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## Sustainable ORNL Showcase Project Report

# ORNL Campus Sustainability and Decarbonization using Waste Heat Recovery from the Oak Ridge Leadership Computing Facility's High-Performance Computing Data Center


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OAK RIDGE National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

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**Building and Transportation Science Division**

# SUSTAINABLE ORNL POTENTIAL SHOWCASE PROJECT REPORT
## ORNL CAMPUS SUSTAINABILITY AND DECARBONIZATION USING WASTE HEAT RECOVERY FROM THE OAK RIDGE LEADERSHIP COMPUTING FACILITY'S HIGH-PERFORMANCE COMPUTING DATA CENTER

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## ABSTRACT

Heat pumps are a clean and efficient technology that can be powered by renewable electricity to transfer heat using a refrigerant from one place to another by different heat sources, making buildings clean and environmentally friendly. With the support of the ORNL Laboratory Modernization Division, this project explored and evaluated an innovative solution that uses water-water cost-effective midtemperature heat pump (MTHP) technology to leverage the low-grade waste heat from ORNL Frontier and the data center to deliver 85°C hot water, which replaces hot steam generated using natural gas combustion boilers for water heating or space heating in the buildings of ORNL campus. Two scenarios were studied. In the first scenario, which considered the 5600-5700-5800 complex only, Carrier's commercial 1,000 kW MTHP technology achieves more than 6,640 MWh/year energy savings, an emission reduction of 858 $TCO_2e$/year $CO_2$, and a payback time of 4.85 years. In the second scenario, which considered the 5600-5700-5800 complex and Buildings 5100, 5200, and 5300, the $CO_2$ emission reduction is 1,483 $TCO_2e$/year, the operating cost savings are $0.21 million annually, and the payback time is 3.74 years.

Additionally, a comprehensive HP ShowCase Tool was developed for evaluating the optimal solution to improve sustainability and decarbonization of the buildings on the ORNL campus. The tool is an Excel-based tool integrated with VBA (Visual Basic for Applications) coding. The tool includes collected ORNL campus building information and an MTHP library, which comprises collected commercial and ORNL-defined MTHPs. The tool was used to evaluate the sustainability and decarbonization of the ORNL campus. The tool can be widely used or referenced for heat pump solutions and building decarbonization renovation strategies to modernize ORNL facilities and energy use–intensive equipment to enable efficient, sustainable, and resilient operations in the future.

## 1. INTRODUCTION

In FY 2022, the ORNL campus greenhouse gas emission (GHG) inventories were evaluated at around 236,456 $MTCO_2e$ based on the consumed electricity, natural gas, fugitive gases and refrigerants, vehicle and equipment fuels, employee commuting, transmission and distribution losses, etc. (Figure 1). As the largest US Department of Energy (DOE) science laboratory, ORNL has more than 200 buildings. Significant energy consumption is required to satisfy heating, cooling, electricity, and steam usage requirements of R&D activities in the buildings, and many facilities and buildings generate substantial waste heat. The representative facility is the Oak Ridge Leadership Computing Facility (OLCF) located at Building 5600, which houses the high-performance computing (HPC) data center, including the current top-ranked Frontier exascale supercomputer. Although Frontier is designed in a highly efficient pattern, it consumes up 8–28 MW of electricity [1], which is equivalent to the power required by several thousand homes. This consumed energy is finally converted into waste heat, which is absorbed from the supercomputer through an internal coolant loop and transferred to the external cooling plant [2]. In the supercomputer, internal coolant at temperatures of 12°C–30°C is typically provided directly to each computing rack cabinet. The coolant returns at 30°C–38°C and is cooled by four large evaporative cooling towers which can eject up to 40 MW of heat from the internal cooling loop to the atmosphere. The process leads to huge energy loss and water consumption.

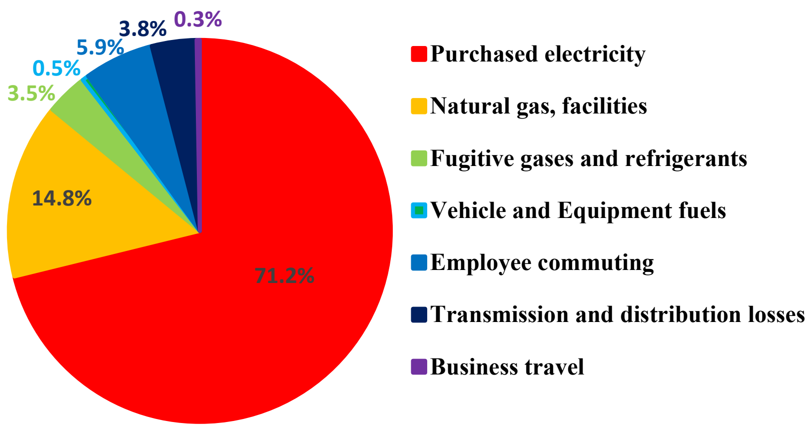



**Figure 1. ORNL campus GHG emissions inventories: total 236,456 MTCO$_2$e in 2022.**

The 5600-5700-5800 complex is the largest ORNL facility, comprising three large buildings that include the Computational Science Building (i.e., OLCF's HPC data center), the Research Office Building, and the Engineering Technology Center. (Building 5600 is 201,958 ft$^2$, Building 5700 is 144,404 ft$^2$, and Building 5800 is 100,916 ft$^2$.) The 5600-5700-5800 complex consumes up to 1–2 MW of 125°C hot steam generated using natural gas combustion boilers at the ORNL steam plant to produce 80°C–90°C hot water for water heating and winter space heating. The hot steam consumption at the 5600-5700-5800 complex contributes up to 4.3 TCO$_2$e daily on the ORNL campus. Figure 2 shows the overall cooling system of the HPC data center and hot steam transported from the ORNL steam plant to the 5600-5700-5800 complex. If some of the 8–28 MW of Frontier's waste heat in the complex could be recovered, that could substantially reduce GHG emissions from the campus and advance the laboratory's mission of efficient, sustainable operations. The challenge is that the water temperature from the waste heat is 30°C–38°C, and low-grade energy cannot be used directly for water and space heating through the complex HVAC distribution system. Consequently, a strategic solution using a novel waste heat recovery technology is required.

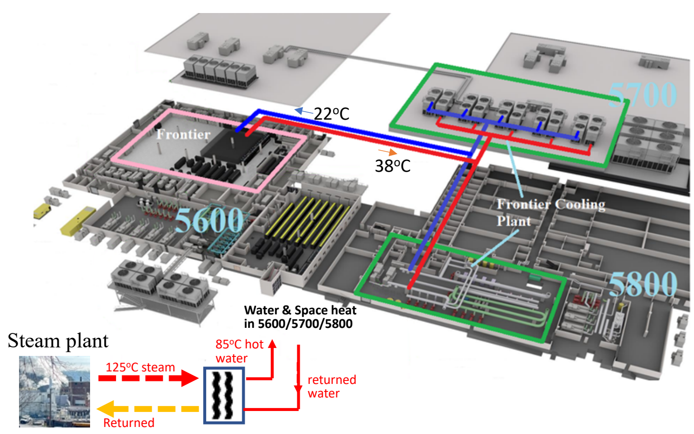



**Figure 2. Cooling system of ORNL Frontier and the HPC data center and the hot steam source for water and space heating in the 5600-5700-5800 complex.**

Heat pumps are a clean and efficient technology that can be powered by renewable electricity to transfer heat using a refrigerant from one place to another by different heat sources, making buildings clean and environmentally friendly [3, 4]. Heat pumps have been widely used in residential HVAC and water heating systems where the heat sink temperature is less than 65°C. Industrial heat pumps are also available for high-temperature manufacturing process heating above 120°C, such as in the chemicals, pulp and paper, primary metals, and food and beverage industries. In this project, with the support of the ORNL Laboratory Modernization Division, the team proposed and evaluated an innovative solution that uses a water-water cost-effective midtemperature heat pump (MTHP) technology to leverage the low-grade waste heat from the HPC data center to deliver 85°C hot water, which replaces hot steam generated using natural gas combustion boilers for water heating or space heating in the 5600-5700-5800 complex and other appropriate buildings on the ORNL campus. The objective is for the solution developed in this project to be well-incorporated into 5600-5700-5800 building renovations and in new construction and to be widely used or referenced for heat pump solutions and building renovation strategies to modernize other ORNL facilities and energy use–intensive equipment, enabling efficient, sustainable, and resilient operations in the future.

Therefore, in this project, the team collected the comprehensive energy data set of the Frontier system, collected ORNL building information, and compiled this information into a building library. The team also collected commercial MTHP technologies, developed ORNL-defined MTHP technologies, and built them into an MTHP library. The tool was used to conduct case studies for the sustainability and decarbonization of ORNL campus buildings.

# 2. FRONTIER SUPERCOMPUTER AND ENERGY DATA SET

## 2.1 FRONTIER SUPERCOMPUTER AND COOLING SYSTEM

Hewlett Packard Enterprise Frontier is the world's first and fastest exascale supercomputer, located at the OLCF in Tennessee, United States. The Frontier computing system was designed to integrate cutting-edge hardware and software technologies with a complex variety of interconnect technologies enabling high-speed data transfer among the system's 9,402 nodes. Figure 3(a) shows the entire Frontier computing system, which comprises 74 computing rack cabinets as well as many supporting rack cabinets and management rack cabinets. Each computing rack cabinet hosts 64 blades, as shown in Figure 3(b) and Figure 3(c). The blades are a type of compact server architecture commonly used in supercomputers and data centers and are designed to be densely packed within chassis to help optimize space utilization. In Frontier, each blade server consists of 2 nodes (Figure 3[d]), which are the individual computing units. Each node contains 4 GPUs and 1 CPU along with 4 terabytes of flash memory and storage (Figure 3[e]).

To prevent the data center or supercomputer from overheating, effective cooling systems are essential to remove the heat generated by nodes within densely packed blade servers and to ensure that the heat is efficiently transferred from the facility and released into the environment. Figure 3(e)–(g) and Figure 4 show the details of the complex cooling loops in Frontier, including the primary, secondary, and tertiary cooling loops for removing the heat from the 9,402 nodes to node cooling circuits, coolant distribution units, large-scale heat exchangers, and cooling towers and other large facilities. Briefly, the heat moves from the tertiary cooling loop to the primary cooling loop. The tertiary cooling loop is the direct computing hardware cooling loop. The secondary cooling loop is the part of the facility cooling system and is responsible for dissipating the heat collected by the tertiary cooling loop. The secondary cooling loop also includes a waste heat recovery subloop, enabling waste heat recovery to heat water for other applications such as building-space and water heating. The primary cooling loop is the cooling tower loop, which primarily helps dissipate the heat generated by the Frontier computing system to the atmosphere.

The cooling of blades and nodes in the tertiary cooling loop are shown in Figure 3(b)Figure 3(e). Figure 3(e) shows the complex cooling circuits in each node, in which a liquid coolant absorbs and carries away the heat generated by the CPU, GPUs, memory modules, and other critical hardware components within the computing nodes. In Figure 3(b), the blue port is the chilled-coolant entry to the blade and nodes, and the red port is the heated-coolant outlet flowing to a coolant distribution unit (CDU). Figure 3(f) displays a CDU, which is a component of the cooling system responsible for distributing chilled coolant to the computing rack cabinets, storage rack cabinets, and other hardware devices. The Frontier supercomputing cabinet cooling group comprises 25 CDUs which each provide cooling for three rack cabinets. CDUs are intended to maintain the allowable temperature of the IT equipment within specified limits (i.e., the allowable temperature from 15°C–32°C based on ASHRAE guidance [5]).

The secondary cooling loop is shown in central energy plant (CEP) B of Figure 4. Every minute, 2,400–6,000 gal of water pumps through the supercomputer's cooling loop to carry away up to 97%–99% of the waste heat. Figure 3(g) displays the coolant return and supply of the secondary cooling loop to CDUs. Also, the secondary cooling loop can be connected to a chiller, enabling waste heat recovery to heat water for building-space and water heating. The primary cooling loop is shown in CEP B of Figure 4. It can handle up to 40 MW heating load using large pumps, heat exchangers, and four 80,000 lb cooling towers. The system processes and eventually dissipates the waste heat into the external atmosphere.

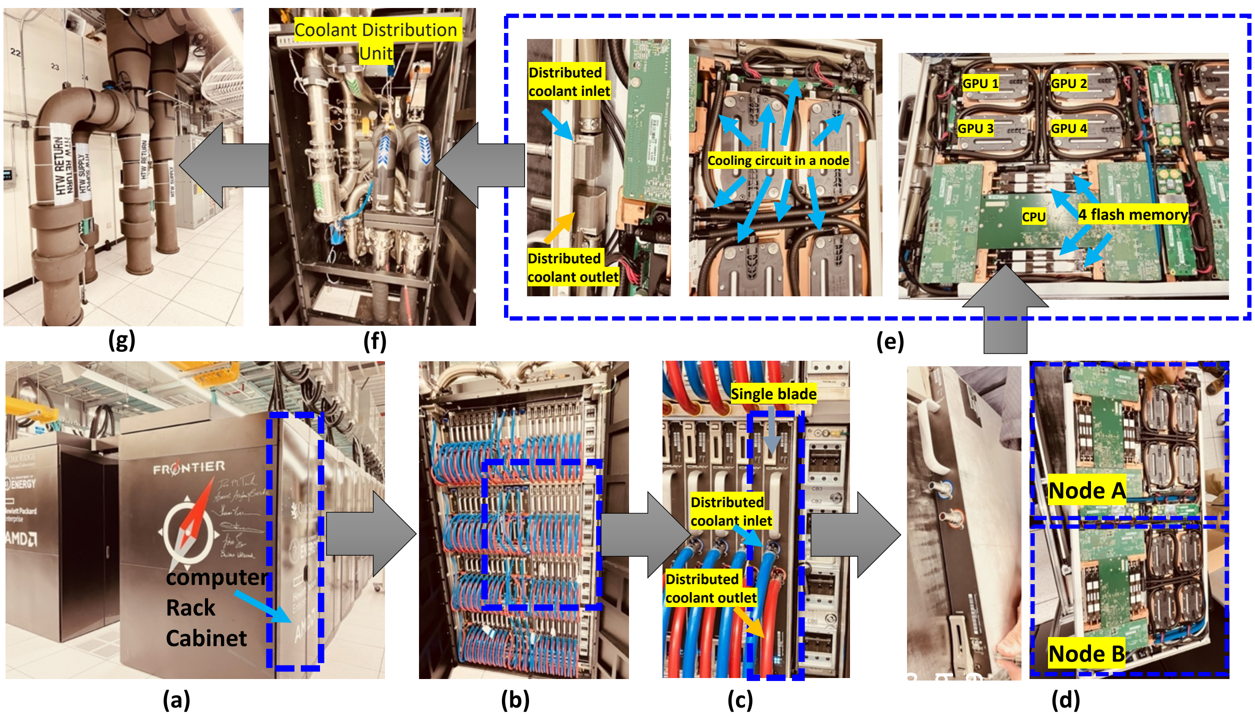



**Figure 3. Frontier supercomputer system real computing components and their cooling hardware.** Frontier consists of (a) 74 computing rack cabinets; (b) 64 blades in each computing rack cabinet; (c) a distributed coolant inlet and outlet in each blade; (d) 2 nodes in each blade; (e) 4 GPUs, 1 CPU, 4 terabytes of flash memory, and their cooling circuit in each node; (f) coolant distribution units; and (g) coolant return and supply in the secondary cooling loop.

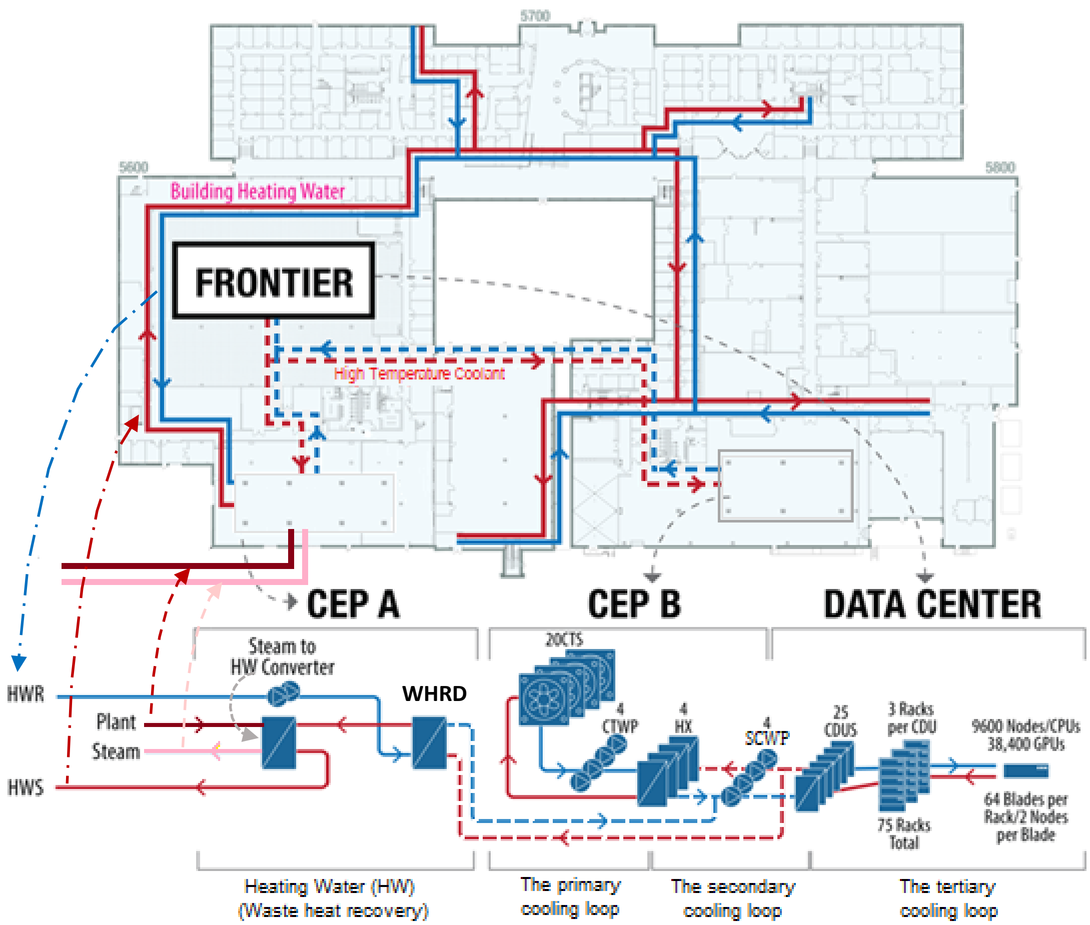
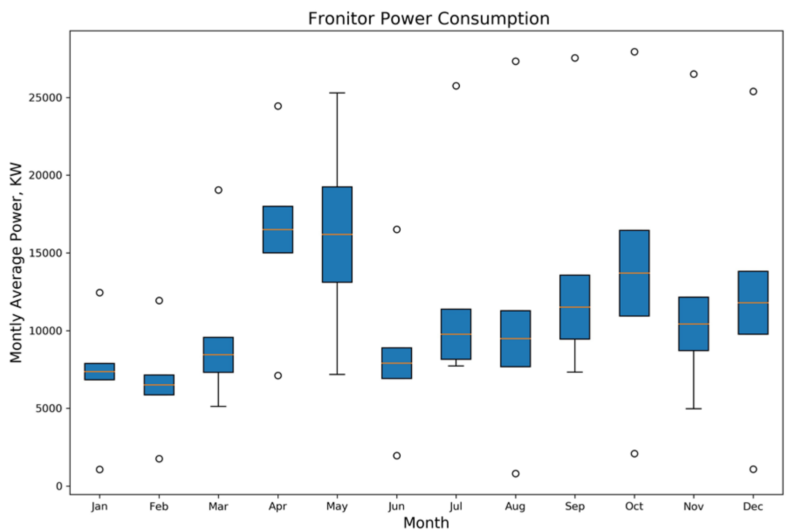


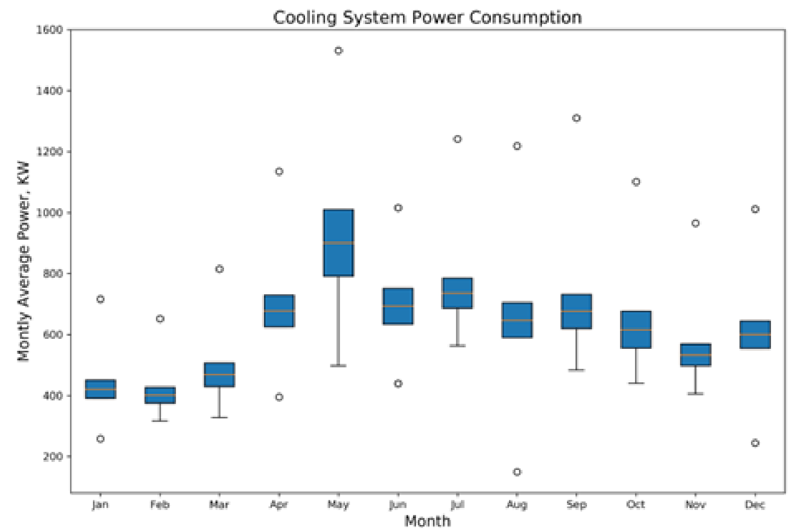

**Figure 4. Cooling architecture of the Frontier system at the Oak Ridge Leadership Computing Facility.**

## 2.2 ENERGY DATA SET OF FRONTIER SUPERCOMPUTER

The Frontier system is fully instrumented to measure and record its performance. The measurements include flow rates, temperatures, pressures, and power consumption. Data are collected from the facility's building automation system (BAS), which is based on a Johnson Controls Metasys system. The BAS's extended application and data server stores all data at 15 min intervals. For this project, the team collected 1 year of real-time measurements from January 1, 2022, to December 31, 2022, and characterized energy performance, including power consumption, power usage effectiveness (PUE), waste heat generation, and waste heat temperature levels. PUE is a ratio that describes how efficiently a computer data center uses energy—specifically, how much energy is used by the computing equipment (compared with cooling and other overhead that supports the equipment). An ideal PUE is 1.0. **Error! Reference source not found.** shows the Frontier system power consumption and PUE. The annual power consumption for Frontier was $1 \times 10^8$ kWh, which is the total electricity usage of 9,422 US homes. The average annual electricity consumption of a US home was 10,632 kWh in 2021 [6]. **Error! Reference source not found.**(a) reveals that the Frontier system's monthly average power consumption was 6.5–16.5 MW with some outliers in cases of extreme conditions (i.e., 0.8 MW system idling power usage and 27.9 MW system peak power usage). The monthly average power consumption for the cooling system, as shown in **Error! Reference source not found.**(b), was 0.4–0.9 MW with a minimum of 0.15 MW and a peak of 1.53 MW. The monthly average PUE was 1.04–1.10. Evaporative cooling devices (i.e., cooling towers) employed in Frontier consumed less energy than mechanical cooling devices (i.e., chillers), resulting in a nearly ideal average monthly PUE (**Error! Reference source not found.**[c]).




**(a)**

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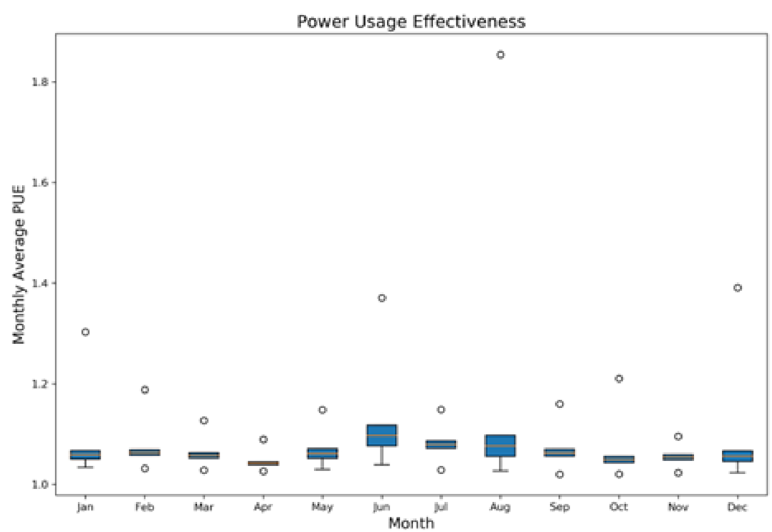
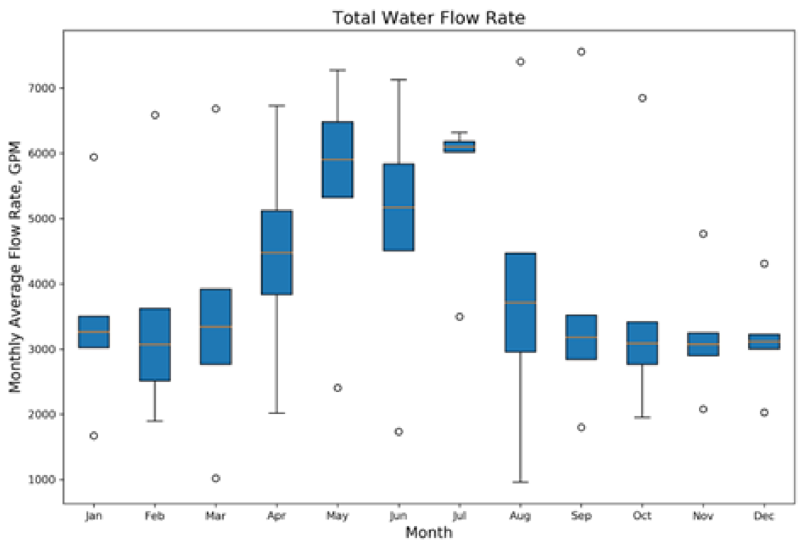


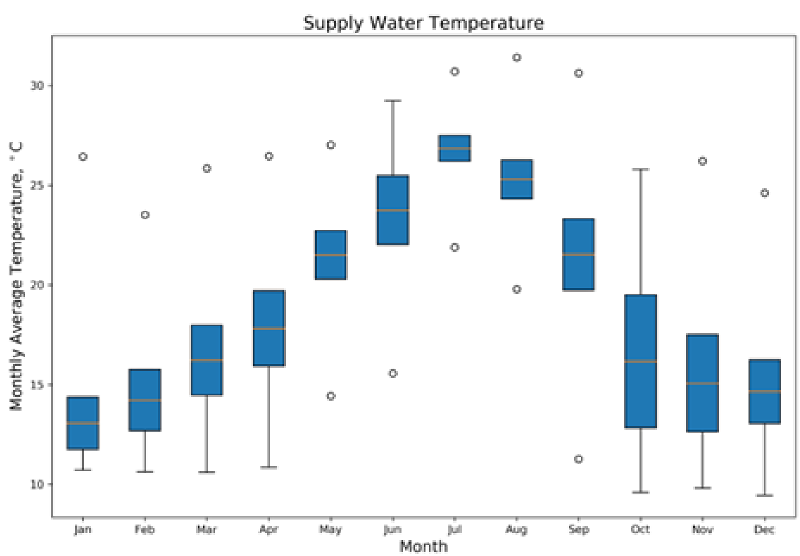

**(c)**

**Figure 5. Frontier supercomputer power consumption and power usage effectiveness. (a) average monthly power consumption of the supercomputer, (b) average monthly power consumption of the cooling system, and (c) average monthly power usage effectiveness.**

Figure 6 and Figure 7 show Frontier's computing cooling loop performance. Figure 6(a) plots the coolant flow rate from the Frontier supercomputer facility, and the coolant supply temperature is shown in Figure 6(b). Based on the analysis of the detailed data, the annual average coolant supply and return temperatures were 18.9°C and 32.4°C, respectively. Figure 7 shows the 1-year transient waste heat from January 1, 2022, to January 1, 2023. The minimum waste heat available was typically 2 MW and could be up to 14 MW, which is a substantial heat source for ORNL campus district heating. More details are included in a manuscript, "Energy Dataset of Frontier Supercomputer for Waste Heat Recovery," that will be submitted to a peer-reviewed journal.




**(a)**




**(b)**

**Figure 6. Frontier cooling loop performance. (a) Average monthly coolant volume flow rate and (b) average monthly coolant supply temperature.**

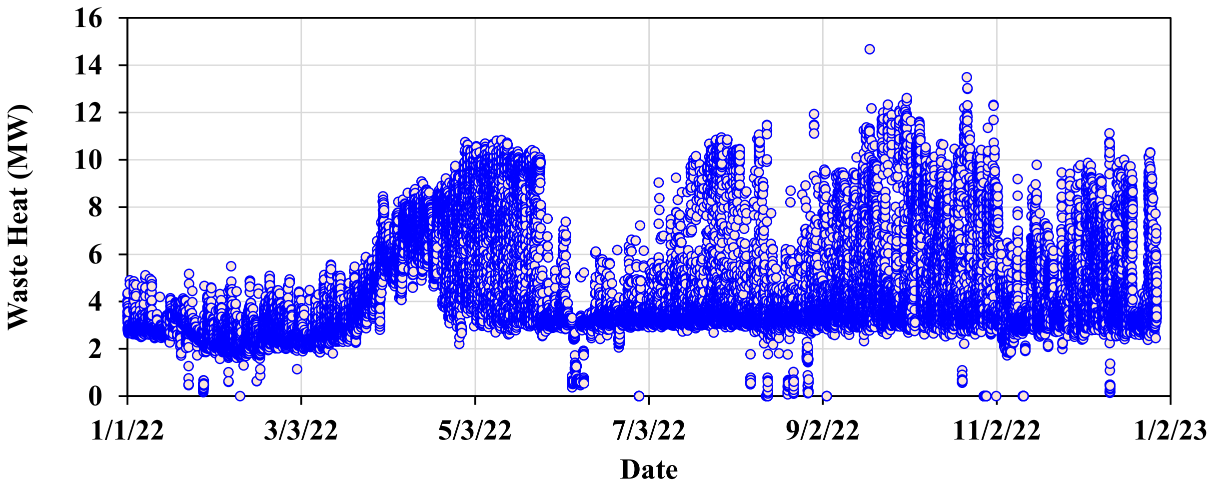



**Figure 7. Transient Frontier waste heat from January 1, 2022, to January 1, 2023.**

## 3. MTHP SOLUTION INNOVATION

### 3.1 COMMERCIAL MTHP TECHNOLOGIES

In the current market, commercial MTHPs are available to produce hot water up to 100°C. Most of these commercial MTHPs are based on electric-driven vapor compression cycles [7, 8]. The MTHPs can be classified into single-stage (SS), two-stage (TS), and multistage (MS) systems as well as by advanced components such as internal heat exchangers (IHX), economizers (Eco), and flash tanks (FT). The compressors include piston, screw, and turbo (centrifugal). The coefficients of performance (COPs) of these MTHPs are around 2.3–4.4. The COP substantially depends on the operation conditions. The refrigerants include R134a, R245fa, and R1234ze(E). Table 1 summarizes the commercial MTHPs capable of recovering the waste heat generated by the data center. As an example, Figure 8 shows the Carrier AquaForce 61XWH-ZEz and its COP map.

**Table 1. Commercially available large-scale MTHPs for district heating**

| Country | Supplier | Model | Cycle | Working fluids | Capacity | Heat source in/out (°C) | Heat sink in/out (°C) | COP |
|---|---|---|---|---|---|---|---|---|
| Austria | Ochsner [9] | IWWHS 570 ER6C2 | TS + Eco + IHX | R1234ze(E) | 520 kW | 18/14 | 82/92 | 2.85 |
| | | | | | 505 kW | 18/14 | 55/65 | 4.20 |
| | | IWWHS 640 ER3b | | R245fa | 650 kW | 45/- | -/85 | 4.0 |
| | Frigopol [10] | — | Two parallel cycles | R134a | 420 kW | 23/17 | 45/75 | 3.50 |
| Australia | Automatic Heating [11] | Rever R134A WW 500S | TS + Eco | R134a | 129 kW | 20/15 | 65/75 | 3.23 |
| China | [12] | — | SS | R245fa | 900 kW | 65/55 | 85/95 | 3.5 |
| | | | | | | 65/- | -/95 | 4.4 |
| | [13] | — | SS | R245fa | 108 kW | 73.9/63.9 | 94.4/97.3 | 4.2 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Denmark | Johnson Control [14] | York Tita OM | MS | R134a or R1234ze | 20 MW | 40/- | -/90 | ~3 |
| Finland | Oilon [15] | ChillHeat S600 | SS | R1234ze | 600 KW | 46/30 | -/75 | 4.0 |
| | | | | R1234ze | 1.1 MW | 30/- | -/95 | 3.5 |
| | | | | R134a | 2.3 MW | 18/8 | 50/65 | 3.0 |
| France | Enertime [16] | — | TS | R1234ze(E) | 2–5 MW | 35/30 | 80/85 | 3.7 |
| | Carrier Europe [17] | AquaForce 61XWHZE | TS | R1234ze(E) | 0.2–2.5 MW | 25/- | -/85 | 2.3-2.8 |
| | | | | | | 30/- | -/85 | 3.08 |
| | | | | | | 35/- | -/85 | 3.35 |
| | | | | | | 40/- | -/85 | 3.36 |
| | | | | | | 45/- | -/85 | 3.38 |
| | Trane [18] | XStream RTWF-360 SE G | SS | R1234ze(E) | 1.23 MW | 10/7 | 47/55 | 3.69 |
| | | RTWF-360 HE G | | | 1.47 MW | 10/7 | 47/55 | 3.72 |
| | | RTWF-420 HSE G | | | 1.55 MW | 10/7 | 47/55 | 3.87 |
| Germany | Combitherm [19] | HWW series | SS or MS | R1234ze, R245fa. R1233zd(E) | 520–937 kW | 30/- | -/80 | 3.2 |
| | | | | | | 40/- | -/80 | 4.1 |
| | | | | | | 40/- | -/90 | 3.4 |
| | Siemens Energy [20] | C600/C750 | TS + FT | R1234ze(E) | 15–45 MW | 32/27 | 60/(85–100) | 3.75 |
| | Viessmann [21] | Vitocal352. AHT119 | TS | R1234ze(E) | 294 kW | 50/- | -/90 | 3.3 |
| Japan | Kobe Steel [22] | HEM-HR90 | TS | Mixed R134a/R245fa | 357 kW | 35/30 | 80/90 | 3.4 |
| | Mitsubishi [23] | ETW-L | TS + Eco | R134a | 547 kW | 50/45 | 80/90 | 3.7 |
| Switzerland | Friotherm [24] | Unitop 50FY | TS | R134a | 18.7 MW | 10.0/5.8 | 67.2/90.0 | 2.83 |

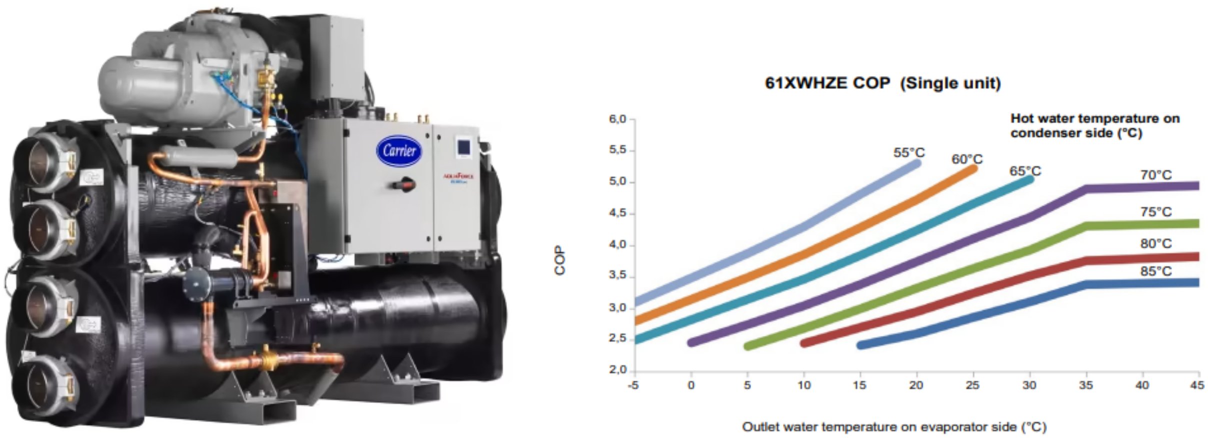



**Figure 8. (a) Carrier AquaForce 61XWHZE and (b) COPs of 61XWHZE heat pumps.**

## 3.2 ORNL-DEFINED ADVANCED MTWH TECHNOLOGIES AND THEIR LOW–GLOBAL WARMING POTENTIAL REFRIGERANTS

Five advanced configurations of heat pumps [25] along with five low–global warming potential (GWP) refrigerants were selected as potential MTHP technologies to upgrade the waste heat from Frontier and ORNL data centers for building-space and water heating. These configurations include SS or TS systems. A TS system compresses refrigerant vapor at two compressors in a series (i.e., a high-stage compressor [HSC] and a lower-stage compressor [LSC]), which can provide feasible condensing temperature and pressure through intermediate vapor injection while reducing HSC discharge temperature [26]. Schematics and pressure-enthalpy diagrams of these vapor compression cycle configurations and a standard SS compression cycle are given in Figure 9. These potential configurations are described in the following:

- **SS**: An SS cycle is a basic configuration comprising four essential components: a compressor, condenser, expansion valve, and evaporator.
- **SS with an IHX (SS + IHX)**: An IHX is added into the SS cycle, enabling heat transfer between the liquid-line and suction-line refrigerants.
- **SS with an ejector (i.e., EJT) and an IHX (SS + EJT + IHX)**: In an SS with an IHX, an EJT is added to recover energy loss resulting from the throttling process. EJT discharges two-phase working fluid into a separator, where saturated vapor and liquid are separated and enter the IHX and evaporator, respectively.
- **SS with an economizer (i.e., Eco), a parallel compressor (PC), and an IHX (SS + Eco/PC + IHX)**: This configuration comprises two parallel loops through an Eco component, a lower-pressure loop, and a high-pressure loop. In the high-pressure loop, a portion of refrigerant evaporates and becomes superheated; the superheated refrigerant is compressed in a PC and is discharged to the condenser. In the lower-pressure loop, the remaining refrigerant is subcooled and compressed in the main compressor.
- **TS with an Eco and an IHX (TS + Eco + IHX)**: An Eco is used to generate the superheated vapor for the vapor-injected compression process in the HSC. The superheated vapor mixes with discharged vapor from the LSC and is finally compressed in the HSC of a TS system.
- **TS with an FT and an IHX (TS + FT + IHX)**: An FT is used to generate saturated vapor for the vapor-injected compression process in the stage compressor of a TS system. The saturated vapor mixes with discharged vapor from the LSC and is finally compressed in the HSC.

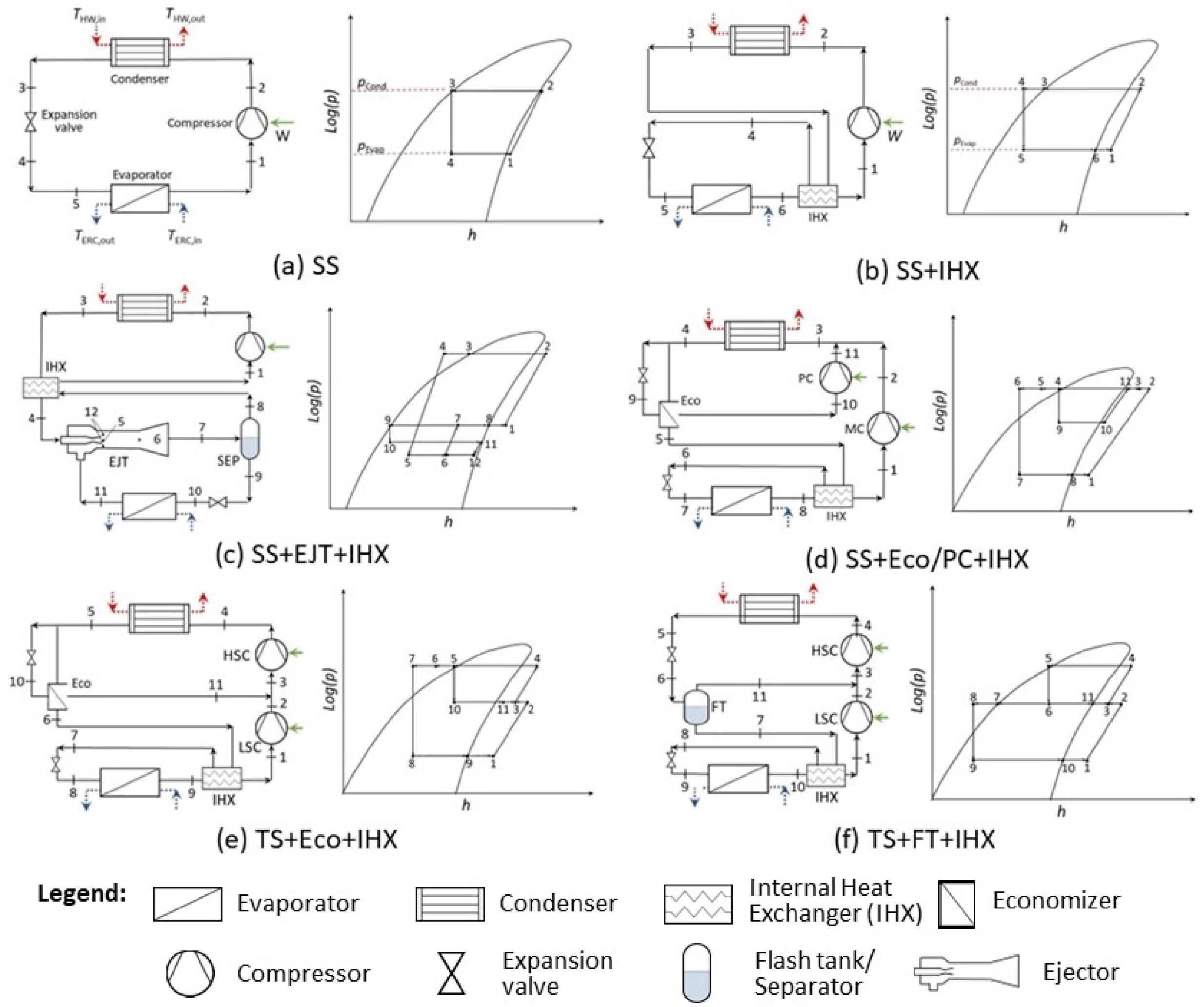



**Figure 9. Schematics and pressure-enthalpy diagrams of six MTWH configurations.**

Moreover, to support ORNL's Sustainable Campus Initiative of reducing refrigerant emissions in line with federal GHG emission goals, five low-GWP refrigerants with high critical points ($T_{cr}$ > 130°C) were selected for MTHP water heaters to deliver heat at $T_{sink}$ < 100°C. Table 2 compares the properties of the selected refrigerants, including chemical formula, critical temperature and pressure, vapor density at 100°C, normal boiling temperature, molecular weight, GWP, ozone depletion potential, and ASHRAE safety group classification. R245fa was considered as a baseline refrigerant. R245fa is widely used in commercial MTHPs and is expected to be phased down soon because of its high GWP.

**Table 2. Low-GWP refrigerants for MTWHs**

| Group | Refrigerant | Formula | $T_{cr}$ (°C) | $P_{cr}$ (MPa) | NBP (°C) | MW (kg/kmol) | ODP | GWP | SG |
|---|---|---|---|---|---|---|---|---|---|
| HCFO | R1234ze(Z) | $C_3F_4H_2$ | 150.1 | 3.53 | 9.8 | 114.0 | 0 | <1 | A2L |
| HFO | R1233zd(E) | $C_3ClF_3H_2$ | 166.5 | 3.62 | 18.0 | 130.5 | 0.00034 | 1 | A1 |
| | R1224yd(Z) | $C_3ClF_4H$ | 155.5 | 3.33 | 14.0 | 148.5 | 0.00012 | <1 | A1 |
| HC | R600 | $C_4H_{10}$ | 152.0 | 3.80 | −0.5 | 58.12 | 0 | 4 | A3 |
| | R600a | $C_4H_{10}$ | 134.7 | 3.63 | −11.7 | 58.12 | 0 | 3 | A3 |
| HFC | R245fa | $C_3F_5H_3$ | 154.0 | 3.65 | 15.1 | 134.0 | 0 | 858 | B1 |

NBP = normal boiling temperature; MW = molecular weight; ODP = ozone depletion potential; GWP = global warming potential; SG = ASHRAE safety group classification; HCF = hydrochlorofluoroolefin; HFO = hydrofluoroolefin; HC = hydrocarbon; HFC = hydrofluorocarbon

The COPs and volumetric heating capacities (VHCs) of the MTHP water heaters with different defined configurations and refrigerants were compared, as shown in Figure 9 and Figure 10. The comparison was carried out over the practical operating scenario of the cooling facility in the OLCF Frontier supercomputer data center and the steam–hot water heat exchangers in the 5600-5700-5800 complex. In the operating scenario, an MTHP water heater can harvest the waste heat from the secondary cooling loop (i.e., cool the coolant from 32.0°C to 19.0°C) and delivers the supply heat as hot water (i.e., heats water from 75.0°C to 85.0°C) in the HVAC and hot water distribution networks of the 5600-5700-5800 complex.

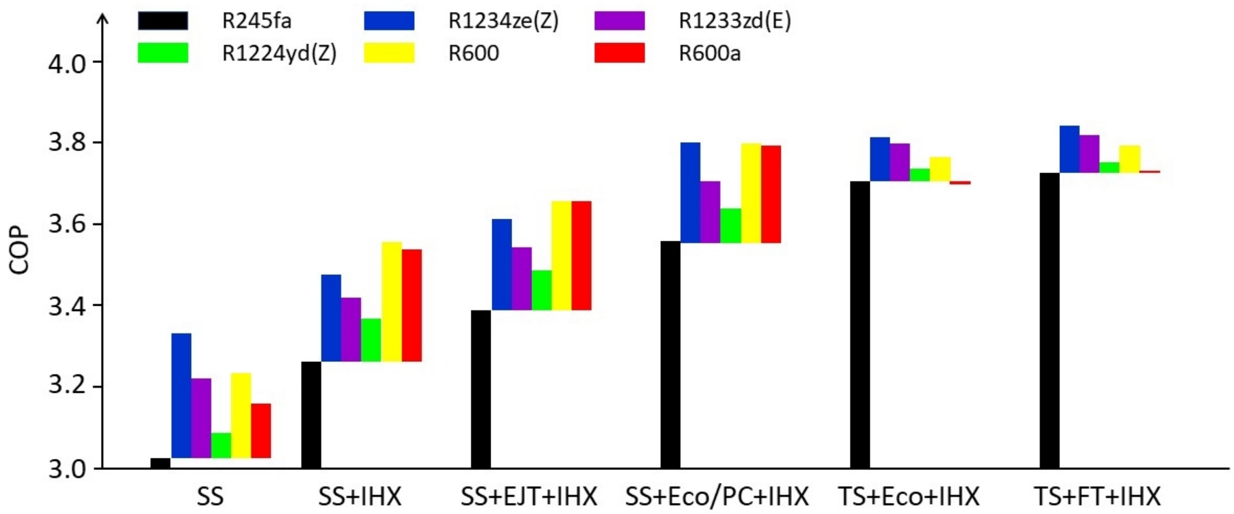
Overall, the performance of R245fa-based MTHP water heaters increases with adding the advanced components proposed in the current studies, as shown in Figure 10. Compared with the basic SS configuration, an IHX and a combination of EJT + IHX increases the COP by 8.4% ± 2.5% and 12.2% ± 2.3%, respectively, and increases the VHC by 13.8% ± 4.1% and 22.5% ± 3.3%, respectively. An additional compressor further improves

- COP by 17.3% ± 2.0% and VHC by 25.5% ± 2.3% for the SS + Eco/PC + IHX configuration,
- COP by 18.4% ± 2.7% and VHC by 19.5 ± 5.1% for the TS + Eco + IHX configuration, and
- COP by 19.2% ± 2.7% and VHC by 20.9 ± 5.2% for the TS + FT + IHX configuration.

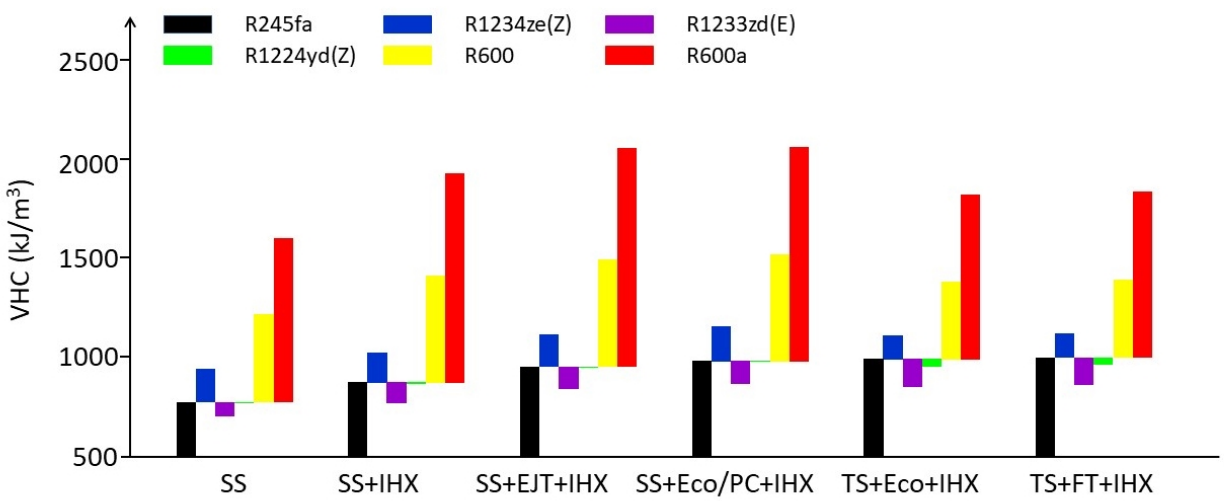
The TS + FT + IHX improves COP the most and achieves the lowest risk of compressor overheating. The SS + EJT + IHX and SS + Eco/PC + IHX offer greater VHC improvements because of the larger volumetric flow in the compressors. TS compressors in a series dramatically improve the COP but slightly reduce the VHC because larger units are required for HSCs. Considering the overall performances of these configurations, the SS + Eco/PC + IHX is the best configuration for MTHPs based on energy savings.

All the low-GWP refrigerants further improve COPs compared with R245fa. Refrigerant R1234ze(Z) provides the highest COPs in the SS + Eco/PC + IHX, TS + Eco + IHX and TS + FT + IHX configurations. Refrigerants R600 and R600a result in slightly higher COPs than R1234ze(Z) in the SS + IHX and SS + EJT + IHX configurations but significantly reduce the COPs of the TS configurations. Regarding VHC, R600 and R600a enable much higher VHC than R245fa, whereas R1233zd(E) and R1224yd(Z) result in lower VHC. Therefore, the trade-off between COP and VHC needs to be considered for these refrigerants. Overall, R600a and R1234ze(Z) show the greatest technical potential in the SS + Eco/PC + IHX configuration.

More details on the parametric studies are included in the manuscript "Advanced Configurations of Industrial Heat Pump Water Heaters with Low-GWP Refrigerants for District Heating Using Data Center Waste Heat," which will be submitted to a peer-reviewed journal.




**(a)**




**(b)**

**Figure 10. Optimum performance of MTWHs with various configurations at $\varepsilon_{IHX,max}$ enabling the cooling process of 32.0°C to 19.0°C and heating water from 75.0°C to 85.0°C. (a) COP and (b) VHC.**

## 4. HEAT PUMP SHOWCASE TOOL

In this project, a comprehensive heat pump (HP) ShowCase tool was developed for evaluating the optimal solution to improve sustainability and decarbonization of the 5600-5700-5800 complex and other buildings on the ORNL campus. It is an Excel-based tool integrated with Visual Basic for Applications (VBA) coding. It can evaluate an innovative and cost-effective solution that uses water-water MTHP technology to leverage the low-grade waste heat from Frontier and ORNL data centers to deliver 85°C hot water, which replaces hot steam generated using natural gas combustion boilers for water heating or space heating in the buildings on the campus.

The HP ShowCase tool comprises five sheets: ReadMe, HPC Waste Heat, Building Selection, Heat Pump Database, and Energy Saving & Decarbonization. The ReadMe sheet, shown in Figure 11, introduces the tool and provides a guide of how to use the tool.

The HPC Waste Heat sheet, shown in Figure 12, provides the HPC and data center energy consumption, coolant flow and temperature, and available waste heat and lists their annual average and maximum values. The sheet has checkboxes that can be used to choose what information is displayed. The 1-year data are attached in the additional sheets named HPC_DATA(FLOW&T2022) and HPC_DATA(POWER2022), which can be used to help check the details of the waste heat.

The Building Selection sheet, shown in Figure 13, was established using the building information collected from ORNL facility information shown on the ORNL Geographic Information System home page [27]. The sheet lists the average and maximum heating demand of each building, which is evaluated based on the recorded 1-year heating data of these buildings. The sheet is designed to select buildings, including single or multiple buildings, that will be considered for replacing hot steam with the waste heat recovered from Frontier using MTHP technologies. The sheet's flexibly allows user-defined building cases to be added.

In the Heat Pump Database sheet, shown in Figure 14, representative commercial MTHPs and ORNL-defined MTHPs with different configurations are listed to offer any potential evaluation. Details on the MTHPs are provided in Section 3, and the key parameters of these MTHP technologies are specified in the sheet. The sheet also allows user-defined heat pump models to be added.

The Energy Saving & Decarbonization Sheet*,* shown in Figure 15, provides the estimated $CO_2$ emission reduction, cost savings, and payback time for any selected MTHP technology and ORNL building for which hot steam generated by natural gas from the ORNL steam plant would be replaced. In the sheet, the default electricity and natural gas prices and their equivalent $CO_2$ emissions and delivery-loss factors are based on US Energy Information Administration data. The parameters can be overwritten with the column of user-defined input.

Overall, the HP ShowCase tool can be widely used or flexibly referenced for heat pump solutions and building decarbonization renovation strategies to modernize ORNL facilities and energy use–intensive equipment to enable efficient, sustainable, and resilient operations in the future.


**Figure 11. HP ShowCase tool: ReadMe sheet.**

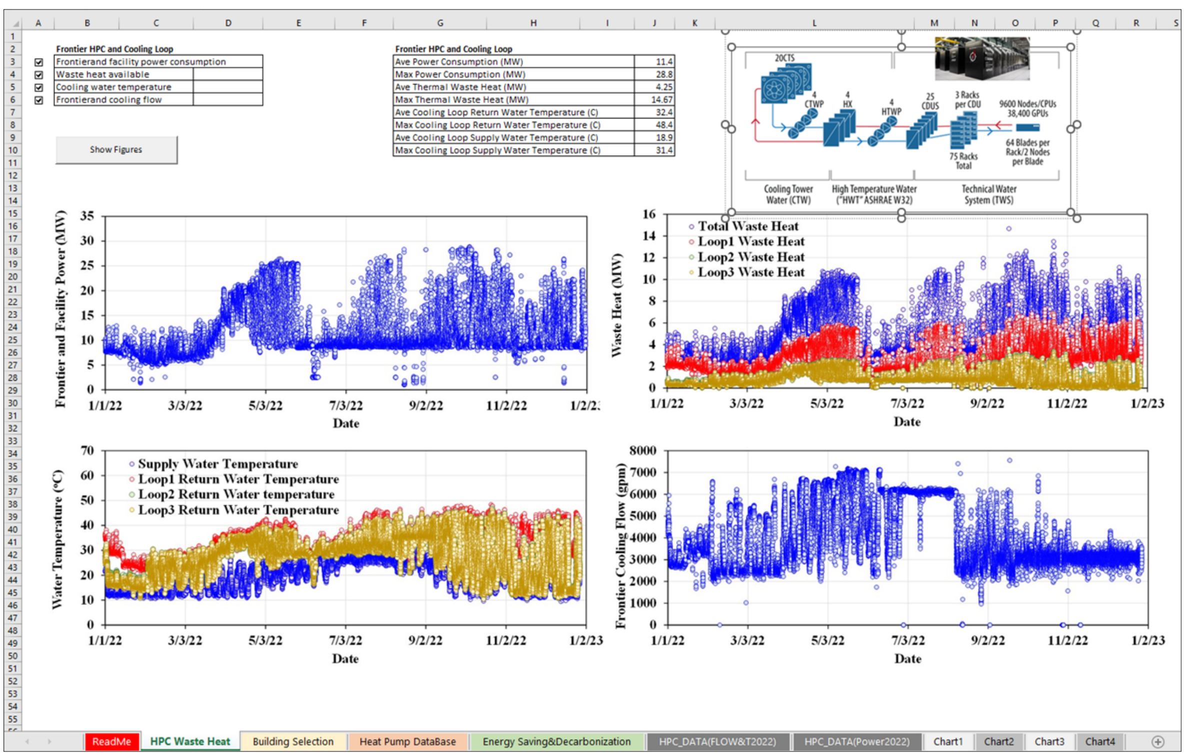
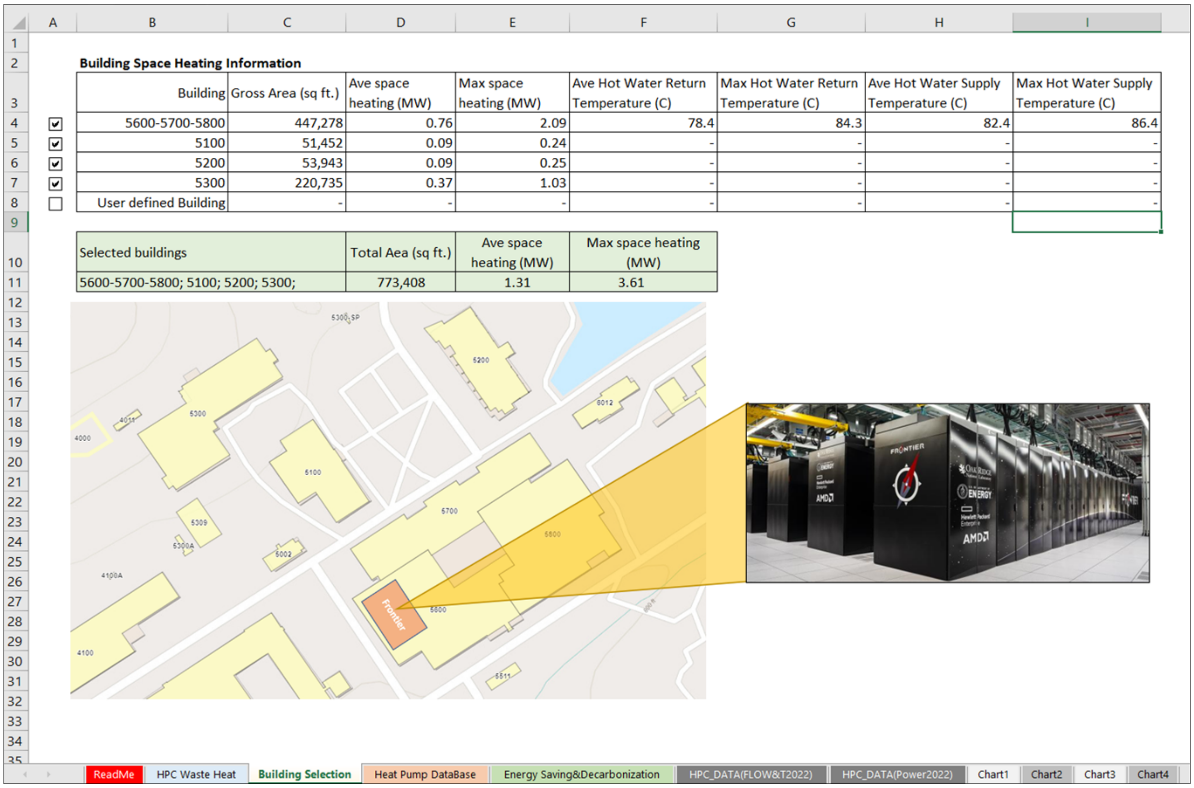



**Figure 12. HP ShowCase tool: HPC Waste Heat sheet.**



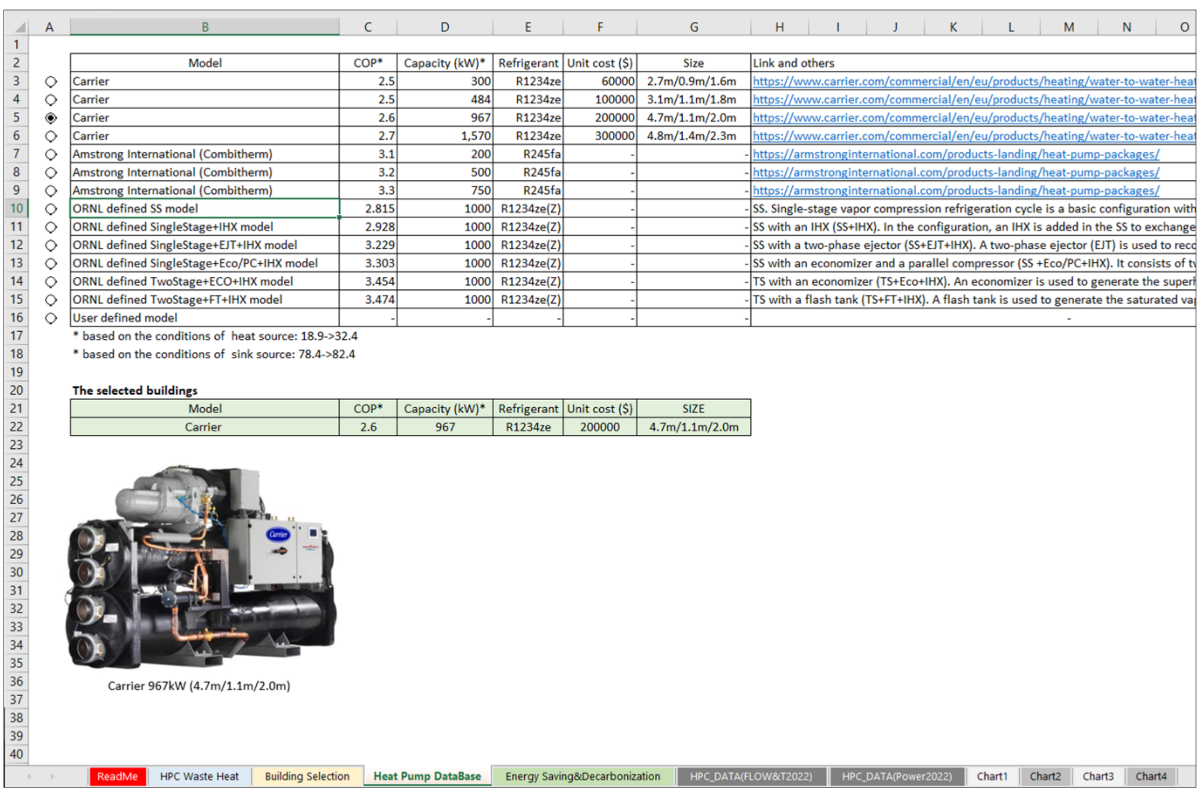
**Building Space Heating Information**

| | Building | Gross Area (sq ft.) | Ave space heating (MW) | Max space heating (MW) | Ave Hot Water Return Temperature (C) | Max Hot Water Return Temperature (C) | Ave Hot Water Supply Temperature (C) | Max Hot Water Supply Temperature (C) |
|---|---|---|---|---|---|---|---|---|
| ☑ | 5600-5700-5800 | 447,278 | 0.76 | 2.09 | 78.4 | 84.3 | 82.4 | 86.4 |
| ☑ | 5100 | 51,452 | 0.09 | 0.24 | - | - | - | - |
| ☑ | 5200 | 53,943 | 0.09 | 0.25 | - | - | - | - |
| ☑ | 5300 | 220,735 | 0.37 | 1.03 | - | - | - | - |
| ☐ | User defined Building | - | - | - | - | - | - | - |

| Selected buildings | Total Aea (sq ft.) | Ave space heating (MW) | Max space heating (MW) |
|---|---|---|---|
| 5600-5700-5800; 5100; 5200; 5300; | 773,408 | 1.31 | 3.61 |



Figure 13. HP ShowCase tool: Building Selection sheet.



| | Model | COP* | Capacity (kW)* | Refrigerant | Unit cost ($) | Size | Link and others |
|---|---|---|---|---|---|---|---|
| ○ | Carrier | 2.5 | 300 | R1234ze | 60000 | 2.7m/0.9m/1.6m | https://www.carrier.com/commercial/en/eu/products/heating/water-to-water-heat |
| ○ | Carrier | 2.5 | 484 | R1234ze | 100000 | 3.1m/1.1m/1.8m | https://www.carrier.com/commercial/en/eu/products/heating/water-to-water-heat |
| ◉ | Carrier | 2.6 | 967 | R1234ze | 200000 | 4.7m/1.1m/2.0m | https://www.carrier.com/commercial/en/eu/products/heating/water-to-water-heat |
| ○ | Carrier | 2.7 | 1,570 | R1234ze | 300000 | 4.8m/1.4m/2.3m | https://www.carrier.com/commercial/en/eu/products/heating/water-to-water-heat |
| ○ | Amstrong International (Combitherm) | 3.1 | 200 | R245fa | - | - | https://armstronginternational.com/products-landing/heat-pump-packages/ |
| ○ | Amstrong International (Combitherm) | 3.2 | 500 | R245fa | - | - | https://armstronginternational.com/products-landing/heat-pump-packages/ |
| ○ | Amstrong International (Combitherm) | 3.3 | 750 | R245fa | - | - | https://armstronginternational.com/products-landing/heat-pump-packages/ |
| ○ | ORNL defined SS model | 2.815 | 1000 | R1234ze(Z) | - | - | SS. Single-stage vapor compression refrigeration cycle is a basic configuration with |
| ○ | ORNL defined SingleStage+IHX model | 2.928 | 1000 | R1234ze(Z) | - | - | SS with an IHX (SS+IHX). In the configuration, an IHX is added in the SS to exchange |
| ○ | ORNL defined SingleStage+EJT+IHX model | 3.229 | 1000 | R1234ze(Z) | - | - | SS with a two-phase ejector (SS+EJT+IHX). A two-phase ejector (EJT) is used to reco |
| ○ | ORNL defined SingleStage+Eco/PC+IHX model | 3.303 | 1000 | R1234ze(Z) | - | - | SS with an economizer and a parallel compressor (SS +Eco/PC+IHX). It consists of t |
| ○ | ORNL defined TwoStage+ECO+IHX model | 3.454 | 1000 | R1234ze(Z) | - | - | TS with an economizer (TS+Eco+IHX). An economizer is used to generate the superh |
| ○ | ORNL defined TwoStage+FT+IHX model | 3.474 | 1000 | R1234ze(Z) | - | - | TS with a flash tank (TS+FT+IHX). A flash tank is used to generate the saturated va |
| ○ | User defined model | - | - | - | - | - | - |

* based on the conditions of heat source: 18.9->32.4

* based on the conditions of sink source: 78.4->82.4

**The selected buildings**

| Model | COP* | Capacity (kW)* | Refrigerant | Unit cost ($) | SIZE |
|---|---|---|---|---|---|
| Carrier | 2.6 | 967 | R1234ze | 200000 | 4.7m/1.1m/2.0m |



Figure 14. HP ShowCase tool: Heat Pump Database sheet.

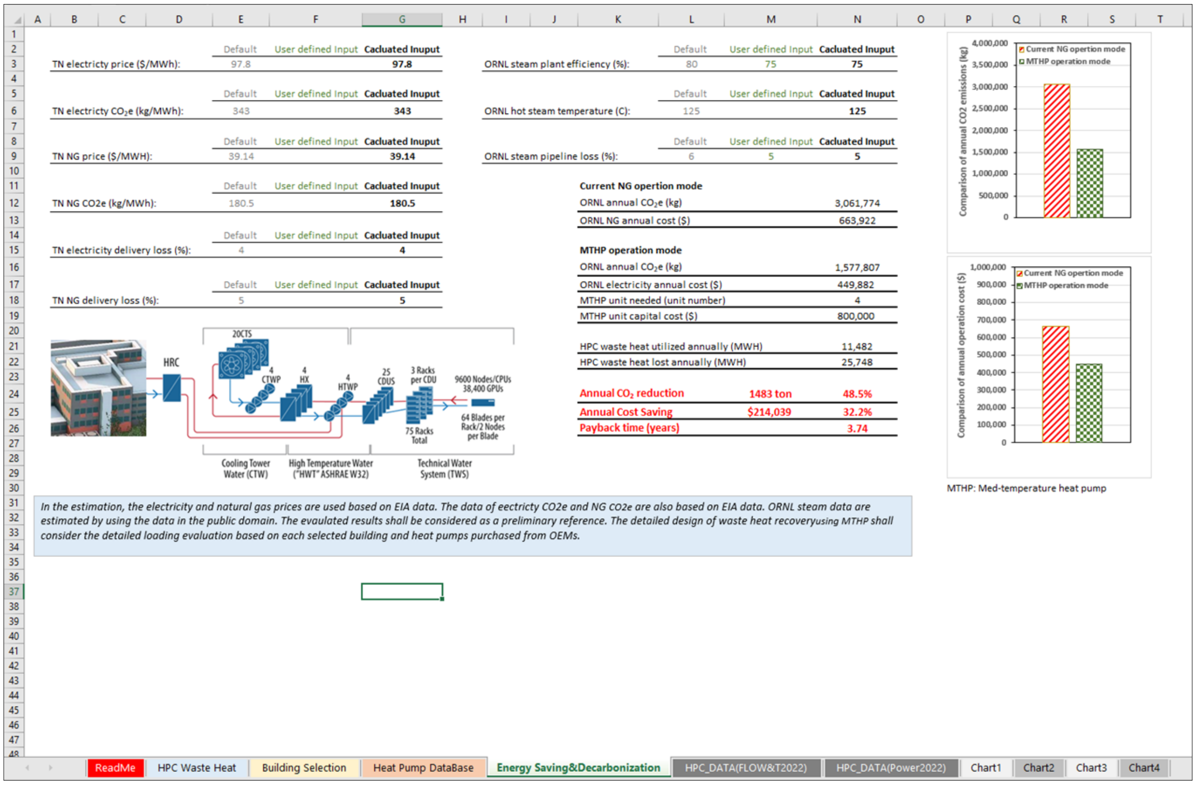



**Figure 15. HP ShowCase tool: Energy Saving & Decarbonization sheet.**

## 5. CASE STUDIES FOR THE SUSTAINABILITY AND DECARBONIZATION OF ORNL CAMPUS BUILDINGS

Using the HP ShowCase Tool, two scenarios (shown in Table 3) were considered to evaluate the sustainability and decarbonization of the ORNL campus. Table 4 shows the 1,000 kW water-water MTHP used for waste heat recovery and efficiently delivering 85°C hot water for direct water and space heating in the scenarios. Because R1234ze improves COP, all the refrigerants considered in both case studies are R1234ze.

**Table 3. Two scenarios evaluated using the HP ShowCase Tool**

| Case | Buildings | Total area (ft$^2$) |
|---|---|---|
| Case A | 5600-5700-5800 complex | 447,278 |
| Case B | 5600-5700-5800 complex, 5100, 5200, 5300 | 773,408 |

**Table 4. MTHP technologies considered for the applications of ORNL campus building decarbonization**

| | |
|---|---|
| **Commercial MTHP technology** | Carrier's AquaForce PUREtec 61XWHZE-1000 |
| **ORNL-defined MTHP technology** | ORNL-defined SS model |
| | ORNL-defined SS + IHX model |
| | ORNL-defined SS + EJT + IHX model |
| | ORNL-defined SS + Eco/PC + IHX model |
| | ORNL-defined TS + ECO + IHX model |
| | ORNL-defined TS + FT + IHX model |

## 5.1 IMPACT OF THE COMMERCIAL MTHP UNIT

Figure 16 shows the results of Carrier's commercial water-water 1,000 kW MTHP technology on $CO_2$ emission reduction, operating cost savings, and waste heat recovery for delivering 85°C hot water for space and water heating in the 5600-5700-5800 complex. In the case studied, the team assumed use the 1,000 kW water-water MTHP to achieve waste heat recovery and deliver 85°C hot water for direct water and space heating in the 5600-5700-5800 complex. Briefly, the water-water MTHP uses an evaporator to extract energy from the 32°C water heat source from Frontier and the ORNL data center and to transform it into a refrigerant gas. The compressor compresses the refrigerant gas, which raises its temperature, and the condenser exchanges the heat from the refrigerant to the 85°C heat sink used for water and space heating in the complex while the refrigerant gas returns to a liquid state. Finally, the expansion valve lowers the pressure of the refrigerant, which triggers evaporation, and then the cycle begins again. The solution efficiently recovers the waste heat of Frontier and the ORNL data center for water and space heating in the complex instead of using hot steam generated by natural gas boilers. The strategy achieves more than 6,640 MWh/year energy savings and a 858 $TCO_2e$/year $CO_2$ emission reduction, thus improving the sustainability and decarbonization of the 5600-5700-5800 complex. Currently, steam that is consumed is transported from the ORNL steam plant located 1 mi away from the 5600-5700-5800 complex, whereas the proposed water-water MTHP could be placed next to the complex. The installation and maintenance cost of a long-distance pipeline is expensive, and the pipeline also leads to significant transportation losses of approximately 8%. The evaluated solution can reduce the operation cost of the complex by approximately \$0.12 million annually. Thus, it can substantially improve energy efficiency while also reducing operation costs of the 5600-5700-5800 complex.

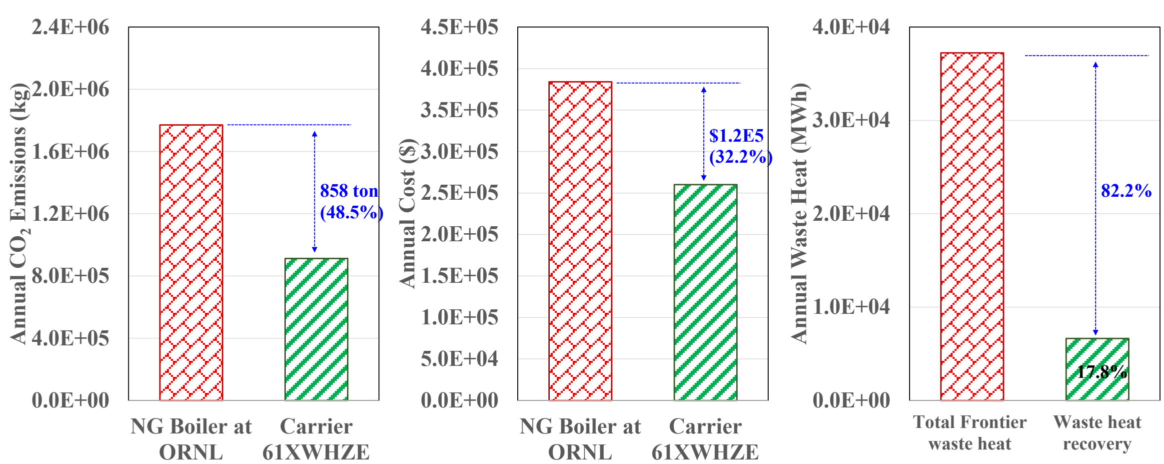



**Figure 16. Impact of Carrier water-water MTHP on annual $CO_2$ emission reduction, operating cost savings, and waste heat recovery for delivering 85°C hot water used in the 5600-5700-5800 complex.**

However, Figure 16 also shows that the waste heat recovered from Frontier and the ORNL data center is just around 18%. Thus, the waste heat recovery solution was extended to other buildings on the ORNL campus. Figure 17 shows the extended solution for waste heat recovery, in which the 5600-5700-5800 complex and Buildings 5100, 5200, and 5300 were considered. In this scenario, the waste heat recovered from Frontier approaches 30.8% (i.e., 11,482 MWh/year energy savings), the $CO_2$ emission reduction is 1,483 $TCO_2$e/year, and the operating cost savings are \$0.21 million annually.

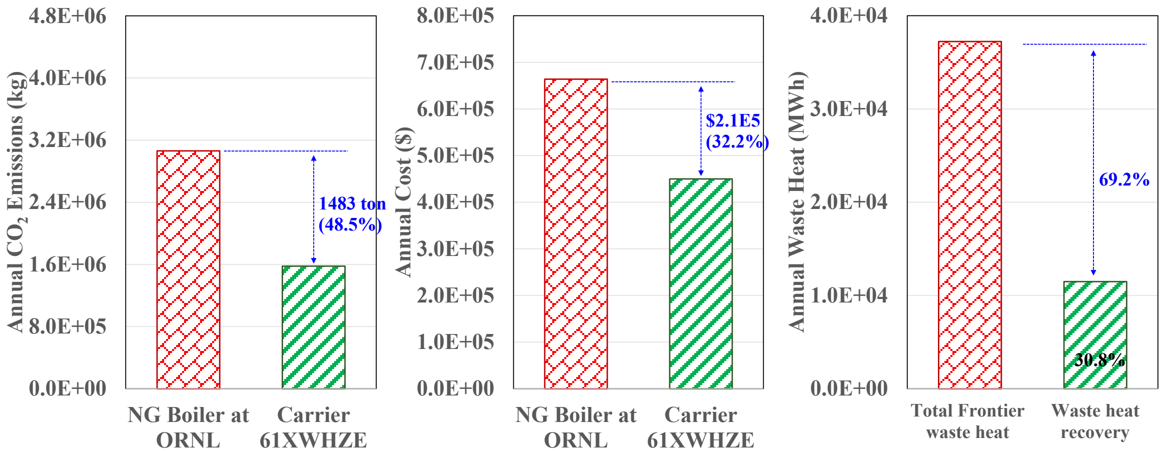



**Figure 17. Impact of Carrier water-water MTHP on annual $CO_2$ emission reduction, operating cost savings, and waste heat recovery for delivering 85°C hot water used in the 5600-5700-5800 complex and Buildings 5100, 5200, and 5300.**

The capital cost for the Carrier 61XWHZE-1000 is \$200,000. Table 5 summarizes the commercial unit needs and payback times for the two scenarios. The payback times are reasonable to invest considering the substantial carbon footprint reductions. Moreover, more waste heat recovery will significantly reduce payback times. The team believes that the waste heat recovery from Frontier and the ORNL data center can be used for space and water heating in 4500S and 4500N in addition to the 5600-5700-5800 complex and Buildings 5100, 5200, and 5300. Maximizing waste heat recovery can reduce payback times while maximizing the sustainability and decarbonization of the ORNL campus.

**Table 5. The commercial unit need and payback time for the two scenarios**

| Case | Buildings | MTHP units needed | Payback time (years) |
|---|---|---|---|
| Case A | 5600-5700-5800 | 3 | 4.85 |
| Case B | 5600-5700-5800, 5100, 5200, 5300 | 4 | 3.74 |

## 5.2 POTENTIAL IMPACT OF ORNL-DEFINED MTHP TECHNOLOGIES

The potential impacts of ORNL-defined MTHP technologies were also evaluated. The results are shown in Figure 18 and Figure 19. In the simulation of case A (Figure 18), the annual $CO_2$ emission reduction is 927–1,087 tons, or 52.4%–61.4% $CO_2$ emissions reduction compared with natural gas boilers. The annual cost savings are around \$0.14–\$0.19 million. $CO_2$ reduction and cost savings are enhanced with the addition of the advanced components, but only slightly. Therefore, considering the complex control and the costs of the additional components, adding advanced components to the MTHPs may not be cost-effective

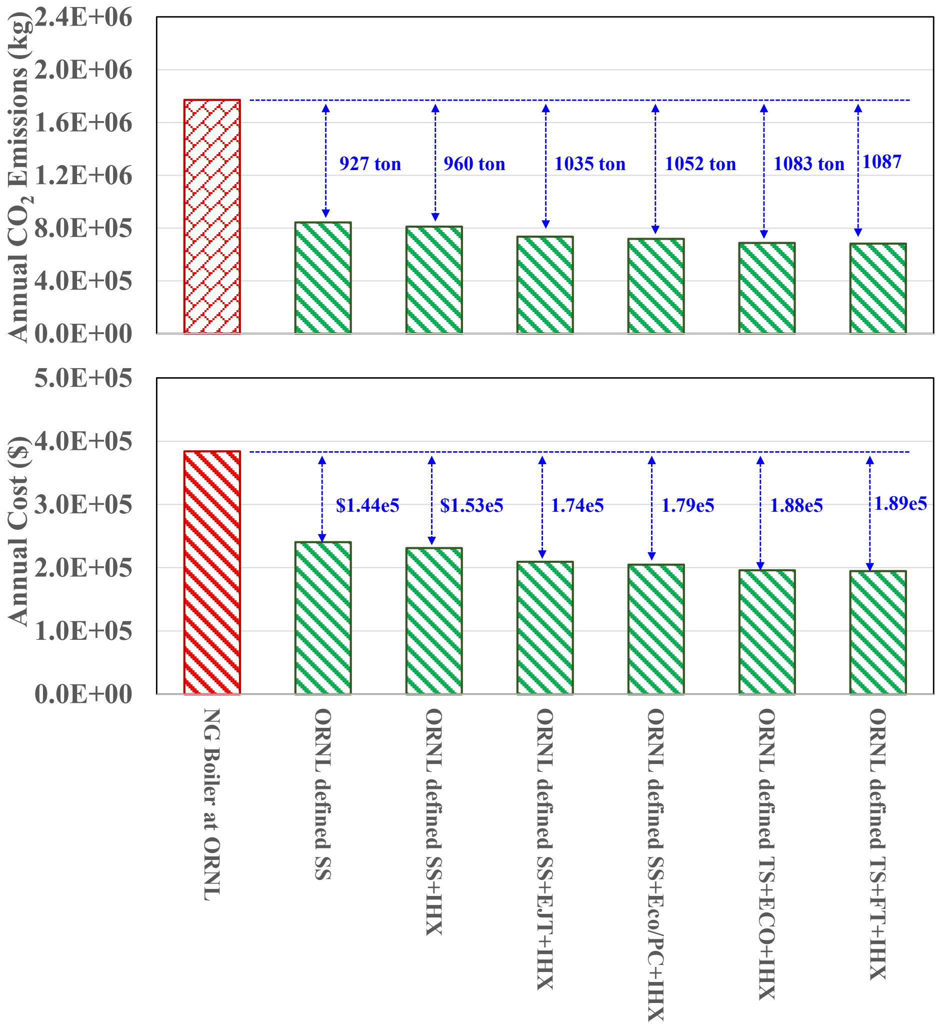



**Figure 18. Impacts of ORNL-defined MTHP technologies on annual $CO_2$ emission reduction and operating cost savings for delivering 85°C hot water used in the 5600-5700-5800 complex.**

Figure 19 shows the impacts of ORNL-defined MTHP technologies on annual $CO_2$ emission reduction and operating cost savings for the 5600-5700-5800 complex and Buildings 5100, 5200, and 5300. Compared with case A, $CO_2$ reduction and cost savings in case B are increased to 1,604–1,880 tons and $0.24–$0.33 million, respectively, because of increased waste heat recovery for the 5600-5700-5800 complex and Buildings 5100, 5200, and 5300. However, the benefits of adding the advanced components are similar to the results shown in Figure 18.

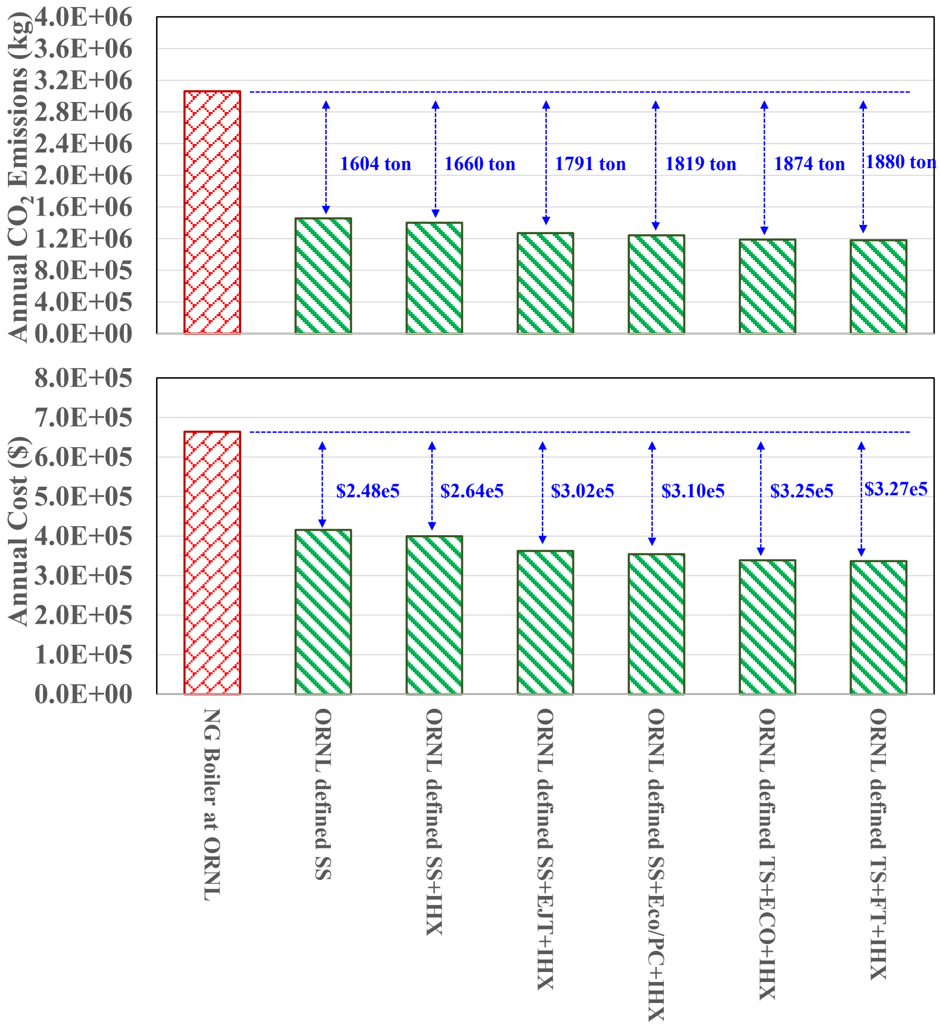



**Figure 19. Impacts of ORNL-defined MTHP technologies on annual $CO_2$ emission reduction and operating cost savings for delivering 85°C hot water used in the 5600-5700-5800 complex and Buildings 5100, 5200, and 5300.**

## 6. CONCLUSION

To support ORNL's Sustainable Campus Initiative goals of reducing GHG emissions, this project explored solutions involving MTHPs using low-GWP refrigerants. The team

- collected the comprehensive energy data set of Frontier and the data center system;
- collected building information for the ORNL campus and established a building library;
- collected commercial MTHP technologies, developed ORNL-defined MTHP technologies, and built these technologies into a MTHP library; and
- carried out case studies for the sustainability and decarbonization of ORNL campus buildings.

The building library and MTHP library can be flexibly extended in future needs. The team collected 1 year of real-time Frontier system measurements from January 1, 2022, to December 31, 2022, and characterized energy performance, including power consumption, power usage effectiveness, waste heat generation, and waste heat temperature levels. The annual power consumption for Frontier was $1 \times 10^8$ kWh, which is the total electricity usage of 9,422 US homes. The Frontier system's monthly average power consumption was 6.5–16.5 MW. The minimum waste heat available was typically 2 MW but could be up to 14 MW, which is a substantial heat source for ORNL campus district heating. In addition, the annual average coolant supply and return temperatures were 18.9°C and 32.4°C, respectively.

Commercial MTHPs recovering the waste heat generated by the data center were collected. The MTHPs can be classified into SS, TS, and MS systems and by advanced components such as IHX, Eco, and FT. The COPs of these MTHPs are around 2.3–4.4. To understand the impact of adding advanced components to MTHPs, ORNL developed five advanced configurations of MTHPs along with five low-GWP refrigerants to upgrade the waste heat from Frontier and the ORNL data center for building-space and water heating.

Two scenarios were studied. In case A, which considered the 5600-5700-5800 complex only, Carrier's commercial 1,000 kW MTHP technology achieves more than 6,640 MWh/year energy savings and a 858 $TCO_2e$/year $CO_2$ emission reduction. The solution reduces the operating cost of the complex by approximately $0.12 million annually, and the payback time is 4.85 years. In case B, which considered the 5600-5700-5800 complex and Buildings 5100, 5200, and 5300, the $CO_2$ emission reduction is 1,483 $TCO_2e$/year, the operating cost savings are $0.21 million annually, and the payback time is 3.74 years. Overall, maximizing waste heat recovery can reduce payback times while benefiting the sustainability and decarbonization of the ORNL campus.

Also, ORNL-defined MTHPs were evaluated to understand their impacts on $CO_2$ emissions reduction and cost savings for the 5600-5700-5800 complex and Buildings 5100, 5200, and 5300. $CO_2$ reduction and cost savings are enhanced with the addition of the advanced components, but only slightly. Therefore, considering the complex control and the costs of the additional components, adding advanced components to the MTHPs may not be cost-effective

In this project, a comprehensive HP ShowCase tool was developed for evaluating the optimal solution to improve sustainability and decarbonization of buildings in the campus. It is an Excel-based tool integrated with VBA coding. The tool was used to evaluate the sustainability and decarbonization of the ORNL campus. The tool can be widely used or referenced for heat pump solutions and building decarbonization renovation strategies to modernize other ORNL facilities and energy use–intensive equipment to enable efficient, sustainable, and resilient operations in the future.

In the project, collecting building data about heating and hot water demand posed notable difficulties within the constraints of the project's tight timeline. Nonetheless, this issue could potentially be addressed in a subsequent phase. Additionally, it might be beneficial to consider extending this analysis to other nearby buildings, especially those located in the district of 5600-5700-5800, to achieve the clean and sustainable district heating in ORNL main campus.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] Oak Ridge National Laboratory. n.d. "High-Performance Computing at ORNL." https://my.matterport.com/show/?m=iBfbj7ET4LT.

[2] Turczyn, C. 2021. "Pioneering Frontier: Planning Ahead." https://www.olcf.ornl.gov/2021/02/18/pioneering-frontier-planning-ahead/.

[3] Baxter, V.D., J. D. Munk. 2017. "Field Testing of Two Prototype Air-Source Integrated Heat Pumps for Net Zero Energy Home (nZEH) Application." *IEA Heat Pump Centre Newsletter* 35(3).

[4] Tomlinson, J.J., C.K. Rice, R.W. Murphy, Z. Gao. 2005. Assessment and Initial Development of a Small, High-Efficiency Heat Pump System for NZEH, September. https://ornl.sharepoint.com/sites/cerd/StyleGuide/SitePages/References%20and%20Citations.aspx

[5] ASHRAE. 2021. *2021 Equipment Thermal Guidelines for Data Processing Environments*.

[6] US Energy Information Administration. n.d. "How much electricity does an American home use?" https://www.eia.gov/tools/faqs/faq.php?id=97&t=3.

[7] Aguilera, J. J., W. Meesenburg, T.n Ommen, W. B. Markussen, J. L. Poulsen, B. Zühlsdorf, and B. Elmegaard. 2022. "A Review of Common Faults in Large-Scale Heat Pumps." *Renewable and Sustainable Energy Reviews* 168: 112826.

[8] Jesper, M., F. Schlosser, F. Pag, T. G. Walmsley, B. Schmitt, and K. Vajen. 2021. "Large-Scale Heat Pumps: Uptake and Performance Modeling of Market-Available Devices." *Renewable and Sustainable Energy Reviews* 137: 110646.

[9] Arpagaus, C. 2019. "From Waste Heat to Cheese." *HPT Mag* 37: 23–26. https://heatpumpingtechnologies.org/publications/from-waste-heat-to-cheese

[10] Eurammon. 2020. *HC Heat Pumps for Light Industrial Applications – One Key Technology for Sustainable Heating Solutions*. Eurammon Web Symposium. https://www.eurammon.com/images/eurammon/events/symposium-2020/presentations/Day-6-Renz-Hydrocarbon-Heat-Pumps-for-Light-Industrial-Applications.pdf.

[11] Automating Heating. n.d. "Revere™ R134A Water to Water Heat Pump." https://www.automaticheating.com.au/product/revere-r134a-water-to-water-heat-pump/#tab-2-2.

[12] He, Y., F. Cao, L. Jin, D. Yang, X. Wang, and Z. Xing. 2017. "Development and field test of a High-Temperature Heat Pump Used in Crude Oil Heating." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* 231(3): 392–404.

[13] Wu, X., Z. Xing, Z. He, X. Wang, and W. Chen. 2016. "Performance Evaluation of a Capacity-Regulated High Temperature Heat Pump for Waste Heat Recovery in Dyeing Industry." *Applied Thermal Engineering* 93: 1193–1201.

[14] York. n.d. "Titan™ OM Custom Design Centrifugal Chiller." https://www.york.com/commercial-equipment/chilled-water-systems/water-cooled-chillers/om_ch/titan-om-custom-design-centrifugal-chiller.

[15] Industrial & Commercial Heat Pump Working Group. 2022. *Large Scale Heat Pumps in Europe: Real Examples of Heat Pump Applications in Several Industrial Sectors*, Vol. 2. European Heat Pump Association. https://www.ehpa.org/wp-content/uploads/2022/11/Large-heat-pumps-in-Europe-and-industrial-uses_2020.pdf.

[16] Enertime. n.d. "Reinforce the Carbon Neutrality of District Heating Networks." https://www.enertime.com/en/applications/district-heating.

[17] Carrier. n.d. "AquaForce® - High temperature water-sourced heat pump using HFO R-1234ze refrigerant 61XWHZE." Carrier Air Conditioning and Heating Systems – Europe. https://www.carrier.com/commercial/en/eu/products/heating/water-to-water-heat-pumps/61xwhze/.

[18] Trane. n.d. *Trane XStream: Water-Cooled Screw Chillers and Water/Water Heat Pumps*. Trane Technologies. https://www.tranebelgium.com/files/product-doc/348/fr/RLC-SLB040-GB-0920.pdf.

[19] Armstrong International. 2022. *Armstrong+COMBITHERM High-Temperature Industrial Heat Pumps*. https://armstronginternational.kr/wp-content/uploads/Broch_HighTemperatureIndustrialHeatPumps_149_EMEA_EN_20220725.pdf.

[20] Siemens Energy. n.d. "Large-Scale Industrial Heat Pumps." https://www.siemens-energy.com/global/en/offerings/power-generation/heat-pumps.html.

[21] https://www.viessmann.se/content/dam/vi-brands/SE/Broschyrer/Varmepumpar/Luft-luft/Vitocal-Pro/Heat_pumps_up_to_2000%20kW.pdf/_jcr_content/renditions/original.media_file.download_attachment.file/Heat_pumps_up_to_2000%20kW.pdf

[22] Oue, T., and K. Okada. 2013. "Air-Sourced 90 C Hot Water Supplying Heat Pump 'HEM-90A'." *Kobelco Technology Review* 32: 70–74.

[23] Mitsubishi Heavy Industries. 2011. "Heat Application Technology by Centrifugal Heat Pump ETW Series for Hot Water – Continuous Supply of Hot Water at temperature of 90°C." *Technical Review* 48(2).

[24] Wilk, V., J. Kramer, A. Arnitz, and R. Riebere. 2019. *Annex 48 IHP, Second Phase. Task 2 Structuring Information on IHP and Preparation Guidelines*. Austrian Report.

[25] Mateu-Royo, C., C. Arpagaus, A. Mota-Babiloni, J. Navarro-Esbrí, and S. S. Bertsch. 2021. "Advanced High Temperature Heat Pump Configurations Using Low GWP Refrigerants for Industrial Waste Heat Recovery: A Comprehensive Study." *Energy Conversion and Management* 229: 113752.

[26] Wei, F., B. Wang, Z. Cheng, and M. Cui. 2023. "Experimental Research on Vapor-Injected Water Source Heat Pump Using R1234ze (E)." *Applied Thermal Engineering* 229: 120595.

[27] Oak Ridge National Laboratory. n.d. "Oak Ridge National Laboratory Facility Information." ORNL Campus Features GIS Site. https://gis.ornl.gov/portal/apps/sites/#/campusfeatures/apps/30dd35a811554b91a36afe964a25786d/explore.

# APPENDIX A.

**Simulation Tool**

- **HP ShowCase tool**: a comprehensive HP ShowCase tool was developed for evaluating the optimal solution to improve sustainability and decarbonization of buildings on the ORNL campus. The tool is an Excel-based tool integrated with VBA coding. The tool was used to evaluate the sustainability and decarbonization of the ORNL campus. The tool can be widely used or referenced for heat pump solutions and building decarbonization renovation strategies to modernize other ORNL facilities and energy use–intensive equipment to enable efficient, sustainable, and resilient operations in the future.

**Publications**

- "Advanced Configurations of Industrial Heat Pump Water Heaters with Low-GWP Refrigerants for District Heating Using Data Center Waste Heat," under preparation for the *International Journal of Refrigeration*

- "Energy Dataset of Frontier Supercomputer for Waste Heat Recovery," under preparation for *Scientific Data*.