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Authors

Excell, L

Anderson, I

Breda, J

et al.

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Heat pump retrofits for central plant hydronic heating systems: A software toolkit for screening and design

Lauren Excell, PhD
Affiliate Member ASHRAE

Ian Anderson, PE

JoeDon Breda
Associate Member ASHRAE

Sang woo Ham, PhD
Associate Member ASHRAE

Gene White, PE

Donghun Kim, PhD
Member ASHRAE

ABSTRACT

Retrofitting existing central plants with high-efficiency heat pump technologies can play a crucial role in achieving long-term planning goals. Modern heat pump technologies are able to use waste heat recovery to meet a building's heating demand, but there is a lack of accessible tools designed for non-HVAC experts, such as building owners, to quickly and easily conduct what-if analysis, e.g., estimating retrofit costs and payback period for their partial or full equipment replacement. This paper introduces an open-source software toolkit designed to facilitate the initial screening and decision-making of heat pump retrofits in existing central plants using a building's yearly load profile from metered or utility bill data. The toolkit evaluates the technical and economic viability of replacing traditional central plant equipment with various options including water-to-water or air-to-water heat pumps, which can provide efficient and lower-cost heating and cooling. It allows users to compare current central plant configurations with retrofit scenarios, assessing energy consumption, life-cycle costs, and environmental impact. The toolkit offers (1) a web-based tool designed for user-friendly access by a broad audience and (2) Python-based source code for researchers and engineers conducting parametric studies and design parameter optimization. The toolkit compares a typical central plant configuration to a configuration that uses a heat pump to supply hydronic heating and cooling. The output metrics include energy consumption and output of each equipment, life-cycle cost analyses and metrics, and environmental impact of the system.

INTRODUCTION

Modern heat pump technologies in the US market are able to meet most hot water supply temperatures, which creates the opportunity for the heat pump to recover waste heat from the building to provide heating. For example, when heating and cooling loads are simultaneous, a water-to-water heat pump can recover heat from the chilled water loop to meet the heating hot water demand. This new system is typically more efficient than a boiler and chiller plant because water-to-water heat pumps can produce heating and cooling simultaneously, resulting in a very high combined COP compared to other equipment. These are being installed in central plant facilities that have concurrent heating and cooling loads or that have sources of waste heat that can be leveraged for heating hot water. Several case studies have shared lessons learned for designing and controlling these systems, which we leverage to create a screening and initial design tool for central plant heat pump retrofits. Heemer et al 2011 shared their implementation of a water-to-water heat pump in a pharmaceutical plant, which can supply up to 170 ºF hot water and can reach 6.3 COP (21.5 EER). They found that analyzing both heating hot water and coincident chilled water load is essential to justifying the economics and properly sizing the heat pump. Campbell et al 2012 shared a load regression-based

Lauren Excell is formerly with Lawrence Berkeley National Lab, Berkeley, Calif., now with TRC, Oakland, Calif. **Sang woo Ham**, and **Donghun Kim** are with Lawrence Berkeley National Lab, Berkeley, Calif. **Ian Anderson** and **Gene White** are with Affiliated Engineers, Inc., San Francisco, Calif. **JoeDon Breda** is with TRC, Oakland, Calif.

sizing analysis which optimizes heat pump size for coincident heating and cooling loads, in order to not oversize the equipment. The principle behind a water-to-water heat pump is that it takes waste heat from the chilled water loop to heat hot water, therefore a coincident cooling load is necessary to meet the heating load unless alternative heat sources are available. Wang et al 2018 built on the lessons learned from this case study and performed a load regression sizing analysis, but chose to undersize in order to run at full load as much as possible. The heat pump must be sized for the heating load so that the condenser can fully reject heat absorbed by the evaporator and the compressor work; it's important to consider balanced loads to ensure the hot water temperature doesn't rise uncontrollably. We built our tool around the analysis of coincident loads and heat sources to explore a wide range of possible equipment sizing scenarios.

The tool presented in this paper facilitates the screening of heat pump retrofits, including heat recovery chillers and air source heat pumps, by analyzing heating and cooling loads and heat sources to determine which type of heat pump retrofit is technically and economically most viable. By providing a standardized tool for these retrofits, we aim to increase the rate of heat pump adoption by expediting their feasibility analysis. Other online evaluation tools exist for different heat pump technologies, including Oak Ridge National Lab's ground-source heat pump screening tool (ORNL 2022), NEEP's cold climate air-source heat pump evaluation tool (NEEP 2025), and paid tools from software companies, engineering firms, or manufacturers. Many tools are geared towards residential homes, such as RMI's Green Upgrade Calculator (RMI 2025). Ours is a free, open-source tool for the screening and initial design of water-to-water and air-to-water heat pumps serving central plants with hydronic heating and cooling loops. It's agnostic to building type, because the user supplies their own heating and cooling demand. While some engineering guides exist for performing these analyses, this tool will increase the speed of replicating these analyses and make it more accessible to users without an engineering background.

METHODS AND MATERIALS

This section describes what scenarios the tool can be used to model, provides detail on how to use the tool from inputs to output, and demonstrates some of the visualizations that can be generated by the tool to understand the results. The tool is being built in conjunction with an ongoing case study of a commercial building in South San Francisco, California; the initial analysis results performed using this tool for this case study are shared in the Case Study Results section. The tool calculates the central plant's hourly energy consumption based on the equipment fuel and efficiency. It compares a baseline scenario (using a boiler and chiller to meet demand) to a heat pump scenario (heat pump operation is prioritized to meet heating demand). The user provides hourly heating and cooling loads from their building or campus of buildings and these loads are assumed constant from year to year. Once annual energy consumption is estimated for baseline and heat pump scenarios, a life cycle cost analysis is performed to determine the net present cost and value of the heat pump configuration compared to the baseline operations. We do not model any changes to the building-side demand due to other retrofit efforts, as these changes in energy demand should be predicted through the use of a building energy modeling tool such as EnergyPlus. The intention is that the heat pump system will be used to leverage simultaneous heating and cooling loads to transfer waste heat from one loop to the other to provide beneficial heating and cooling.

System configurations

A typical hydronic central plant has a boiler to meet the heating load and a chiller and cooling towers to meet cooling loads, as seen in Figure 1a. The heat pump system modeled by this tool is part of a central plant that provides hydronic heating and cooling. The heat pump recovers heat from waste heat in the building (for a water-to-water heat pump) or from the ambient air (for an air-to-water heat pump) and provides heating hot water. The water-to-water heat pump also produces chilled water that can be used for cooling. An additional heat source can be used when heating and cooling loads are not coincident. Figure 1b shows a potential configuration considered in the case study that can be modeled by the tool: a water-to-water heat pump connected to the chilled and hot water loops.

The heating load is primarily met by the heat pump; any demand that is higher than the capacity of the heat pump is met by the boiler. The heat pump tracks the heating setpoint and any resulting chilled water is used to meet the cooling load; if the heat pump cannot meet the cooling demand, then the demand is met by the existing chiller. The tool has the capability to model two heat pump technologies: a water-to-water (WTW) heat pump and an air-to-water (ATW) heat pump, with or without simultaneous heating and cooling. In addition, the user can evaluate an additional heat source for the system, and the heat source can be constant, variable, or the sum of a constant and a variable heat source. In the ATW heat pump system, this heat source is modeled on the hot water loop, to lower the load that the heat pump is required to meet. In the WTW heat pump system, this heat source is modeled on the chilled water loop; this would allow the WTW heat pump system to stay operational even when loads are unbalanced, such as an exhaust air heat recovery coil. The additional heat source acts as an artificial cooling load for the system, which allows for the WTW heat pump to operate in heating-mode when the building's cooling load provides insufficient heat. The inverse scenario, where there is not enough heating demand for the WTW heat pump to produce chilled water in cooling-only mode, would require a heat dump system to release the extra heat to the environment or be stored in a tank for future use. The heat dump mechanism is not modeled in the current version of the tool. The ATW heat pump can operate under two different control logic: 1) heating-only or cooling-only mode (typical of 2-pipe units), and 2) a simultaneous heating and cooling mode (typical of 4-pipe units). The ATW heat pump prioritizes heating-only mode to ensure that the heat pump provides heating as much as possible. Simultaneous heating and cooling mode, if selected by the user, will run when there are coincident heating and cooling loads that support this operation; cooling output will be calculated using the combined COP provided by the user. In the case that there are no heating loads from the building, the unit will run in cooling-only mode.

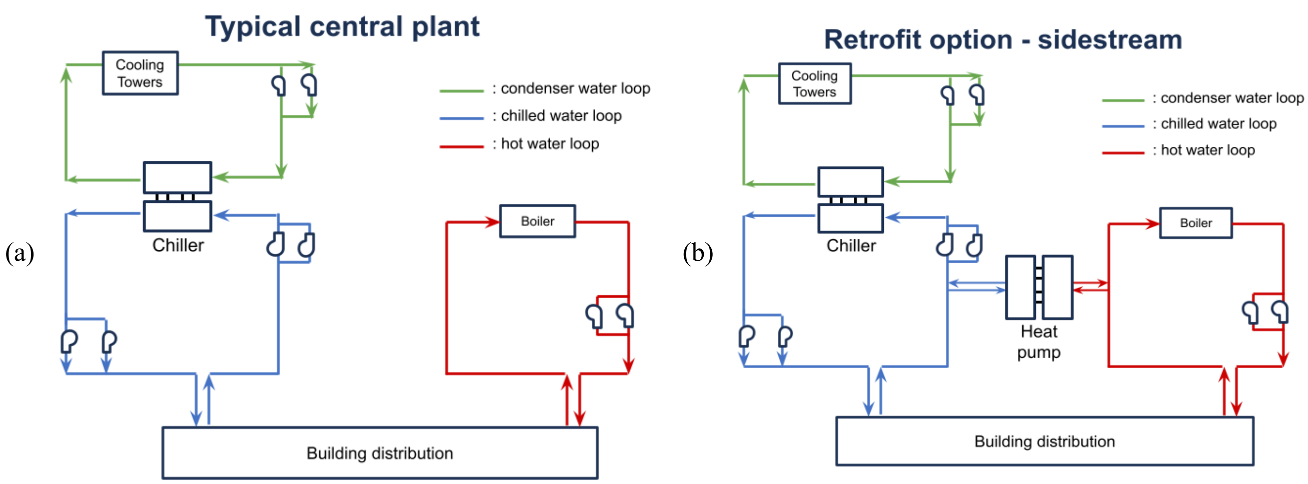

Figure 1 (a) Configuration of typical central plant and (b) example configuration of a water-to-water heat pump retrofit. Note that the condenser water loop is not modeled in this tool, but it is included in the figure for completeness.

Heat pump modeling

The performance of the heat pump technologies can be modeled using performance curves or the COP at nominal conditions. The performance curves are used to calculate the heating and cooling capacity and the input power to the machine (DOE, 1980). The performance curves are selected from a library of performance curves based on the nearest capacity to the user input. Alternatively, the user can choose to use the nominal conditions of the equipment when not enough information is available, which may be less accurate. Using the nominal COP method, the model assumes that the user input for nominal capacity is the maximum available capacity for heating. The cooling capacity is calculated using the COP. Although this doesn't capture real-time dynamics, it is a good approximation at the design stage where there is limited information on operating conditions. Similarly, the existing chiller can be modeled using the performance curves or the COP. The model selects performance curves from a library of chiller performance curves based on capacity; note that using the performance curves for the chiller will require providing additional metered data for the condenser water supply and return temperature.

Input parameters

Extensive documentation of model inputs can be found in the Documentation section of the website and source code. In order to run the model, the user needs to provide one year of hourly time series load data for their heating and cooling load, as well as some parameters about their potential retrofit configuration. The time series load data should include the date and time, heating load, and cooling load; if modeling an ATW heat pump, also include the outdoor air temperature. To use the performance curves method of modeling the heat pump and chiller equipment, include the hot water supply and return temperatures, the hot water flow rate, the chilled water supply and return temperatures, and the chilled water flow rate.

The input parameters describe the baseline system, the heat pump configuration, the retrofit costs, and the calculation methodology. For the baseline system, the user must input the boiler efficiency and the chiller efficiency. For the heat pump configuration, the user designates whether to evaluate a WTW or ATW heat pump. Based on this selection, they input the capacity of the equipment, the performance data (efficiency), and equipment specific information. The user designates whether to evaluate an additional heat source besides the building's cooling load, the capacity of the additional heat source, and whether it is constant or varies throughout the year. There is the option to upload a file containing the time series for a heat source that varies throughout the year. The retrofit cost inputs include the capital cost, yearly costs, upfront incentives, and yearly incentives. The capital cost includes the equipment and installation costs. The incentives are broken down by taxable and nontaxable incentives. The methodological inputs include escalation rates for various cost inputs, the discount rate, the federal tax rate, the life-cycle analysis period, and whether to use time-of-use utility rates. The time-of-use utility rates option requires additional inputs if used: the user can upload a CSV with their hourly utility rates for the year, or they can input their utility's name and the name of their rate structure and the tool will search the OpenEI utility rate database for their time-of-use rate.

Pre-processing tools. The website contains two optional pre-processing tools to help users prepare their building's load and heat source data. The Load Estimation tool produces an hourly time series file with the estimated heating and cooling loads from a user's monthly utility bill data or their hourly metered data from the hot and chilled water loops. The utility bill method relies on a typical load profile for a large office building to create an hourly load shape, and this is scaled to match the monthly utility data. The more accurate approach, which is able to capture the building's particular energy consumption patterns, is to upload the hourly metered data for hot and chilled water temperature and flow rate. The tool then calculates the heating and cooling load for each hour. The Heat Source Estimation tool takes hourly air temperature data (for ambient air or an exhaust air stream), water inlet temperature, and basic information about the heat exchanging equipment (e.g., efficiency) and returns a file with the estimated amount of heat exchanged per hour. The hourly air temperature should be measured as close to the heat source as possible. For example, an exhaust air heat recovery coil's heating capacity should be estimated using air temperature readings from the exhaust air plenum. The heat transfer rate of the coil is calculated using the U-value for the coils and fluid, surface area of the heat recovery coil, and temperature difference between the exhaust air temperature and water temperature, and is scaled by the overall efficiency of the system.

Parametric analysis. The tool provides the option to run a parametric analysis of two parameters if desired by the user. This function holds all other inputs constant while varying these two inputs to determine the effect that they have on the outputs. The user selects two parameters to vary and inputs the minimum, maximum, and increment values. The scenario analysis will be run for every combination of these parameter values.

Output metrics

The outputs of the tool cover engineering and life-cycle cost metrics. The engineering metrics include the annual gas consumption, the annual electricity consumption (heat pump, chiller, and total), the annual utility cost (gas, electricity, and total), the annual energy savings (gas and electricity) over the baseline scenario, the annual cost savings (gas, electricity, and the total), the annual CO_2 emissions, and the annual CO_2 emissions avoided. The basic equipment sizing analysis is run, as recommended in prior case studies of similar heat pump retrofits (Heemer et al. 2011 and Campbell et al. 2012), which outputs a load regression plot to identify the design heat pump capacity. The life cycle cost analysis metrics include the annual utility cost (gas cost, electricity cost, and total), the annual savings broken down by expense category (capital cost, electricity, gas, operation and maintenance, incentives, cost of carbon), the simple payback period, the net present value, the net present cost and the internal rate of return (IRR). Yearly discounted cash flows for the expense categories are available for detailed analysis.

Visualizing optimization in 3D. The optimization functionality of the tool can be used by conducting a parametric analysis and visualizing the desired output metric in 3D space. First the user should run a parametric analysis using the tool to vary two variables of interest. Using the results of this analysis, the user then selects their desired output metric to visualize in the "Optimization" tab, and the tool will create a plot of the output in 3D space and allow the user to identify the optimal values of the two variables that maximizes or minimizes their desired metric.

CASE STUDY RESULTS

We demonstrate the capabilities of this tool using a case study of a heat pump retrofit project in a large commercial building in South San Francisco, California. The current central plant uses a natural gas boiler to produce heating hot water and a water-cooled chiller to produce chilled water. The water loops provide heating and cooling to the building's air handlers. The baseline data was collected from December 21, 2023 to December 20, 2024, and the project team is considering a WTW heat pump, a WTW heat pump with exhaust air heat recovery, or an ATW heat pump. The capacity of the machine is also under consideration, to assess the tradeoff of being able to meet peak heating demand and running at full load for a higher percentage of the time. Candidate heat pump information collected from vendors is used as the basis of this case study, and the configurations analyzed in this case study are shown in Table 1.

Table 1. Heat Pump Parameters

Configuration	Heat Pump Type	Heating Capacity (kBTU/hr / kW)	Heating COP / EER	Additional Heat Source Capacity (kBTU/hr / kW)
1	Water-to-water	2790 / 818	4.3 / 14.67	1200 / 351
2	Water-to-water	2790 / 818	4.3 / 14.67	0
3	Water-to-water	4000 / 1172	3.78 / 12.91	1200 / 351
4	Water-to-water	4000 / 1172	3.78 / 12.91	0
5	Air-to-water	3412 / 1000	2.2 / 7.5	0
6	Air-to-water	1256 / 368	2.96 / 10.10	0
7	Air-to-water	1560 / 457	2.97 / 10.14	0

Using the web tool will generate all of the same plots and output metrics shown in this case study. Users will be able to visualize the energy demand from their building and the energy output produced by the central plant equipment to meet the demand. There are several summary data tables that outline the costs, savings, and statistics of the output metrics for each retrofit scenario.

A basic sizing analysis based on the heating and cooling loads throughout the year was performed. A regression line is plotted for both the heating and cooling load observations throughout the year, and the intersection of these two lines is the design capacity for the heat pump. For a scenario with an additional heat source, this increases the design capacity of the heat pump to the amount of capacity provided by the heat source. Because the case study building has a larger cooling load than heating load, the heat pump will be able to meet most of the heating demand using just the cooling load as a heat source. To meet 100% of the heating demand with the heat pump, an exhaust air heat recovery is being considered, as seen in Figure 2b.

(a)

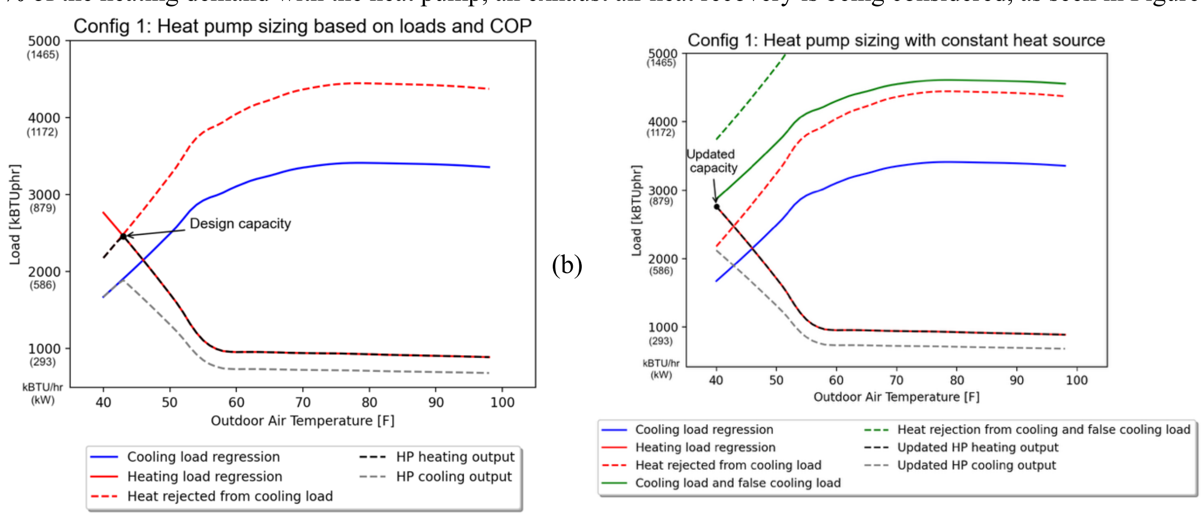

Figure 2 (a) Sizing analysis based on the load regression for the case study building's heating and cooling loads, and (b) sizing analysis based on load regression, considering a constant source of heat in addition to the cooling load. For Option A, the maximum heat pump heating capacity is around 2500 kBTU/hr (730 kW), but for Option B, the heat pump heating capacity is around 2800 kBTU/hr (820 kW).

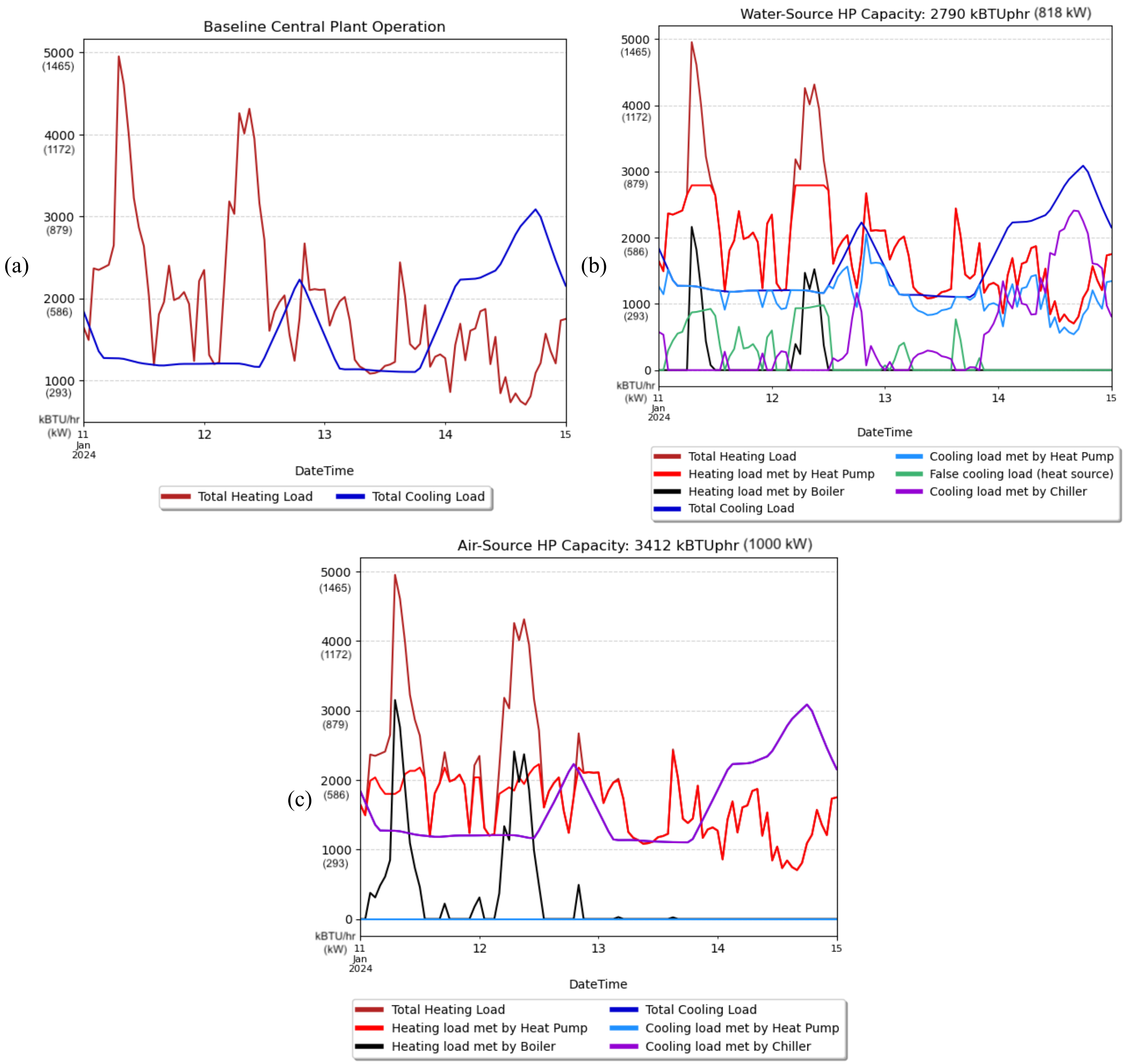

Figure 3 Four-day operation for (a) the baseline operation at the case study site, (b) a WTW heat pump with a 1200 kBTU/hr (351 kW) constant heat source (i.e. exhaust air heat recovery), and (c) an ATW heat pump.

After running the analysis, we plot the time series for heating and cooling demand and which equipment are used to meet the demand under the system conditions in Figure 3. The baseline scenario graph (Figure 3a) shows the heating and cooling demand calculated from the user input data for their building. The retrofit scenario graph assumes the same heating and cooling demand from the baseline case, but it prioritizes the heat pump equipment operation over the boiler and the chiller to meet the demand. In the case where the heat pump capacity isn't high enough to meet the demand, the existing equipment (boiler or chiller) runs to meet the rest of the demand. This can be seen in Figure 3b, where the heat pump heating coil load (in red) is not high enough to meet the peak heating demand (in dark red), and therefore the boiler (in black) needs to run to meet the peak demand. Similarly, the heat pump cooling output (in blue) is not high enough to meet the entire cooling load (in dark blue), and therefore the chiller (in purple) needs to run to meet the peak cooling demand. In the WTW heat pump scenario shown in Figure 3b, there is an exhaust air heat recovery coil that allows the heat pump to run when the heating and cooling loads are unbalanced. This additional heat source, also referred to as a false cooling load, is shown in green on the chart - when the cooling demand from the building is too low, the exhaust air is used as a heat source so that heat can be produced by the heat pump to meet the heating demand. Figure 3c shows the same time period for the ATW heat pump; the heat pump can meet most of the heating demand, but it can't produce beneficial chilled water to meet the cooling demand, thus leading to a lower combined efficiency compared to the WTW heat pump.

The results of the life cycle cost analysis can be seen in Figure 4. The net present costs for the baseline and retrofit scenarios are both shown on the bar chart, allowing the user to compare whether the heat pump retrofit will save money over the lifetime of the investment compared to the baseline scenario. Equipment replacement costs may be necessary in the baseline scenario to maintain boiler operation, but are not reflected in this analisys. The benefits of the projects can also be understood from the net present value, internal rate of return, simple payback period, and annual savings metrics displayed in Table 2. The upfront cost was estimated from industry averages for cost per unit capacity and labor rates, and accounts for a $1.2 million upfront incentive. Configuration 1, despite having the highest upfront cost, has the highest net present value because it generates the highest annual savings. Figure 4 shows the net present costs broken down by each of the major expenditure categories: the capital cost is incurred one time at the start of the project, and the other expense categories represent the sum of the discounted cash flows for the annual expenses, using a 6.5% discount rate. The electricity, gas, and operation and maintenance expenses are subject to an escalation rate of 5%, 6% and 3% respectively, for which the expense will increase each year. This case study does not contain any annual incentives. Due to the heat pump replacing a majority of the boiler operation, the electricity cost in each configuration is higher than the baseline; however, the WTW heat pumps still show annual savings because the cost per unit of energy is higher for gas than for electricity. Because this is an initial analysis early in the design phase, the upfront cost figures are highly uncertain. Working with a contractor to create an accurate cost estimate will lead to more likely estimates for internal rate of return and simple payback period. These metrics are highly impacted by the upfront cost of a project.

Table 2. Life Cycle Analysis Results

Configuration	Upfront Cost	Net Present Value	Annual Savings	Internal Rate of Return	Simple Payback Period
1	$3,315,852.00	$2,038,635.00	$79,733.00	3%	42
2	$3,195,852.00	$1,878,563.00	$71,170.00	3%	45
3	$3,227,281.00	$1,285,437.00	$39,323.00	1%	82
4	$3,107,281.00	$1,111,799.00	$30,020.00	1%	104
5	$2,712,500.00	$(4,901,966.00)	$(291,014.00)		
6	$2,593,500.00	$(2,357,257.00)	$(152,842.00)		
7	$2,622,400.00	$(2,454,074.00)	$(159,375.00)		

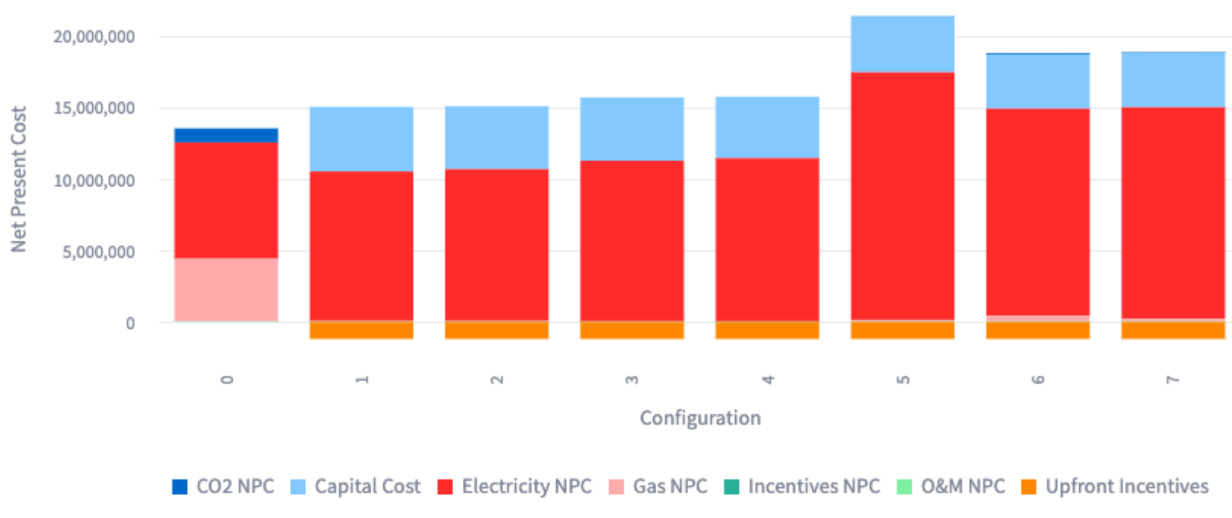

Figure 4 Results of the life cycle cost analysis showing the net present cost for electricity, gas, operation and maintenance, incentives, capital cost, and an optional cost of carbon.

To further understand the expenses incurred by the building owner, we calculate the utility bill for each month of the year under the baseline and retrofit scenarios, as seen in Figure 5. This allows us to see that the WTW heat pump consistently saves money on the utility bill throughout the year. The ATW heat pump scenario actually increases the utility bill each month because the heat pump and chiller are running close to full load most of the year to meet demand. As we can see from plotting the timeseries data in Figure 3, this scenario requires running the heat pump, chiller, and boiler to meet all of the heating and cooling demand for the building. Overall, this is less efficient and more costly than the WTW heat pump, which is using the heat recovered from the chilled water loop to produce both hot and chilled water.

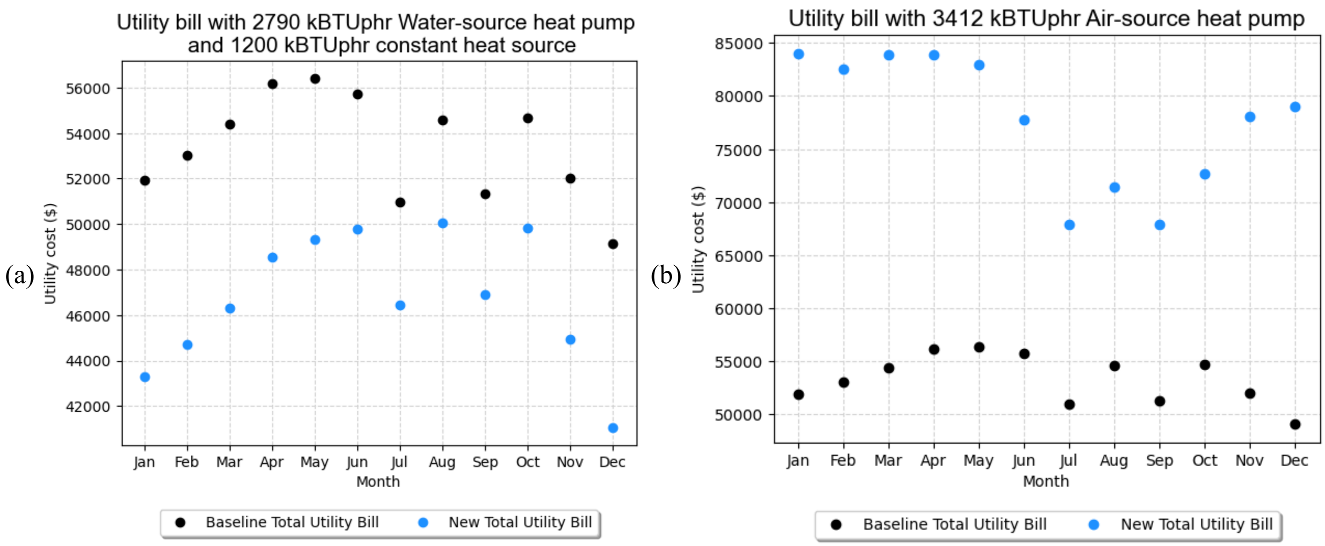

Figure 5 Utility bill comparison for the baseline and retrofit scenarios for (a) Configuration 1 and (b) Configuration 5. The utility bill is calculated using the estimated loads for each equipment and the user-input utility costs.

CONCLUSIONS

In this paper, we developed an initial decision-making tool for central plant retrofits, which helps users determine what type of heat pump to use to meet their loads (water-to-water vs air-to-water), whether a heat source is needed in addition to the cooling load, and which heat pump performs best for their building based on its specifications (i.e. capacity, COP, and cost). It aims to facilitate the heat pump selection process for a given site by reducing the time to analyze multiple scenarios and generate visualizations. Its scalable functionality also makes it a useful screening tool to identify buildings and campuses that would benefit from a heat pump installation. This tool will continue being tested and validated on the case study site in South San Francisco, California. After thorough testing, the website will be hosted on a server at Lawrence Berkeley National Lab and will be free to use. The code is publicly available on LBNL's repository (https://bitbucket.org/berkeleylab/eta-react).

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