CSU Decarbonization Framework
Task 5: Conceptual Recommendations

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Section 5.1: Introduction

Task 5 – Conceptual Recommendations provides a framework for campuses in the California State University (CSU) system to approach decarbonizing existing fossil fuel-based heating systems. The recommendations outlined in this report includes an overview of potential strategies that can be implemented to reduce carbon emissions on campus and best practices for developing a long-term campus decarbonization plan. This includes engaging campus stakeholders, understand existing conditions and operations and taking steps to improve the cost effectiveness of electrification strategies. The report is broken into the following sections.

5.2 – Campus Decarbonization Process
This section outlines a recommended process for campuses to approach the assessment and planning. This section includes universal recommendation that every campus can take to ready and optimize their campus for decarbonization

5.3 – CUP Decarbonization Strategies
This section outlines five viable strategies for establishing a low-to-no carbon heating system, all of which could be applicable to any CSU campus. These combine technologies outlined previously in Task 4 – Technology Review with design criteria and provide an overview into designs of different decarbonized strategies

5.4 – Conceptual Recommendations
Addresses each of these strategies as the apply to the given infrastructure types on CSU campuses

Recommendations in this Task include immediate actions campuses can take to plan and prepare for a long-term, phased decarbonization of the campus. In many cases, it is not economically viable to retire existing fossil fuel-based heating systems before the end of their useful lives. However, there are various steps campus can take now to improve operational efficiency of existing systems and prepare for the future implementation of infrastructure upgrades to reduce carbon emissions. As part of this process, it is critical to develop a clear understanding of existing conditions and a vision for a fossil fuel free campus to prevent investing in the prolonged life of existing fossil fuel-based heating systems. Replacement plans should be in place to install decarbonized heating systems as equipment begin reach the end of its useful life.

Section 5.2: Campus Decarbonization Process

The section of the report outlines a universal framework for CSU campuses to approach the process of cost effectively decarbonize existing fossil fuel (natural gas) systems. The diagram below provides an overview of the recommended campus decarbonization stages for CSU campuses to follow.

While many campuses have already started to seriously address their direct carbon emission from campus operations (scope 1 emissions) through strategies such as energy efficiency and electrification, it is important to establish a long-term vision and strategy early on to ensure that all infrastructure investments are in the best long term interest of a campus. Developing this strategy starts with a data driven campus assessment and decarbonization planning process to systematically evaluate the existing conditions and establish a viable path towards meeting climate action targets.

The integration of technologies and strategies to decarbonize CSU campuses will be a phased, long term implementation as existing infrastructure reaches the end of its useful life and funding becomes available. This includes projects to reduce heating loads, electrify heating systems and to optimization central utility system and building controls to improve the efficiency of new heat pump technologies.

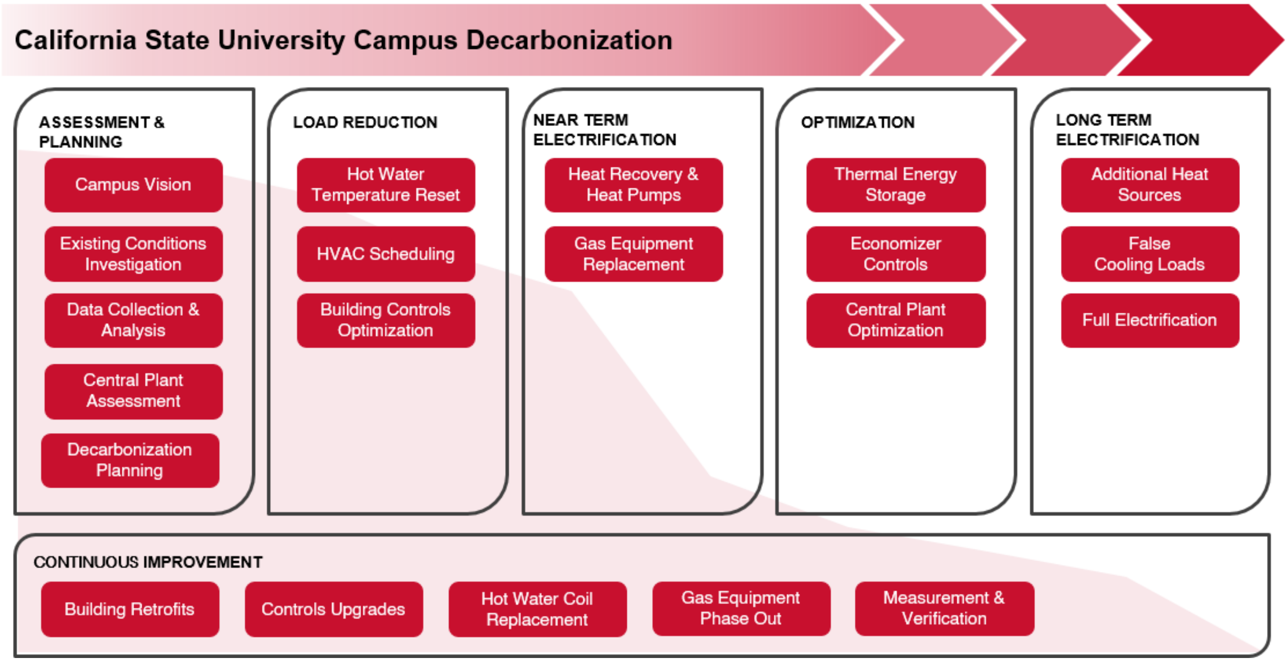
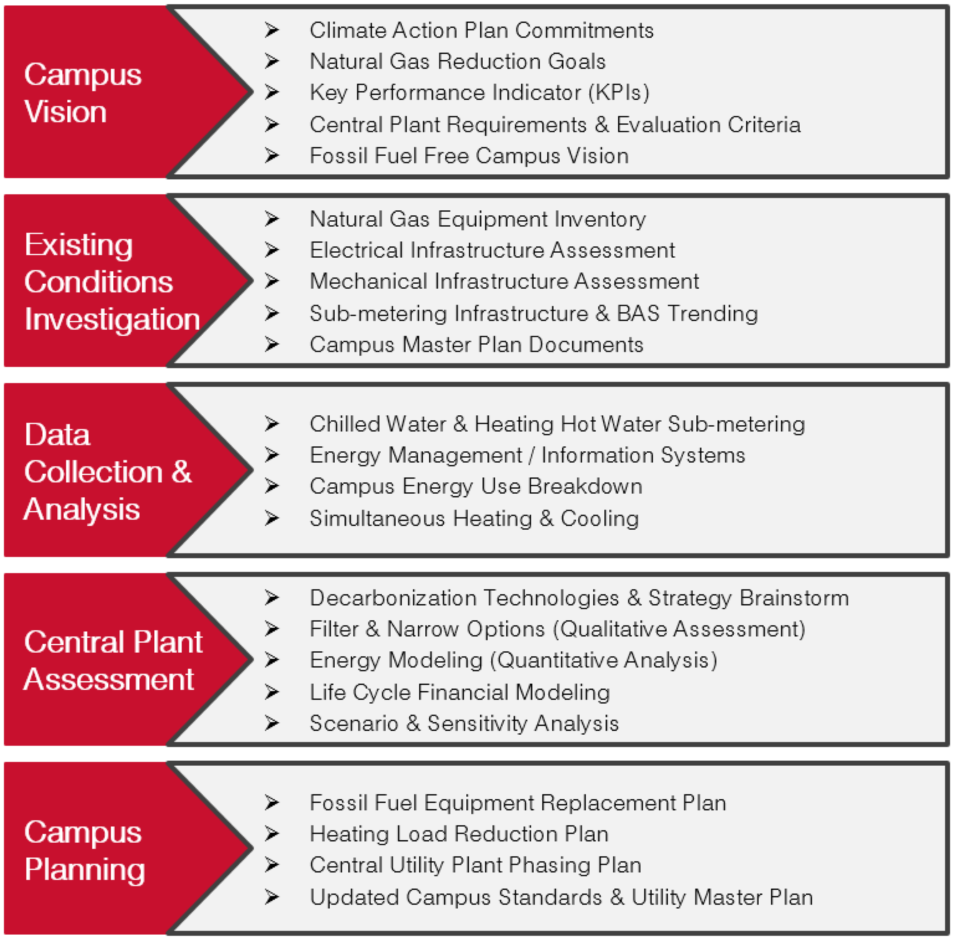


Figure 5.1: CSU System Decarbonization Framework

5.2.1 Assessment & Planning

The following section outlines an Assessment & Planning process that campus can adopt to begin establishing a pathway to decarbonize their campus. This includes both high level tactics and specific tasks that can support developing an implementation plan and getting buy in across campus.



Campus Vision

- Climate Action Plan Commitments
- Natural Gas Reduction Goals
- Key Performance Indicator (KPIs)
- Central Plant Requirements & Evaluation Criteria
- Fossil Fuel Free Campus Vision

Existing Conditions Investigation

- Natural Gas Equipment Inventory
- Electrical Infrastructure Assessment
- Mechanical Infrastructure Assessment
- Sub-metering Infrastructure & BAS Trending
- Campus Master Plan Documents

Data Collection & Analysis

- Chilled Water & Heating Hot Water Sub-metering
- Energy Management / Information Systems
- Campus Energy Use Breakdown
- Simultaneous Heating & Cooling

Central Plant Assessment

- Decarbonization Technologies & Strategy Brainstorm
- Filter & Narrow Options (Qualitative Assessment)
- Energy Modeling (Quantitative Analysis)
- Life Cycle Financial Modeling
- Scenario & Sensitivity Analysis

Campus Planning

- Fossil Fuel Equipment Replacement Plan
- Heating Load Reduction Plan
- Central Utility Plant Phasing Plan
- Updated Campus Standards & Utility Master Plan

Figure 5.2: Decarbonization Planning Framework

Campus Vision

Reducing Scope 1 emissions will require support from many stakeholders across various campus groups. It is important to develop a central vision around a fossil fuel free campus to gain support around the work required for decarbonizing existing infrastructure. This process should be an inclusive process and include input from various campus stakeholders and should outline what the campus considers key when assessing various pathways towards reducing Scope 1 emissions (cost of carbon, financial rates, O&M impact, etc.). Ensuring the campus vision is agreed upon among the key decision makers, such as the Chief Engineer, Director of Facilities Operations, Executive Facilities Officer and Vice President of Admin & Finance is of particular importance as it will be these groups who are responsible for decision making. Campuses must also establish a mutually agreed upon framework for evaluating system, technologies and operational policies will improve the ability to communicate the value of decarbonizing campus utilities. It is recommended that each campus develop a unique framework, tailored to specific constraints and conditions. The following actions should also be included as part of this process.

- Develop requirements and evaluation criteria for assessing future infrastructure investments
- Establish long-term natural gas reduction goals based on existing climate action commitments
- Establish key performance indicators (KPIs) to continually track progress

Existing Conditions Investigation

It is essential to understand how their campus operates and the opportunities to decarbonize across the building stock. Whether individual buildings, groups of buildings or the Central Utility Plant (CUP), different locations on campus will offer different opportunities to decarbonize and at different phases.

The potential to reduce Scope 1 GHG emissions at each CSU campus will vary depending on building operations, climate zone and type, or lack, of centralized heating systems. It is recommended that each campus conduct these following tasks as soon as possible to determine the realistic Scope 1 GHG emission reduction targets for the campus.

Table 5.1: Existing Conditions Investigation Tasks

Task	Actions	Reason
Fossil Fuel Equipment Inventory	Develop comprehensive list of all existing natural gas equipment on campus, including: Condition of equipment • Age of equipment • Expected useful life expectancy	Help each campus target systems that are at, or nearing, the end of the life. Decommissioning equipment in good working condition is not recommended. Assessing the age and condition of all existing equipment will allow campuses to target specific buildings/section of campus and/or systems for decarbonization
Electrical Infrastructure	Conduct an electrical infrastructure assessment to determine if it has sufficient electrical capacity on campus to electrify heating systems Understand campus/building requirements (Resiliency Assessment) • Identify critical buildings • Identify 24/7 conditioned facilities	Reducing the emissions of heating systems will require significant electrification across campus. If there is insufficient electrical capacity to support this, infrastructure improvements may be required prior to decarbonization

Mechanical Infrastructure	Conduct a mechanical infrastructure assessment to determine the expected useful life of existing heating equipment and distribution network.	Retiring equipment prior to the end of its useful life will likely not be financially feasible. It is therefore important that each campus understands when their existing equipment will come to the end of its life, allowing for planning and funding to be allocated for decarbonization projects. Additionally, campus distribution networks are a significant source of heat loss and ensuring these are in good condition is key to optimize decarbonization strategies
Campus Master Plan	Determine future building type and location on campus to predict future heating loads and their location	Decarbonized heating system will be required to meet heating loads over the next 50 years. They should therefore be sized to accommodate future loads to minimize requirement for additional equipment being installed in future.

Data Collection & Analysis

Decarbonization will require a fundamental understanding of the campus heating and cooling loads. This understanding, along with that from the electrical infrastructure assessment, will allow campuses to identify areas on campus that are well suited for different forms of decarbonization, such as heat recovery or heat pump technologies.

Table 5.2: Data Collection Tasks

Task	Actions	Reason
Energy Management / Information System	Determine the extent of data that is currently being trended on the campus EMS & set up trends if data is missing. See Simultaneous Heating & Cooling Assessment section for more information	Heating and cooling load profiles are required in order to accurately determine heat recovery potential on campus. The ability of a campus to provide simultaneous heating and cooling will significantly impact the technologies that are best suited for decarbonization
Sub-Metering	Develop / update a master list of campus sub-meters and ensure each is calibrated / working correctly	Determining load profiles not only for the campus CUP (if applicable) but also for individual building / groups of buildings, will be required for full campus decarbonization assessment.
Campus Natural Gas Consumption	Analyze the energy use of the campus, including building level natural gas consumption	Identify where a detailed breakdown for where fossil fuel is consumed on campus

Building Energy Use	Establish energy at major buildings. Include sub-metered data (hot water, steam, chilled water, etc) where available.	Identify problem buildings and ones that could potentially be impacting turndown and/or reset of campus chilled/hot water systems.
Future Campus Loads	Determine future building type and location on campus to predict future heating loads and their location	Decarbonized heating system will be required to meet heating loads over the next 50 years. They should therefore be sized to accommodate future loads to minimize requirement for additional equipment being installed in future.

Simultaneous Heating & Cooling Assessment

After conducting a full analysis of the existing and future building stock, it is recommended that each campus determines their heat recovery potential through assessment of the existing campus heating and cooling load profiles. This will help guide decision on what technology to utilize and whether to centralize or decentralize installations. The following workflow can be used as a guideline of the steps necessary to determine an accurate heating and cooling load profile for the campus.

I. Establish a metering strategy
  a) Any installed meters should comply with the CSU Chancellor Office Energy Metering for Utility Management Guideline. The following process should be followed to ensure accurate load profiles are developed for the campus:
II. Develop comprehensive list of all central plant and/or building level meters
III. Assess condition of all meters and replace if damaged and/or irreparable
IV. Calibrate meters to ensure accuracy
  a) Campuses with centralized heating or cooling systems:
    i) If there are no meters - install where necessary to ensure plant loads can be determined. At minimum, the following meters should be installed:
      (1) Chilled Water – Flow, supply and return temperature
      (2) Hot Water – Flow, supply and return temperature
  b) Campuses with decentralized heating or cooling systems
    i) If there are no meters - install temporary ultrasonic meters to record flowrates and supply and return temperatures for chilled and hot water systems
      (1) Meters should be installed for a minimum of three months during winter months and record at 15-minute intervals
V. Map all meters onto campus EMS and start trending metered data at 15-minute intervals
VI. Heat Recovery Potential analysis
  a) Assess current campus load profiles
  b) Develop future lad profiles based on the campus master plan
  c) Identify and resolve wasted heat issues on campus
  d) Assess the potential future load profiles after optimizing the cooling and heat profiles for heat recovery
VII. Technology assessment

  - Assess what technology is the best fit for the campus based on heat recovery potential and distribution of loads across campus

VIII. Central plant modeling
  - Model selected central plant options to assess total energy consumption and energy cost (including time of use rates)

IX. Assess optimization options (TES, economizer controls)

Central Plant Assessment

After establishing an understanding for the existing conditions and energy uses, campuses should begin to develop a long-term implementation strategy for decarbonizing central heating systems. Campuses should identify all potential technologies and strategies and narrow these down based on an established set of criteria. A detailed evaluation should then be provided to establish the what is the most viable options.

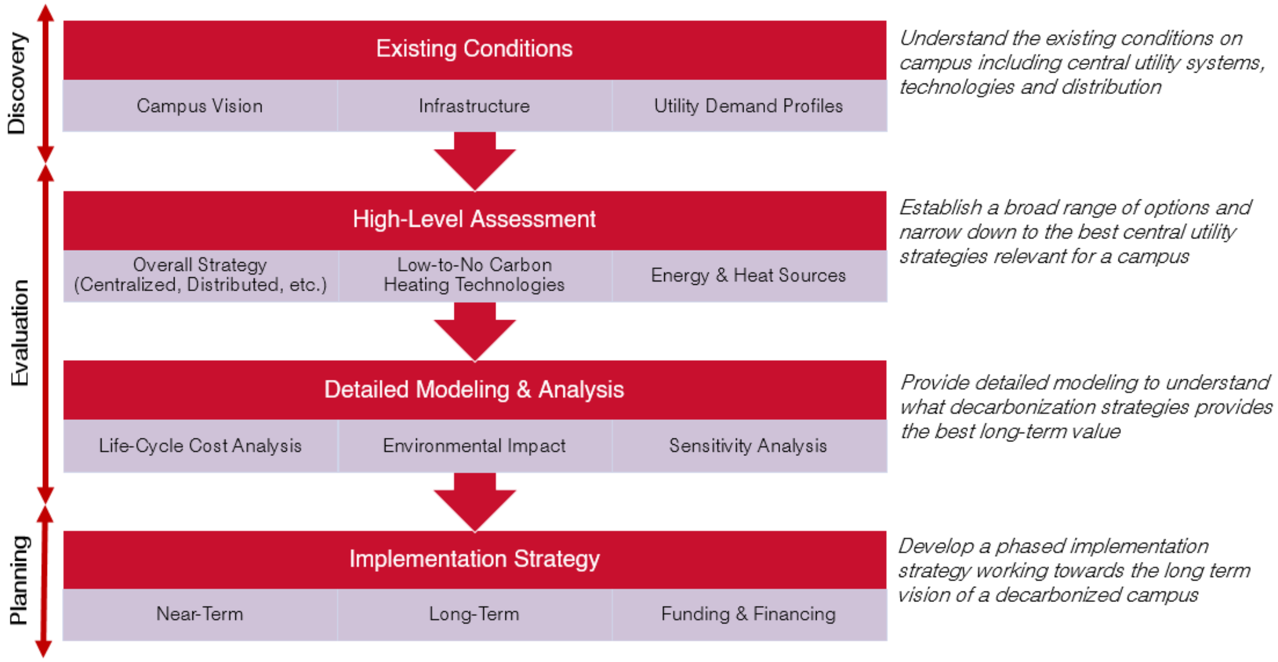


Figure 5.3: Central Plant Assessment Approach

Campus Decarbonization Planning

The following steps should be completed by each campus looking to decarbonize. Following these steps will ensure all campus stakeholders understand the steps they must take to allow for successful decarbonization in both the near and longer term.

Fossil Fuel Equipment Replacement Plan

After developing a fossil fuel equipment inventory cataloging the age and condition of existing equipment, campuses should develop replacement plans to gradually phase out carbon intensive equipment. As fossil fuel as equipment on campus reaches the end of its lifecycle and burns out, replacements plan should be in place to allow for a transition to decarbonized equipment rather than an emergency like for like replacement.

Outlined in this section are the recommended products that each campus transitions to after burnout occurs in order to avoid installation of new fossil fuel based heating or domestic hot water systems. Details regarding larger system types such as centralized boilers and Cogen, and strategies to transition away from these fossil fuel-based sources of energy are outlined later in this report.

Table 5.3: Equipment Replacement Plan

Existing Equipment	Replacement Option	Best Application
Decentralized Gas Boilers	Heat Pumps	Air-Source: When larger campus wide retrofits are not possible, or building is isolated and not connected to any campus loop Water-Source: When building is isolated, however does has a source water loop that can be utilized
	Electric Boilers	When larger campus wide retrofits are not possible, or building is isolated and not connected to any campus loop. Better suited for lower building loads and when electrical infrastructure can support large loads
	Electric Reheat	For instances when heating loads are relatively small, hot water pumping is in poor condition and would require replacement and when electrical infrastructure can support this strategy, electric resistance heating offers a cost-effective method of providing space heating
Rooftop Units (RTUs) w/ Gas Furnace	Heat Pump RTUs	Single unit failure and building not able to undergo large retrofit
	Air-Cooled VRF	Numerous failures occur at same point and/or building needs large scale HVAC retrofits

Gas Water Heaters (Small DHW Load)	Heat Pump Water Heater [Tank Type]	Building load distributed and distribution piping in good condition. Building has adequate space to accommodate heat pump and ventilation requirements
	Electric Water Heater [Point of Use]	Building domestic hot water load minimal and restricted to few locations building wide. Distribution piping not in good condition and would require maintenance/replacement
	Electric Water Heater [Tank Type]	Building load distributed and distribution piping in good condition. Building does not have adequate space to accommodate heat pump and ventilation requirements
Gas Water Heater (Large DHW Load)	Heat Pump Water Heater [Built-Up]	Building has significant domestic hot water load that requires storage and controls to optimize for demand peak shedding. Building has adequate roof space to accommodate heat pump
	Electric Water Heater [Tank Type]	Building has significant domestic hot water load that requires storage and controls to optimize for demand peak shedding. Building has limited roof space or cannot accommodate heat pump water heater
Gas Cooking Equipment	Induction Stovetop	All applications. Induction cooking is the preferred option due to high efficiency and lowered heating loads as a result of improved cooking equipment downtime
	Electric Stovetop	All applications where induction cooking is not viable due to costs, compatibility with existing cooking utensils, and or not desired
	Convection Oven	All applications
Pool / Spa Water Heaters	Heat Pump Water Heaters	All applications
	Electric Water Heater	All application where heat pumps are determined to not be acceptable
Laundry Facilities Dryers	Heat Pump Dryer	All applications
	Electric Dryer	All applications where heat pump dryers are determined to not be acceptable

Load Reduction Plan

A load reduction plan should be created and shared with all campus stakeholders. This should provide different campus entities with the necessary information for them to begin reducing heating loads on campus. Strategies to lower heating loads are discussed in further detail in the following section, and include:

- Low-to-no cost controls upgrades
- Heating hot water reset strategies
- Building retrofits

Campus Standards

Campus design standards should be reviewed and updated to accommodate future decarbonization of heating equipment. These design standards should be followed for all construction projects on campus. It is recommended that each campus review their existing standards and ensure these incorporate all recommendation outlined in the Design Guidelines section. Measures that should be incorporated into future design standards include:

- Implement policies to support divesting from fossil fuel-based systems, potentially including a no new gas equipment policy ban
- Updated design standards for heating system design conditions and sizing recommendations for decarbonized equipment
- Heating hot water coils sized for low temperatures (<130F) mandated for all heating coils installations and replacement across campus, potentially requiring two-row coils
- Heating hot water coils sized for a delta T to match existing campus delta T. This will ensure existing hot water piping is adequately sized
- The electrical infrastructure for all campus retrofits and new construction projects is designed to accommodate future electrification
- Update and enforce thermal comfort policies on campus

Utility Master Plan

Campus utility master plans should be updated with specific focus on assessing existing electrical infrastructure and the additional its additional capacity. Master plans should be focused on assessing central plant locations to ensure these can accommodate future loads.

5.2.2 Implementation

Load Reduction

Reducing loads in existing buildings across campuses is a vital step in decarbonizing heating systems as balanced heating and cooling loads are required to optimize decarbonization strategies. The first step in decarbonization is therefore to lower the need for heating and reduce sources of wasted heat across campus. Using existing load profiles to determine decarbonized system sizing will lead to oversized equipment once building operations are optimized and building HVAC equipment is replaced at the end of its useful life. It is therefore recommended that the first stages of decarbonization focus on lowering heating loads and reducing sources of wasted heat.

Peak heating and cooling periods on campus rarely occur at the same time. These unsynchronized peaks in traditional heating and cooling systems do not affect campus operations significantly as chillers and boilers are sized to meet these loads. However, when implementing decarbonized strategies, synchronizing and lowering peak heating and cooling loads will increase the heat recovery and operational efficiency of the heat pump technologies. Balancing heating and cooling loads on campus is key to ensure heat recovery potential on campus is maximized. In order to achieve this, control strategies should be optimized to ensure both heating and cooling peaks are reduced synchronized to the greatest extent possible. Additional information regarding optimizing for decarbonized heating is included in the Optimization Phase section.

All strategies outlined in the table below should have minimal cost impacts if modern Building Automation System (BAS) controls are already in place. Installation of DDC controls will be a necessary step in decarbonization and should not be considered as required for peak load reduction strategies alone.

Low-Cost / No Cost Measures

Table 5.4: Low-Cost / No-Cost Energy Efficiency Measures

Measure	Description	Comfort Impact
Building Scheduling	Ensure HVAC schedules align with building operating schedules, limiting potential for heating when building unoccupied • Basic HVAC schedules • Classroom scheduling: Optimize classroom scheduling to ensure classrooms throughout building do not alternate between occupied and unoccupied throughout the day. Optimal scheduling will have the same classroom fully occupied all day, with other classroom unoccupied to the greatest extent possible	HVAC schedules should align with occupancy schedules, so thermal comfort should not be affected. Scheduling should account for morning warm-up to ensure occupants are satisfied at first occupancy Classrooms that are unoccupied should be placed into temperature setpoint setbacks and have OSA reduced to zero. When occupancy is sensed, desired setpoints will be restored and the space will achieve acceptable thermal comfort ranges

Campus Control Optimization	Ensure all large pieces of equipment on campus have <u>calibrated</u> DDC controls • All CUP equipment • AHUs Operate CUP and buildings per ASHRAE 36 Guidelines • e.g. Building optimal start • e.g. Dual maximum reheat control	N/A
Plant and/or Building Heating Sequence Optimization	Conduct a sensitivity analysis on HHW supply temperatures to determine minimum that maintains thermal comfort • Applicable for centralized HHW/steam systems or decentralized boilers • Lowers distribution losses in piping Care should be taken to ensure no single buildings drives water temperatures versus the wider campus loads	See Heating Hot Water Reset Section for more information
Supply Air Temperature Resets	Supply air temperature resets should be programmed into AHUs across campus, per ASHRAE 36 recommendations, to reduce reheat hot water loads when outside air conditions allow	When resets are controlled per ASHRAE 36 Section 5.16.2.2, thermal comfort will not be impacted
Optimized Start Controls	Morning warmup / cooldown represent a high volume of the heating and cooling spikes on CSU campuses. All buildings should have Optimum Start Controls implemented per ASHRAE 90.1 2016 Mandatory Provisions section 6.4.3.3.3	Optimal start controls are designed to ensure thermal comfort is maintained whilst energy is saved. Provided buildings are programmed to startup at consistent times, no thermal comfort issues should arise

Heating Hot Water (HHW) Reset

Campuses in different climate zones have different opportunities when decarbonizing. Cooling dominated campuses may be able to reset hot water temperatures to a greater extent throughout the entire year, and shutoff heating entirely over a wider range of months. This will allow cooling dominated campuses to focus on technologies that operate optimally at lower supply temperatures. Heating dominated campuses on the other hand may not have the same opportunities to reset their hot water supply temperature. However, it is recommended that all campuses assess their hot water supply temperatures and reset these to the lower that meets thermal comfort across campus

Traditional CSU campus heating systems have typically been sized for 180 F heating coil entering water temperatures, regardless of whether there is a centralized heating hot water, steam, or decentralized heating system. The capacity of the coils is dependent on the flowrate and coil delta T. Lowering entering water temperatures may lower overall heating coil capacity as the coils will not achieve their design dT at the lower entering water temperatures, potentially affecting thermal comfort throughout the building. As outlined previously, the efficiency of decarbonized heating equipment is significantly improved at lower supply temperatures, and 180 F cannot be achieved through existing heat recovery technologies. Replacement of existing coils may therefore need to occur to ensure thermal comfort is maintained across campus.

The following process has been developed to allow campuses to assess the lowest hot water supply temperature that will satisfy thermal comfort on campus. This process should be followed in order to determine optimal heating hot water supply temperatures and identify problematic areas on campus that may be driving the need for higher temp hot water.

I. Conduct sensitivity analysis to determine lowest hot water temperatures that maintain thermal comfort.
    a. Lower supply temperature in the secondary hot water distribution loop by 5-degree increments. Maintain this supply temperature until all heated spaces on campus are satisfied. This should be conducted in both summer and winter months to determine what the lowest supply temperatures are during peak heating and cooling periods
        i. Note – return water temperatures to non-condensing boilers must remain above 140-degrees to ensure condensing does not occur, which will damage boiler. However, in a primary-secondary loop configuration the primary loop can maintain this minimum temperature whilst the secondary loop is lowered to a greater extent. It is recommended the secondary loop is reset whilst the primary temperature is maintained to ensure boilers are not damaged
    b. Assess campus EMS and determine if buildings are operating at peak heating conditions at this supply temperature. If building and/or coil valves are not at 100% open, additional capacity is available from the coil and supply temperature can be reduced
        i. Note – Heating hot water coil valves should be calibrated to ensure they are being read correctly
        ii. Installation of Pressure Independent Control Valves (PICVs) present potential addition energy savings. PICVs react well to pressure fluctuation within a system. Hydronic loops can see large pressure fluctuation as loads change within the loop. This is made worse in large campus loops with numerous buildings with different load profiles. PICVs can ensure coil flowrates are better maintained through coils, resulting in design delta T being maintained. If flowrates increase through a coil, delta T will decrease. Low delta T results in additional energy consumption at the central plant in both pumping and chiller energy.
    c. Repeat step (a)
        i. Note – analysis should be completed to determine whether there are specific cold spots within a building or locations on campus. Isolated areas that force higher overall supply temperatures should be identified and investigated. Causes for cold spots may include:
            1. Buildings located at end of distribution lines may not receive hot water at sufficient pressure to distributed to coils throughout building. Booster pumps installed in buildings may solve this issue
            2. Coils in building may be in poor condition, limiting heating capacity further. Coil replacement and/or cleaning may solve these issues. If coil condition cannot be improved, hot water boosters may be installed. See Section 5.3 Cascade Heating Systems for more information

II. Determine existing capacity of heating coils
    a. If coils are connected to BAS, use trended data (coil entering/leaving air, cfm or coil entering/leaving water temperatures, gpm) to determine coil operating capacity.
        i. Note - ensure meter reading are accurate through verification of live results as compared to manual testing. If trends not available, set up trending on BMS
    b. If coils not connected to BMS, install temporary airflow and temperature sensors in AHU
        i. Recommended portable temperature sensors such as HOBO data logger that can be installed and reused across campus.
III. Assess existing campus AHU heating coils. Focus on buildings that high heating demand and that have prolonged period of low occupancy in summer to minimize impact of system downtime during occupied periods
    a. Campuses looking for centralized system:
        i. Identify coils in worst condition
    b. Campuses looking for decentralized system:
        i. Identify coils in worst condition within decentralized campus location
    c. Determine if there is space at heating coils to replace with a two-row heating coil. Two row coils optimize heat transfer, which is important at lower hot water temperatures.
    d. Size replacement two-row heating coils for a maximum of 130 F entering water temperature. Sizing for 140-degrees prepares AHU for fully decarbonized system operating at this temperature. Hot water supply temperatures above this prior to decarbonization will not impact thermal comfort.
        i. Note - for decentralized systems: care to be taken to ensure this will not result in return water temperatures to non-condensing boilers are below 140 F. Building with decentralized non-condensing boilers will likely need boilers replacement at same time as heating coils to ensure this does not occur.

Building & Control Retrofits

CSU campus buildings have been widely upgraded through energy efficiency projects. This has proven successful and allowed savings to be reinvested into further efficiency projects. However, certain buildings continue to operate with legacy equipment. This legacy equipment typically operates inefficiently when compared to modern technology, increasing heating and/or cooling loads, resulting in a reduction in heat recovery potential. As funds allow, legacy equipment should be retrofit, both helping to reduce inefficient operation and allowing for precision control of equipment in the future. However, it should be noted that legacy equipment should only be replaced when the system it serves is required for building operation, and the building operation is expected continue as is into the foreseeable future. Retrofitting equipment that will be removed before the of it its useful life should be avoided. Common legacy equipment installed throughout CSU campuses, and the typical upgrade options includes:

Table 5.5: Campus Building Retrofit Projects

Measure	Description
Pneumatic Controls to DDC Controls	Removal of pneumatic controls and installation of DDC controls will allow for improved levels of control throughout campus, in addition

	to increased ability to trend and ablaze data to ensure that thermal comforts levels are being met The CSU Chancellors Office is currently working on a case study of four campuses that successfully completed pneumatic to DDC conversions. It is recommended that this is reviewed as new conversion processes begin at other campuses
CAV to VAV Conversion	Constant Air Volume (CAV) systems should be retrofit or retired in favor of Variable Air Volume (VAV) systems across CSU campus buildings. CAV systems consume significantly more fan, heating and cooling energy than VAV systems. Retrofitting to VAV systems to allow heating airflows to be reducing to minimums when space conditions allow and will allow supply air to be reduced to zero when occupancy-based ventilation is implemented
Envelope Upgrades	Building envelopes often provided the number one source of heating and cooling loads in typical campus buildings. Single pane glazing, poor insulation levels, and infiltration from old / damaged window frames will drive heating and cooling loads, potentially significantly Upgrades to these systems often require significant capital expenditure, and these projects may be considered a deferred maintenance project as opposed to an energy efficiency project. It is recommended these are considered in specific circumstances, especially when large HVAC retrofits are ongoing. Improving the envelope may result in smaller HVAC equipment sizing, providing additional economic benefits in addition to the energy savings through reduction of loads

In addition to these retrofits, the following upgrade is recommended when significant building upgrades are being completed, such as pneumatic to DDC controls or significant lighting fixture upgrades.

- Occupancy based controls: Ventilation & Temperature
    - It is recommended that occupant sensing controls are tied into the HVAC controls for ventilation and temperature setbacks. 2019 California Energy Code Section 120.2(e)3 mandates that HVAC controls reduce airflow to zones that are required to have occupant sensing controls to significantly reduced or zero, and temperature setpoints set back. This lowers the energy required to heat or cool outside air, which accounts for significant energy consumption, and the energy to maintain space setpoints
    - University classroom buildings offer a significant savings potential, particularly if they switch between occupied and unoccupied over the course of a typical day. It is recommended this control strategy is implemented where possible due to their limited capital expenditure requirements and significant savings potential
    - Similarly, Table 3.1.1.1 Default Set Points, of ASHRAE 36 outlines recommended heating and cooling setpoints during occupied and unoccupied periods. At minimum, these should be complied with to ensure energy savings are achieved, whilst thermal comfort maintained

Electrification & Optimization

It is not recommended that CSU campuses retire their existing fossil fuel-based heating equipment before the end of its expected useful life. However, the implementation of decarbonization strategies can be phased and a campus infrastructure readied for decarbonized alternatives, with the actual installations delayed until equipment has failed or funds are available.

Continual Implementation

All campuses should follow the guidelines outlined in the Campus Investigation and Load Reduction sections. The low / no-cost measures should be first implemented due to their low capital expenditure and significant saving potential. Additionally, these and can be implemented continuously as campus loads change over time. Capital intensive retrofit projects can be phased as funds allow, focusing on the worst performing buildings that will offer the highest savings. Once completed, the savings in energy consumption can be reinvested into decarbonization projects throughout campus. Additionally, the Campus Equipment Burn Out Plan should be implemented, restricting the installation of new fossil fuel-based heating equipment.

Near-Term Electrification

In the near term, electrification of campus equipment should be focused on equipment at the end of its useful life. Larger centralized projects should be prioritized if possible as these will have the largest impacts on campus emissions, with smaller systems being phased as funds are available. As part of their decarbonization assessment process, each campus should determine what type of savings to target, such as carbon reduction, energy, or financial savings. Therefore, if centralized equipment is not yet at the end of its useful life, projects that offer significant savings opportunities in the desired end use should be prioritized, whilst campus investigation and load reduction strategies for the larger equipment are completed. Campus polices such as planned campus growth should be assessed and location of future buildings considered. This will allow the campus to include future building in their decarbonization assessment, increasing the ability of the campus to effectively decarbonize.

When large central plant equipment is not near the end of its useful life, campuses may investigate implementing near term decarbonization strategies such as installation of decarbonized equipment that is sized for the campuses base heating loads only. This will ensure fossil fuel-based heating equipment only operates during colder months, on peak design days. Outlined below is the heating distribution for a typical heating dominated and typical cooling dominated campus. Most of the heating on these campuses is not a result of peak demand but occurs as a base load. It is expected installation of decarbonized equipment for this base load will provide significant reduction in carbon emissions whilst minimizing the initial capital expenditure.

Heating load profiles show that it is possible to significantly reduce in GHG emissions on campus throughout the CSU system, regardless of climate zone, by installing decarbonized heating sized to the base heating load. It is not necessary to provide a decarbonized heating system even close to the peak campus heating demand to immediately have a significant impact. The following pages show the GHG emissions reduction potential for typical CSU campuses in the northern region and southern region.

The San Marcos campus was used as a typical CSU campus in the southern region. A decarbonized heating system sized for 50% of the peak heating demand (6,150 kBtu), based on load profiles measured between December 2018 and December 2019, would satisfy 98% of the annual heating loads. This demonstrates that decarbonized equipment sized significantly lower than campus peak heating demand can have a significant impact and cover most of the heating loads. For additional information on optimizing system sizing, refer to Task 3, which provides guidance on sizing of decarbonized equipment.

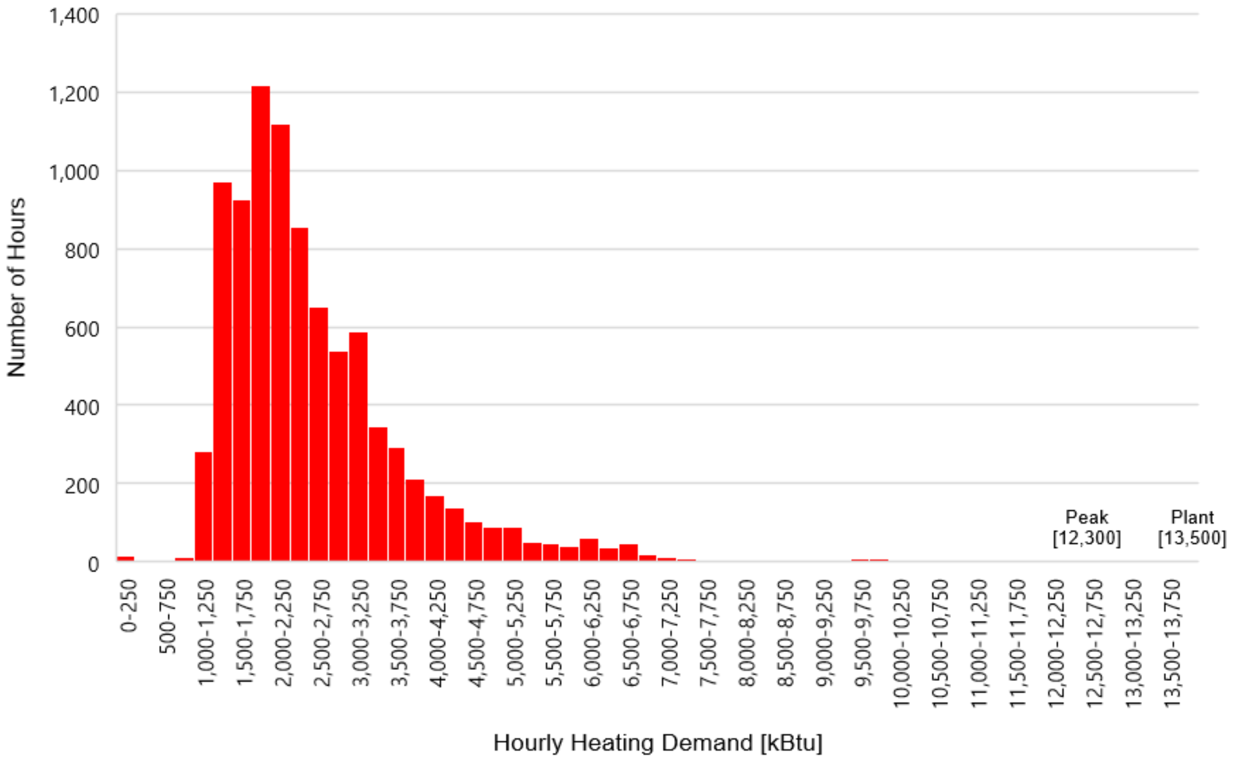


Figure 5.4: Heating Load Distribution – Example Southern Campus (SM)

The table below shows the natural gas savings potential of a range of heating capacities for decarbonized heating systems.

Table 5.6: Natural Gas Savings Potential at different heating capacities (SM)

Heating Capacity [kBtu]	Percent of Hours [%]	Gas Savings [therms]*	Gas Savings [%]	
2,250	50%	93,823	33.4%	
3,000	75%	156,131	56.2%	
4,000	90%	214,919	77.4%	
5,000	95%	241,604	87.0%	
7,000	99%	268,376	96.6%	
12,300	100%	277,757	100.0%	*Peak demand*
13,500	100%	277,757	100.0%	*Plant capacity*

**Assumes 80% average boiler efficiency*

The Stanislaus campus was used as a typical CSU campus in the northern region. A decarbonized heating system sized for 50% of the peak heating demand (4,250 kBtu), based load profiles provided for between April 2018 and April 2019, would satisfy 95% of the annual heating loads. This demonstrates that decarbonized equipment sized significantly lower than campus peak heating demand can have a significant impact and cover most of the heating loads.

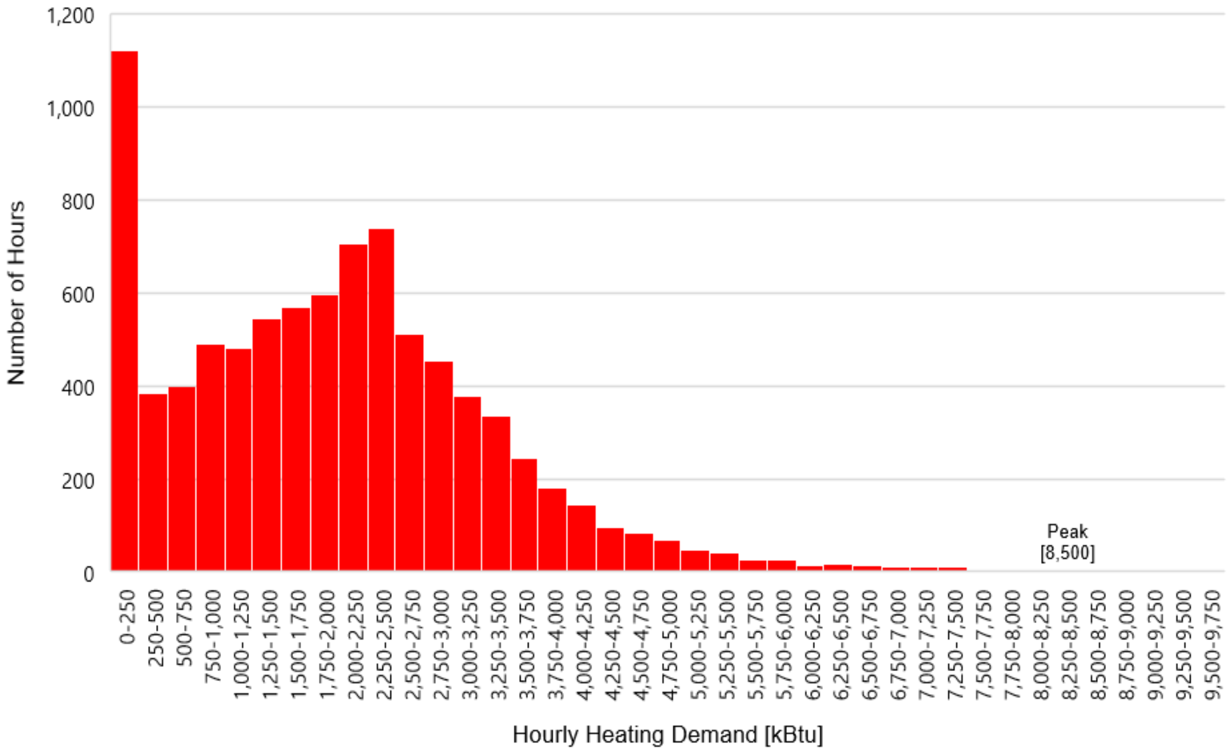


Figure 5.5: Heating Load Distribution – Example Northern Campus (ST)

The table below shows the natural gas savings potential of a range of heating capacities for decarbonized heating systems.

Table 5.7: Natural Gas Savings Potential at different heating capacities (ST)

Heating Capacity [kBtu]	Percent of Hours [%]	Gas Savings [therms]*	Gas Savings [%]	
2,000	50%	52,818	24.6%	
2,750	75%	110,203	51.4%	
3,750	90%	166,334	77.6%	
4,250	95%	182,481	85.1%	
6,250	99%	207,435	96.8%	
8,500	100%	214,385	100.0%	*Peak demand*
20,000	100%	214,385	100.0%	*Plant capacity*

**Assumes 80% average boiler efficiency*

Long-Term Electrification

Full decarbonization of campus heating systems should be implemented in the long term and optimization strategies implemented. This will include large infrastructure projects such as retirement of Cogen systems and removal of all centralized natural gas boilers. For campuses with decentralized systems or a steam loop, sections of campus should be identified and combined in a low temperature hot water loop as phasing will likely be required due to financial constraints.

Optimization

After heating systems on campus have started to transition towards lower emission electrified technologies, campus should focus on additional strategies to increase the heat recovery potential on campus and optimize the efficiency of generating hot water.

Building Stock Optimization

The majority of buildings throughout the CSU system typically do not operate overnight. For campuses with central heating hot water or steam loops, decentralization of buildings that require continuous heating may allow for heating plants to be shut down overnight. Once buildings that do require heating year-round are decentralized, hot water shut down over the summer months is also a viable option for many CSU campuses. Shutting off a system when loads allow will result in significant savings in overall heating energy, directly lowering GHG emissions. When system shut offs are undertaken, care should be given to maintain chemical treatment to avoid issues within the hydronic system. Reducing the runtime of heating equipment, will also help extend the lifetime of said equipment and reduce maintenance costs.

For buildings that do require continuous heating, such as lab buildings with 100% OSA systems, a building level heating hot water system will be required to satisfy building loads. Decarbonized systems should be first investigated in these circumstances to identify whether such system can provide acceptable how water conditions. It is expected that a decentralized heat pump or heat recovery systems will be optimal for individual buildings requiring continuous heating and cooling. If required, high efficiency condensing boilers can also provide the required heating hot water needs. In either case, connections to campus loops can remain, allowing the centralized system to provide heating during operational hours, with local heat pumps or boilers providing heating overnight or over the summer months.

Thermal Energy Storage

Thermal Energy Storage can play a key role in full decarbonization of heating systems on campus, particularly when heat recovery is implemented. It provides a way to shift campus load so that heat recovery chillers can operate at optimal efficiency and cover larger portion of campus load.

Outlined in Figure 5.6 below is the heat recovery potential of a typical cooling dominated CSU campus with heat recovery chillers. In this analysis, heat recovery chiller is sized for maximum simultaneous heating and cooling load. Figure 5.7 shows the same campus heat recovery potential when TES is incorporated. Both figures outline campus monthly heating and cooling load, showing the total heating / cooling load and the load that could be produced via heat recovery. In this example, without TES, the heat recovery can cover 73% of the heating load and 33% of the cooling load, taking care of all heating load from June to September. The total amount of heat recovery increases by 9.3% on heating and 4.3% on cooling with the inclusion of TES for load balancing. This results in an increase in heating COP from 2.02 to 2.52, and a reduction in natural gas consumption of 13%; the heat recovery chiller can now address all heating load from April to October. This is expected to increase further when loads on a campus are balanced during the Optimization phase, resulting in a further increase in heat recovery potential.

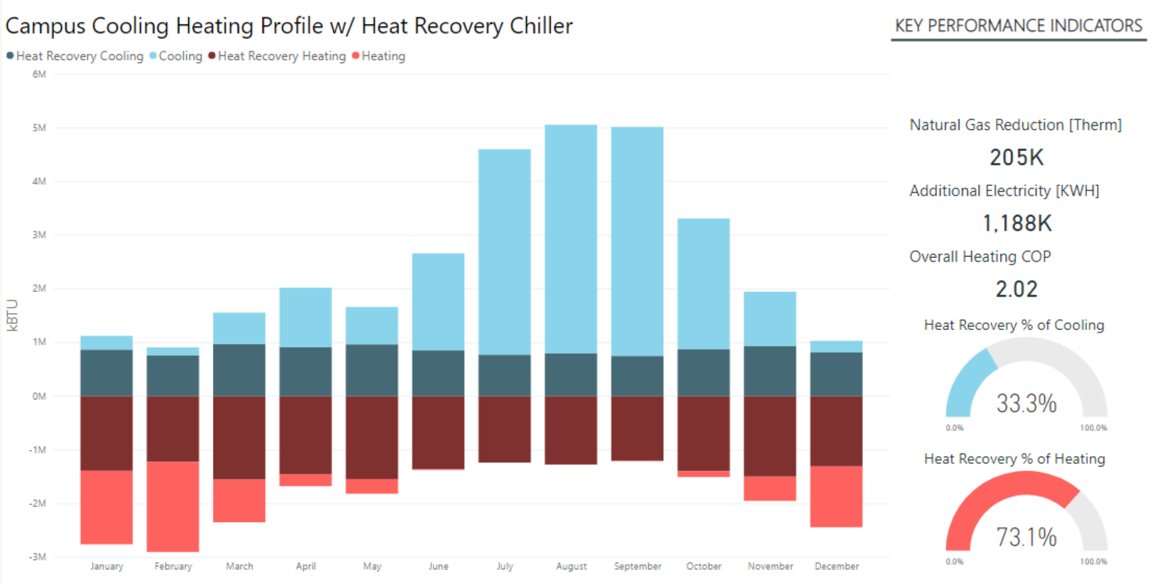


Figure 5.6: Heat Recovery Potential

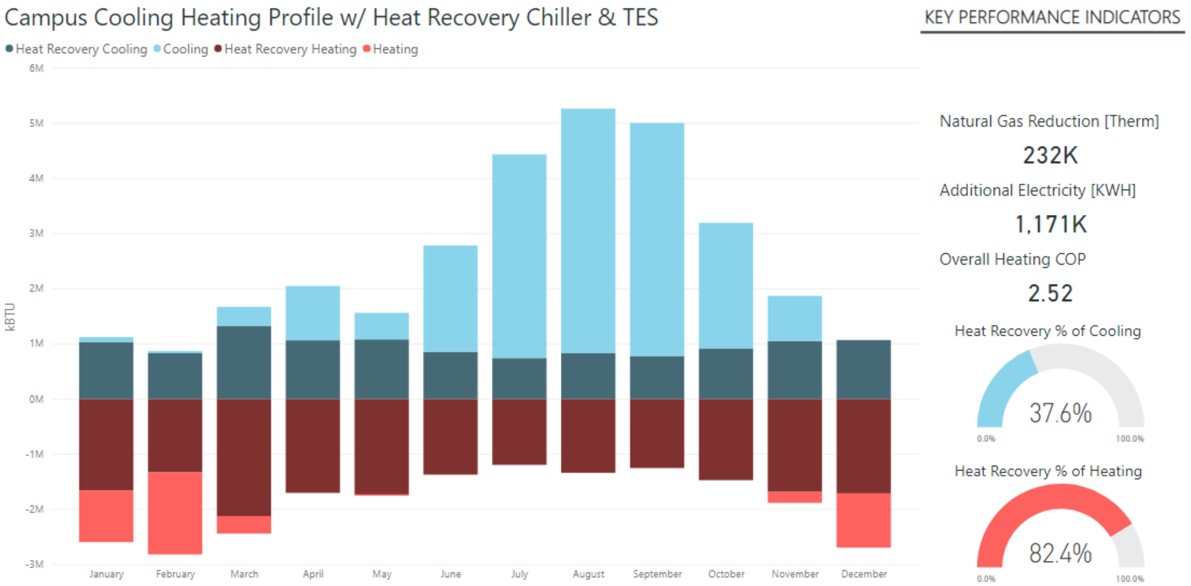


Figure 5.7: Heat Recovery Potential – Thermal Energy Storage (TES)

In addition to the benefits outlined above, TES provide additional financial benefits. TES chilled water storage tanks allow for chillers to operate during conditions that optimize their efficiency, and not during times of peak demand. For example, when outside air wet bulb temperatures are low, condenser water temperatures are also reduced, which helps improve chiller efficiency. Similarly, during periods when higher heating loads are expected on campus, such as during morning warm-up, heat recovery chillers can operate to generate the necessary heating, whilst storing chilled water for use during the day.

TES hot water storage tanks allow for heat recovery chillers to be utilized even during period of peak cooling on campus, when heating loads may be minimal. During the afternoon and early evening, heat recovery chillers can operate to provide the necessary cooling, while charging hot water TES tanks. These tanks can then be discharged in the evening or during morning warm up, allowing the chiller and/or other heating sources to remain off for longer periods. Similarly, if removal of 24/7 facilities from the central heating loop is not feasible, charging hot water storage tanks during the day with heat recovery chillers when there is a cooling load and discharging overnight will allow for all large pieces of mechanical equipment to be shutdown overnight.

A cost-benefit analysis should be conducted when determining TES tank sizes. Sizing for maximum heat recovery may not be financially feasible, particularly if large excavation work is required to clear space for tanks. If the campus utility costs could be lowered significantly though a reduced demand charge, chilled water storage may be the optimal solution, allowing for chillers to be shut down during peak demand periods. However, if a significant portion of campus heating loads occur overnight and/or during morning warmup, and demand charges are not dominated by central chillers, a hot water TES may be more beneficial than chilled water. With either option, a study of the campus load profiles is necessary to assess the optimal system.

It is also recommended that campuses investigate locations where above ground TES tanks are feasible. Excavation costs add significant capital expense to TES installations, therefore when space allows, above ground tanks may be a more economical option. In addition, above ground tanks and visual CUP locations can present an educational opportunity for students who are able to better understand how large centralized heating and cooling systems operate through visits to the CUP and TES location.

False Cooling (Economizer Controls)

Air-side economizers have played a vital role in HVAC energy savings by using outside air to condition spaces when outside air condition is favorable, reducing the amount of heat rejected from the supply airflow into either a chilled water or refrigerant coil. Lowering this rate of heat rejection allows for less compressor and heat rejection energy, potentially savings overall energy consumption significantly.

When optimizing a campus system for heat recovery however, reducing the amount of air-side economization can play a vital role in balancing the heating and cooling loads during periods when heating on campus is dominant. During periods in which there is not sufficient cooling loads to meet 100% of the campus heating, air-side economizers can be deactivated to increase the total load on the chilled water system. Although this increases the cooling energy consumption, it improves the heat recovery potential on campus, allowing for an increase in the total campus heating loads that can be met through decarbonized heating sources. Figure 5.8 shows the heat recovery potential of the same campus as shown in Figure 5.6 and Figure 5.7, however includes the addition of false cooling loads from economize controls and a TES to optimize heat recovery potential. In this case, the heat recovery chiller can be sized slightly larger due to higher simultaneous heating and cooling load. Heat recovery can now produce 92.1% of the heating load compared to 83.4% in a heat recovery plant with just TES for load balancing. The heating COP increase to 3.36 from 2.52. This clearly indicates the impact that false cooling loads can have on campus heat recovery potential. However, extreme care must be taken to ensure than false cooling loads never result in a heat recovery potential greater than the campus heating load. It is therefore recommended that analysis into false cooling loads is completed as the final optimization task, after heat recovery potential has already been optimized to the fullest extent. If false cooling loads are adopted, close monitoring and control though an automated control system should be implemented to ensure the energy tradeoff between false cooling and heat recovery provides an overall reduction in campus emissions

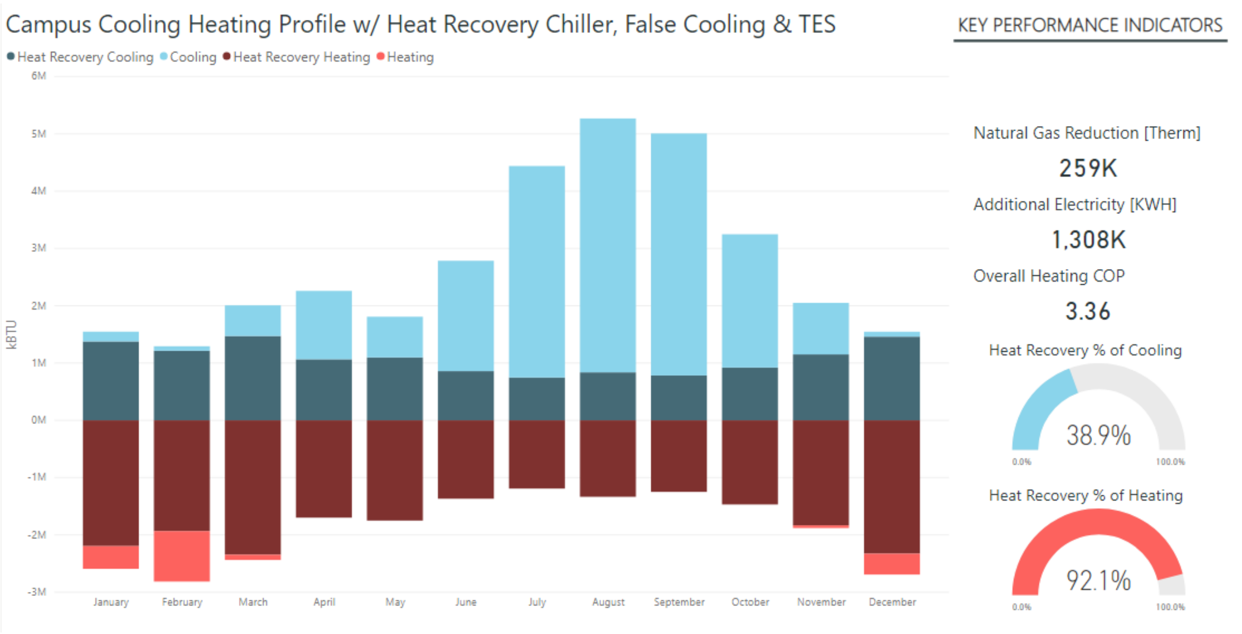


Figure 5.8: CSU Campus Heat Recovery Potential – Heat Recovery Chiller, TES & False Cooling Loads

Additional Heat Sources & Sinks

Each campus must investigate additional sources of heat that can be utilized to electrify their heating systems. These would include, but not limited to:

- Ground Source Heat Pumps – utilizing the ground as a heat source, coupled with a heat pumps to produce heating hot water. Ground source can be coupled with 6-pipe heat recovery chillers, with all heating and cooling requirement met via ground source, eliminating requirement for additional heat source or sink within the system
- Geothermal Wells – utilizing the ground at a heat source and / or sink to provide heating requirements. Geothermal requires unique geological conditions that may not be viable at all CSU campuses, however if available, geothermal may provide the ability to provide heating

without the need for heat pumps

- Sewer Heat Recovery – utilizing existing sewer lines as a heat source, coupled with a heat pumps to produce heating hot water.
- Solar Hot Water (SHW) – installation of SHW to produce heating hot water for campus distribution

Additional False Cooling Loads

Introducing false cooling loads to the campus will help balance loads during periods in which there is a heating demand with minimal cooling load. When implemented, there should be tight control on these systems to ensure chilled water loads do not exceed the maximum required to meet all heating loads. It is recommended all false cooling loads are controlled to maintain a specific chilled water temperature differential and with the ability to shut off these systems when campus cooling loads are sufficient to achieve heat recovery with standard operation. This should be predetermined based on expected campus heating loads to minimize risk of unnecessary cooling energy. It is key that any false cooling loads on campus are controlled via close precision in to ensure there are no instances in which additional cooling load, past that required to maximize heat recovery potential, is added to the chilled water loop.

Strategies include:

- Solar Hot Water (SHW) – installation of SHW to increase chilled water return temperature, increasing chilled water load on campus
- Chilled water coils on building exhaust to pick up wasted heat from the building, increasing chilled water return temperature to central plant

Section 5.3: CUP Decarbonization Strategies

5.3.1 Approach

Outlined in this section are conceptual recommendations for different approaches to decarbonize existing central plants. The table below outlines a common set of criteria against which each decarbonization strategy is assessed in the remainder of the report. The criteria are applicable for all campus infrastructure types and are used in Section 5.4 when comparing different decarbonization strategies across similar existing infrastructure types.

Table 5.8: Decarbonization Strategy Evaluation Criteria

Criteria Group	Criteria	Overview
Environmental	GHG Emissions	Potential for campus Scope 1 GHG emissions to be reduced to zero
	Energy Consumption	Overall energy efficiency of technology as compared to existing gas boilers
	Heat Recovery	Ability of technology to provide simultaneous heating and cooling via heat recovery.
	Water Consumption	Overall water consumption of technology
Total Cost of Ownership	CAPEX	Capital expenditure impacts
	OPEX	Operational expenditure impacts in terms of utility costs
	Electrical Demand Flexibility	Ability of system to minimize electrical demand charges and shift electrical loads
	Adaptive Reuse	Opportunity that technology offers to reuse campus infrastructure
Comfort	Comfort	Potential impact on thermal comfort within space
Maintainability	Complexity	Complexity of technology and controls
	Technology Readiness	Availability & maturity of technology, and number of manufacturers
Infrastructure	Phasing	Phasing potential and impact to the ongoing operation of the campus during construction
	Electrical Infrastructure	Potential impact on electrical infrastructure
	Space & Location Requirement	Spatial impacts and code considerations of equipment installation
Resiliency	Redundancy & Backup	Levels of redundancy offered by technology
	Resiliency	Ability of technology to offer resiliency to campus
	Climate Adaptation	Ability to adapt to climate change and future weather conditions

All technologies deemed applicable in the remainder of this section have been outlined previously in Task 4, with information on the technology and optimal operating conditions outlined. For further information on these technologies, refer to Task 4.

5.2.2 Primary Strategies

Centralized Heat Recovery

Design Overview & Recommendations

Heat recovery chillers installed in existing campus central plant sized to provide campus heating hot water requirements and to supplement campus chilled water needs. Centralized heat recovery plants have the greatest applicability on CSU campuses with centralized chilled water and heating hot water distribution loops. Campus should size heat recovery chillers by assessing campus loads and conducting a cost-benefit analysis on meeting peak heating loads via heat recovery versus utilizing additional sources of heat for these periods, such as existing boilers.

Applicable Technologies

- Air-to-Water Heat Pump
    - Desuperheater *(preheat only)*
    - 4-pipe
- Water-to-Water Heat Pump
    - Desuperheater *(preheat only)*
    - 4-pipe
    - 6-pipe

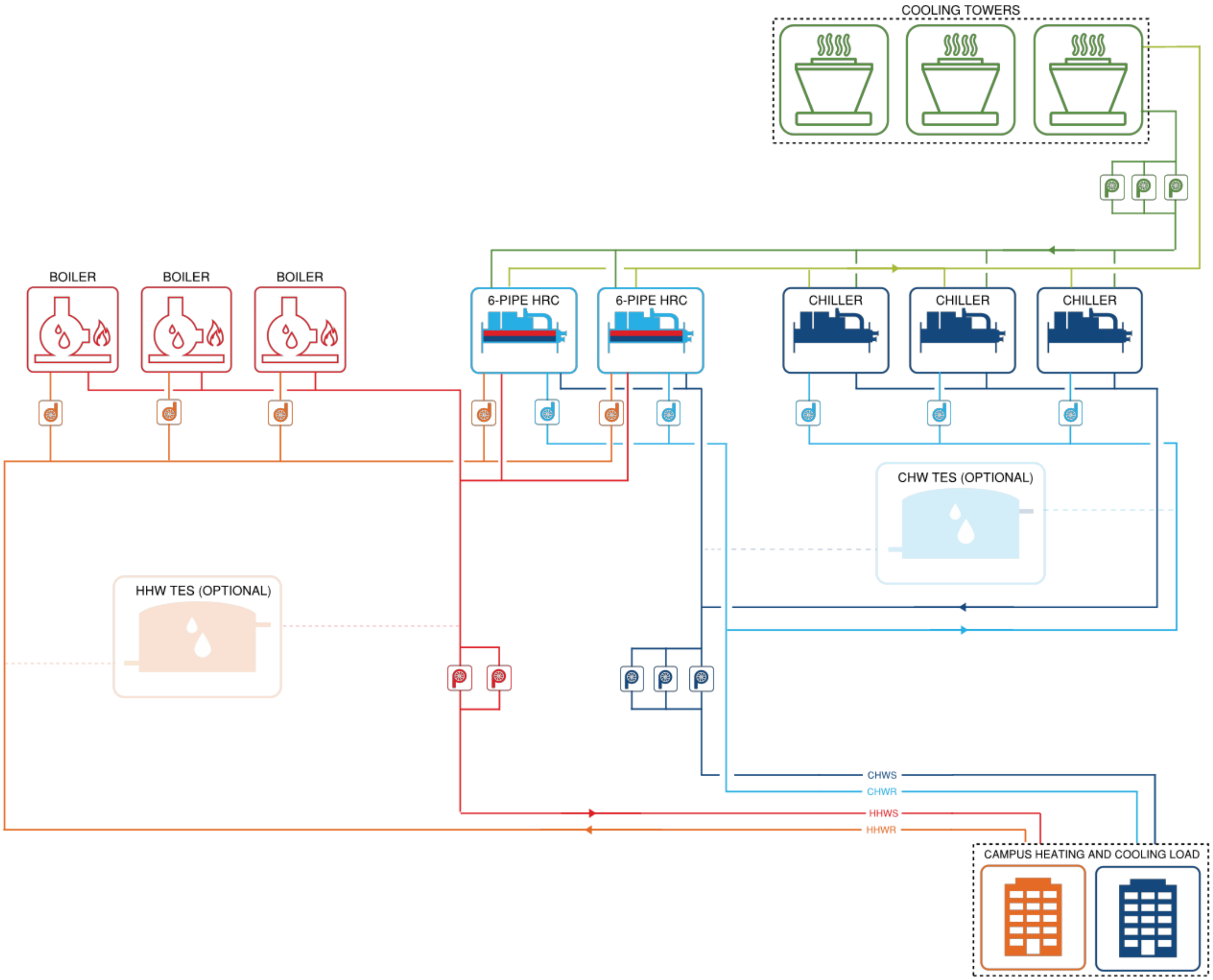


Figure 5.9: Centralized Heat Recovery Strategy Schematic

Table 5.9: Centralized Heat Recovery - Criteria Assessment

Criteria Group	Assessment
Environmental	Scope 1 emissions can be significantly reduced through heat recovery from CHW loop. Supplemental heat sources are likely required for full fossil fuel decarbonization
Total Cost of Ownership	Existing campus distribution loops, building piping & HHW coils can be maintained and reused. If applicable, existing steam piping may be repurposed, however will likely need replacement If combined with storage, campus can operate without chiller running during peak demand periods
Comfort	Lower HHW temperatures required to sustain heat recovery operation> refer to HHW Reset section for strategies to mitigate thermal comfort issues. Cascade type heating system available if thermal comfort issues continue.
Maintainability	All new mechanical equipment remains in CUP and can be serviced at one location. Requires advanced control systems to maintain tight control sequences and additional control valves to modulate CHW flow to central CUP chillers Heat recovery chillers are commercially available with numerous successful units in operation
Infrastructure	Modular HR chillers are available, allowing for phasing within central plant if desired Fully electrified technology may require upsizing of electrical infrastructure, however central plants may have additional capacity available
Resiliency	Additional heating and cooling capacity provided to campus with 6-pipe chiller installation.

Table 5.10: Centralized Heat Recovery – Design Assessment

Design Benefits	Design Concerns	Design Considerations
Extremely high efficiencies can be achieved through combined heating and cooling Design allows for existing campus distribution piping and existing building valves and piping to remain in place Potential for modular HR chillers that allow for capacity growth & phasing of decarbonization as funds allow Centralized systems will achieve the highest amount of heat recovery as heating and cooling	Heat recovery may not always be possible as the heat recovery capacity is dependent on CHW loads. If campus heating loads surpass cooling loads, additional heat sources will be required Limits on maximum supply water temperature may result in reduced capacity coils across campus Tight controls will be required for efficient operation. This will require precision commissioning and operations	Although TES may be required to optimize HR potential, as system is centralized, full decarbonization may be possible with TES alone Addition of HR chillers will increase CHW capacity on campus. If central facility is operating at near full capacity, HR chillers can be used to meet future loads as campus grows 6-pipe HRC opens CHW, HHW and condenser water loops to each other, potentially posing issues. System adds complexity

loads across campus can be shared and balanced Reduced maintenance cost through centralized and larger systems versus decentralized systems with compressors and refrigerant based systems distributed across campus Reduced amount of refrigerant versus decentralized system	TES may be required to optimize system. Expensive construction costs if excavation required	and requires tight controls on valving

Decentralized Heat Recovery

Design Overview & Recommendations

Decentralized heat recovery chillers utilize the same technology as centralized systems; however, they are better suited to campuses with distributed boilers, which are already set up for a decentralized solution. This approach allows campuses to connect a group of buildings together or utilize existing groupings to create a quadrant of the campus that is served by a heat recovery chiller. Sizing of systems should account for ease of connecting building together and consider ease of balancing loads (e.g. connecting building with a data center to a housing building will provide a balanced load of cooling and heating)

Applicable Technologies

- Air-to-Water Heat Pump
    - Desuperheater
    - 4-pipe
- Water-to-Water Heat Pump
    - Desuperheater
    - 4-pipe
    - 6-pipe

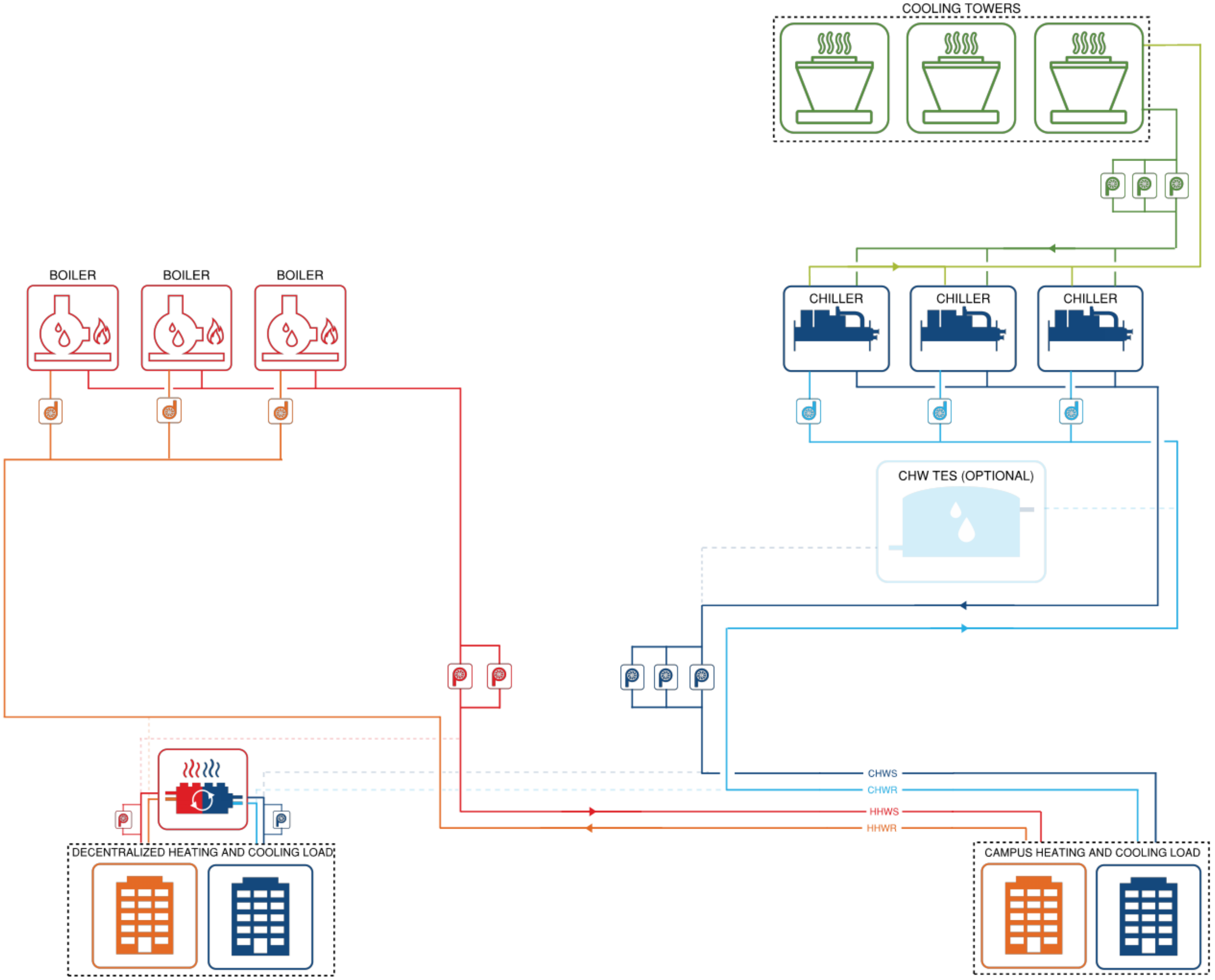


Figure 5.10: Decentralized Heat Recovery Strategy Schematic

Table 5.11: Decentralized Heat Recovery - Criteria Assessment

Criteria Group	Assessment
Environmental	Scope 1 emissions reduced in building served by decentralized plant. Emissions remain at campus central plant, however after all phases complete, Scope 1 emissions can be fully removed from campus heating either through full heat recovery from CHW loop, or supplemental sources of heat
Total Cost of Ownership	Existing campus distribution loops, building piping & HHW coils can be maintained and reused. Some piping may have to be reconfigured to separate building and/or quadrant from existing loop If applicable, existing steam piping may be repurposed, however will likely need replacement Difficult to control to electrical demand peaks with multiple plants operating independently across campus
Comfort	Lower HHW temperatures required to sustain heat recovery operation> refer to HHW Reset section for strategies to mitigate thermal comfort issues. Cascade type heating system available if thermal comfort issues continue
Maintainability	Requires advanced control systems to maintain tight control sequences and additional control valves to modulate CHW flow to central CUP chillers Heat recovery chillers are commercially available with numerous successful units in operation
Infrastructure	Optimal phasing strategy as campus can implement heat recovery in stages across campus Fully electrified technology may require upsizing of electrical infrastructure. Building / quadrants may not have required infrastructure for large pieces of mechanical equipment, leading to upgrade requirements
Resiliency	Increase in overall campus heating and cooling capacity, and if not connected to same electrical feed, decentralized buildings may still operate if main campus loses power

Table 5.12: Decentralized Heat Recovery - Design Assessment

Design Benefits	Design Concerns	Design Considerations
Extremely high efficiencies can be achieved through combined heating and cooling Design allows for existing campus distribution piping and existing building valves and piping to remain in place Quadrants can be phased systematically, with building upgrades coordinated simultaneously to lower risk of thermal comfort issues due to lower HHW supply temperatures	Heat recovery may not always be possible as the heat recovery capacity is dependent on CHW loads. If building/quadrant heating loads surpass cooling loads, additional heat sources will be required Limits on maximum supply water temperature may result in reduced capacity coils across campus Tight controls will be required for efficient operation. This will require precision commissioning and	Heat recovery will likely always be possible during first phases as decentralizing HHW from CHW will ensure the CHW load remains above quadrant HHW loads. However, as system expands across campus, this effect will be minimized As not a centralized system, multiple smaller TES tanks may be required, which is potentially not feasible Depending on location of

Lower capital expense on “day one”, allows for phased financing	operations Additional control will be required to maintain CHW flow between decentralized HR chiller and central CUP TES may be required to optimize system. Expensive construction costs if excavation required	decentralized plant, installation of equipment containing refrigerants may alter building space classifications and/or require installation of refrigerant exhaust systems Campuses with distributed boilers that serve existing groups of buildings are ideally suited as infrastructure already exists to distributed HHW from a single point Additional CHW capacity will be added to campus, potentially prolonging the life of existing chillers that do not need to run as often, or allowing the campus to expand without additional chillers added If quadrants contain buildings of different load profiles, cooling and heating profile can also be balanced across buildings to produce optimal efficiency

Centralized Heat Pumps

Design Overview & Recommendations

Centralized heat pumps installed in an existing campus central plant to provide heating hot water to campus loop. This design separates chilled water and heating hot water production and does not recover heat from the campus cooling load. It is therefore better suited to campuses with a heating hot water loop that have minimal or no chilled water load. Heat pumps should be sized by assessing campus loads and conducting a cost-benefit analysis on meeting peak loads via the heat pumps versus utilizing additional sources of heat for these periods, such as existing boilers.

Applicable Technologies

- Air-to-Water Heat Pump
  - Heating Only
  - Heating / Cooling Only
- Water-to-Water Heat Pump
  - Heating Only
  - Heating / Cooling Only
- Water Source Heat Pump

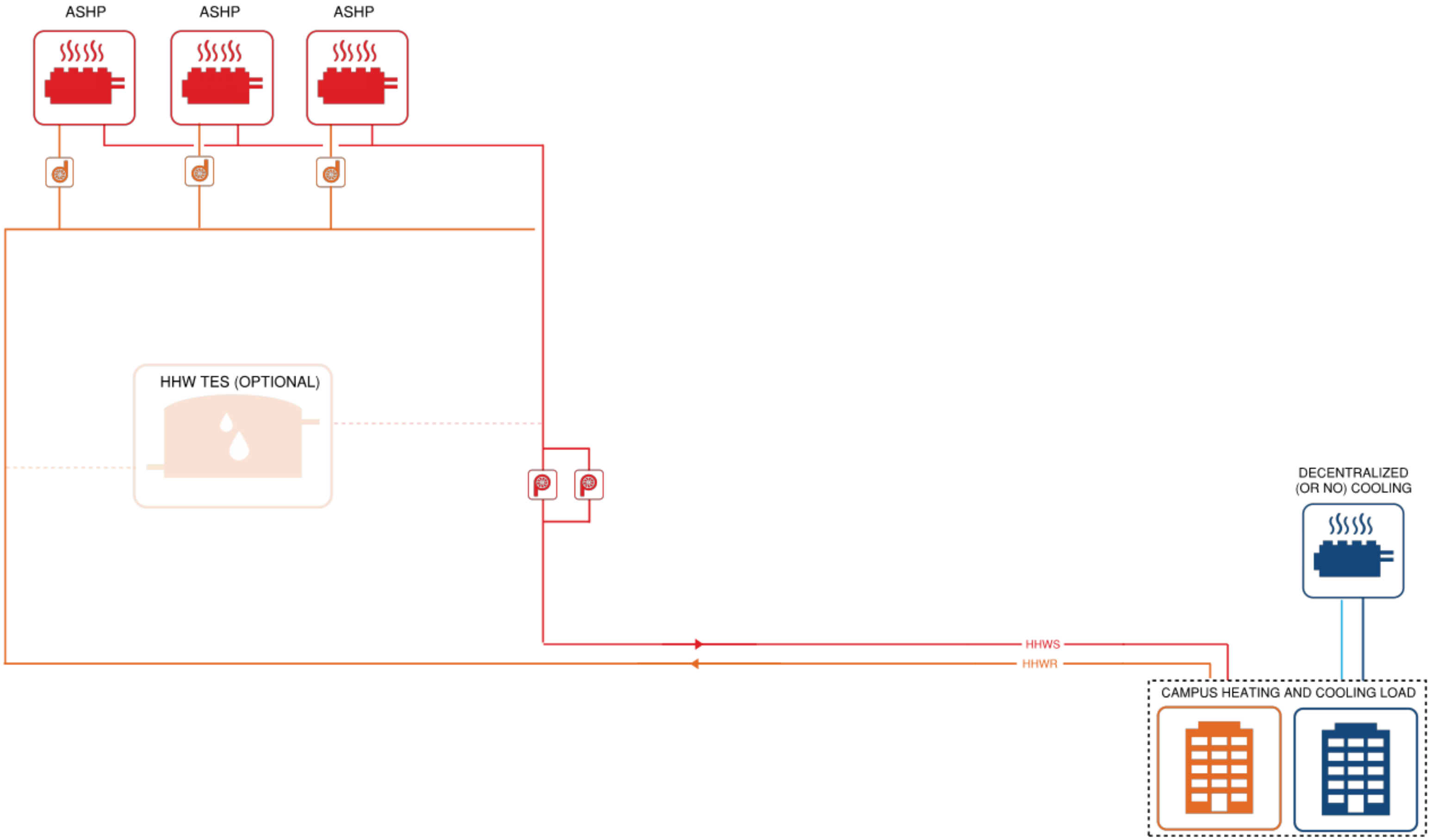


Figure 5.11: Centralized Heat Pump Strategy Schematic

Table 5.13: Centralized Heat Pump - Criteria Assessment

Criteria Group	Assessment
Environmental	Scope 1 emissions can be fully removed from campus heating and technology not dependent CHW load
Total Cost of Ownership	Existing campus distribution loops, building piping & HHW coils can be maintained and reused. If applicable, existing steam piping may be repurposed, however will likely need replacement If combined with storage, campus can operate without heat pumps running during peak demand periods
Comfort	Lower HHW temperatures required to sustain heat recovery operation> refer to HHW Reset section for strategies to mitigate thermal comfort issues. Cascade type heating system available if thermal comfort issues continue.
Maintainability	All new mechanical equipment remains in CUP and can be serviced at one location. As system separated from CHW loop, control sequences simplified over HR chillers Heat pumps are commercially available with numerous successful units in operation
Infrastructure	Modular heat pumps are available, allowing for phasing within central plant Electrical load expected to increase as chillers and heat pumps will need to operate simultaneously. Centralized plants may have additional capacity available
Resiliency	Limited impact on resiliency as compared to natural gas boiler. As distribution network still requires electricity, if there is a power outage heating will be lost with heat pump or natural gas options

Table 5.14: Centralized Heat Pump - Design Assessment

Design Benefits	Design Concerns	Other Design Considerations
Full decarbonization is possible as HHW capacity is not based on CHW loads Design allows for existing campus distribution piping and existing building valves and piping to remain in place Reduced maintenance through centralized and larger systems versus decentralized systems with compressors and refrigerant based systems distributed across campus Higher HHW supply temperatures	Optimal efficiencies are not achieved as heat is not being recovered from CHW loop. Additional energy consumption in CW loop if water-source system If water-source heat pumps installed, additional source of heating will be required to maintain source loop temperatures (boilers or geothermal) Tight controls will be required for efficient operation. This will require precision commissioning and operations	Although HHW storage is not required, installation will allow for operations to be controlled to account for outside air conditions and electrical peak demand periods Ground source heat pumps can be utilized, offsetting any additional energy consumption from CW loop Design and installation of heat pumps that can provide heating or cooling will allow additional CHW capacity during summer months if HHW is shutoff

are achievable, resulting in less potential for thermal comfort issues from high temp HHW coils across campus. As coils are replaced, HHW temperatures can be lowered, further increasing efficiency HHW storage not required to optimize decarbonization potential, lowering construction costs Reduced amount of refrigerant versus decentralized system	Potential for space concerns within central plant as all cooling equipment is required to remain in place	Upgrades to electrical infrastructure may be required at central plant if replacing non-electric heating infrastructure with electrified sources.

Decentralized Heat Pump Strategy

Design Overview & Recommendations

Decentralized heat pumps installed in quadrants and/or individual buildings across campus to provide heating hot water to individual loop and/or building. This strategy primarily applies to campuses without centralized heating or chilled water loops and may be ideally suited for existing campuses that have a 2-pipe changeover system currently installed. Decentralized heat pumps installed directly in place of boilers and utilized during the heating season only. Heat pumps should be sized by assessing campus loads and conducting a cost-benefit analysis on meeting peak loads via the heat pumps versus utilizing additional sources of heat for these periods, such as existing boilers. In the case of direct replacement for boilers, heat pumps should be sized appropriately for peak heating loads.

Applicable Technologies

- Air-to-Water Heat Pump
  - Heating Only
  - Heating / Cooling Only
- Water-to-Water Heat Pump
  - Heating Only
  - Heating / Cooling Only
- Water Source Heat Pump
- Air-to-Air Heat Pump

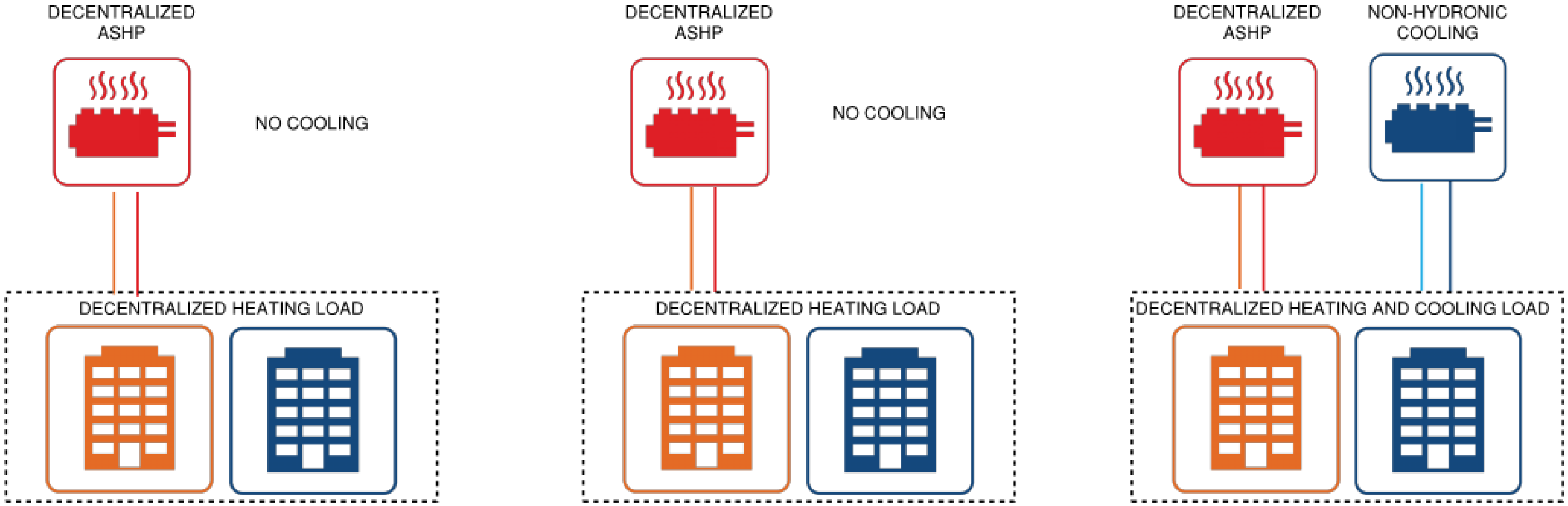


Figure 5.12: Decentralized Heat Pump Strategy Schematic

Table 5.15: Decentralized Heat Pump - Criteria Assessment

Criteria Group	Assessment
Environmental	Scope 1 emissions can be fully removed from campus heating and technology not dependent CHW load
Total Cost of Ownership	Existing campus distribution loops, building piping & HHW coils can be maintained and reused. Some piping may have to be reconfigured to separate building and/or quadrant from existing loop. If applicable, existing steam piping may be repurposed, however will likely need replacement If combined with storage, campus can operate without heat pumps running during peak demand periods Electrical load expected to increase as chillers and heat pumps will need to operate simultaneously
Comfort	Lower HHW temperatures required to sustain heat recovery operation> refer to HHW Reset section for strategies to mitigate thermal comfort issues. Cascade type heating system available if thermal comfort issues continue
Maintainability	Reduced control complexity when compared to other options, however increased O&M as mechanical system distributed across campus Heat pumps are commercially available with numerous successful units in operation
Infrastructure	Optimal phasing strategy as campus can implement decarbonization in stages across campus
Resiliency	Limited impact on resiliency compared to natural gas boiler. As distribution network still requires electricity, if there is a power outage heating will be lost with heat pump or natural gas options

Table 5.16: Decentralized Heat Pump - Design Assessment

Design Benefits	Design Concerns	Other Design Considerations
Full decarbonization possible as HHW capacity is not based on CHW loads Design allows for existing campus distribution piping and existing building valves and piping to remain in place Higher HHW supply temperatures are achievable, resulting in less potential for thermal comfort issues from high temp HHW coils across campus. As coils are replaced, HHW temperatures can be lowered, further increasing	Optimal efficiencies are not achieved as heat is not being recovered from CHW loop. Additional energy consumption in CW loop if water-source system If water-source heat pumps installed, additional source of heating will be required to maintain source loop temperatures (boilers or geothermal) Increased O&M due to heat pumps being installed across campus	Although HHW storage is not required, installation will allow for operations to be controlled to account for outside air conditions and electrical peak demand periods Depending on location of decentralized plant, installation of equipment containing refrigerants may alter building space classifications and/or require installation of refrigerant exhaust systems Design and installation of heat

efficiency HHW storage not required to optimize decarbonization potential, lowering construction costs Quadrants can be phased systematically, with building upgrades being coordinated simultaneously		pumps that can provide heating or cooling will allow additional CHW capacity during summer months if HHW is shutoff Campuses with distributed boilers that serve existing groups of buildings are ideally suited as infrastructure already exists to distributed HHW from a single point

Condenser Water Loop Distribution Strategy

Design Overview & Recommendations

Centralized or decentralized condenser water loop, providing a heat source and sink to individual WWHPs in each building. This strategy may be particularly relevant for expanding campuses, or campuses with existing capacity issues within their distribution networks. Cooling towers provide a heat sink and heat pumps or boilers can provide a heat source to the loop. If heat pumps are utilized, full decarbonization of campus loop is possible, however if so, care must be taken regarding water chemistry when combining heat pumps with stainless steel plate and frame heat exchangers. Phasing of source and sink equipment can be achieved as more buildings are added across campus.

Applicable Technologies

- Water-to-Water Heat Pump
    - Heating Only
    - Heating / Cooling Only
- Water Source Heat Pump
- Variable Refrigerant Flow

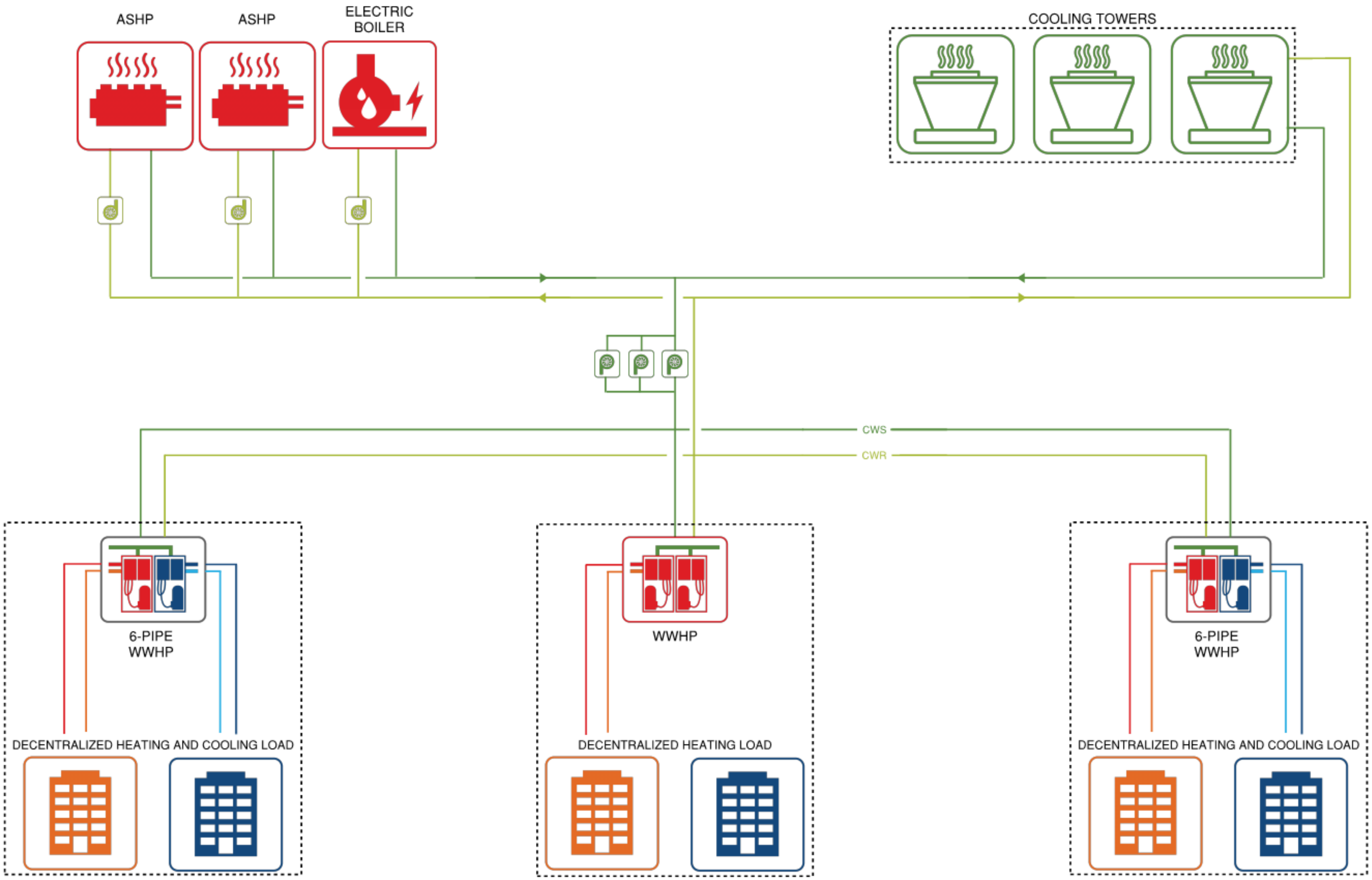


Figure 5.13: Condenser Water Loop Distribution Strategy Schematic

Table 5.17: CW loop w/ Distributed Heat Pumps - Criteria Assessment

Criteria Group	Assessment
Environmental	Scope 1 emissions can be fully removed from campus heating if combined with ground source loop for source heating
Total Cost of Ownership	Existing distribution piping may be repurposed for CW loop. Existing cooling towers / boilers can be repurposed for use as heat source/sink for CW loop Limited ability to control to peak electrical demand periods due to number of heat pumps across campus
Comfort	Lower HHW temperatures required to sustain heat recovery operation> refer to HHW Reset section for strategies to mitigate thermal comfort issues. Cascade type heating system available if thermal comfort issues continue
Maintainability	Removal of chillers reducing complex equipment and control in central plant. however Increased number of compressors across campus in individual buildings Heat pumps are commercially available with numerous successful units in operation
Infrastructure	CW loop capacity can be phased as additional buildings added to loop Potential issues with electrical infrastructure both on campus scale with numerous heat pumps being installed, and at individual buildings
Resiliency	Limited impact on resiliency as compared to natural gas boiler. As distribution network still requires electricity, if there is a power outage heating will be lost with heat pump or natural gas options

Table 5.18: CW loop w/ Distributed Heat Pumps - Design Assessment

Design Benefits	Design Concerns	Other Design Considerations
System solves issues with thermal comfort in buildings as heat pumps can provide high HHW temperatures. As coils replaced, HHW temperatures can be lowered, further increasing efficiency System can be implemented across campus in phased process Full decarbonization is achievable through methods such as connection of heat pumps to the loop or the utilization of geo-thermal technologies to provide required heating to loop in winter months	Increase in amount of complex mechanical distributed across campus Installation of heat pumps in every building will increase O&M for campus staff. Larger building may require heat exchanger installation to provide pressure break between heat pumps and building Additional pumping energy as a result if building level pumping, especially in campuses where existing distribution loops provide sufficient pressure and existing building level pumps do not operate	Existing CHW / HHW piping (if applicable) may be re-purposed for use, however, system may be better suited to future expansions to campus as existing loops will be required to remain operational as construction is completed

Electric Boilers

Design Overview & Recommendations

Centralized or decentralized solution, providing electric boilers as a direct replacement for heating hot water or steam boilers. This strategy is viable for campuses with existing heating hot water loops who are unable to reset heating hot water temperatures to those required for heat pump operation, for campuses with existing steam loops that are in good condition and have significant expected useful life, or for specific buildings that require high temperature hot water whilst the remainder of campus can be served by heat pumps. Boilers should be sized on trended load data to ensure electric boilers are not oversized.

Applicable Technologies

- Electric Boiler – hot water
- Electric Boiler – steam

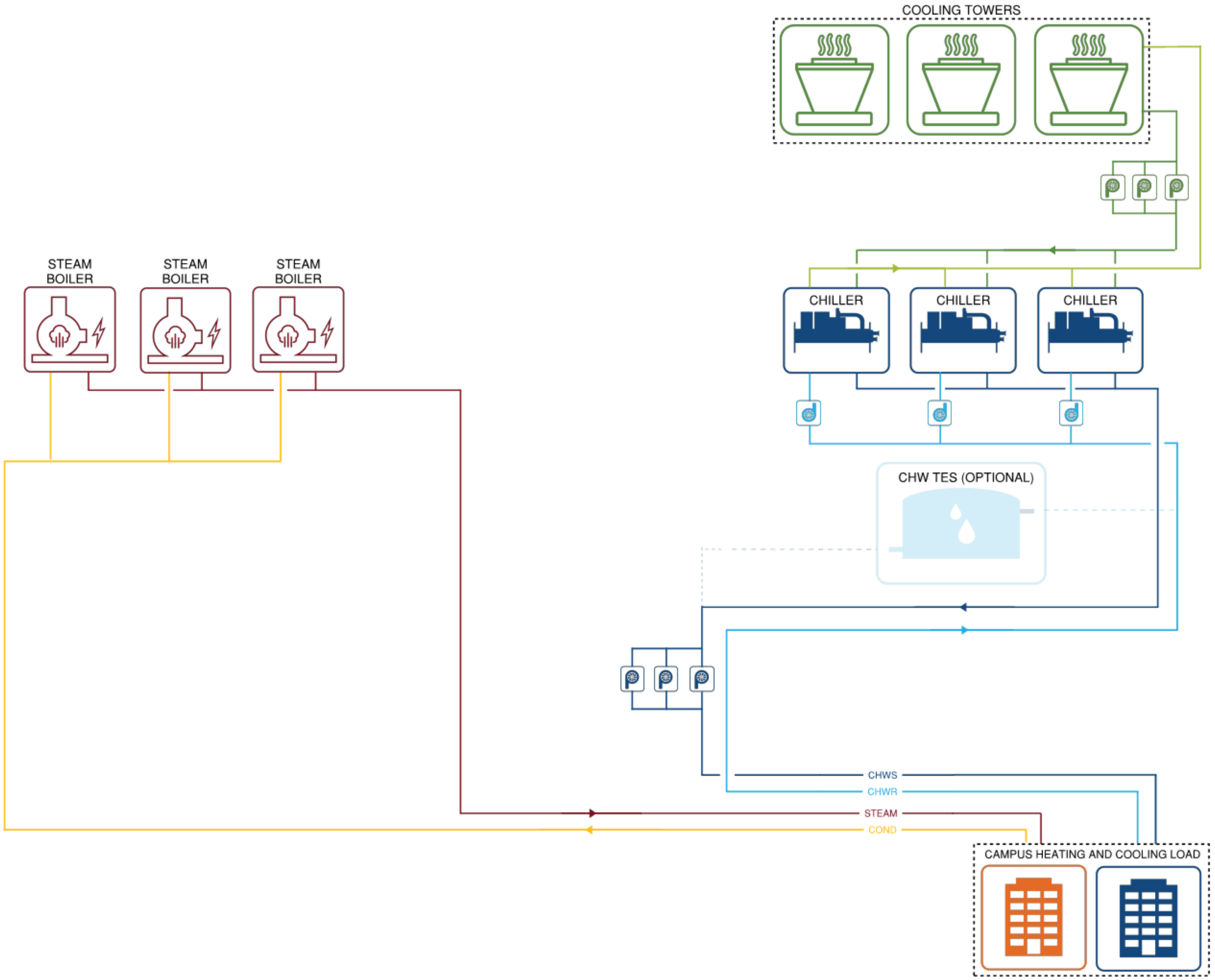


Figure 5.14: Electric Boiler Schematic

Table 5.19: Electric Boilers - Criteria Assessment

Criteria Group	Assessment
Environmental	Scope 1 emissions can be removed completely
Total Cost of Ownership	HHW boilers can produce high temp HHW, therefore existing campus distribution loops, building piping & HHW coils can be maintained and reused High utility consumption and demand costs can be expected
Comfort	Thermal comfort unaffected due to HHW temp being maintained from gas boiler
Maintainability	All new mechanical equipment remains in CUP and can be serviced at one location
Infrastructure	Fully electrified technology may require upsizing of electrical infrastructure, however central plants may have additional capacity available
Resiliency	Limited impact on resiliency as compared to natural gas boiler. As distribution network still requires electricity, if there is a power outage heating will be lost with heat pump or natural gas options. No additional resiliency is added to CHW system.

Table 5.20: Electric Boilers - Design Assessment

Design Benefits	Design Concerns	Design Considerations
Boiler can produce HHW temps in line with gas boilers, mitigating concerns with thermal comfort Design allows for existing campus distribution piping and existing building valves and piping to remain in place Boilers can be installed in place of existing natural gas equipment, keeping central plant centralized and minimizing disruption to plant operations Reduced maintenance cost through centralized and larger systems versus decentralized systems with compressors and refrigerant based systems distributed across campus No refrigerant in system	Electric boilers operate at a COP = 1, significantly lower than other decarbonized equipment included in this study. Lower efficiency will lead to high electrical consumption, increasing electrical utility bills Electric boilers have significant electrical loads, potentially significantly increasing electrical demand chargers	HHW TES may offset electrical demand charges, however will not reduce electrical consumption charges

5.3.3 Additional Opportunities

Additional Heat Sources

The heat pump technologies outlined in this section can all operate 100% carbon free if a heat source is available. Similarly, additional heat sources may be available on campus that will allow for hot water generation without the need for heat recovery or heat pump operation. These have been outlined in the Implementation Optimization section in this report, and include:

- Ground Source Heat Pumps
- Geothermal Wells
- Sewer Heat Recovery
- Solar Hot Water (SHW) – installation of SHW to produce heating hot water for campus distribution
- Solar Hot Water (SHW) – installation of SHW to increase chilled water return temperature
- Chilled water coils on building exhaust to pick up wasted heat from the building

Additional information on design considerations for low-carbon heat sources has been included in Section 4.5 of Task 4.

Cascade Heating Systems

A solution to help improve the efficiency of decarbonized systems while mitigating issues with thermal comfort and heating capacity within a building would be to install a cascade heating system. This system would be applicable to both centralized and decentralized heat recovery and heat pump infrastructure.

A cascade type system distributes hot water at lower temperatures throughout the campus via air-source heat pumps or heat recovery chillers. With lower hot water temperature, air-source heat pumps can operate at optimal efficiencies, producing water at around 100-115F. At the buildings, water to water heat pumps can further increase the temperature to a maximum of 176F for space heating and/or domestic hot water needs. As additional equipment is required outside of the central plant, additional O&M expenditure will be required. For that reason, it is recommended that cascade systems are only installed under specific conditions.

- Campuses that are expanding and desire to combine existing and new buildings onto the same hot water distribute loop can install water boosters in the existing buildings, whilst designing the new buildings for low temperature heating hot water. This allows campus to retain existing piping, coils, and terminal units.
- Campuses with high heating loads in specific buildings and are therefore unable to reset their hot water supply temperatures. A cascade system will allow heat recovery and/or heat pump operations at either a centralized or decentralized location, supplying the campus with lower temperature heating hot water. In specific buildings that require high temp hot water, this can still be provided, ensuring loads are met across all campus buildings.

An additional benefit of such systems is the ability to bypass the building level heat pumps when low temperature hot water satisfies building loads. It may only be in the winter months that high temperature hot water is required, and there the ability of bypass when loads allow will further reduce energy consumption across campus.

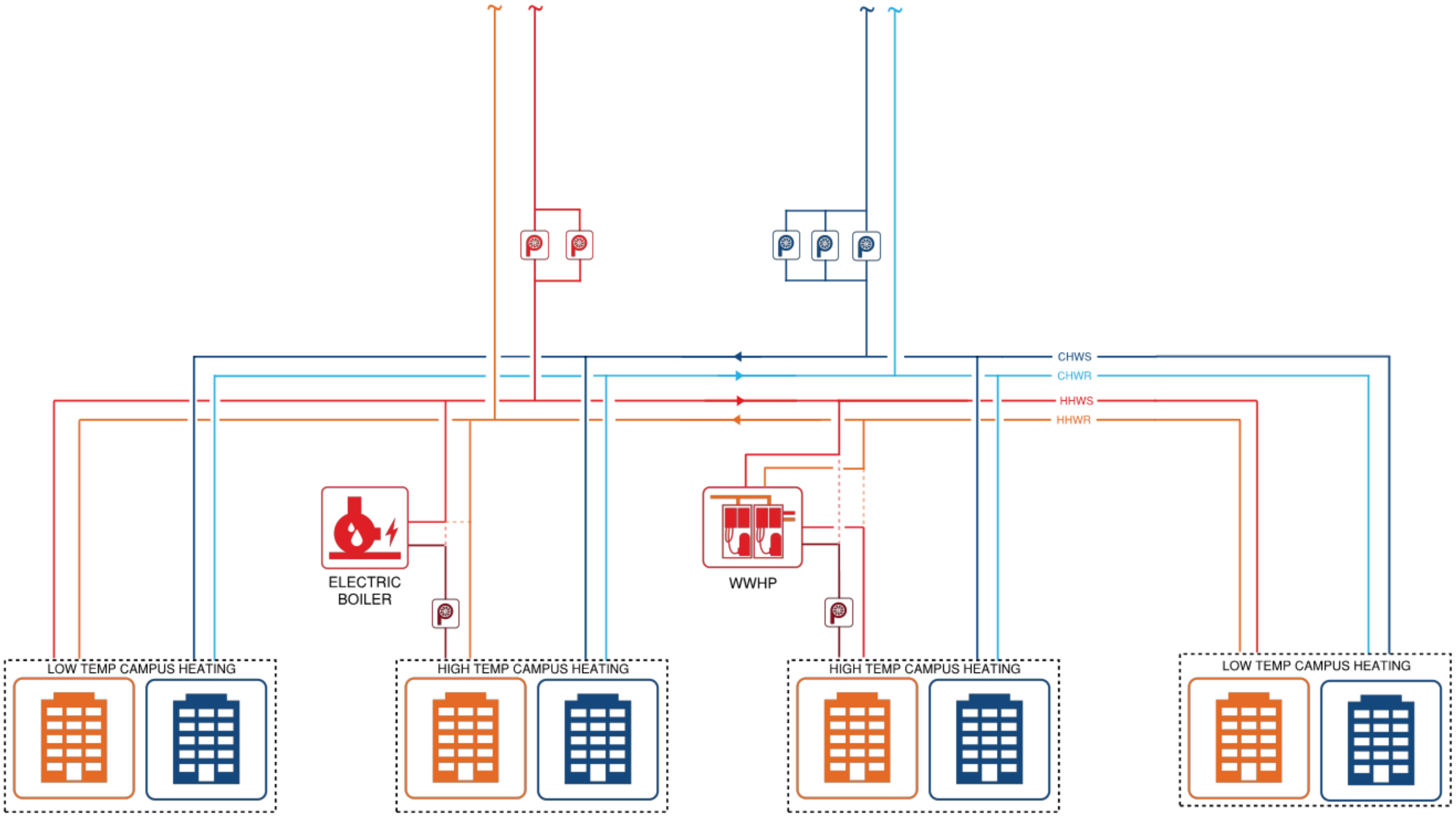


Figure 5.15: Cascade Style Heating Schematic

Section 5.4: Conceptual Recommendations

5.4.1 CSU Central Utility Plant Infrastructure Overview

The CSU system has several different heating and cooling equipment across its 23 campuses. Although each campus has their own unique load profiles and operations, many share common infrastructure types that allow for a holistic approach to decarbonization to be established. Outlined below are the different campus infrastructure types:

Table 5.21: CSU System - Individual Infrastructure Types

Existing Infrastructure	Campuses
Central HHW & CHW Loops	BA, CI, DH, FR, LB, NO, PO, SA, SB, SLO, SM, SO, ST
Central CHW Loop, Distributed Boilers	LA
Central HHW Loop, no Central CHW Loop	MB, SF
No Central Loops, Distributed Boilers	EB, HU, MA
Cogeneration – Steam Loop	SD, SJ
Cogeneration – HHW Loop	FL
Central Steam & CHW Distribution	CH

As the campuses share common infrastructure when considering the heating system on a campus scale, campuses can be grouped into the following five common infrastructure types.

Table 5.22: CSU System – Common Infrastructure Types

Infrastructure	Campuses
Central HHW & CHW Loops	BA, CI, DH, FR, LB, NO, PO, SA, SB, SLO, SM, SO, ST, FL
Central CHW Loop, Distributed Boilers	LA
Central HHW Loop, no CHW Loop	MB, SF
No Central Loops, Distributed Boilers	EB, HU, MA
Central Steam & CHW Loop	SD, SJ, CH

The remainder of this section focuses on the primary and alternative decarbonization strategies for each common infrastructure type. Included for each common campus infrastructure type outlined in the remainder of this section is a decarbonization assessment matrix. The purpose of this matrix is to allow each campus to score each decarbonization strategy and compare against one another. Each table includes a weight factor that should be determined on a campus-by-campus basis as each CSU campus is unique. Some may value resiliency over the environmental impact of the strategy, whilst others vice versa. Assigning a weight factor to each will allow the assessment to be unique to each campus, aiding in the decision-making process.

5.4.2 Central Heating Hot Water & Chilled Water Loops

Table 5.23: Central HHW & CHW Loop - Decarbonization Assessment

Weight Factor	Central CHW Loop, Distributed Boilers	Existing System	Centralized Heat Recovery Plant	Decentralized Heat Recovery Plants	Centralized Heat Pumps	Decentralized Heat Pumps	CW-Loop w/ Distributed WSHP	Electric Boilers
	Environmental	0	5	4	3	3	3	2
	CAPEX	5	4	3	3	2	3	4
	OPEX	3	5	4	3	3	4	1
	Total Cost of Ownership	4	4	4	2	3	2	1
	Comfort	5	3	3	3	3	3	5
	Maintainability	5	3	3	3	2	2	3
	Infrastructure	5	3	4	3	4	3	4
	Resiliency	3	4	4	2	2	3	2
	Total Conceptual Scoring							

Primary Strategy:

1. Centralized Heat Recovery

Alternative Strategies:

1. Decentralized Heat Recovery
2. CW-loop w/ Distributed WSHPs

Centralized Heat Recovery

Centralized heat recovery plants have the greatest potential to cost effectively decarbonize existing heating systems on CSU campuses with centralized chilled water and heating hot water distribution loops. Existing centralized systems are well suited to balance heating and cooling loads as a single location supplies heating and cooling needs for the campus. Maximizing the heat recovery potential on campus is vital to ensure heat recovery chillers operate at optimal efficiencies and centralizing their operation will best achieve this goal.

Operating and maintaining centralized equipment is a task that campuses with existing centralized systems are familiar with. Continuing operation of campus heating and cooling systems in a centralized location will therefore have minimal impact on existing O&M procedures, when compared to decentralized options. Reuse of existing system can also be maximized through continued centralization of the campus heating hot water and chilled water distribution networks. Reconfiguration of piping within the central plant may be required, however this work can be completed before connection to the existing loop, allowing the existing loop to remain operational and unaffected during construction. Connection to existing distribution lines can then be made with minimal disruption to existing service, especially if done so during the summer months when heating loads are minimal, and the existing campus infrastructure reused without new piping installed.

Campuses with centralized heating hot water that is generated via steam from a cogeneration system are still capable of utilizing a centralized heat recovery plant. As campus heating and cooling is already centralized, the benefits outlined above are applicable. However, it is not recommended this is completed before the end of the cogeneration systems useful lifetime. Therefore, a phased installation of centralized heat recovery may be an optimal solution in these circumstances, with a heat recovery chiller being installed for the base heating needs on campus, allowing the cogen engine (or turbine) operation to be optimized for power production and only to provide heating during cooler months.

Nine of the thirteen CSU campuses with centralized heating hot water and chilled water loops already have existing TES tanks that allow for facility staff to better balance the instantaneous heating and cooling loads on campus. These campuses have the ability to increase their campus heat recovery potential without the additional CAPEX required for TES. Campuses without existing TES tanks should assess the added heat recovery potential benefit against the TES construction costs and identify if there are potential locations near the centralized facility to accommodate a TES tank.

A 6-pipe centralized heat recovery option will provide additional chilled water capacity to the existing campus loop, as well as provide additional redundancy to the chilled water system. This additional capacity may allow for additional buildings being added to the campus distribution loops, and as the campus expands, significant additional CAPEX investments in chillers may not be required.

Decentralized Heat Recovery

Campuses that are expanding in locations not served by the central heating hot water and chilled water plant should investigate decentralized heat recovery plants in specific campus locations. Similarly, for campuses that have concerns on the electrical capacity at their central plant, installing a decentralized heat recovery plant(s) elsewhere on campus may remove the requirement for costly electrical infrastructure upgrades at the central pant.

Decentralized heat recovery plants, especially if connected to a separate electrical service, also offer greater levels of resiliency to a campus. If the electrical power is lost to the central plant, it may not necessarily be lost to the decentralized plant, allowing the decentralize plant to continue providing heating and cooling needs.

Although heat recovery potential may not be optimized through decentralization, the items outlined above should be considered and included in the weight factors for each design criteria.

Condenser Water Loop Strategy

As with decentralized heat recovery, a CW-loop with distributed WSHPs in building may be an optimal solution for expanding campuses, or campuses with existing capacity issues within their distribution networks. A CW loop is also capable of reusing existing infrastructure within buildings.

5.4.3 Central Chilled Water Loop, Distributed Boilers

Table 5.24: Central CHW Loop, Distributed Boilers - Decarbonization Assessment

Weight Factor	Central CHW Loop, Distributed Boilers	Existing System	Centralized Heat Recovery Plant	Decentralized Heat Recovery Plants	Centralized Heat Pumps	Decentralized Heat Pumps	CW-Loop w/ Distributed WSHP	Electric Boilers
	Environmental	0	5	4	3	4	3	3
	CAPEX	5	3	4	2	4	3	4
	OPEX	3	4	4	3	3	4	1
	Total Cost of Ownership	4	2	4	2	4	3	5
	Comfort	5	3	3	3	3	3	5
	Maintainability	5	3	3	3	3	2	3
	Infrastructure	3	1	4	1	3	2	2
	Resiliency	3	4	4	2	2	3	2
	Total Conceptual Scoring							

Primary Strategy:

1. Decentralized Heat Recovery

Alternative Strategies:

1. Decentralized Heat Pumps
2. CW-loop w/ Distributed WSHPs
3. Centralized Heat Recovery

Decentralized Heat Recovery

Campuses with a chilled water loop and distributed boilers are ideally suited to decentralized heat recovery plants due to the existing infrastructure that can be reused. As existing boilers reach the end of their useful life, heat recovery chiller plants can be installed, utilizing existing heating hot water and chilled water distribution networks. This will have minimal impact on existing operations and is optimal for phasing as funds are available.

The campus infrastructure at CSULA, the sole CSU campus with a chilled water loop and distributed boilers, is already set up to take advantage of decentralized plants. Numerous buildings are currently served via small distribution networks, with boilers in individual buildings serving nearby buildings. These distribution networks can be utilized and reused. Connections between existing loops can be made, increasing the heat recovery potential of each decentralized plant.

Decentralized plants increase the chilled water resiliency on campus, adding additional capacity to the existing chilled water loop. This may offer an opportunity to expand the chilled water loop on campus to additional and/or future building, as well as prolong the life of the existing chillers that may be able to operate less frequently. Overall chilled water redundancy will also be improved as a level of chilled water supply can be maintained if centralized chillers are shut down for unforeseen maintenance.

Decentralized Heat Pumps

If heat recovery is not a viable solution due to space constraints, or other issues, direct replacement of distributed boilers with heap pumps is recommended. These can be installed either on the roof or in existing mechanical rooms and will require minimal re-piping. Downstream of the connection to the existing heating hot water piping their distribution network and pumping can remain unaffected.

Centralized Heat Recovery

If funds are available, installing a centralized heat recovery plant and connecting individual heating hot water loops together is a feasible option that will maximize heat recovery potential on campus. A centralized heating hot water distribution loop will need to be installed, with potentially significant CAPEX requirements, however, existing loops within and between buildings can remain operational.

5.4.4 Central Heating Hot Water Loop, No Chilled Water Loop

Table 5.25: Central HHW Loop, no CHW Loop - Decarbonization Assessment

Weight Factor	Central HHW Loop, no CHW Loop	Existing System	Centralized Heat Recovery Plant	Decentralized Heat Recovery Plants	Centralized Heat Pumps	Decentralized Heat Pumps	CW-Loop w/ Distributed WSHP	Electric Boilers
	Environmental	0	3	3	4	3	3	2
	CAPEX	5	1	2	4	3	3	4
	OPEX	3	4	3	4	3	3	1
	Total Cost of Ownership	4	2	2	5	4	3	4
	Comfort	5	3	3	3	3	3	5
	Maintainability	5	3	3	3	3	2	3
	Infrastructure	4	2	3	4	3	3	3
	Resiliency	3	4	4	2	2	3	2
	Total Conceptual Scoring							

Primary Strategy:

1. Centralized Heat Pumps

Alternative Strategies:

1. Decentralized Heat Pumps
2. Decentralized Heat Recovery
3. Centralized Heat Recovery Plant

Centralized Heat Pumps

Centralized heat pumps offer campuses with a central heating hot water loop, but no chilled water loop an opportunity to decarbonize their campus whilst utilizing existing infrastructure to the furthest extent. Hot water distribution piping and coils across campus can be reused, and when future building(s) are added to the loop, designing for lower hot water temperature will help drive plant efficiency. This solution is ideally suited to campuses that currently do not have large cooling loads on campus and therefore the heat recovery potential is limited. As this technology is not dependent on chilled water loads, full decarbonization can be achieved whilst using heat pumps alone.

Decentralized Heat Pumps

When centralized heat pump installation is not feasible, decentralizing heating into campus segments and phasing the installation of heat pumps that serve these quadrants is a feasible decarbonization solution.

Decentralized Heat Recovery

Locations on campus with high cooling loads may be suitable for a decentralized heat recovery option as distributed boilers and chillers serving these building reach the end of their useful life. A 6-pipe heat recovery chiller option would allow for both simultaneous heating and cooling when loads allow or either heating or cooling, utilizing a heat source/sink when loads are unbalanced. Buildings can be combined into smaller loops if feasible, slowly converting the campus have a centralized chilled water loop.

Centralized Heat Recovery

If a campus is looking to centralize cooling, or plans to add centralized cooling in the future, a centralized heat recovery plant is also a viable solution. All the advantages outlined under central heating hot water and chilled water distribution are applicable, however, extensive capital expenditure would be required to install a central chilled water loop across campus.

5.4.5 No Chilled Water or Heating Hot Water Loop, Distributed Boilers

Table 5.26: No HHW or CHW Loop, Distributed Boilers - Decarbonization Assessment

Weight Factor	No CHW or HHW Loop, Distributed Boilers	Existing System	Centralized Heat Recovery Plant	Decentralized Heat Recovery Plants	Centralized Heat Pumps	Decentralized Heat Pumps	CW-Loop w/ Distributed WSHP	Electric Boilers
	Environmental	0		4		3	3	2
	CPAEX	5		3		4	3	4
	OPEX	3		4		3	4	1
	Total Cost of Ownership	4		2		3	3	0
	Comfort	5		3		3	3	5
	Maintainability	5		3		3	2	3
	Infrastructure	3		2		5	1	4
	Resiliency	3		4		2	3	2
	Total Conceptual Scoring							

Primary Strategy:

1. Decentralized Heat Pumps

Alternative Strategy:

1. Decentralized Heat Recovery

Decentralized Heat Pumps

Campuses without centralized heating or cooling loops should focus on decentralized solutions, which may be more financially feasible than installing centralized distribution networks. Heat pump replacement projects can be phased as boilers near end of their useful life and can be installed either on the roof or in existing mechanical rooms and will require minimal re-piping. Downstream of the connection to the existing heating hot water piping their distribution network and pumping can remain unaffected.

Decentralized Heat Recovery

For campuses that have significant existing cooling loads in addition to heating, decentralized heat recovery also offers an opportunity to decarbonize whilst modernizing existing HVAC systems. A 6-pipe heat recovery chiller option would allow for both simultaneous heating and cooling when loads allow or either heating or cooling, utilizing a heat source/sink when loads are unbalanced. Buildings can be combined into smaller loops if feasible, slowly converting the campus have a centralized chilled water loop.

5.4.6 Central Steam & Chilled Water Loop

Table 5.27: Central Steam & CHW Loop - Decarbonization Assessment

Weight Factor	Central Steam & CHW Loop	Existing System	Centralized Heat Recovery Plant	Decentralized Heat Recovery Plants	Centralized Heat Pumps	Decentralized Heat Pumps	CW-Loop w/ Distributed WSHP	Electric Boilers
	Environmental	0	5	4	3	3	3	2
	CAPEX	5	3	4	2	3	4	5
	OPEX	3	4	4	3	3	3	1
	Total Cost of Ownership	4	2	3	2	3	3	5
	Comfort	5	3	3	3	3	3	5
	Maintainability	5	3	3	4	3	2	3
	Infrastructure	4	3	5	2	3	3	4
	Resiliency	3	4	4	2	2	3	2
	Total Conceptual Scoring							

Primary Strategy:

1. Decentralized Heat Recovery

Alternative Strategies:

1. Centralized Heat Recovery
2. CW-loop w/ Distributed WSHPs
3. Centralized Electric Steam Plant

Decentralized Heat Recovery

Campuses with existing steam distribution networks are in a unique situation when considering decarbonization. To transition to a decarbonized solution, conversion to heating hot water will likely provide the highest efficiency system. However, significant CAPEX will be required in order to install a hot water distribution network. Some steam piping may be suitable for reuse; however, it is expected a significant amount of hot water piping will be required. For this reason, decentralized heat recovery plants may provide the most cost-effective method to phase the transition over time.

Existing campuses with steam distribution utilize steam-to-hot water heat exchangers at the building level and distribute hot water throughout the buildings to individual coils. It is recommended that campuses combine buildings into decentralized loops through installation of heating hot water piping. The first stage of this may include a temporary steam-to-hot water heat exchanger skid serving this decentralized loop. Once a heat recovery chiller has been installed, the temporary skid can be removed, and hot water supplied solely via the chiller. Over time, as more sections of the campus are combined, full phase out of the steam loop will be possible.

Centralized Heat Recovery

A centralized solution is also feasible and would allow for a campus to transition to a decarbonized heating system at once. However, significant CAPEX will be required in order to do so and although it is therefore a viable option that should be investigated, a decentralized option will likely be a more realistic approach.

Centralized Electric Steam

For campuses that have a steam distribution network in good working condition and that would find retiring steam distribution economically non-feasible, a centralized electric steam boiler plant will offer a means to decarbonize their existing heating systems. Electrical infrastructure upgrades may be required to support electric steam boilers, and significant electrical consumption and demand charges may occur, however, if the strategies on reducing heating loads outlined in Section 5.2 and are successfully implemented, electric steam boilers may be a cost effective decarbonization solution.