Modelling Waste Heat Recovery for Renewable Thermal Energy

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Abstract

Waste heat recovery combined with geo-exchange is a key part of the net-zero carbon strategy proposed for the Centre Block Rehabilitation project. The project will create large below-grade areas which will need year-round cooling. We propose that this heat be re-used for space heating through the use of a water-to-water heat pump. The energy model for the project was created in IESVE, which does not include a native model for a loop-to-loop heat recovery system. We present a spreadsheet tool developed to carry out external calculations and model the potential energy and carbon savings from waste heat recovery.

Introduction

Centre Block is the main building on Parliament Hill in Ottawa, Ontario, and is one of Canada's most recognizable buildings. Centre Block contains the House of Commons, the Senate, and other high heritage spaces of great historical and ceremonial importance. The building is currently undergoing a major rebuilding project (the CBR) projected to last several years. As discussed in Michalak et al. (2021) the potential updates include the closing in of the courtyards of Centre Block by covering them with skylights and the addition of an underground building called the Parliament Welcome Centre (PWC) in the front lawn of Parliament Hill. The potential architectural updates drastically change the heating, and cooling load profiles relative to the existing building. Closing in the courtyards changes the exterior walls facing onto the courtyards to interior walls facing onto a conditioned courtyard. This changes the building from being heating load dominated with most offices exposed to the exterior, to a load profile more typical of a large office building with increased cooling loads in interior office spaces. The addition of the below-grade PWC also drastically changes the load profile. The conditioned floor area of the combined CB and PWC building is nearly doubled, and the PWC is cooling dominated throughout the year. This is due to the fact that PWC is entirely underground. Cooling loads are dominated by high internal gains and heating loads are minimized by energy recovery ventilators.

A large portion of the heating and cooling loads are determined to occur simultaneously. This is a unique situation for a project in Ottawa, Ontario (ASHRAE climate zone 6), which is harnessed by the implementation of a waste heat recovery loop (see Figure 1). Waste heat recovery forms the heart of the low carbon strategy proposed in the CBR Net Zero Feasibility Study (Michalak et al. (2021)). This measure reduces the annual heating and cooling energy along with the GHG emissions of the project significantly. The measure includes a tempered water loop, named the Heat Recovery Loop (HRL), distributed between CB and PWC. IT closet cooling equipment and refrigeration equipment reject heat directly to this loop through distributed water-loop heat pumps. A chiller is installed in PWC to meet the cooling demands for the PWC and reject heat into the HRL. Heating for CB and PWC is provided by a central loop-to-loop heat pump which provides hot water by acquiring and upgrading heat from the HRL. Additional heating and cooling are provided by a geo-exchange system or by the DES as needed. The HRL allows heat rejected from cooling loads to be reused to offset the heating demand of the buildings during periods of simultaneous heating and cooling loads. The addition of a geo-exchange system allows the recovery of additional waste heat by providing a mechanism for seasonal thermal storage. Together, these measures reduce the demand for heating and cooling energy from the DES, reducing the associated GHG emissions and energy costs.

Although a whole building simulation model for the project was built in the IES Virtual Environment (IESVE) software[1], IESVE does not have the capability to directly model this plant design[2]. In addition, many of the potential uses of the rejected waste heat (to other buildings, or to process loads such as snow melt) are calculated outside of IESVE and are not included in the IESVE model. As a result, an external calculation is done in Microsoft Excel. A complete whole building simulation is first carried out in IESVE, and hourly loads and supply/return temperatures on HW, CW, and CHW loops are collected. These loads are en-

[1] `https://www.iesve.com`

[2] Note that the more recent version of IESVE 2021 has added a water-to-water heat pump that can be used to calculate heat transfer between water loops.

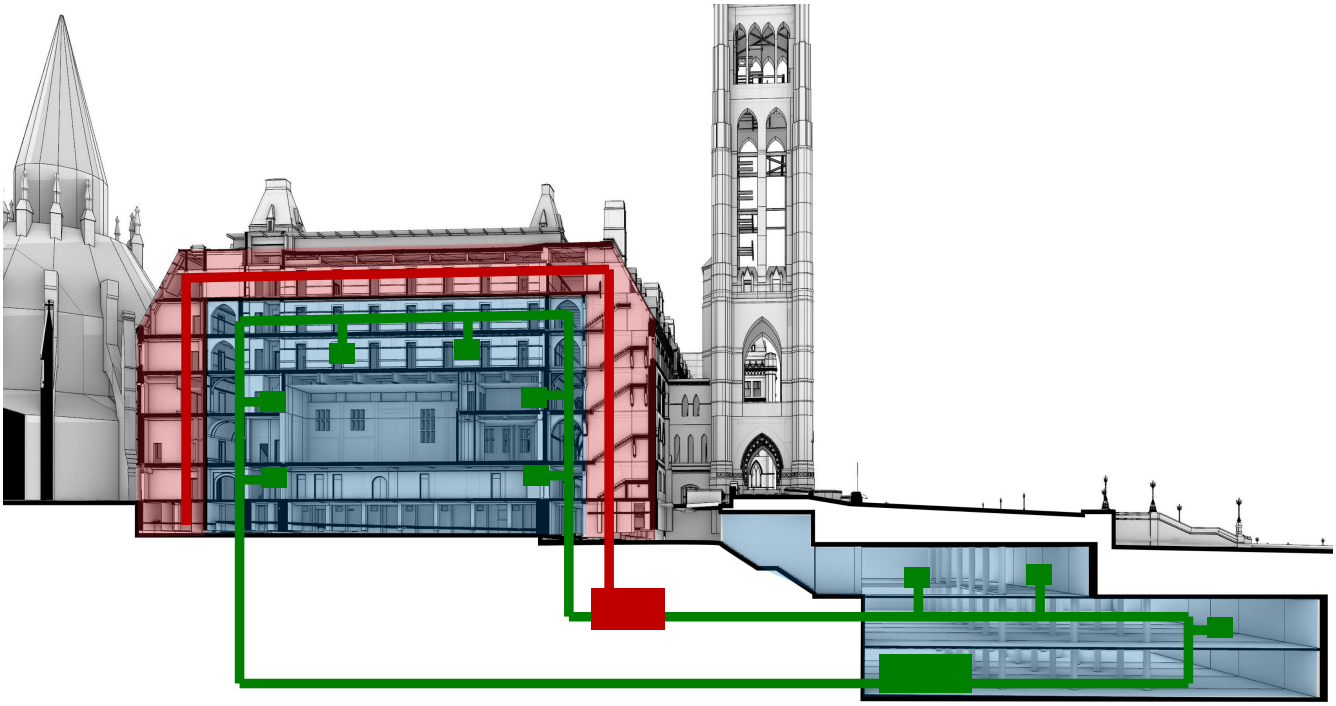

Figure 1: Waste heat is recovered from core zones and computer rooms in CB and from below-grade zones in PWC. This waste heat is upgraded and used to provide heat to perimeter zones in CB.

tered into the Excel calculator where the heating and cooling energy provided by the heat pump are calculated along with the electrical energy required to operate the heat pump. Remaining loads are then sent first to the geo-exchange system (modelled in GLD Ground Loop Design software[3]) and finally to the DES. The focus of this paper is on the methodology developed to calculate the operation of the loop-to-loop heat pump.

Methodology

The goal of the calculation tool developed is to determine the amount of heat that can be recovered from the condenser water loop and usefully applied to meet the demand for hot water, along with the electricity input required by the heat pump. As inputs to the heat pump calculation, IESVE calculates the hot water supply and return temperatures and the condenser water supply and return temperatures along with the associated heating and cooling loads on an hourly basis. In carrying out this calculation the simplifying assumption that the water temperatures are not changed by interaction with the loop-to-loop heat pump is made.

The electricity input, E, to the heat pumps is calculated on an hourly basis using the following equation (following the model used in DOE-2 for a loop-to-loop heat pump and described by Hirsch (2006))

$$\begin{aligned} E = &\mathrm{Cap}_0 \times \mathrm{Cap}(T_1, T_2) \\ &\times \mathrm{EIR}_0 \times \mathrm{EIR}(\mathrm{PLR}, \Delta T) \times \mathrm{EIR}(T_1, T_2) \end{aligned} \tag{1}$$

where Cap_0 is the rated heating capacity and EIR_0 is the rated electrical input ratio (1/COP) at the design conditions. PLR is the part-load ratio which in turn is dependent on the available capacity ($\mathrm{Cap}_0 \cdot \mathrm{Cap}(T_1, T_2)$). The input energy is calculated from three performance curves which depend on the leaving condenser water temperature, T_1, the entering hot water temperature, T_2, and the part-load ratio, PLR.

$$\mathrm{Cap}(T_1, T_2) = a_c + b_c T_1 + c_c T_1^2 + d_c T_2 + e_c T_2^2 + f_c T_1 T_2 \tag{2}$$

is assumed to be a bi-quadratic equation that adjusts the capacity of the heat pump depending on the water temperatures,

$$\begin{aligned} \mathrm{EIR}(\mathrm{PLR}, \Delta T) = &a_1 + b_1 \mathrm{PLR} + c_1 \mathrm{PLR}^2 + \\ &d_1 \Delta T + e_1 \Delta T^2 + f_1 \mathrm{PLR} \cdot \Delta T \end{aligned} \tag{3}$$

is assumed to be a bi-quadratic equation that adjusts the EIR depending on the part load ratio, and the difference in water temperatures ($T_2 - T_1$), and

$$\mathrm{EIR}(T_1, T_2) = a_2 + b_2 T_1 + c_2 T_1^2 + d_2 T_2 + e_2 T_2^2 + f_2 T_1 T_2 \tag{4}$$

[3] `https://www.groundloopdesign.com`

is assumed to be a bi-quadratic equation that adjusts the full-load EIR depending on the water temperatures. All three performance curves are designed to evaluate to one at the rated design conditions. In this case, the design conditions are PLR = 1, ΔT = 35°F (19.4°C), T_1 = 85°F (28.3°C), and T_2 = 120°F (48.9°C). The leaving hot water temperature is 140°F (60°C), and the COP for heat transfer specified for the Multistack heat pump analyzed in this exercise is 4.29 (or 5.29 if one includes waste heat from the compressor as is typical for a heating COP). If one considers the benefit to meeting simultaneous heating and cooling loads, the effective COP is 9.6.

The coefficients of the bi-quadratic equations are determined by multi-regression fitting to performance data obtained from the heat pump manufacturer. To cover the full range of operating conditions observed in the model, the capacity and input power were obtained for over 100 operating points, including a range of leaving condenser water temperatures from 50 to 85°F and entering hot water temperatures from 70 to 135°F. For each set of temperatures, the input power was obtained at part-load ratios of 25%, 50%, 75%, and 100%. It is important to keep in mind that providing these data required a significant investment of time on the part of the manufacturer's representative who had to enter each of the operating points into their heat pump modelling software manually. It is recommended that energy modellers seek out a mechanical engineer who has a good working relationship with a representative in making a request for this type of information.

The performance curves obtained from the performance data and used in the heat pump model are shown in Figures 2, 3, and 4, and the coefficients used are given in the Table 1.

The calculation of the electrical energy, E, is done in the following steps.

1. Collect loads and water temperatures from IESVE.
2. Compare heat rejected from the condenser water loop to the demand for heat in the hot water loop.
3. Calculate the available capacity, Cap(T_1, T_2), of the heat pump and the full load EIR(T_1, T_2).
4. Solve a quadratic equation to determine the heat transferred from the condenser water loop along with the electrical energy required to drive the heat pump.

The total heat transferred to the hot water loop,

$$Q = H + E, \tag{5}$$

where H is the heat transferred from the condenser water loop, and E is the electrical energy required to drive the heat pump as defined in Equation 1. E can

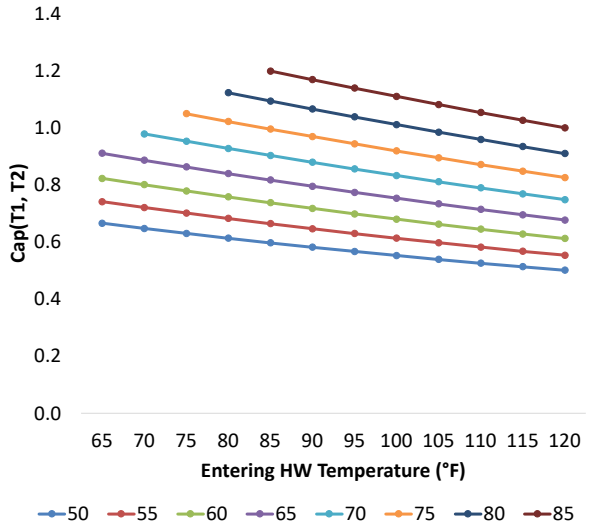

Figure 2: Adjustment to the heat pump capacity as a function of LCW temperature (separate curves) and EHW temperature (x-axis).

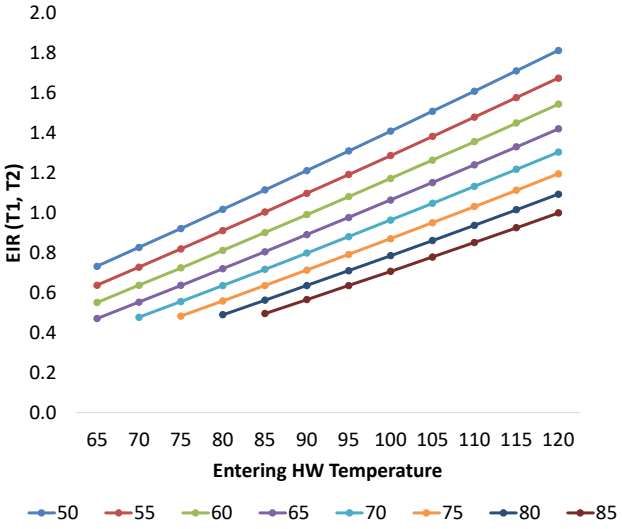

Figure 3: Adjustment to the EIR as a function of LCW temperature (separate curves) and EHW temperature (x-axis).

Table 1: Coefficients used in the biquadratic performance curves for the water-to-water heat pump.

	a	b	c	d	e	f
$\text{Cap}(T_1, T_2)$	2.78e-1	-1.11e-3	1.26e-5	7.29e-3	1.26e-4	-8.41e-5
$\text{EIR}(T_1, T_2)$	4.07e-1	2.47e-2	1.57e-5	-2.39e-2	1.46e-4	-1.59e-4
$\text{EIR}(\text{PLR}, \Delta T)$	1.28e-1	-1.51e-1	4.77e-1	-4.94e-3	5.82e-5	1.85e-2

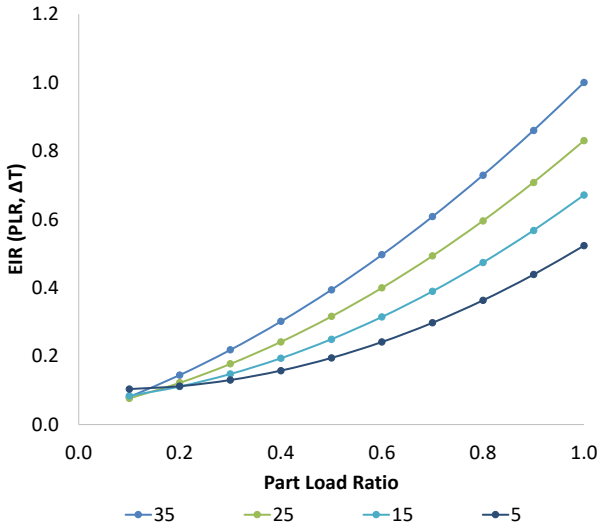

Figure 4: Adjustment to the EIR as a function of PLR (x-axis) and ΔT (separate curves).

be rewritten as

$$E = g(T_1, T_2) \cdot \text{EIR}(\text{PLR}, \Delta T), \tag{6}$$

where

$$g(T_1, T_2) = \text{Cap}(T_1, T_2) \cdot \text{EIR}_0 \cdot \text{EIR}(T_1, T_2). \tag{7}$$

The part-load ratio can be expressed as

$$\text{PLR} = \frac{H}{\text{Cap}(T_1, T_2)}, \tag{8}$$

and substituted back into Equations 6 and 3 to generate a quadratic equation in H. Thus solved, the quadratic equation yields

$$H = \frac{-b' + \sqrt{b'^2 - 4a'c'}}{2a'}, \tag{9}$$

where

$$a' = \frac{c_1 \cdot g(T_1, T_2)}{(\text{Cap}(T_1, T_2))^2}, \tag{10}$$

$$b' = 1 + \frac{g(T_1, T_2) \cdot (b_1 + f_1 \Delta T)}{\text{Cap}(T_1, T_2)}, \tag{11}$$

and

$$c' = g(T_1, T_2) \cdot (a_1 + d_1 \Delta T + e_1 \Delta T^2) - Q. \tag{12}$$

The above quantities are calculated in a spreadsheet on an hourly basis to determine the heat transfer H and the electricity input E. The hourly results are then summed to obtain the heating and cooling energy savings and the heat pump's electrical input energy.

Conclusion

The methodology presented in this paper can be used to create a calculation tool which, when used in concert with an energy model for a building, allows for the calculation of the electrical energy required to operate a loop-to-loop heat pump between chilled or condenser water loops and hot water loops. This methodology could be extended to a range of situations provided that the modeller is able to obtain sufficient performance data for the heat pump of interest. In the absence of detailed performance data default curves obtained from energy modelling software packages could be used.

In the CBR model, it is found that waste heat recovery is able to meet over 90% of the primary heating load for the building with a seasonal COP for heat transfer of 6.9. This leads to a significant reduction in demand for both chilled and hot water from the district energy system, yielding dramatic energy and GHG emissions savings.

Acknowledgment

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