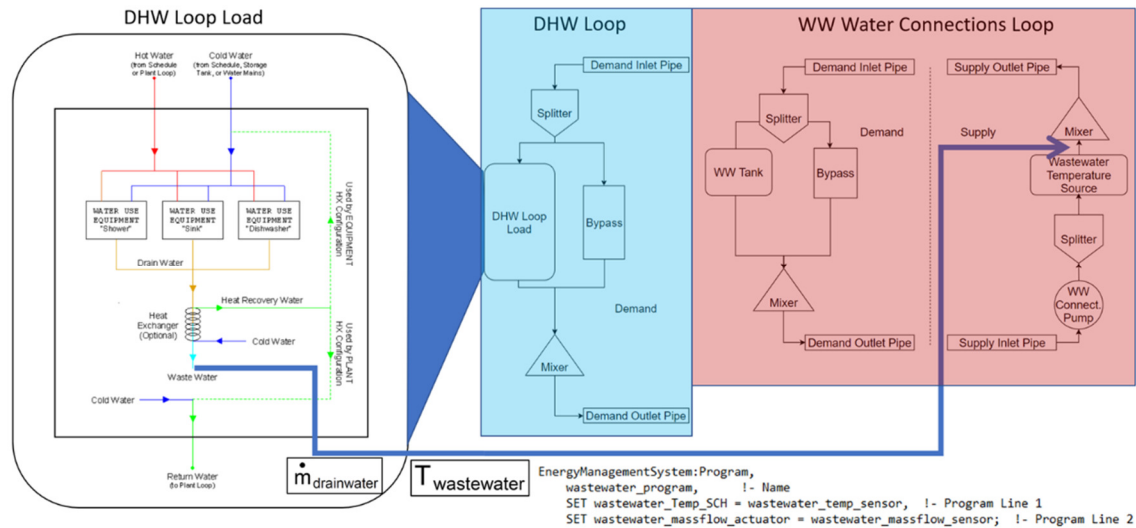


Figure 6. EMS solution to the WaterUse:Connections challenge

Model inputs

To prevent redundancy, Table 4 displays model inputs that were consistent across several objects. Table 5 displays where inputs deviated from those in Table 4.

Table 4. Global EnergyPlus model inputs

Object name	Field	Input	Source
Ambient temperature	Schedule value [°C]	22	General room temperature
Pumps	Design power consumption [W]	Autosize	EnergyPlus Engineering Reference, EnergyPlus Input-Output Reference
	Motor efficiency [-]	0.9	EnergyPlus default
	Performance curve [-]	Linear	Engineering consulting firm
Pipes	Type [-]	Adiabatic	EnergyPlus default
	Pressure loss [-]	None	EnergyPlus default
Tanks	Use/Source side effectiveness [-]	1	EnergyPlus default

Several parameters were set to autosize. This was done to allow for models to run without capacity constrictions. The linear performance curves in the components that were autosized prevented this model flexibility from distorting the results. Additionally, some objects were modelled that are not present in an installed system. An example is the WW-Water loop. As described in the Energy Management System section, this loop was added to improve model fidelity. Thus, the loop pump power was set to zero to prevent accounting for excess energy consumption.

Table 5. Specific EnergyPlus model inputs

Object name	Field	Input	Source
WW water loop pump	Design pump head [Pa]	179,352	EnergyPlus default
	Design power consumption [W]	0	Pseudo loop object
WW-HP pump	Design pump head [Pa]	59,782	Pump manufacturer, Engineering consulting firm
DPW loop pump	Design pump head [Pa]	59,782	Pump manufacturer, Engineering consulting firm
Top-Off loop pump	Design pump head [Pa]	59,782	Pump manufacturer, Engineering consulting firm
DHW loop pump	Design pump head [Pa]	179,352	EnergyPlus default
Boiler	Nominal capacity [W]	Autosize	EnergyPlus engineering reference, EnergyPlus input-output reference
	Nominal thermal efficiency [-]	80%	ASHRAE 90.1 2010 min. = 80% [19] (p 63)
	Curve coefficient C1 [-]	1.1249	EnergyPlus dataset [20]
	Curve coefficient C2 [-]	0.0149	EnergyPlus dataset [20]
	Curve coefficient C3 [-]	-0.0259	EnergyPlus dataset [20]
	Curve coefficient C4 [-]	0	EnergyPlus dataset [20]
	Curve coefficient C5 [-]	0	EnergyPlus dataset [20]
	Curve coefficient C6 [-]	-0.0015	EnergyPlus dataset [20]
	Operating temperature [°C]	82.2, 54.4	DOE reference building models (large hotel, mid-rise apartment)
WWHR-HP	Reference load side flow rate [L/s]	1.64	Maximum from lab test data/product cut sheet
	Reference source side flow rate [L/s]	6.62	Represents constant flow from lab test
	Ref. heating capacity [W]	43,892	Maximum from lab test data
	Ref heating power consumption [W]	12,625	Maximum from lab test data
WW tank	Off-Cycle loss coefficient [W/K]	2.36	Example project from WWHR-HP manufacturer
	Tank volume [m ³]	3.785	Example project from WWHR-HP manufacturer
DPW tank	Off-Cycle loss coefficient [W/K]	6.311	R-25 equivalent, well insulated tank
	Tank volume [m ³]	1.514	Example project from WWHR-HP manufacturer
Top-Off tank	Uniform skin loss coefficient per unit area to ambient [W/K]	6.311	R-25 equivalent, well insulated tank
	Tank volume [m ³]	1.514	Example project from WWHR-HP manufacturer

Economics

Economic viability was established using Simple Payback Period (SPP). This simple economic metric is calculated using eq. (19) where CF_0 is the annual net cost savings and I is the initial investment [21]:

$$SPP = \frac{CF_0}{I} \quad (19)$$

SPP is measured in years and does not account for the time value of money, but provides a good proxy for the quality of the investment opportunity. The shorter the SPP, the more attractive the investment is. For context, a 2010 white paper by Siemens displayed the results of an energy efficiency survey in which only 21% of respondents were willing to accept a payback of longer than four years, while 39% of respondents required a shorter payback period to invest in a project [22]. The remaining proportion used other metrics such as internal rate of return to make decisions.

REFERENCE BUILDING MODEL DESCRIPTIONS

Once the EnergyPlus model was assembled, it was integrated into holistic building energy models in order to quantify potential environmental and cost impacts in different climate zones and building types. The U.S. DOE has teamed up with 3 of its national

laboratories to create reference commercial building energy models. There are 16 different reference building types that cover approximately 70% of the U.S. national building stock [23]. The previously described T-10 unit setup was integrated into these reference buildings with few other modifications. The Large hotel and Mid-rise apartment building models were chosen, as these building types traditionally have above average DHW consumption rates and thus the greatest opportunity for WWHR. The two mentioned building types were modelled in 4 different climate zones, as each geographical location featured different ground water-main temperatures, primary fuel costs and electricity source fuel ratios. The four ASHRAE climate zones used were: 1A-Miami, Florida, 4C-Seattle, Washington, 5B-Boulder, Colorado and 7A-Duluth, Minnesota.

The unmodified reference model is henceforth referred to as the 'Baseline' model. Version 1.4_7.2 was used for all DOE reference buildings, which was last updated in 2012 [24]. For each climate zone and building type combination, a 'T-10 unit' model was created by removing the existing service hot water system objects from the model IDF and replacing those objects with the loop objects shown in Figure 3. Component names were modified to make connections as needed.

Large hotel

The Large hotel model features 11,345 m² of conditioned spaces in six above-ground floors and a basement. The baseline model consumes 44,333 m³ of domestic hot and cold water per annum, which results in a large volume of wastewater. Baseline model water heating is done with 80% efficient natural gas-fired boilers with a supply water setpoint of 60 °C. The average utility costs are seen in Table 6 [24].

Table 6. Average utility prices and costs for the Large hotel baseline model

		Miami	Seattle	Boulder	Duluth
Electric utility rates	Average annual rate [USD/kWh]	0.073	0.066	0.037	0.053
	Total cost [USD/m ²]	26.54	13.79	7.85	11.28
Gas utility rates	Average annual rate [USD/MJ]	0.0104	0.0081	0.0073	0.0067
	Total cost [USD/m ²]	4.75	7.21	6.91	8.87

Mid-rise apartment

The Mid-rise apartment model features 3,135 m² of conditioned spaces in 4 above-ground stories. The baseline model consumes 1,875 m³ of domestic hot and cold water per annum. Baseline model water heating is done with 80% efficient natural-gas fired boilers with a supply water setpoint of 60 °C. The average utility costs are seen in Table 7 [24].

Table 7. Average utility prices and costs for the Mid-rise apartment baseline model

		Miami	Seattle	Boulder	Duluth
Electric utility rates	Average annual rate [USD/kWh]	0.079	0.072	0.038	0.057
	Total cost [USD/m ²]	8.04	4.92	2.72	4.01
Gas utility rates	Average annual rate [USD/MJ]	0.0104	0.0081	0.0073	0.0067
	Total cost [USD/m ²]	4.75	7.21	6.91	8.87

Results: Large hotel

Table 8 shows the results of the 8 Large hotel simulations. Significant savings were seen in all climate zones and categories. The greatest energy savings percentage occurred in climate zone 4C-Seattle. The greatest energy cost savings occurred in climate zone

7A-Duluth. Also, the greatest GHG reduction by percentage occurred in Seattle, while the greatest absolute GHG reduction occurred in Duluth.

Table 8. Large hotel model results

Model run	EUI [MJ/m ² yr]	Energy savings [%]	Energy cost [USD/yr]	Energy cost savings [USD/yr]	SPP [yrs]	GHG emissions [MT CO ₂ e/yr]	GHG reduction [%]
1A Baseline	1,192	-	242,200	-	-	504	-
1A T-10 Unit	1,001	16	219,400	22,800	6.6	479	5
4C Baseline	1,528	-	221,000	-	-	314	-
4C T-10 Unit	1,149	25	184,700	36,300	4.1	254	19
5B Baseline	1,639	-	156,500	-	-	673	-
5B T-10 Unit	1,249	24	123,400	33,100	4.5	619	8
7A Baseline	2,076	-	215,100	-	-	650	-
7A T-10 Unit	1,602	23	177,500	37,600	4.0	573	12

The cost of a WWHR system for a typical large hotel with the specifications of the reference model was estimated by the T-10 manufacturer to be about USD 150,000. This estimate was for WWHR equipment only and did not include installation, design or other equipment. Nevertheless, USD 150,000 was used to estimate SPPs. Duluth featured the shortest SPP of 4.0 years. Figure 7 shows Energy Use Intensity (EUI) reductions by end use for the entire building.

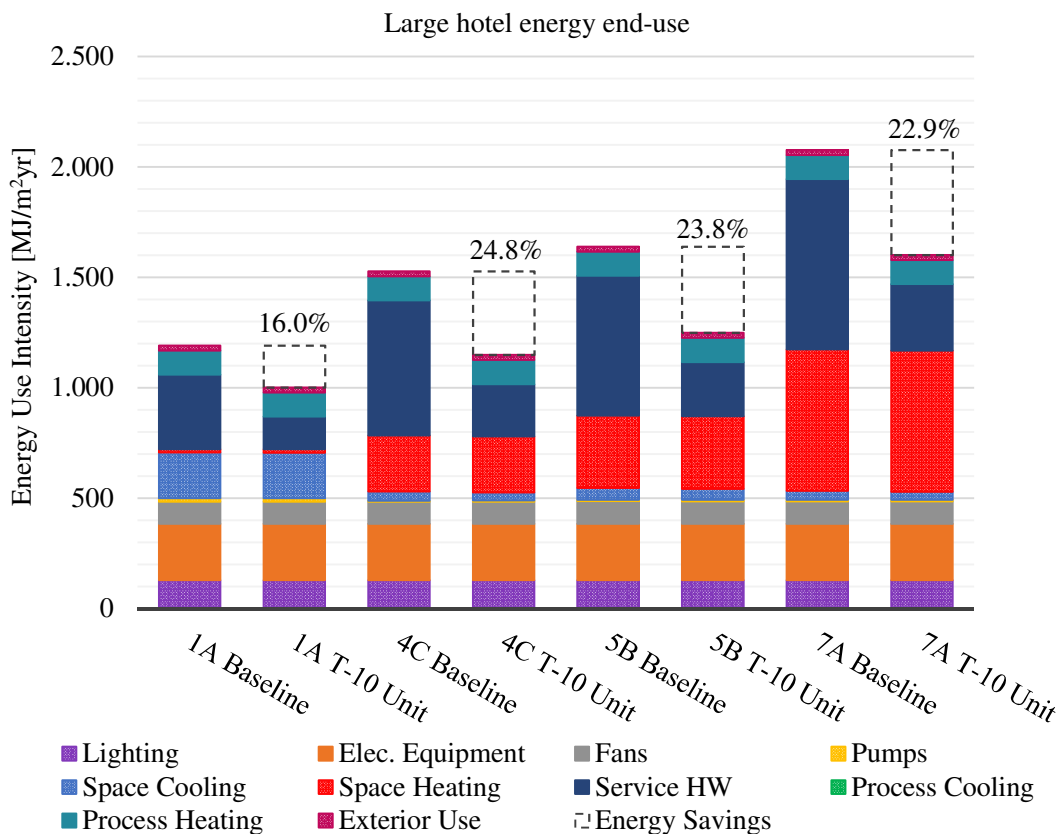


Figure 7. Large hotel model EUI and energy end-use reductions

Results: Mid-rise apartment

Table 9 shows the results of the 8 Mid-rise apartment simulations. In contrast to the Large hotel results, savings were either minimal or non-existent across almost all categories. In fact, GHG emissions increased in 3 out of 4 climate zones. The greatest

EUI reduction occurred in climate zone 7A-Duluth. The greatest energy cost savings occurred in climate zone 5B-Boulder and the greatest GHG reduction occurred in Seattle, which was the only climate zone that resulted in a GHG reduction.

Table 9. Mid-rise apartment model results

Model run	EUI [MJ/m ² yr]	Energy savings [%]	Energy cost [USD/yr]	Energy cost savings [USD/yr]	SPP [yrs]	GHG emissions [MT CO ₂ e/yr]	GHG reduction [%]
1A Baseline	413	-	26,700	-	-	60	-
1A T-10 Unit	384	7	26,000	700	114	61	-1
4C Baseline	435	-	20,500	-	-	27	-
4C T-10 Unit	377	13	19,700	800	100	26	7
5B Baseline	470	-	13,200	-	-	71	-
5B T-10 Unit	412	12	12,100	1,100	73	74	-3
7A Baseline	672	-	21,500	-	-	69	-
7A T-10 Unit	599	11	20,500	1,000	80	70	-2

The cost of a WWHR system for a Mid-rise apartment was estimated by the T-10 unit manufacturer to be about USD 80,000. This estimate only includes the cost the T-10 heat pump units and does not include installation, design, other pieces of equipment in the DHW production system or taxes. Nevertheless, USD 80,000 was used to estimate SPPs. All payback periods were unacceptably long with Boulder having the shortest at 73 years. Figure 8 shows EUI reductions by end use for the entire building.

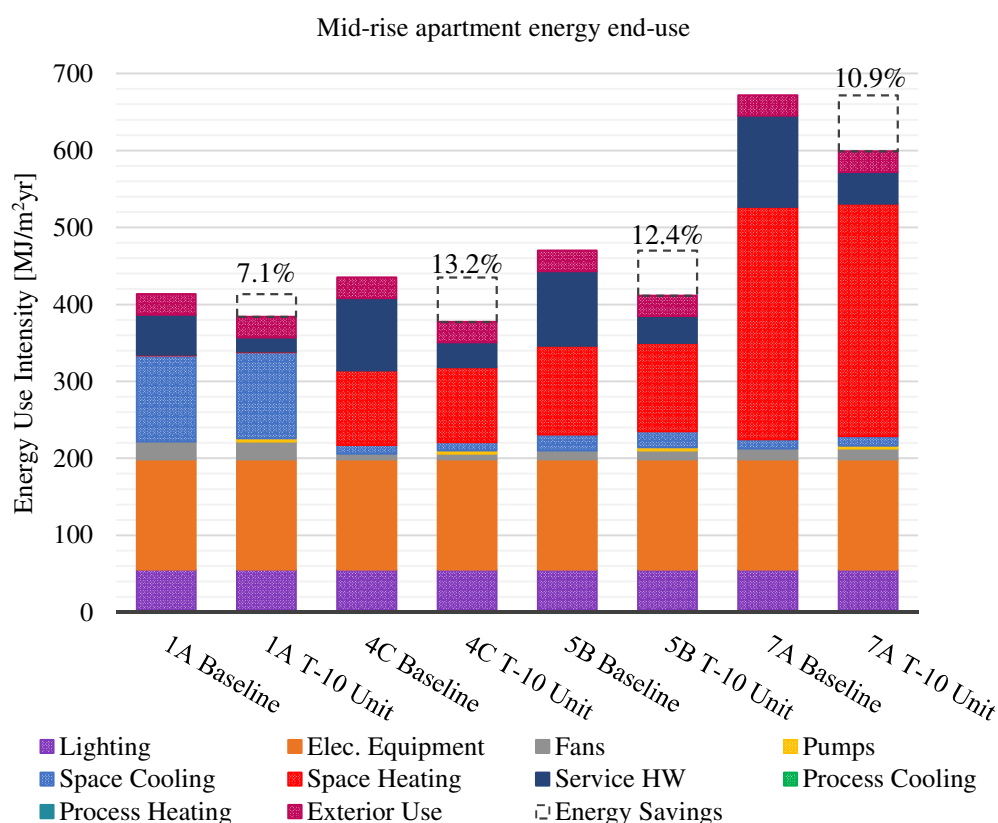


Figure 8. Mid-rise apartment model EUI and energy end-use reductions

DISCUSSION

The reason that the GHG percentage reduction and energy use percentage reduction are not equal in some cases is due to the electricity source mix. The U.S. Northwest takes advantage of a lot of hydropower and has a low carbon footprint. Because natural gas is

the baseline water heating fuel, reductions in natural gas use (by recovering wastewater heat to preheat water) have an outsized impact for buildings in Seattle. In essence, the T-10 unit displaces natural gas water heating and replaces it with more efficient electricity. This is economically conducive for states with low electricity rates.

Additionally, the unacceptably long SPPs for the Mid-rise apartment models are a result of the relatively low initial energy usage. DHW demand, and thus potential heat recovery, is not large enough to justify the initial investment required. Also, the global hydraulic fracturing and shale oil boom have led to relatively inexpensive natural gas. Cheap natural gas depresses the economic incentives to invest in heat recovery systems of all types including the WWHR-HP systems.

SPP for the Large hotel was much more reasonable. While a 4-7 year SPP is likely longer than the leisure and hospitality industry is accustomed to, the recent increase in environmental activism and social responsibility by corporations may help to overcome the longer SPP.

Additionally, cities and municipalities in the United States are beginning to enact regulations to reduce GHG emissions. New York City's Climate Mobilization Act imposes GHG emission limits on building owners [25]. The City of Berkeley, California recently banned new natural gas connections [26]. These new regulations could provide a tailwind for WWHR adoption and lead to system cost reduction over time. Until that point, WWHR systems will likely not be cost competitive with traditional technologies and will likely only be installed on projects where governments, designers, and building owners have aggressive sustainability goals.

CONCLUSIONS

The development of this EnergyPlus model will allow practitioners to consider WWHR systems more often due to the increased ease of modelling. DOE reference building models were successfully used as test cases for the model and were indicators of WWHR potential. At this time, WWHR is likely only appropriate for large commercial buildings and not for small residential settings. Projects with net-zero energy ambitions will also want to further explore WWHR solutions. As more WWHR systems are installed, initial capital costs will likely decrease, leading to positive momentum in the market. In summary, both of the main objectives for this project, creating a high-fidelity EnergyPlus model for a WWHR-HP system and assessing the potential building types/climates that would be most ideal for system deployment, were successfully achieved.

There remains a plethora of opportunities for future work following this project. One of these opportunities is to develop a WWHR OpenStudio measure. The National Renewable Energy Laboratory is currently developing this measure, which is simply a computer script that will add the WWHR-HP system to a wholistic building energy model in a single step. Additionally, controls for the T-10 unit model could be improved. In the models created for this project, the evaporator side of the heat pump was assumed to have continuous flow. Batch flow behaviour would more accurately represent actual system performance and would capture more nuanced performance effects. There is likely the potential to use EMS to model this behaviour. Finally, WWHR metered data or additional lab testing data would help to improve model validation. Installed T-10 unit metered data, including usage rates, COP, energy consumption, wastewater temperatures, etc., would allow for better calibration and validation of the EnergyPlus model.

ACKNOWLEDGMENT

The authors would like to thank the University of Colorado-Boulder Architectural Engineering Department, the National Renewable Energy Lab and Sharc Energy Systems for their time, resources and technical support.

NOMENCLATURE

A	water tank surface area	[m ²]
A1-A4	pump curve coefficients	[-]
B1-B6	boiler curve coefficients	[-]
BoilerEfficiencyCurveOutput	boiler efficiency curve value	[-]
BoilerLoad	boiler heating demand	[W]
BoilerNomCapacity	boiler maximum heating capacity	[W]
C1-D5	heat pump equation fit coefficients	[-]
CF ₀	annual net cost savings	[USD/yr]
c_p	specific heat of water	[kJ/kgK]
COP _h	heat pump coefficient of performance	[W/W]
FracFullLoadPower	fraction of full load pump power	[-]
FuelUsed	boiler fuel consumption rate	[W]
LoopDemand	loop heating or cooling demand	[W]
LoopDensity	loop water density	[kg/m ³]
LoopSetPoint	loop supply-side outlet setpoint temperature	[°C]
LoopTempIn	loop supply-side inlet temperature	[°C]
I	initial investment	[USD]
\dot{m}	loop mass flow rate	[kg/s]
NomPowerUse	pump maximum power	[W]
NominalThermalEfficiency	user-input boiler thermal efficiency	[-]
NomVolFlowRate	maximum pump volumetric flow rate	[m ³ /s]
PLR	part load ratio	[-]
Power _h	heat pump power consumption	[W]
PumpMassFlowRate	loop water mass flow rate	[kg/s]
PumpPower	pump electrical power	[W]
Q_h	heat pump load side heat transfer rate	[W]
q	heat transfer rate	[W]
$Q_{\text{source,h}}$	heat pump source side heat transfer rate	[W]
SPP	simple payback period	[yr]
$T_{L,\text{in}}$	heat pump entering load side water temperature	[K]
T_{ref}	heat pump reference temperature	[K]
$T_{S,\text{in}}$	heat pump entering source side water temperature	[K]
T_{water}	boiler operating temperature	[°C]
UA	off cycle loss coefficient	[W/K]
V	tank water volume	[m ³]
VolFlowRate	loop water volumetric flow rate	[m ³ /s]
\dot{V}_L	heat pump load side volumetric flow rate	[m ³ /s]
\dot{V}_S	heat pump source side volumetric flow rate	[m ³ /s]

Greek letters

ρ	tank water density	[kg/m ³]
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Subscripts

amb	ambient
b	boiler

h	heating
L	load
net	net
offcycloss	water tank heater off cycle loss
p	pump
ref	reference
S	source
source	water tank source side
use	water tank use side

Abbreviations

CO ₂ e	Carbon Dioxide Equivalent
DHW	Domestic Hot Water
DOE	Department of Energy
DPW	Domestic Pre-heated Water
E+	EnergyPlus
EMS	Energy Management System
EPW	EnergyPlus Weather File
EUI	Energy Use Intensity
GHG	Greenhouse Gas
HP	Heat Pump
IDD	Input Data Dictionary
IDF	Input Data File
IPCC	Intergovernmental Panel on Climate Change
WW	Wastewater
WWHR	Wastewater Heat Recovery

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Paper submitted: 11.12.2019
Paper revised: 27.04.2020
Paper accepted: 28.04.2020