TEST-FIT REPORT FOR DISTRIBUTED HEAT-PUMP INSTALLATIONS AT MIT

Analysis of Six MIT Campus Buildings – Stratton Student Center (W20) and the Athletic Complex (W31-35) for a Pilot Program

ABSTRACT

MIT has committed to eliminate carbon-based emissions from buildings, which account for 97% of all emissions on campus. An outside engineering firm hired by the Institute presented a range of approaches to 'decarbonize" campus. A small group of alumni who are experts in advanced HVAC design and implementation and students who have won several DOE competitions formed a team to offer MIT a lower cost, easier to implement alternative that achieves zero emissions by 2035. The plan proposes a Pilot Program to confirm operating performance projections for the six buildings. This report describes the: (i) proposed thermal-energy network; (ii) technology and general system design; (iii) specific equipment and how the equipment can be integrated into existing spaces without major disruption; (iv) estimated cost for the Pilot and the entire campus; (v) projected performance of the proposed approach and the minimum $500 million savings vs the highest rated approach offered by the consulting company. The report includes an extensive array of tables, charts and some 3D renderings of equipment installations and locations. Team bio sketches are also included.

Note: This report, Iteration 1 – September 9, 2024, will be updated periodically as new information becomes available. If you are reviewing projected performance data or financial estimates, please check for updates.

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Executive Summary

MACA/Geo@MIT, a collaboration of students and MIT Alumni for Climate Action, is working to help MIT achieve a 100% decarbonized campus by 2035. Our team has explored potential technologies and believes that investing in "thermal energy networks" can help achieve the decarbonization goal. We have been working with MIT's Department of Facilities to 1) explore demonstrating the cost-effectiveness and energy efficiency benefits of a thermal energy network and 2) learn more about how our work can contribute to current campus decarbonization plans. One of the first steps in our efforts was a Test Fit for a cluster of six buildings, the subject of this report, to affirm cost and efficiency assumptions.

The thermal energy network consists of distributed water-source heat pumps (WSHP) to provide heating and cooling in each building, supplied by temperate water pumped from the central utility plant (CUP) through existing chilled water distribution piping, a system that would be repurposed as the ambient loop. The six Test Fit buildings include: W20, Stratton, Student Center; W31, Dupont Athletic Gymnasium; W32, Dupont Athletic Center; W33, Rockwell Cage; W34, Johnson Ice Rink; and W35, Zesiger Sports and Fitness Center.

MACA/Geo@MIT assumes that, regardless of the decarbonization pathway MIT selects, building envelope upgrades and additional energy recovery from exhaust systems will be implemented to reduce campus-wide heating and cooling demand. We also assume solar systems will be installed, where practical, to minimize the amount of electric energy purchased when the existing gas-fired combined cycle equipment in the CUP is decommissioned.

Focusing on delivering heating and cooling to campus buildings, evidence from the Test Fit suggests that the proposed thermal energy network could be leveraged to maximize energy efficiency and minimize disruption as MIT decarbonizes its campus because:

- WSHPs provide both heating and cooling, eliminating the need to invest in, operate, and maintain parallel systems.
- WSHPs attached to an ambient loop can leverage electric energy input with an annual average Coefficient of Performance of 5.0 and higher.
- Commercially available WSHPs are inexpensive and easy to maintain.
- An ambient loop maximizes heat pump efficiency and eliminates at least half or more of the pumping power used in a 4-pipe system.
- The ambient loop eliminates transmission losses from the CUP to the 6-building cluster.
- Building-located heat pumps enable exhaust energy recovery to reduce HVAC loads.
- Concurrent system-wide heating and cooling will significantly reduce total HVAC energy costs.

Based on available data, this Test-Fit analysis affirms:

- Paths for converting the existing chilled water loop to an ambient loop exist and have been laid out on an architectural plan and put into a 3D Model.
- There is sufficient space in each building to accommodate distributed WSHPs.

- A pilot project will be designed to demonstrate that it is possible to maintain ambient loop water temperature in the target range year-round by using the existing Cambridge Water Department infrastructure as a thermal battery, supplemented on peak days with thermal storage in the winter and cooling towers in the summer. Alternatively, shallow geothermal boreholes can be used to maintain ambient loop temperature.

Based on these Test Fit results, MACA/Geo@MIT recommends that MIT's Department of Facilities authorize a pilot program for the MITTEN (MIT Thermal Energy Network) Project. The pilot will decarbonize six buildings (W20,W31-35), which will need to be decarbonized anyway. The actual cost data from construction could influence the decision as to how the rest of the campus might be upgraded. Additionally, if the project gets underway soon there may be federal, state, and utility subsidies available to significantly reduce the capital cost of implementation.

Acknowledgements

Our MACA/Geo@MIT team has been grateful for the opportunity to partner with MIT Facilities to explore the feasibility of thermal energy networks on MIT's campus. We acknowledge the support of Joe Higgins, who initiated the Test Fit Project and Memorandum of Understanding, to Facilities engineers and planners Carlo Fanone, Karen Bowes, and Vasso Mathes, for providing regular expert feedback and technical support, in weekly or monthly meetings. Additionally, we would like to thank Facilities staff Kim Bigelow, Paula Tierney, and Mike Murphy for managing the logistics of buildings, rooms, and Zoom access and to our 6-building walk-through guides, Mark Cataldo and Dave Luria, who had keys to every mechanical room and roof space that most rarely see. We hope success at MIT could provide a framework for other universities to assess and integrate distributed thermal energy networks into their decarbonization plans, accelerating global efforts to protect our planet, our only home.

MIT alumni and student volunteer team members who have devoted endless hours to this project:

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David Williams, Herb Zien
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Table of Contents - Test Fit Report

Executive Summary 2
Acknowledgements 3
Table of Contents - Test Fit Report 4
1 Introduction 6
1.1 Overview 6
1.2 Goals, Objectives, and Test Fit 7
2 3D Model 8
3 Energy Analysis 10
3.1 Energy Analysis Overview 10
3.2 Existing Buildings' Energy Sources 12
3.3 Energy Assessment 12
3.4 Model for Thermal System Element Sizing 26
4 Thermal Energy Network Technologies and Applications 26
4.1 Heat Pump Basics 27
4.2 Energy Recovery 28
4.2.1 Inherent Ambient Loop Energy Recovery 29
4.2.2 Active Exhaust Energy Recovery 29
4.3 Available Energy Sources and Sinks 29
4.3.1 Cambridge Water Dept Network 30
4.3.2 Ground Heat Exchange/Boreholes 31
4.3.3 Ground Heat Exchange/Thermal Batteries 31
4.3.4 Concentrating Solar 32
4.3.5 Solar PV 32
4.3.6 CUP Options 33
4.3.7 Surface Water - Charles River 34
4.3.8 Sewer Thermal 34
4.3.9 Snow Melt and Other Heat Rejection 34
4.4 Thermal Energy Network Design 35
4.4.1 Top Level Distributed Heat Pump Design Considerations 35
4.4.2 Topologies 36
4.4.3 Operational Strategies and Control Systems Methodologies 37
4.4.4 Maintenance Considerations 38

5 Test Fit Proposal 38
5.1 Test Fit Thermal System Overview 38
5.2 Proposed Ambient Loop 39
5.2.1 Conversion of the Chilled Water Loop to an Active Ambient Loop 39
5.2.2 Proposed Active Ambient Loop Design /Location 40
5.2.3 Connecting the Ambient Loop to the CUP Utilities 41
5.3 New Mechanical Equipment 42
5.3.1 Building W20 43
5.3.2 Building W31 44
5.3.3 Building W32 46
5.3.4 Building W33 47
5.3.5 Building W34 48
5.3.6 Building W35 49
5.4 Electrical System Requirements 51
5.5 Ground Heat Exchanger and Ground Thermal Storage 52
5.6 Proposed Solar Photovoltaic and Thermal Collectors 53
5.6.1 Summary 54
5.6.2 Assumptions 54
5.6.2.1 Size, Weight, and Power 54
5.6.3 Placement Options 56
5.6.4 Solar System Modeling 60
6 Logistics Plan/Sequence of Construction 64
6.1 Pilot Program: Working Timeline for MIT Approval 64
6.2 Pilot Program: Building Conversion, Performance Data 64
7 Impacts 65
7.1 Cost 65
7.2 Carbon Emissions Reductions 66
7.3 Low Levels of Campus Disruption 68
8 Summary and Recommendation 68
9 Team Members 71
10 References 73
Annex 1 Abbreviations and Key Concepts 75
Annex 2 Questions Raised about Consultant Pathway Costs 77

Annex 3 Comparison: MACA/Geo@MIT Plan with AEI's Pathways 81
Annex 4 Further Considerations 83
List of Figures/Renderings 84
List of Tables 85

1 Introduction

1.1 Overview

In the long tradition of those affiliated with MIT developing affordable, practical solutions to complex problems, the MIT Alumni for Climate Action together with the Geo@MIT student team (MACA/Geo@MIT) is pleased to have developed a decarbonization pathway that can help achieve MIT's goal of a zero-carbon emissions campus and could set a new standard for decarbonizing clusters of buildings worldwide.

This proposal shows how to achieve zero-carbon emissions from MIT campus buildings by 2035. The concept enables implementation in stages. The initial stage as shown here uses well-known, well-proven technology in an integrated thermal energy system with "custom fit" solutions for individual buildings to achieve the zero-carbon target.

Proposed upgrades to the system also incorporate emerging technologies aimed at reducing both capital expense and operating costs. Initiating a Pilot Program can serve as a demonstration and learning experience for the entire MIT community. Upon success, the project could be scaled campus wide. This approach paves the way to achieving the zero-carbon target by 2035, while reducing financial risk and minimizing disruption to campus activities.

Our plan aligns with the U.S. Federal government's aggressive goals to reduce economy-wide emissions and achieve 100% pollution-free electric power by 2035 (supply-side decarbonization targets) and a net zero emissions economy by 2050 (demand-side decarbonization targets).[1] It also assists MIT in meeting the emission regulations of the City of Cambridge BEUDO Amendment, thereby avoiding Alternate Compliance Tax penalties and potentially "climate laggard" publicity.

This report specifically describes the Test Fit of a potential Pilot Program on the West Campus. The Pilot Program would be a demonstration of MIT as a test bed, allowing MIT Facilities, faculty, students and other groups to (i) measure the actual performance of the proposed equipment; (ii) evaluate several thermal management options designed to further improve the efficiency of modern district energy systems, and (iii) accurately estimate the savings in capital expenditures and operating expense if the approach were applied campus-wide.

The Pilot Program for the six-building cluster, the W20 Stratton Student Center plus the W31 - W35 Athletic Complex, proposes to convert these six buildings to renewable energy and be operational by late 2025 assuming approval in the next few months (See Section 6). Data gathering would begin as each conversion is completed. Data-driven results from the Pilot Program would allow MIT to

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[1] Oak Ridge National Laboratory. Grid Cost and Total Emissions Reductions through Mass Deployment of Geothermal Heat Pumps for Building Heating and Cooling Electrification in the United States. Nov. 2023

make a final decision no later than late 2026 on the preferred Pathway to zero emissions, allowing the entire campus to be converted by 2035 with minimal disruption.

Based on these Test Fit results, MACA/Geo@MIT recommends that MIT's Department of Facilities authorize a Pilot Program to build a thermal energy network for these six buildings. They will need to be decarbonized eventually, and actual cost data from construction could influence the decision as to how the rest of the campus should be upgraded. Additionally, if the project gets underway soon, there may be federal, state, and utility subsidies available to significantly reduce the capital cost of implementation

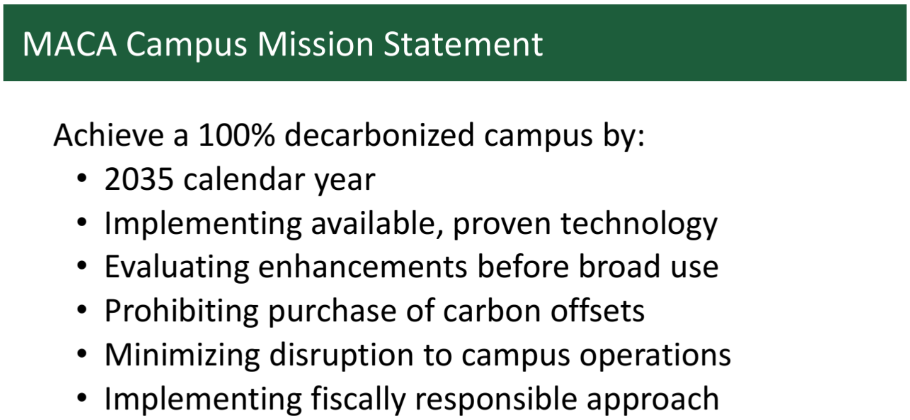
We are grateful to have been given the opportunity to partner with MIT Facilities to explore the feasibility of thermal energy networks on MIT's campus. We welcome any feedback and questions, especially regarding other important considerations that our work may have overlooked. We also request more clarity on how our work can be integrated into formal campus decarbonization plans.

We know success at MIT could provide a framework for other universities to assess and integrate thermal energy networks into their decarbonization plans, accelerating global efforts. We look forward to continuing working on this project, and exploring how to accelerate decarbonization at MIT and beyond.

1.2 Goals, Objectives, and Test Fit

A central focus of the MACA/Geo@MIT partnership is to assist MIT achieve zero emissions from buildings. While much attention in 2023-2024 within our group has focused on developing a Business Plan and a Technical Plan, the group's "Mission Statement" is much broader. As noted in our Business Plan:

Figure 1: Mission Statement



MACA Campus Mission Statement

Achieve a 100% decarbonized campus by:
- 2035 calendar year
- Implementing available, proven technology
- Evaluating enhancements before broad use
- Prohibiting purchase of carbon offsets
- Minimizing disruption to campus operations
- Implementing fiscally responsible approach

Our primary evaluation criteria for this proposal are:

- Cost-effective, fiscally responsible approach,
- Implementing available, proven technology,
- Minimum disruption to campus operations.

These evaluation criteria align with those presented in the MIT Campus Decarbonization Workshop #9 (6/4/24): evaluation criteria of Feasibility, Relevance, Technical Compatibility and Risk. In Annex 3, we seek to apply the same measurement criteria to this Test Fit endeavor as was applied to all Pathways recommended by MIT's decarbonization consultant, AEI.

The chief focus of this Report is to provide details of the Test Fit. As summarized in the Memorandum of Understanding: MIT Dept of Facilities 3/22/2024, the Test Fit should:

1. Produce a site plan highlighting areas for modification or replacement of current HVAC systems,
2. Detail placement and capacity of the ambient loop distribution network and
3. [Detail] new stand-alone geo-exchange heat pumps. [plus, consider additional energy sources]
4. Estimate the additional space needed,
5. List redundancy requirements,
6. List electric service upgrades [W33 only].

Both here, and at the end of this Report, we propose a Pilot Program to demonstrate this Test Fit in line with attaining the goal of 100% decarbonization of the MIT campus by 2035. The 6-building MIT campus cluster to decarbonize W20 and W31-W35 in the next two years is the first stepping-stone to that 2035 goal.

2 3D Model

3D Model Development and Lidar Integration for MIT's Decarbonization by 2035

A detailed 3D model has been created of the six-building proposed pilot project including the W20 Stratton Student Center and the W31-W35 Athletic Complex in support of MIT's decarbonization effort. This model was developed using Sketchup 3D software and includes proposed mechanical equipment as part of the Test Fit plan provided in this report. The 3D Model is designed to work with future Building Information Modeling (BIM) tools. It provides a clear view of campus infrastructure, including all mechanical systems and other energy components. This model is not just for visualization; it is a key tool for undertaking energy equipment upgrade planning, equipment installation planning simulations, and to facilitate more efficient and effective decision-making. By visually demonstrating equipment fit, it assists MIT to more rapidly reach its goal of optimizing energy use and achieving campus-wide decarbonization. A few elements of the 3D model are shown used to demonstrate new equipment "fit" are shown below.

In addition to its current use, there's potential for this 3D model to be used in MIT courses. By incorporating it into the curriculum, students could work on real-world projects, gaining practical experience in sustainable design, energy efficiency, and using 3D tools to solve complex architectural and engineering challenges.

Lidar Technology: Improving Space Planning

Lidar, which stands for Light Detection and Ranging, is a crucial part of this project. The Lidar scans were made using the iPhone 12's lidar scanner through the polycam app (paid Version), which uses laser pulses to capture highly accurate 3D data about specific parts of the subject buildings, in particular the mechanical rooms where new or upgraded HVAC equipment will be placed. By integrating Lidar data into the 3D model, we can ensure that all spatial dimensions, surfaces, and structural details are precise. This accuracy is essential for making informed decisions for adding new energy systems to existing buildings. The Lidar models have been instrumental in "showing" how distributed heat pumps can readily fit the available non-programmed spaces in the Test Fit 6-building cluster.

Links:
SketchUp 3D: www.sketchup.com
Polycam App: www.polycam.ai

Figure 2: 3D Model Example View

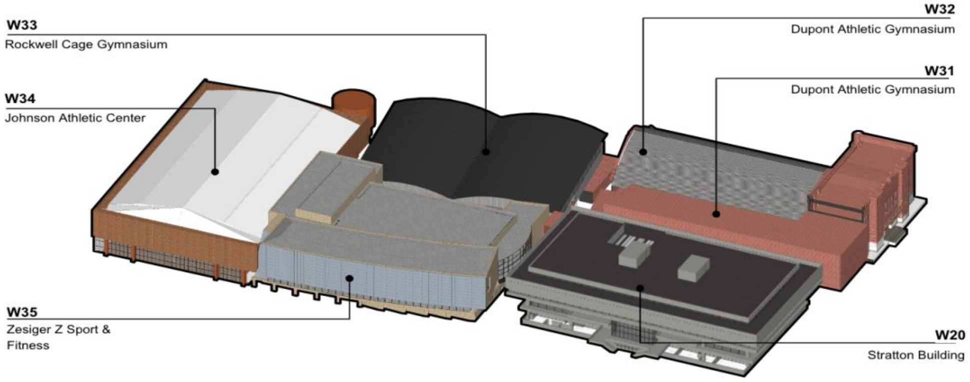


Figure 3: Lidar Scan W34-228 Mechanical

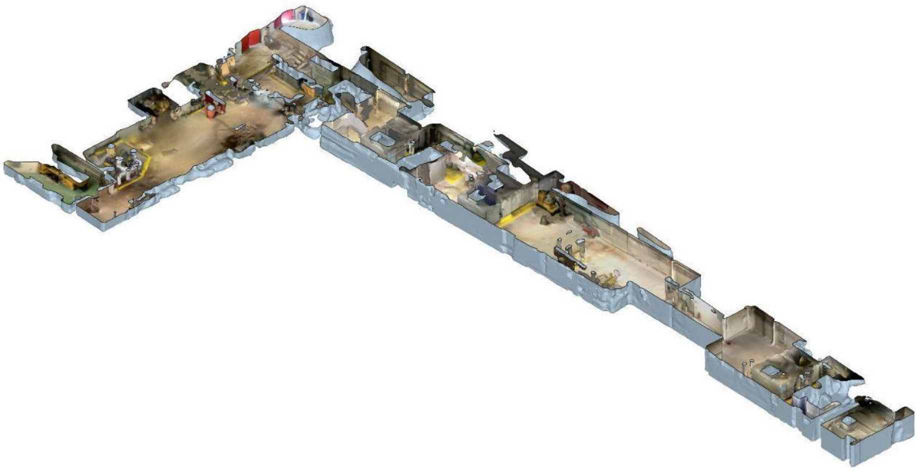
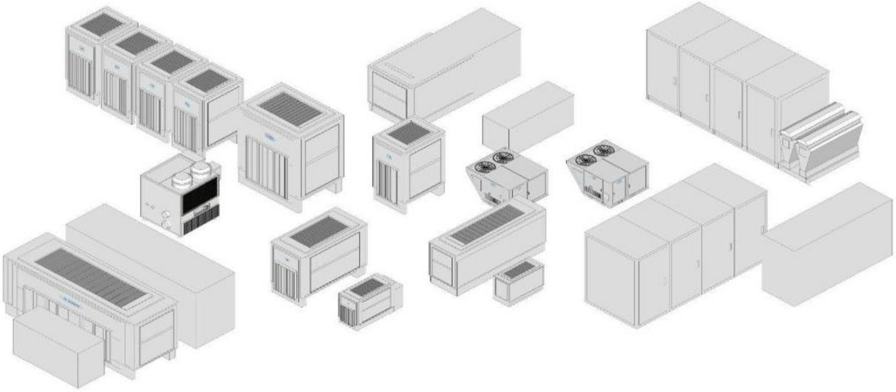


Figure 4: Test Fit Heat Pump Equipment



3 Energy Analysis

Design of decarbonized district "thermal energy network" heating and cooling requires a thorough understanding of many factors, first of which is the building thermal loads. In this section, we examine the current energy consumption of the Test Fit cluster of buildings, including as impacted by some of the proposed building load enhancements. Both an hourly energy load analysis and an operation model/simulation must be completed to properly design a thermal energy network. Belatedly in the process, we did obtain detailed load data for many of the building loads involved. An initial assessment of that data is provided here. This work is also the subject of the ongoing MIT D-Lab effort to create an interactive decision support tool for Advanced Thermal Energy Network Decarbonization Support which is planned for early release by the end of the Fall 2024 semester.

3.1 Energy Analysis Overview

A critical component of any program to eliminate emissions is ensuring adequate energy is available to meet operating needs under the zero-emission configuration. Further, an energy model is required to size any energy storage or ground thermal components in a thermal energy network. This Energy Analysis section includes data and analysis that helps size the system so both energy needs are met.

Included in the section are:

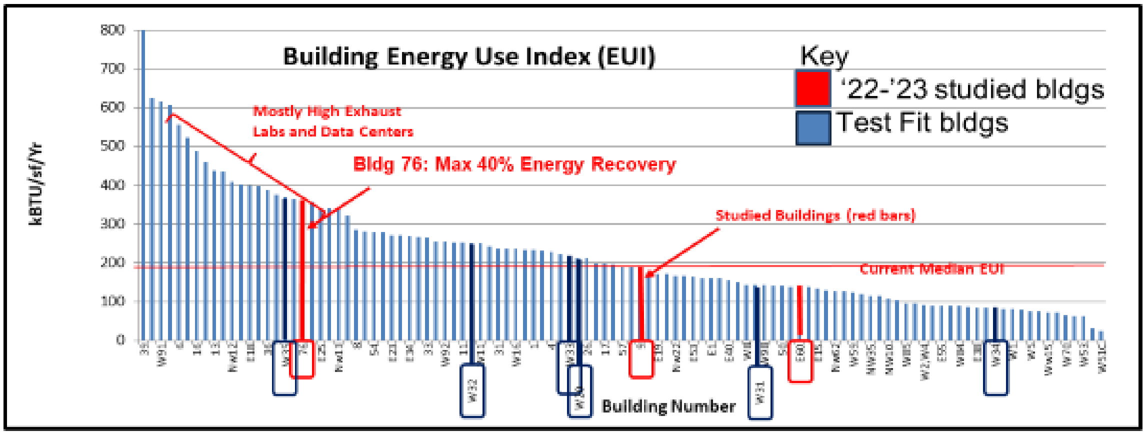
1. Information about existing energy sources by building.
2. How those energy sources are used or consumed throughout the year.
3. Special considerations for some buildings – Zesiger Sports & Fitness Center (W35), for example, has high demand for steam and chilled water, which combined, account for over 80% of the energy needs for that building. (Figure 4).
4. Introduction to how energy needs would be met under the proposed plan.

During the transition to the new design, one issue is how to maintain operations before all the equipment and/or infrastructure is converted. For example, even though the new equipment might be installed in existing space with little or no modification, the infrastructure for the new equipment might still need to be upgraded. This energy analysis will be used to ensure the solutions proposed in other sections of the Test-Fit Report to account for such issues.

The 6 buildings proposed for the Pilot Program are representative of challenging buildings throughout the campus. The goal for the Pilot Program is to achieve zero emissions while not requiring major changes to infrastructure and not causing major disruption. The Pilot also will demonstrate how installation of some equipment can significantly reduce overall energy needs e.g., installing or enhancing an exhaust heat recovery system.

The Energy Section includes many tables and charts. Figure 5 "Energy Use by Building" shows a wide range of energy use by buildings and highlights our 6-building cluster. The buildings are sorted by "energy-use index" (EUI) which reflects total energy use per square foot. The difference in EUI by type of buildings is dramatic, with labs and some athletic buildings, such as W35, being the most energy intensive. The proposed Pilot Program would significantly improve the EUI of all 6 buildings, and especially the ones with high EUI.

Figure 5: Building EUI



6 Test Fit Buildings: W35 W32 W33 W20 W31 W34

3.2 Existing Buildings' Energy Sources

A Test Fit is a planning process, applied by architects, engineers, and planners, to determine if there is sufficient physical space, in our case, in the mechanical, electrical rooms or on the roofs or in basements such that newly proposed mechanical and electrical equipment "fits." The first step in that process is to access the existing building energy systems. Table 1 shows a summary of the existing building energy sources supplied to the 6-building Test Fit cluster.

Table 1: Summary of Existing Buildings Energy Sources

Building	Chilled Water	Electricity	Gas	Steam
W20	X	X	X	X
W31		X	X	X
W32		X		X
W33		X		X
W34	X	X	X (?)	X
W35	X	X		X

(Source: MIT Sustainability DataPool)

Note that only three buildings have cooling systems supplied by chilled water (W20, W34 and W35). Electricity is used in all buildings both for HVAC equipment (such as pumps, fans, and air handling units) and spaces such as offices. Three buildings (W20, W31, and W34) have additional natural gas -- which is used for kitchen appliances in W20, and hot water in W31 and W34. Steam is used in all buildings for heating.

3.3 Energy Assessment

Table 2 and Table 3 present the monthly heating and cooling loads respectively for 2022 from the Sustainability Datapool. Table 4 contains the monthly average outdoor air temperature from air-handling units on Clockwork Analytics. Examining the monthly heating and cooling data in the tables, it is important to note that buildings W31, W32, and W33 have data issues due to faulty metering and other operational interruptions. The 2023-2024 hourly data provided through the PI system also have some of the same issues. Thus, the analysis below filters out and excludes erroneous data and provides estimates and assumptions where appropriate to fill in the gaps.

Table 2: 2022 Monthly and Total Heating 6 Bldgs

(Unit: kBtu/hr)

Date	W20	W31	W32	W33	W34	W35	Total Heating
1/1/2022	2862	2834	639	1027	1095	3853	12,309
2/1/2022	2363	2834	469	512	801	3233	10,212
3/1/2022	2229	2834	293	136	591	326	9,350
4/1/2022	1473	2834	124	28	351	3390	8,200
5/1/2022	765	2834	58	14	209	2819	6,699
6/1/2022	547	2834	8	11	70	2359	5,828
7/1/2022	442	2834		14	60	2197	5,546
8/1/2022	396	2834		18	63	2275	5,586
9/1/2022	619	2741	3	21	119	2509	6,012
10/1/2022	1108	2742	40	24	356	2953	7,223
11/1/2022	1696	75	81	205	584	2515	5,155
12/1/2022	2189	83	403	438	506	3120	6,739
					Total	***(kBtu/hr)***	88,859
					Total	(Tons)	7,405

Table 3: 2022 Monthly and Total Chilled Water Usage for MIT W20, W34, W35

Date	W20	W34	W35	Total
1/1/2022	109	0.1	2258	2,367
2/1/2022	132	0.08	2044	2,177
3/1/2022	200	85	2573	2,857
4/1/2022	499	295	2573	3,367
5/1/2022	1345	407	4216	5,968
6/1/2022	1616	512	3991	6,119
7/1/2022	2840	823	4793	8,456
8/1/2022	2816	810	4906	8,531
9/1/2022	1740	457	4000	6,197
10/1/2022	1086	242	3987	5,315
11/1/2022	897	143	2901	3,940
12/1/2022	187	0.02	2693	2,879
			Total kBTU/yr	58,174
			Total Tons	4,847

Table 4: Monthly Average Outdoor Air Temperature 2021-2023 (degrees F)

Source: W46 AHU1 and W20 Outdoor Air Conditions from Clockworks Analytics Data (cross-referenced with other air temperature data sets)

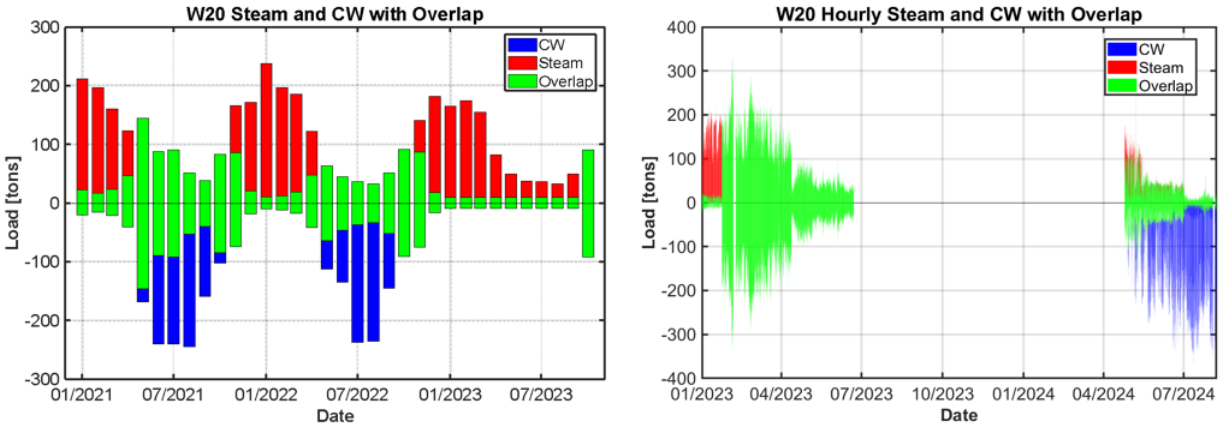
Jan 2021	33.1239	Jan 2022	28.5027	Jan 2023	37.9394
Feb 2021	33.5505	Feb 2022	34.3050	Feb 2023	35.8252
March 2021	43.0472	March 2022	42.3170	Mar 2023	41.1852
Apr 2021	50.4836	Apr 2022	50.1204	Apr 2023	51.5628
May 2021	60.9195	May 2022	61.6874	May 2023	60.5816
Jun 2021	73.3143	Jun 2022	68.8521	Jun 2023	66.3945
Jul 2021	70.7660	Jul 2022	78.2752	Jul 2023	75.6008
Aug 2021	74.3920	Aug 2022	76.4938	Aug 2023	70.9648
Sep 2021	68.3123	Sep 2022	64.7255	Sep 2023	66.8518
Oct 2021	59.5558	Oct 2022	55.6948	Oct 2023	58.4807
Nov 2021	45.7950	Nov 2022	49.0918		
Dec 2021	40.1919	Dec 2022	36.9368		

The following section presents an energy and overlap analysis based on monthly data for three buildings – W20, W34, and W35 – which currently have both heating and cooling systems and make up a significant portion of the total load in the cluster. The term "overlap" refers to the portion of the loads that require simultaneous heating and cooling, which, in the case of heat pumps, will be handled by the same or directly interacting units. This allows energy use to be resolved locally, with the resulting electric power load and heat/cool balance influenced by the equipment's coefficient of performance (COP). For this analysis, the COP is fixed at 5 although it always varies with current conditions, and in energy recovery scenarios it typically exceeds COP=5. The COP represents the total amount of heat generated per unit of electricity, with a simultaneous cooling output equal to COP minus 1. The graphs in this section utilize monthly data from 2021 to 2023 from the Sustainability Datapool, hourly temperature data from Clockwork Analytics, and hourly heating and cooling load data from the PI system during the time frame of January 2023 to August 2024.

Additionally, active exhaust energy recovery is employed to retain the existing thermal energy within the buildings rather than being wasted to the atmosphere. This method necessitates the installation of small recovery units or heat pump-driven heat exchange coils in exhaust systems, which are currently mostly absent from this cluster of buildings.

Building W35, characterized by high-volume exhaust, exemplifies the potential for significant improvements through the implementation of local distributed heat pumps. This analysis does not yet include the full scope of exhaust/make-up air or “ASHP overdrive,” which will be incorporated once additional data analysis is completed.

Figure 6: W20 Monthly Load Distribution for Chilled Water (CW) and Steam Usage

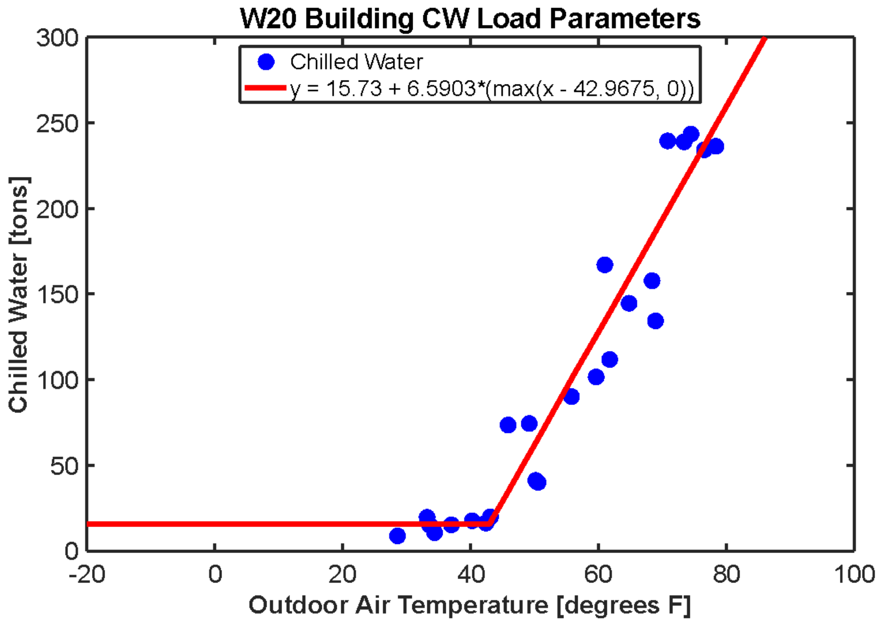


The bar chart on the left in Fig. 3 displays the monthly load distribution in tons for chilled water (CW) and steam usage from January 2021 to October 2023. The green bars represent the overlap in usage, indicating concurrent loads. Positive values indicate steam consumption, while negative values represent chilled water consumption. Simultaneous heating and cooling accounts for 43% of the total load. The required steam balance is 228 tons, and the required chilled water balance is 202 tons. On the right in Fig. 3 is the hourly load distribution

Change-point models are a crucial tool in regression analysis, particularly for determining the baseline energy consumption of buildings. These models are designed to identify points at which the relationship between dependent and independent variables changes, providing a more accurate representation of energy usage patterns across different temperature, weather, and operational conditions.

Figure 7 illustrates the relationship between outdoor air temperature and chilled water usage for building W20. The blue dots represent the monthly chilled water usage at various outdoor air temperatures, with a red line overlaid representing the regression model. Based on the analysis, the baseline chilled water usage for W20 is about 15.7 tons for outdoor temperatures below 43 degrees F. This suggests that the building’s cooling system maintains a baseline operation even when the outdoor temperature is low, possibly to handle internal heat gains from equipment and other sources. After the balance point temperature of 43 degrees F, the cooling demand starts to increase significantly with the chilled water usage increasing linearly with a slope of 6.6 tons per degree F. The relatively high slope indicates that the building’s cooling system has significant demand increase with temperature rise, which points to inefficiencies in the building envelope or HVAC system performance that could be mitigated through addressing issues like the single-pane glass windows.

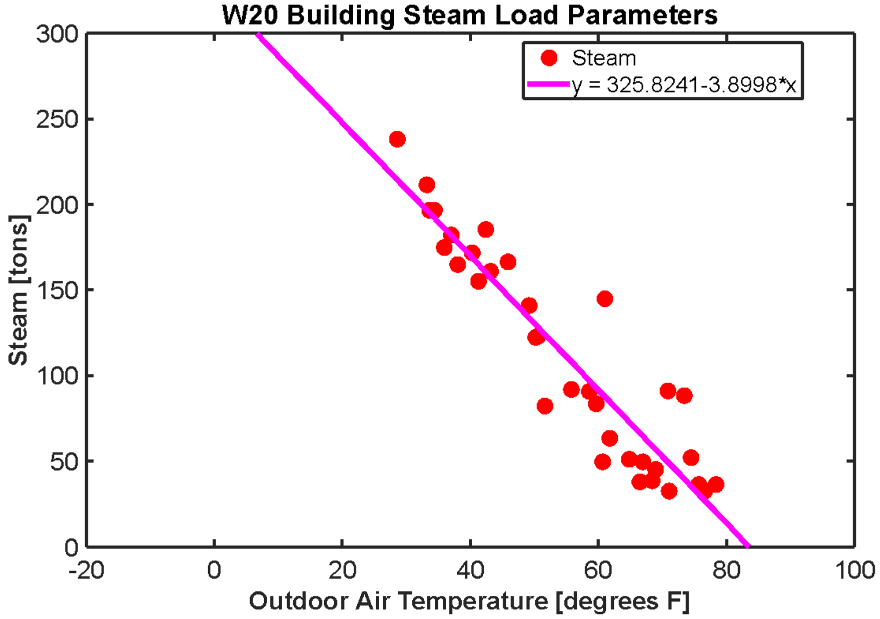
Figure 7: W20 Building Monthly CW Load Parameters



The balance point temperature based on the regression is 43 degrees F. This analysis only includes 2021-2022 data for CW since W20 was closed during most of 2023. The monthly outdoor air temperature used in the analysis was taken from the air-handling units and outdoor air conditions on Clockworks Analytics in Table 4.

Figure below illustrates this analysis with the steam usage in W20 in relation to outdoor air temperature. The intercept value (326 tons) represents the steam usage at 0 degrees F. This high intercept suggests significant heating requirements at very low outdoor temperatures. As outdoor temperatures rise, the building's heating demand reduces at a rate of 3.90 tons per degrees F. This trend highlights the potential for energy savings during milder weather conditions.

Figure 8: W20 Building Monthly Steam Load Parameters



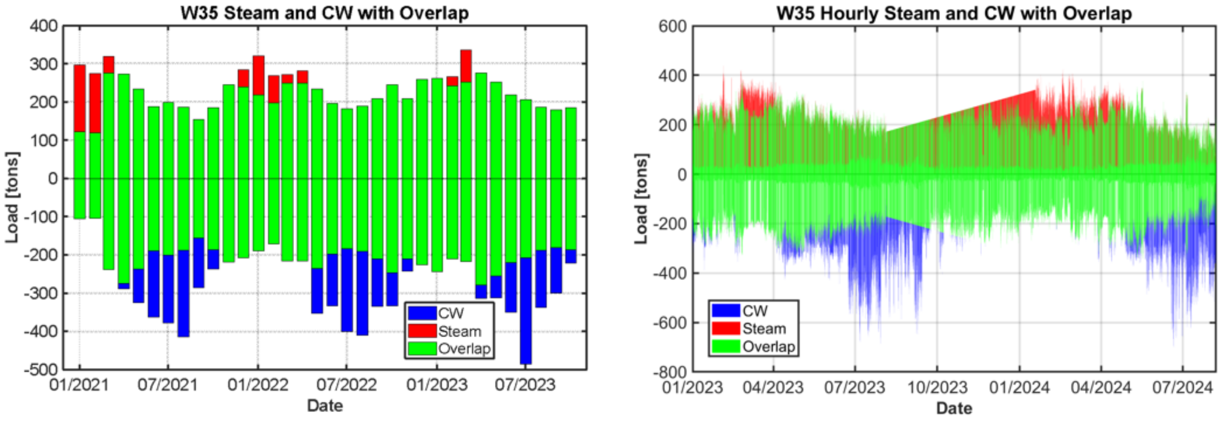
The 95% confidence interval for the line of best fit displayed is:

b0 = [295.0538, 356.5944]

b1 =[-4.4411, -3.3585]

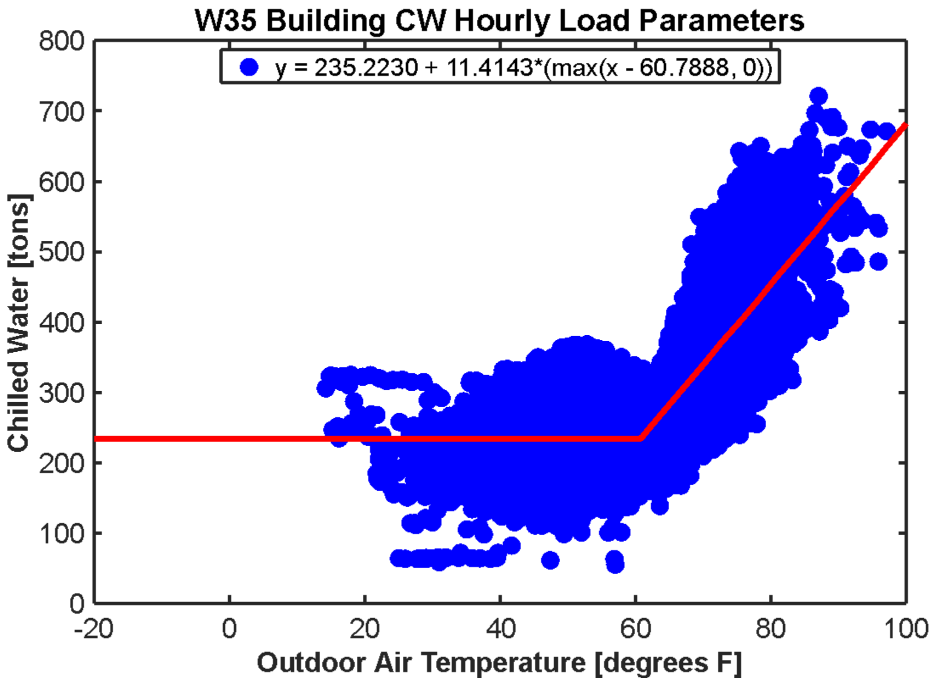
Line of best fit: y = 325.8241 – 3.8998*x

Figure 9: W35 Monthly Load Distribution for Chilled Water (CW) and Steam Usage



The calculated simultaneous heating and cooling is 81% of the total building energy load. The required steam balance is 175 tons, and the required chilled water balance is 277 tons. Building W35 presents a large opportunity to capture and recover waste heat energy from the large amounts of high-volume exhaust. The significant overlap demonstrates the potential for massive gains through implementing local distributed heat pumps and active exhaust recovery units that will significantly decrease the peak loads of operation.

Figure 10: W35 Building Chilled Water Hourly Data Load Parameters



The balance point temperature for the building based on the regression analysis is 61 degrees F. The 95% confidence interval for the regression fit of the form:

$$f(x) = a + b((x - c, 0)\ )$$

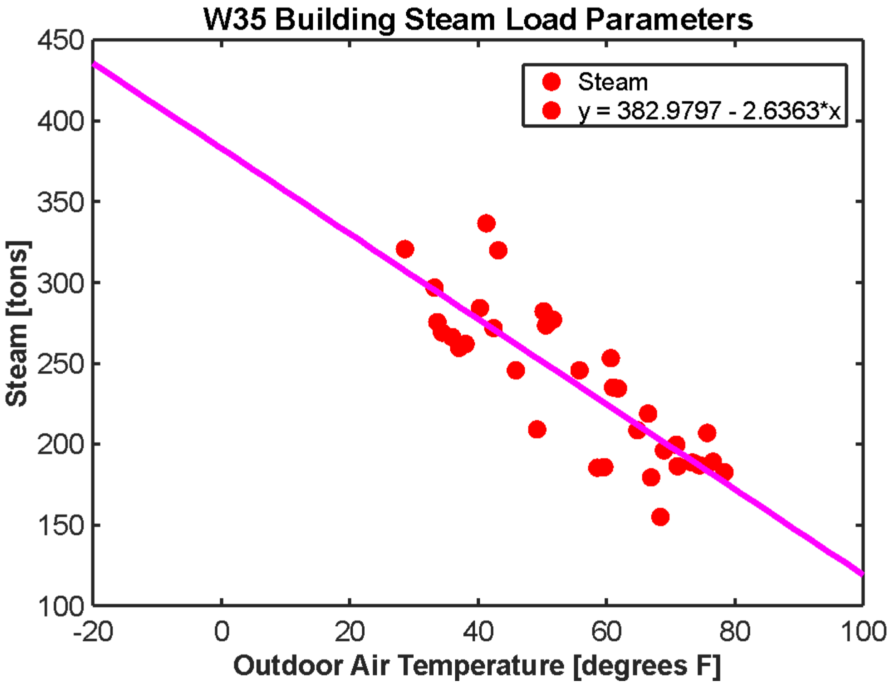
a = [233.2161, 237.2299]

b = [11.0648, 11.7638]

c = [60.3657, 61.2119]

All parameters are statistically significant based on the confidence interval. Based on this analysis we can say with 95% confidence that the base chilled water load for building W35 is between 233 tons and 237 tons. For outdoor temperatures above 61 degrees, the chilled water usage increases rapidly at a rate of 11.4 tons per degree F.

Figure 11: W35 Building Monthly Data Steam Load Parameters



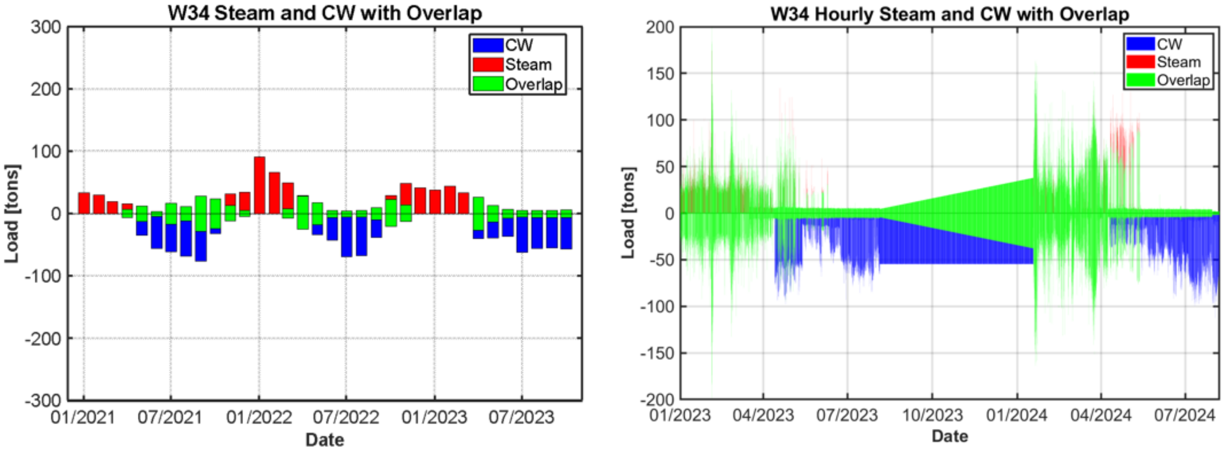
95% Confidence Interval for the Linear Fit: y = b0 + b1*x

b0 = [347.3612, 418.5982]

b1 =[-3.2629, -2.0097]

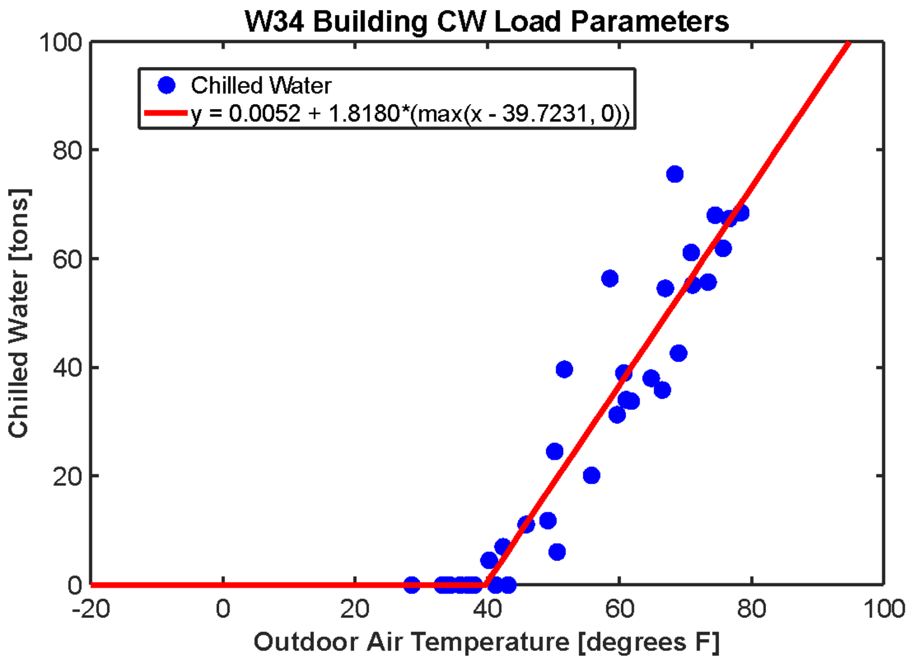
Line of best fit: y = 382.9797 – 2.63638*x

Figure 12: W34 Monthly Load Distribution for Chilled Water (CW) and Steam Usage



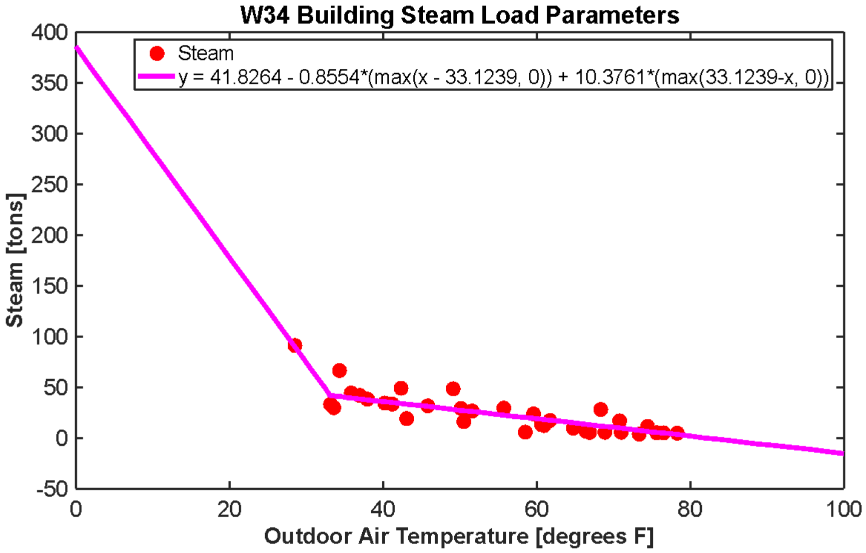
The calculated simultaneous heating and cooling is 33% of the total building energy load. The required steam balance is 91 tons, and the required chilled water balance is 64 tons.

Figure 13: W34 Building Monthly Data Chilled Water Load Parameters



Based on the regression analysis, the balance point temperature for the building is 40 degrees F. Below this temperature, the chilled water load for this building is essentially negligible.

Figure 14; W34 Building Monthly Data Steam Load Parameters



A four-parameter heating model regression was applied to the monthly steam data for building W34. Based on the fit, we can see that at 33 degrees F, there is a shift to lower steam consumption from 10.4 tons per degree F to 0.86 tons per degree F.

Figure 15: Monthly Chilled Water, Steam, Electricity, and Natural Gas Consumption

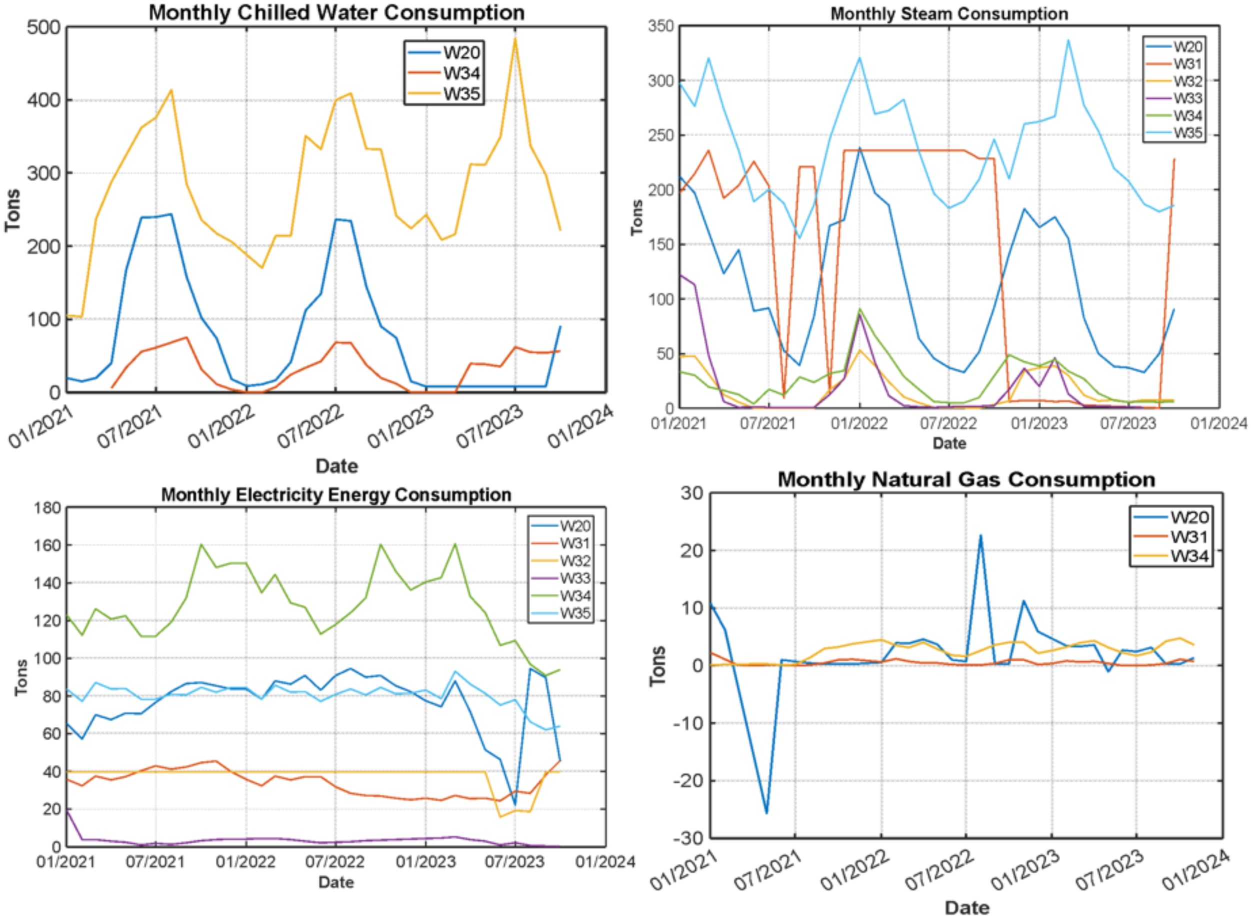
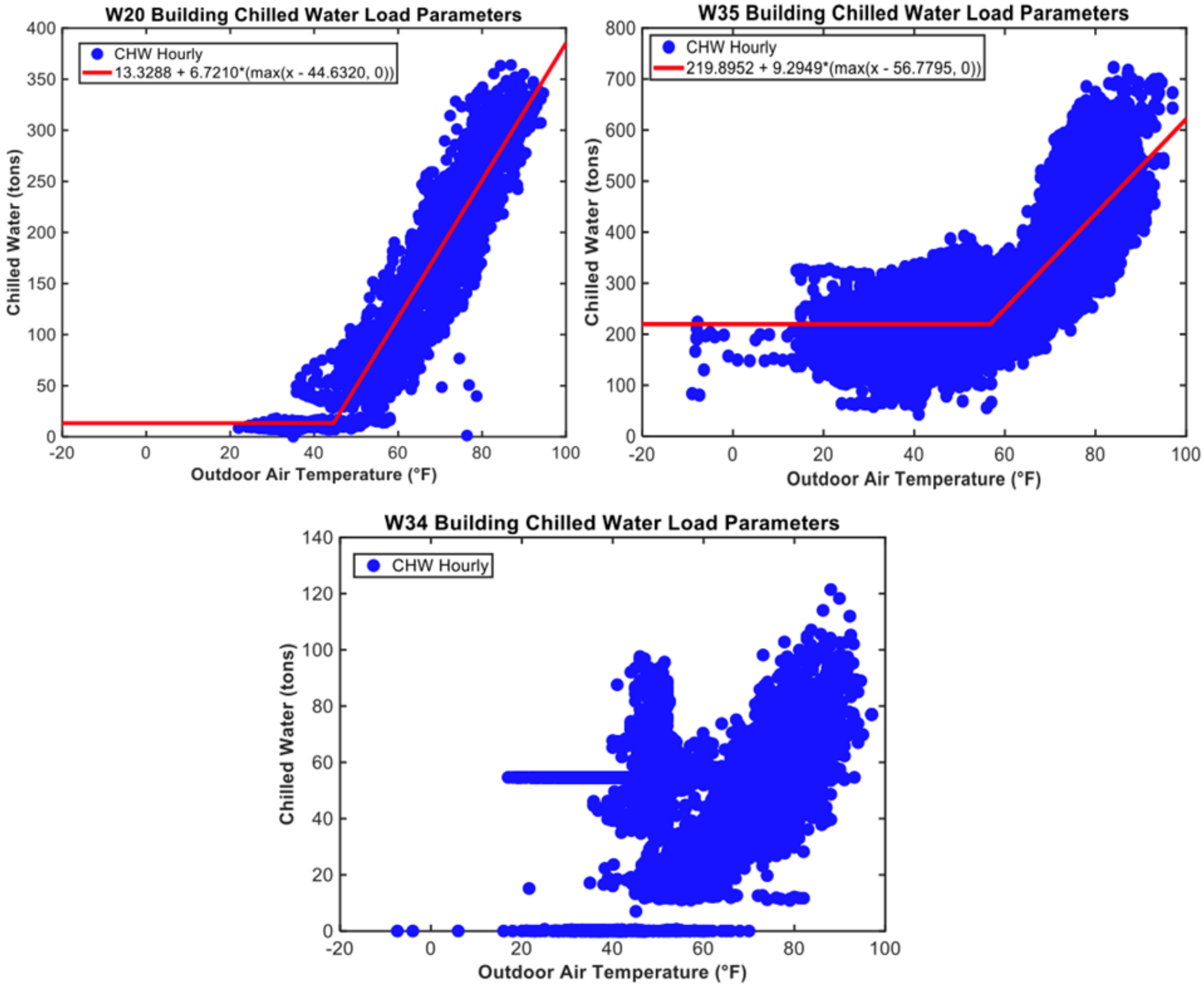
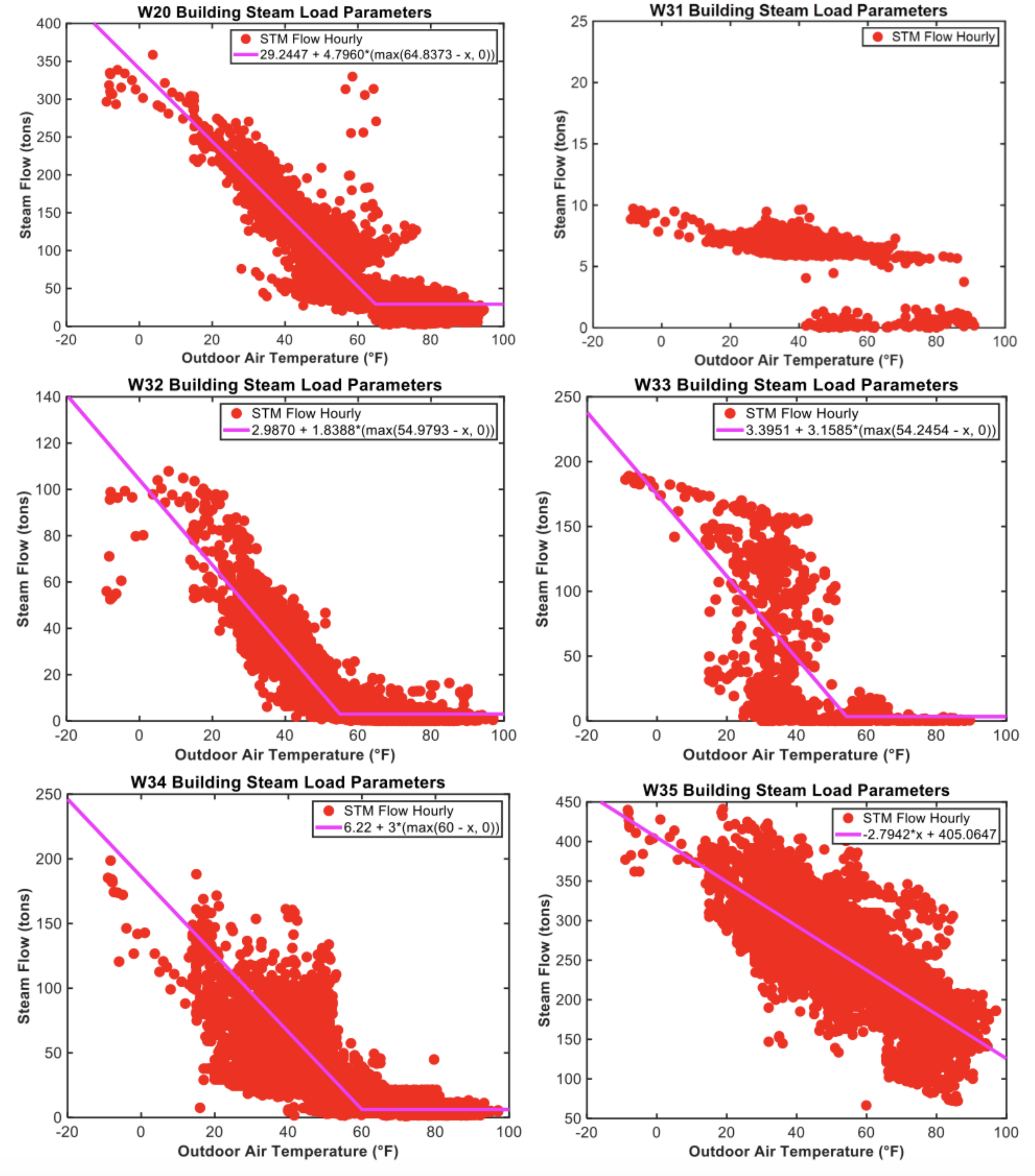


Figure 16: W20, W34, and W35 2023 - 2024 Hourly Chilled Water Analysis



Note: W34 has some incorrect meter data as illustrated by the irregular points.

Figure 17: Six-Building 2023 - 2024 Hourly Steam Analysis



Examining the plots in Fig. 17, we see that there are several irregularities in the steam meter data in buildings W31, W33, and W34. Because of these inaccuracies, creating a more comprehensive analysis of the load reductions from subsequent energy conservation measures was more difficult.

Figure 18: W34 2022 Daily Peak Chilled Water Loads

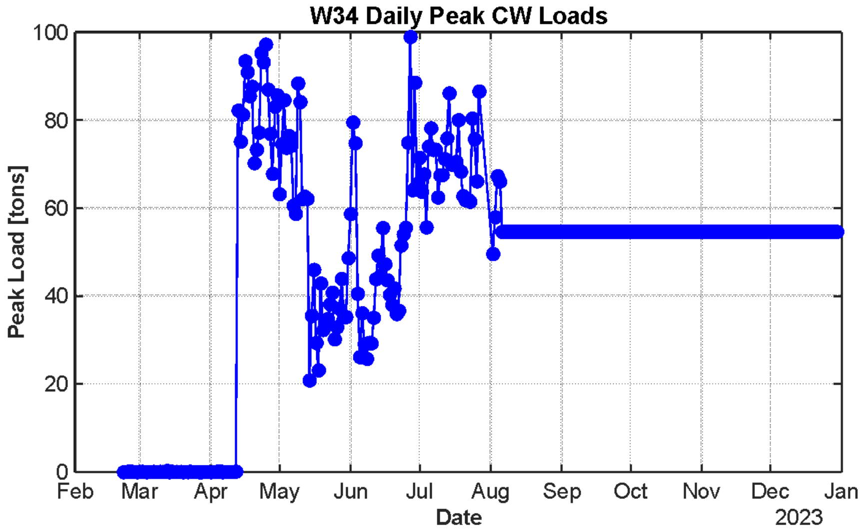


Figure 19: W35 2022 Daily Peak Chilled Water Loads

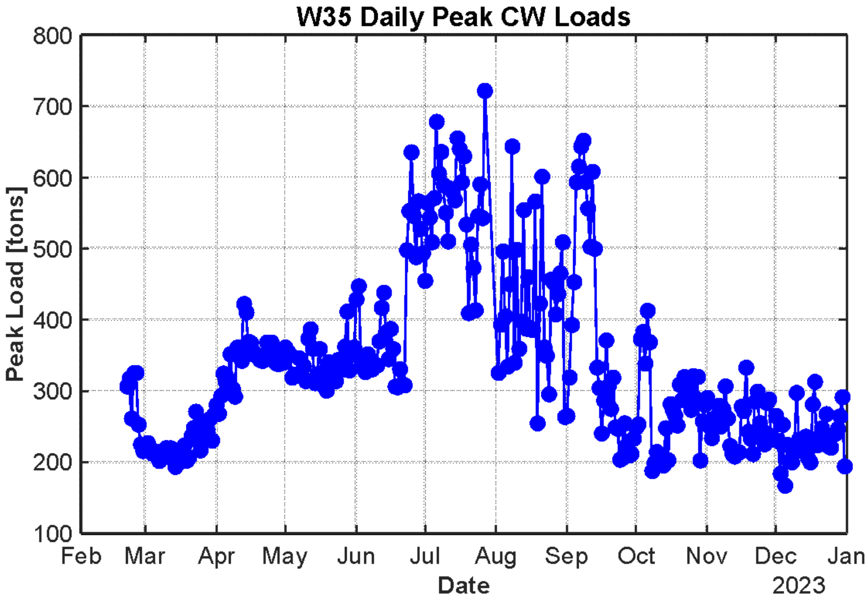
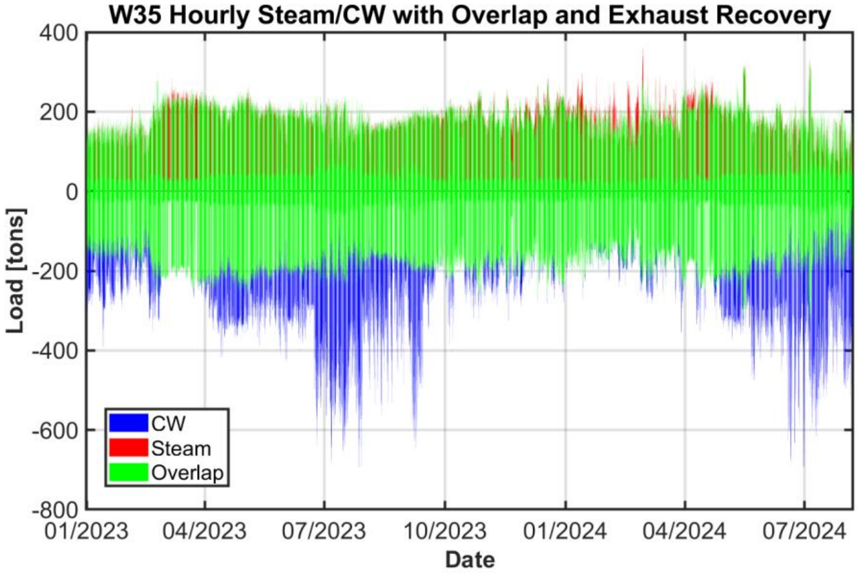


Figure 20: W35 Hourly Steam/CW Load Reduction from Overlap and Exhaust Recovery



3.4 Model for Thermal System Element Sizing

As mentioned earlier, the hourly or better detailed data required for our analysis was received too late in the Test Fit process to complete the comprehensive Model and Simulation necessary for advanced thermal system sizing and trade-off analysis. This work is currently in progress and will be updated upon completion. Additionally, this project is part of the ongoing effort at MIT D-Lab to develop an En-ROADS style Interactive Decision Support Tool for Decarbonization with Advanced Thermal Energy Networks like being proposed for decarbonization at MIT. Currently, such analyses are all one-off and are thus costly, and the quality of the analysis depends heavily on the level of expertise involved. This software effort is meant to bridge that need and enable a rapid advancement of thermal energy networks for Climate Action.

4 Thermal Energy Network Technologies and Applications

Design of decarbonized district "thermal energy network" heating and cooling requires understanding and coordinating several factors beyond those of typical HVAC solutions. These advanced thermal systems require design and operation that balance five principal elements: A) building thermal loads, B) building and site characteristics, C) district/network thermal and electric loads, D) weather, and typically E) thermal storage. Such decarbonized HVAC solutions cover a spectrum from being fully air source heat pump (ASHP) driven to fully ground source heat pump (GSHP a.k.a. "geothermal") with the more cost-effective solution being a carefully chosen combination of those two extremes.

Numerous mixes of thermal storage in several forms can be used including buried ground heat exchangers (GHEX), above ground thermal energy storage (TES) tanks, and phase change materials (PCM) potentially applied in several ways and in combination with both GHEX and TES. Equipment options typically include multiple optional approaches, down-selected to best fit each building involved. Trade-offs between the various elements affect all of space/impact, CapEx, and OpEx. Such systems have now been in fairly widespread use for about 20 years and have been proven to be cost-effective when designed and operated correctly. However, when using other than simply ASHP which represents the least cost-effective and highest electric grid load approach, the required design process requires special knowledge as taught in the Certified GeoExchange Designer (CGD) course. Such thermal energy systems are also the subject of the bi-national ANSI/CSA/IGSHPA C448 "Design and installation of ground source heat pump systems" standard which should always be invoked when considering such advanced systems to ensure best practices are being employed.

The solutions commonly involve significantly more pieces of "active" equipment such as heat pumps as opposed to the simpler fan coils of typical central plant solutions, yet interestingly experience has shown that this does not increase maintenance costs. In all, there are about 15 parameters that an expert heat pump-based district system will juggle to seek an optimal solution for each specific combination of buildings, sites, weather, and geology. Final designs describe and pre-prove via an hourly 1-year operational simulation with 10–20-year ground thermal storage simulation before one can be confident of the solutions. Thus, it is essential that system "designers" or engineers with specific knowledge in these systems are enlisted in the design process, and equally so in a district setting that significant validation of the design is undertaken. Once a valid design and simulation have been shown, engineering and construction can proceed. During operation, the measured data will be continuously compared with the simulated results to both validate the design and to ensure the system is being operated as needed to meet the thermal targets established. These are all factors, and the various roles involved are described in the CGD course and the C448 design standard.

In this section, we introduce many of the elements in a decarbonized district HVAC system explaining briefly how they are involved in design and operation of the system.

4.1 Heat Pump Basics

There are many forms of HVAC heat pumps, with several of them being pertinent in some form for decarbonizing existing buildings at MIT. It is critical to understand that at their root, all of the HVAC heat pumps are the same machine that uses electricity to power a compressor, and which moves energy from one place to another by creating one hot "coil" and one cold "coil" at the same time. All the heat pumps involved use scroll compressors which are hermetically sealed devices that are cooled and lubricated by the refrigerant and an included oil. They are fully hermetically sealed to vastly reduce the possibilities of refrigerant leakage compared with industrial compressors such as those used in the CUP.

The relationship between the electricity used to drive the heat pump's compressor and the heat and cold produced in the two coils is characterized by the Coefficient of Performance (COP) which is the unitless comparison of heat output (COPh) or cold output (COPc) to the amount of electricity used. The kinds of heat pumps used for decarbonization all have COP's over 4.0 which is literally over 400% better than any fossil fuel heat source. In many situations, the heat pumps specified for this project will operate over COP=6.0, especially in low-lift exhaust recovery air-to-air applications and in non-peak seasons. As an example of how COP affects the heating/cooling/electricity balance, when a system has COP=5 in heating mode this means it will produce both 5 times the amount of electricity used and also 4 times the amount of cold than electricity used. Likewise in cooling mode, a COP=5 means it will produce 5 times as much cold but also 6 (COPc+1) times as much heat because the heat from the electricity adds to the heat from the cold. Thus, there is always a bit more heat produced by heat pumps, and this fits well for building HVAC use in the Boston area.

The two coils involved, whether hot or cold, have two basic forms in HVAC. One is a finned tube coil for exchanging energy between the refrigerant and air, either to heat or cool the air both indoors and outdoors. This is the most efficient way to transfer energy to and from the air because the refrigerant temperatures involved far exceed that of the chilled water loop, and they equally exceed the air temperature to heat it, but in a fully recycled way, where the refrigerant is reused indefinitely instead of producing CO2 emissions as all fossil fuel heat does. The other kind of “coil” used in the heat pumps being specified are to transfer energy both to and from water or glycol mix to heat or cool the fluid. This is a core form of heat transfer in a water loop or ground loop system, both of which are proposed here for MIT.

Combining these air and water coils in heat pumps produces three key heat pump forms proposed in this report. First is the Air Source Heat Pumps (ASHP) where energy is transferred between air both inside and outside for heating or cooling, or between air in the exhaust stream and the make-up air stream for energy recovery. Second is the Water Source Heat Pump (WSHP) where energy is transferred between either water and air (W-2-A) for space conditioning or between water and water (W-2-W) such as for domestic hot water (DHW). Third is a combination of these two forms that can transfer energy between air and air and water (A-2-A-2-W) which is used both for exhaust energy recovery and for dehumidification which are both primary functions of HVAC systems in commercial and laboratory use. These are unique capabilities of heat pumps that simply are not possible with a fossil fuel central plant system. These combined unique heat pump features together with their high COP and the emerging 100% renewable energy grid are the secret to cost-effective building decarbonization.

The final core heat pump approach in cost-effective decarbonization is the use of a common fluid loop to transfer energy between all the heat pumps and all thermal rejection and extraction elements. This is called an “Ambient Loop” which is in reality for MIT the same pipe system as the chilled water loop, but where the temperature range of normal operation is far larger being, in general, from 45°F to 87°F, which is the range where WSHP readily operate over COP=4. Moreover, because this pipe never gets hot and because of significant material advancement, high-grade HDPE and fiber-reinforced PP are used instead of expensive to install, and water quality sensitive steel piping. The geothermal heat pump industry has over decades proven these new pipe materials are not just more cost-effective than steel, but better, with no known failure mode due to water quality issues. All new piping proposed for installation is high-grade heat fusion welded HDPE and PP pipe as specified in the binational ANSI/CSA/IGSHPA C448 standard for “Design and installation of ground source heat pump systems”.

4.2 Energy Recovery

Energy recovery is key to cost-effective decarbonization. It is a simple fact that energy you do not lose from a building is energy you do not need to supply. There are multiple ways energy recovery is involved in cost-effective decarbonization.

4.2.1 Inherent Ambient Loop Energy Recovery

An “ambient loop” is used to connect all of the heat pumps and other thermal assets in a distributed decarbonized heat pump HVAC system. That means that both heat pumps in heating mode and heat pumps in cooling mode are thermally interconnected by the fluid stream in the ambient loop. In this way, those heat pumps that are cooling are rejecting heat to the loop at the same time those heat pumps that are heating are extracting heat from the loop. This mixed-mode heat pump operation is a very common reality in buildings' HVAC at all times except, perhaps, the winter’s most extreme temperature when most heat pumps will be heating. At the summer peak, there will always be at least the heat pumps for DHW that are in the opposite mode and benefiting fully from the heat being rejected to the ambient loop. This shared energy being recovered from one heat pump to another significantly increases the COP and cost-effectiveness of the distributed heat pump system.

4.2.2 Active Exhaust Energy Recovery

Perhaps the most important part of decarbonizing HVAC at MIT is exhaust energy recovery. It is clear from the extremely high EUIs of the numerous high exhaust/make-up labs at MIT that it is the energy being lost in the exhaust which is perhaps 50% of all current energy expended to heat and cool the buildings at MIT. This energy lost to exhaust is thus also the largest part of the carbon footprint of MIT, which is 97% attributable to its buildings.

Many believe that recovering exhaust energy is already happening and some believe it cannot be done in all circumstances. From the energy analyses already completed by the MACA/Geo@MIT team, neither of these suppositions is correct. Some solutions already exist such as Energy Recovery Ventilators (ERV), but they are limited to only non-problematic exhausts because they mix the outgoing and incoming air, and they are limited to recovering about 70% of the energy being exhausted even when operating perfectly.

Active exhaust energy recovery breaks through both of these barriers, enabling energy recovery from nearly any exhaust stream and enabling not only 100% energy recovery from any exhaust but also the ability to exceed 100% recovery to use an exhaust stream as an ASHP for energy gain when needed. This is one of the key heat pump advantages and is especially enabled by

W-2-A-2-A heat pumps which can both recover any exhaust energy for the make-up air stream and enable energy transfer from the air to the ambient loop and vice versa as needed.

4.3 Available Energy Sources and Sinks

Cost-effective district thermal system design and implementation requires a broad consideration of all available capabilities for thermal gain/extraction and loss/rejection. The current MIT CUP-based system uses fossil energy for all heat gain which must be eliminated to fully decarbonize, thus other thermal gain/extraction opportunities are needed. The CUP plan has some electrically driven cooling facilities that could be used for campus cooling (energy loss/rejection) in a fully decarbonized system, and certainly for supplemental cooling as needed. Also, the CUP as an existing thermal source/sink is available to assist in the decarbonization process such as to provide supplemental heating and cooling until all glazings are upgraded as is always included in good decarbonization design – it is far less expensive to fix those energy loss/gain problems than to both build and run a fully decarbonized system to overcome them.

Looking at the available and potentially available thermal energy sources and sinks, the following section of this report provides a list of energy options with a short explanation of each. The order of these options is not material – as stated in Section 1, cost-effectiveness, implementing available, proven technologies and minimizing campus disruption are the key evaluation criteria used in this Test Fit analysis.

4.3.1 Cambridge Water Dept Network

Working with the City of Cambridge Water Department (CWD), our team proposes to use existing water utility infrastructure as a thermal source and sink. As shown in the following figure, this solution involves a Thermal Transfer Station connected to one or more municipal water mains. CWD would own the potable water from source to point-of-entry and operate the Energy Transfer Station which could be located in the basement of W31 utilizing the space used now by a boiler that will be eliminated, or in a hermetic vault adjacent to W31. (See Slide deck). The Energy Transfer Station would pump water from the utility mains on Massachusetts Avenue and Vassar Street through the double-wall plate & frame heat exchangers, to raise or lower ambient loop temperature as needed. The water would then be reintroduced to the main at a slightly different temperature. A study done on a similar arrangement by Oak Ridge National Laboratory[2] has shown there are no water quality problems with this approach but, in an abundance of caution, CWD's water lab and MIT would run a pilot study to initially test the water for bacteria before returning it to the main.

In addition to gathering data proving that a CWD piped network will be a "best fit" solution for thermal energy supply towards decarbonizing the MIT campus, our team, working with CWD, seeks to confirm that using existing water utility infrastructure as a thermal battery is a practical alternative to complement geothermal boreholes because it leverages free energy and is minimally disruptive to implement. It also provides benefits to the City of Cambridge and the Cambridge Water Department utility itself.

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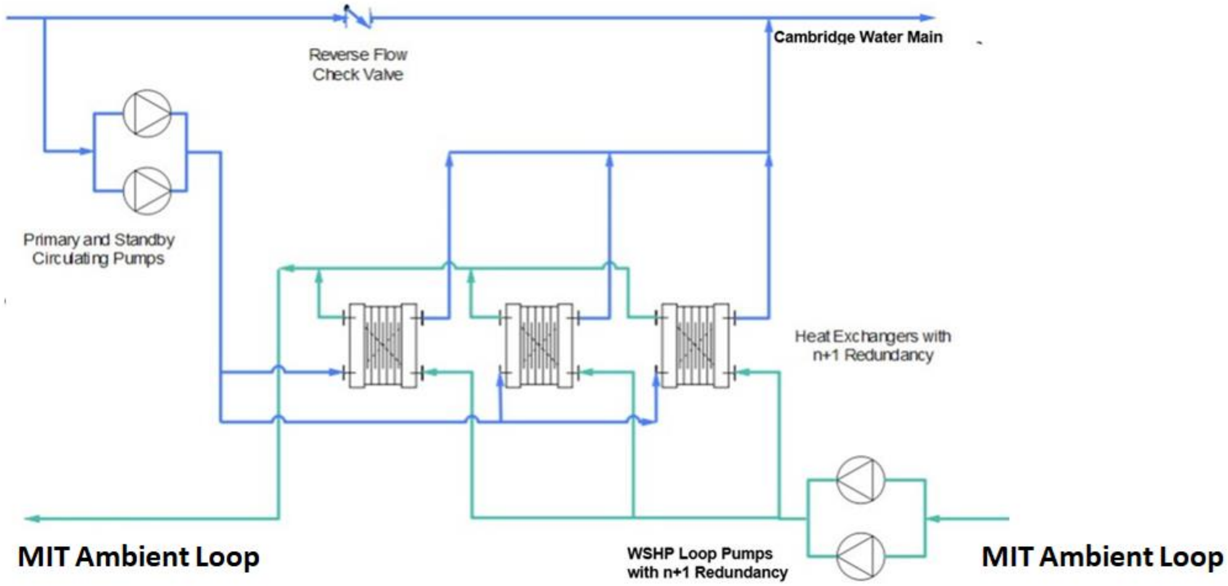
[2] Oak Ridge National Laboratory. Evaluation of the Impacts of Heat Exchanger Operation on the Quality of Water Used as Heat Source and Sink. June 10, 2018.

Figure 21: MIT Ambient Loop



4.3.2 Ground Heat Exchange/Boreholes

A looped bore in the thermally stable earth is the central element of most “geothermal” heat pump systems. This is a small pipe loop placed in a bore usually 300’ to 800’ into the earth then backfilled with a special “grout” that seals the hole to protect all aquifers and to provide a reliable thermal conductivity between the pipe and the ground. These looped bores are tied together into a ground heat exchanger (GHEX) and connected to the Ambient Loop to provide stable thermal energy both to and from the heat pumps.

The secret of a GHEX is not that it can provide heat in the winter, but that it is in fact a thermal battery that uses the heat rejected in the summer from cooling for heat extraction in the winter to heat buildings. It is this dual charge/discharge via heat rejection/extraction relationship that is the cornerstone of good geothermal system design.

On the flip side, the installation of a GHEX can be both noisy and messy until the area is recovered. The only way to overcome this is to use good design as taught by the Certified GeoExchange Design (CGD) course. The focus is on modifying the HVAC system, correcting envelope problems, and employing all the available thermal sources and sinks in a unified and balanced geothermal system.

This MACA/Geo@MIT system we propose in this report takes all of this into account in a balanced way for an optimal MIT-specific solution, just as one would with every well-designed advanced decarbonized HVAC system.

4.3.3 Ground Heat Exchange/Thermal Batteries

The industry has used large tanks as thermal batteries for decades to generate and store “cold” during the night with heat pumps when the cost of power is low, for use the next afternoon at the time of peak load. Using the earth as a GHEX with geothermal HVAC is using the earth as a “thermal battery” that is charged in the summer as heat is rejected for cooling and discharged in the winter as heat is extracted for heating.

There is a new form of thermal battery that mixes these two forms of “tank” and “ground” and that has passed validation testing by ORNL’s Thermal Energy Storage Research Group showing significant economic and GHEX reduction benefits. These thermal batteries, which are a tank bored into the soft ground straight down, but above the hard bedrock, are nearing initial commercial introduction and could potentially play a role in decarbonizing MIT. Since they are installed in soft “overburden” which at MIT is over 100’ of soft and fully saturated clay, these thermal batteries could provide the least possible campus impact ground heat exchange in combination with daily and weekly energy transfer from periods of low power cost to periods of peak load and high-power cost.

With these vertical ground-coupled thermal batteries, the ORNL team has also added phase change materials (PCM) that release and absorb large amounts of energy when transitioned between liquid and solid similar to ice. ORNL has uncovered thermal storage substances that store over 47 times the energy as chilled water and over 3 times as much as ice. These Thermal Batteries enable a 6th generation approach to district energy systems to rapidly store and use energy based on grid power cost. Electricity on the spot market where MIT gets power is already highly fluctuating and will become more so as clean energy becomes more dominant such as has already occurred in CA and TX where significant periods of free or better power already exist. The ability to utilize such low-cost power and avoid the already 10x periodic costs will create a cost-effective HVAC system and help accelerate the Clean Energy Grid to avoid curtailment.

4.3.4 Concentrating Solar

Decarbonization of W32 and W35 involves significant hot water production for showers. W35 also involves pool water heating, although that will be mostly handled by the pool's special HVAC equipment that recovers the pool evaporation energy from the exhaust stream to continuously heat the pool. For these heavy shower usage buildings and for in general lowering the amount of GHEX otherwise required, we propose including high-temperature solar thermal gain collectors and special heat pumps that are designed to efficiently provide the high-temperature water.

4.3.5 Solar PV

Every building decarbonization effort requires emissions-free electric power. In keeping with national guidelines for zero carbon buildings, this power can be produced at the building, within the site, nearby, or elsewhere on the grid and purchased under either a PPA that produces RECs (renewable energy certificates) or a utility rate structure that produces RECs. In addition to the above solar thermal elements in support of DHW year-round, we show areas of roof identified that could support solar PV installation in a low mount format. Some of the roof areas are concrete such as over the W32 penthouse mechanical room and squash courts which can obviously support PV, but some are over trussed roof areas and will require structural considerations. It is worth pointing out that any roof built to survive a wet snow load can readily support PV installation, especially if consideration of snow melt is taken into consideration. The list of available sites is meant to challenge all to consider what roofs can be used for local building rooftop solar to meet the overall decarbonization goals at both the local MIT level and in support of overall grid decarbonization.

4.3.6 CUP Options

The existing MIT Central Utilities Plant (CUP) will provide several key roles in a decarbonized campus HVAC system. The CUP or some other central facilities management location will always house the campus BMS system and all support capabilities including the herein described "Supervisor" system. Additional roles include:

1. Central mixing facility for the now chilled water converted to the thermal network "ambient loop." The CUP and a supporting East Campus facility at Bldg E40 are the current sources for all chilled water and the central pumping facility for the same. While more pumping will transition to equipment locations for efficiency purposes, there will always be a need to mix the energies from different areas of the campus which will be accomplished by pumps already installed at the CUP.
2. supplemental cooling support utilizing existing chiller resources to limit the need for over-building GHEX resources for Summer peak loads. This is an important cost-effective factor in commercial thermal networks which are almost always cooling dominant and thus need extra heat rejection in some form.
3. Supplemental heating during the transition to a fully decarbonized system using the existing steam system and existing building steam to water loop heat exchangers. This support will need to end with completion of the decarbonized thermal network because heat energy from the CUP is fossil fuel based.
4. Possibly a new heat pump capability using some of the existing CUP available chiller compressors in the reverse mode of application with new dry chiller/fan coil exchangers once enough chiller capacity is retired due to the campus transition progression.
5. Possible installation of some thermal storage tanks at the CUP for Thermal Energy Storage if the space is available now or as other assets are retired and for some reason ground coupled thermal battery installation must be avoided in some areas of the campus because of ground contamination. In general, ground coupled thermal batteries should be more cost effective than above ground tanks, but flexibility will exist because not all of the CUP functions will be needed once the decarbonized network is complete.
6. Provide a location for efficient "depot service" handling of some small heat pump repairs on a swap-out basis. This mode of refrigerant system servicing can provide an increased service throughput because several steps in the process like reclamation, evacuation, and pressure testing require time but not technician involvement. In this mode of servicing, small in building units are swapped out by less skilled teams using simple techniques instead of being repaired in situ, then many of the swapped units can be repaired in parallel at the depot location by one higher trained technician. This depot service can be very time effective by using the process times required for several units to perform the limited amount of skilled technician work required on another unit. This approach to service supports the use of numerous small 2–4-ton split system units, which are easy to disconnect and move, and may be the ideal solution to the key campus decarbonization challenges of flexible non-custom lab exhaust energy recovery which is well served by such numerous small units.

4.3.7 Surface Water - Charles River

Some have suggested that the Charles River be used to both heat and cool MIT. This is a technically feasible idea, however, there are numerous challenges ranging from physical to political. First, the river is a flooded estuary due to the dams at the Museum of Science and at the New Charles River Dam & Locks (east of the Zakim Bridge). It has a depth averaging 15 feet in the lower section near the Esplanade to an average of two to three feet in the upper section between the Newton Yacht Club and Watertown Square. Thus, it is not very deep, and any water intake would involve a lot of biological contamination and debris that could cause significant ongoing O&M costs and problems. Once MIT or anyone said they wanted to use the river for thermal extraction and rejection, countless other players both institutional and government would want to get involved. Therefore, one best use of the Charles is to drill a large cadre of low impact overburden-only zero-maintenance looped bores along the Memorial Drive side of the campus that will provide highly river flow impacted thermal advantage, thereby gaining the thermal asset of the Charles without actually having to work with the river's problematic physical and political challenges.

4.3.8 Sewer Thermal

Similarly to thermal exchange described in 4.3.1 with a water distribution main which has a predictable flow, an active sewer like such as from the locker rooms in both W32 and W35 can be used for thermal extraction and rejection. Specific products have been created for this purpose providing safe separation of the thermal transfer fluid and the sewer line contents. This solution is commonly used where significant hot water is generated and flushed down the sewer line. At least a significant part of that currently lost energy can be recovered with this solution. The same solution can be used to reject additional heat as needed provided one meets the restrictions set by the sewer authority and where needed to protect the plastic drain piping sometimes involved.

The proposed test fit solution does not at this point include sewer energy recovery in principal part because there is no current data for this fluid flow.

4.3.9 Snow Melt and Other Heat Rejection

Commercial building HVAC is generally a cooling dominant application meaning that more cooling than heating is needed on an annual basis. In a heat pump system, this creates an even more out of balance need for heat rejection because the heat from the electricity used to operate the compressors is rejected together with the heat from cooling, whereas the opposite occurs in winter where the heat from the electricity adds to the building heat. Thus, in systems which utilize inter-seasonal thermal storage such as a GHEX, one generally must have a net annual heat rejection other than to the GHEX. Using that excess heat for DHW production is one of the common approaches to eliminating excess heat and should always be among the first options selected as it will be for the dorms and other general use buildings. Sewer thermal rejection is another technique. But where snow and ice removal are commonly needed, it is also common to install shallow radiant tubing under sidewalks and parking lots for seasonal excess heat rejection as well as periodic ice and snow melting. These are the common tools used in advanced thermal systems design, and should always be considered whenever installing or rebuilding sidewalks and parking lots. Such loops can also be easily installed in lawn areas such as in front of the W20 Student Center using shallow burial vibratory plows which are commonly used for residential utility and gas line installation. These lines will join into the valve box vaults that will be present wherever GHEX and Thermal Batteries are used.

4.4 Thermal Energy Network Design

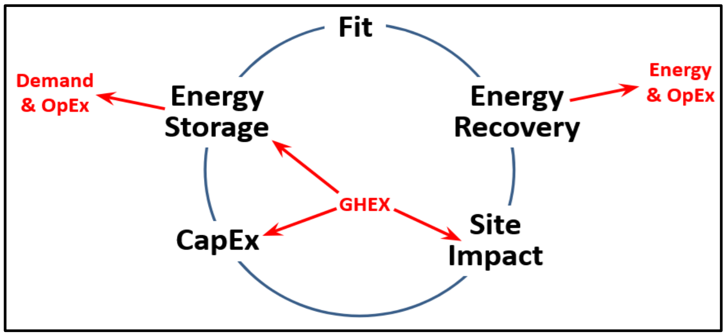
There are numerous approaches in general to applying the above collection of technologies for a cost-effective Thermal Energy Network as proposed at MIT. The decision on which technologies to use in this particular retrofit situation with six extremely varying aged buildings is highly dependent on the buildings themselves, the spaces available, and geology around and under the buildings. It is not significantly dependent on what others have done elsewhere which likely involved very different situations. There are trade-offs at all levels which is why designers and engineers who have significant experience with such systems is important, and it is also essential that key individuals in the design process have Certified GeoExchange Designer (CGD) course experience and well understand the skills involved in this level of design.

In this section, we present some of the design trade-off decisions involved and why certain approaches are better than others in this particular application.

4.4.1 Top Level Distributed Heat Pump Design Considerations

The overall design of an advanced cost-effective HVAC system requires balancing numerous factors beyond those required for strictly dealing with the building loads. In a conventional system, load drives equipment, and equipment drives the amount of energy "supply" needed for the building. In designing cost-effective advanced thermal energy systems for decarbonization of HVAC with heat pumps, the design approach is more complex because there are more elements, and they must operate together well over the entire year.

Figure 22: Decarbonization with Distributed Heat Pump Design Considerations



This graphic depicts the key top-level factors involved in this work and applied to this Test Fit. The process is to 1) determine what equipment will "fit" in the available space, 2) determine optimal solutions for cost-effectiveness, and 3) include thermal sources and sinks based on cost-effectiveness, implementation of available technologies and minimizing campus disruption.

As depicted in the graphic, there are numerous secondary relationships involved that complicate the decision-making process, including others not shown. For example, one can simplify the task to finding the optimal balance between ASHP and GSHP/GHEX use, but these parameters have complex and seasonal peak variations and other factors covering all of CapEx, OpEx, and site impact. Especially important in the decarbonization process is the peak electric power demand required which is, in some ways, a factor that limits the ability to decarbonize the whole campus and beyond cost-effectively and at the desired pace. This complexity is the level of design consideration taught in the CGD course, and the level of consideration required for this Test Fit process.

To undertake this level of design, construction of a digital twin model and simulation are essential. This model is used to identify where deficiencies in the hourly, daily, weekly, and annual energy flows occur and how to solve them before engineering and construction are considered. The same digital twin model will be run continuously after the system is in operation to ensure its thermal properties match the design. Where any differences are found, the root issues are analyzed and fixed, or the model is upgraded to the as built system. It is this same digital twin model that will be used throughout the life of the system to monitor its performance and to use for more complex functions such as grid power cost driven thermal storage and utilization.

While the goal on the surface is to create a self-contained thermal system within this six-building cluster which can operate in a stand-alone mode, many factors suggest taking a long view of 100% campus decarbonization conversion. For example, it will almost always require more GHEX for a few buildings than for many buildings of varying types together in a network. This is because the loads in residential buildings and classrooms and labs are all different, and the overall network once completed will share all those loads and thus need the least amount of GHEX to operate. Thus, it could be a sound decision to install only the GHEX that is convenient for this location or even only enough to "prove" operation which will always be analyzed against the similarly configured digital twin model, then to fill in more GHEX over time in conjunction with a campus-wide plan for placements.

There are also questions of if and when to make envelope upgrades to buildings which in this six-building cluster principally involves the glazing. The W20 Student Center in particular is all single pane glass which is an extreme energy loss issue, but there seem to be conflicting factors about envelope upgrades requiring further code upgrades that push back on completing all glazing upgrades in conjunction with the pilot project. While we do believe the upgrades are required in W20 due to its very large amount of poor thermal performing glazing, trade-offs can be made to continue to supplement the cluster with additional heat and cool from the CUP until all the "design planned" building envelope upgrades are complete. Again, this would all be part of the ongoing digital twin model and well tracked during operation.

Thus, design of a heat pump based Thermal Energy Network system has significant flexibility and trade-offs involved. The key factors involved include limiting increased electric load, overall cost-effectiveness at all levels, and limiting campus disruption. However, other factors can be added including equipment alternatives and variations in staging of the implementation.

4.4.2 Topologies

An interview was completed with Colorado Mesa University (CMU) which showed a completed and growing advanced Thermal Energy Network system. This system that was begun ~2008 is so efficient that their utility has approached the school to discover why the campus electric power "demand" has not increased in proportion with the campus' very significant growth. The thermal network at CMU is a 1-pipe system where the campus has an 18" loop going to all buildings, but where each building connects to only one side of the loop. This configuration of loop is especially oriented to reducing pumping load as the bulk of the fluid is kept in motion with pumps so small that it takes days for it to get into full circulation. With pumping power demand being a significant portion of the overall electric load required, this represents a well-considered approach. However, the approach also required that buildings and "loop fields" in this mostly GHEX based site are interspersed, an approach which only works at some sites.

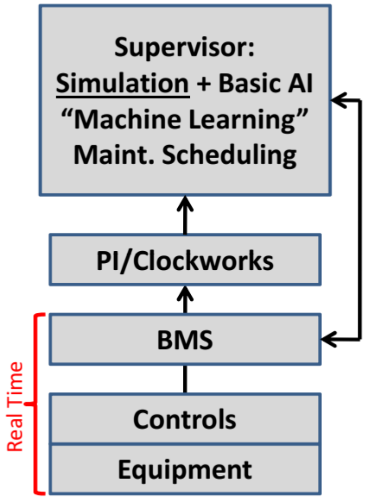
Other existing and "proven" decarbonization sites utilize a completely central plant-based approach with somewhat more conventional 4-pipe distribution to buildings. Ball State University is an example of this approach, but it again demands having significant space available for large GHEX loop fields which are not present at MIT. Ball State and other central plant centric sites also require the very extensive and expensive addition of a hot water loop.

MIT has an existing "2-pipe loop" network that goes to almost every building already, thus this defines the approach for MIT. MIT's Chilled Water loop is a "branched star" form, with the largest pipes coming from the CUP and reducing to smaller ones as each leg of the loop reaches its final building and system. This branched star configuration is well suited to a highly distributed system as it provides ready mixing as needed between all areas of the campus. It is also already proved to have sufficient capacity to meet all of the cooling loads for the campus which are generally the same as the heating loads or will be after the building envelope and exhaust recovery upgrades are complete. This mostly already existing "2-pipe" distribution loop makes for an excellent ambient loop conversion, with a few not yet connected buildings needing short extensions and one long additional run needed to reach the west campus dorms along Memorial Drive – this last run is required by every decarbonization upgrade proposed. With this existing loop piping for an ambient loop conversion almost entirely in place already, MIT's campus is prepared for a rapid and low-cost decarbonization upgrade.

4.4.3 Operational Strategies and Control Systems Methodologies

One often repeating issue with advanced thermal systems is that the controls are more complex than typical building controls system staff are used to. In the ideal condition, they are operated exactly as designed in the model and simulation used to determine the system's configuration and sizing. This would be a challenge to integrate into BMS systems which are principally focused on basic operation and system safety, and not on more advanced questions of when to run and not run excess ASHP capabilities to store energy based on a model of future power costs and when to store energy for additional resilience due to weather forecasts.

Figure 23: Control Systems Methodologies



This controls issue is solved by implementing an overseeing "Supervisor" capability built on a Machine Learning platform. This basic AI capability is trained on the model and simulation used to design the system, and provides "points" to the BMS for capacity and control requests. The layers in this approach are as shown in the graphic with the bottom 3 layers being as currently implemented in commercial building controls systems. At MIT, there is an added 'reporting' level in the 'PI' and Clockworks systems. The advanced thermal system "Supervisor" is a new level which only communicates with the BMS as simple points that include triggers for each capability available. The principal output of this system will be a dashboard capable of showing the historical and planned/scheduled changes in thermal energy storage levels and capacity availability. This system also provides

4.4.4 Maintenance Considerations

The interview with CMU and follow-up inquiries with the designer of that system, industry expert and approved CGD Trainer Cary Smith, show that the CMU system is not just highly distributed but also almost exclusively based on small unitary WSHPs. While this seems to be an extreme solution, it is in fact among the most efficient and lowest cost to install and operate and thus also the most commonly used approach to decarbonization in new construction. As said above, the reason these systems are used is because they are very high efficiency which is ideal for decarbonization. The high efficiency is due in large part to the combination of a large coil size to air flow ratio using multi-part 'A' and 'N' coil configurations together with direct refrigerant to air thermal transfer.

First, any solution will have roughly the same number of filters which drives the majority of every maintenance program. Second, with typically more units involved, that modularity brings inherent graceful degradation only of the air conditioning function involved for a greater degree of resilience. Third, these units will all have BACNet reporting including operational efficiency so they will be scheduled for service typically before any failure occurs to optimize servicing and to reduce the service time needed. Finally, they are all roughly the same system regardless of size consisting of scroll compressors, a refrigerant control valve, two coils typically one refrigerant to air and one refrigerant to water, with sensors and a control board. Thus, servicing the systems when needed is a simple process carried out everywhere by HVAC mechanics using common refrigeration tools and techniques. As reported by CMU and documented in a few reports on the subject, these systems with large numbers of individual unitary units actually result in a lower maintenance cost than large central systems, especially steam systems. One change perhaps needed is to train more technicians in servicing refrigerators systems, which generally means how to properly handle refrigerants and brazing – both things that can be readily taught in a couple of days.

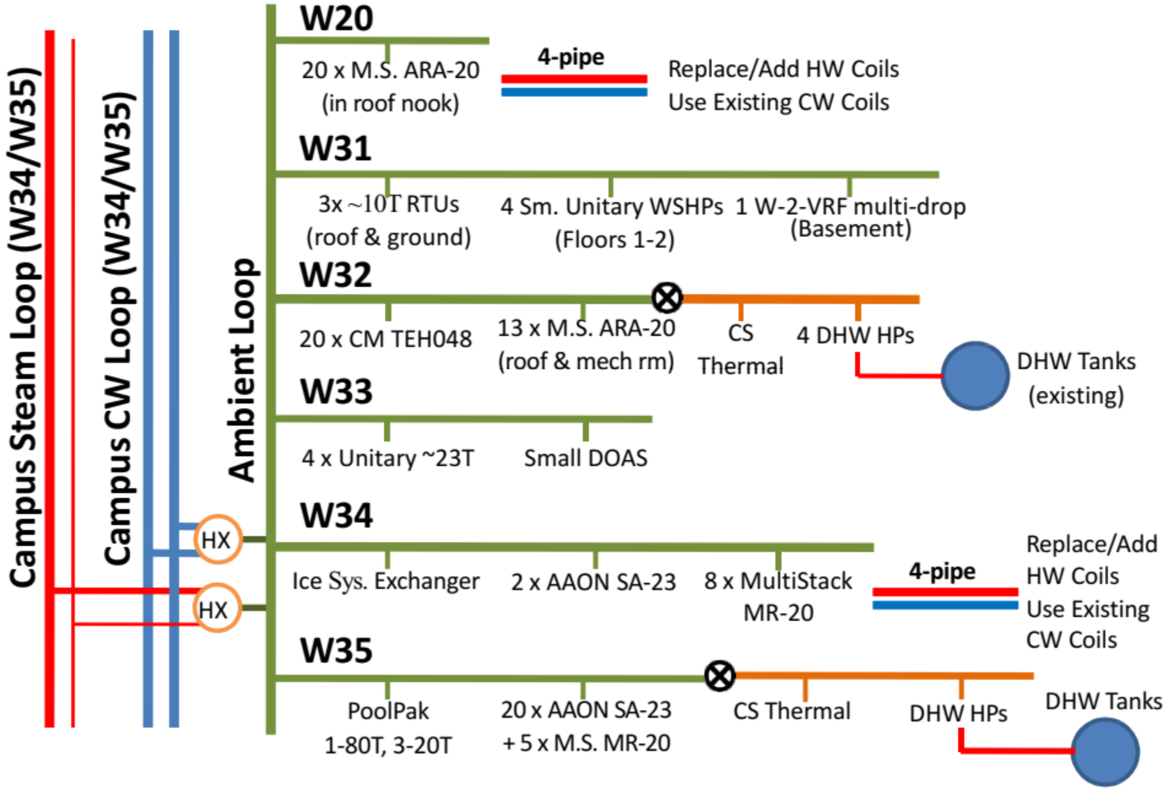
5 Test Fit Proposal

The following sections depict the first pass “test fit” analysis performed to date. In keeping with proper advanced thermal system planning, further iterations of this fit will be performed until an optimal cost-effective solution is complete. Also, since the data analysis began so late in the process and it is still incomplete, some of the elements are early estimations of a solution and not precisely a fit analysis. They will be updated as the data analysis together and modeling and simulation are completed. Some details about the exhaust energy recovery and specific equipment selections are also being refined as well as alternative approach comparisons. However, the analysis completed to date does A) prove a fit is possible with distributed heat pump approach, and B) does show that sufficient power appears to be available in all buildings already except for W33 which is minimally powered.

5.1 Test Fit Thermal System Overview

Based on the broad collection of technologies and design considerations identified above, the proposed decarbonized system for the MIT W20 & W31-W35 building cluster is as depicted in the below 1-Line diagram showing most of the thermal system elements which are explained further in this section.

Figure 24: Line Drawing of Test Fit Proposal



The proposal is an advanced distributed heat pump system for decarbonization of the 6-building cluster of MIT campus buildings W20 and W31-W35. These buildings include three (3) that are not currently on the campus chilled water loop and four (4) that have single-pane glass. Cost-effective decarbonization of HVAC requires a connecting ambient loop to enable the sharing of energy between all the heat pumps and other thermal sources and sinks. Thus, in this proposal, the current chilled water loop will be isolated from the campus, transitioned to an ambient loop, and extended to all these buildings. Cost-effective decarbonization also requires correcting all large building envelope thermal problems, so all single pane glazing must be upgraded. Otherwise, the Central Utility Plant (CUP) will be needed to supplement the system's operation until the building envelopes are upgraded.

The following is a step-by-step presentation of the upgrades needed to convert the cluster to fully decarbonized HVAC.

5.2 Proposed Ambient Loop

5.2.1 Conversion of the Chilled Water Loop to an Active Ambient Loop

A key component of the proposed design is to convert the existing chilled water loop to an active ambient loop. As said above, an ambient loop is a "district thermal loop" operating with wide thermal limits (e.g., 42°F - 85°F). These are significantly lower temperatures than traditional high-temperature heating systems. MIT's existing 45°F Chilled Water (CW) loop can be readily transitioned to an "active" ambient loop. This will require expanding the line to those buildings not currently on the loop (W31, W32, W33). Because the existing loop was designed for chilled water only, it may require additional mounting adjustments and expansion joints.

One "complication" exists with the Test Fit building cluster in that the W20 connection to the Chilled Water loop comes from the lines running to Kresge and beyond. This connection must be re-routed to connect it with the ambient loop in the cluster. The following depicts our recommendations after surveying the buildings, available buried utility plans, and the spaces around and especially between W20 and W32.

5.2.2 Proposed Active Ambient Loop Design /Location

In the 6-building cluster, the existing chilled water loop currently serves W20, W34, and W35. We propose extending the chilled-water loop to buildings W31, W32, and W33. We recommend Option 1, but believe that there are two other workable alternatives for the extension:

1. Recommended Option: W34/W35 -> W33 -> W32 -> W20 & W31
2. Back-up Option A: same except through Zesiger Center level 1 locker room ceilings instead of across W33, or,
3. Back-up Option B: same except through Zesiger Center level 2 hallway above north-side bleachers instead of across W33

The following graphics depict the available options:

Figure 25: Recommended Path for New Ambient Loop Piping through Rockwell Cage

Figure 26: Alternate Path Ambient Loop

All heat pumps added will have dedicated variable speed circulators and be connected to the active ambient loop via reversing valves. The valves enable one side of the loop to be operated warmer and the other colder, letting each heat pump select the thermally optimal inlet based on operating mode to improve overall efficiency. This approach has proven much more cost-effective than central pumping, in some cases eliminating central pumping – an important factor as poorly pumped systems can waste over 40% of their electric power consumed in pumping alone. This active ambient loop yields the most efficient thermal energy sharing possible.

5.2.3 Connecting the Ambient Loop to the CUP Utilities

The Ambient Loop will be thermally connected to the CUP steam and chilled water loops both temporarily to enable supplemental energy exchange for lowering and raising the ambient loop temperature. This is especially important in transitions such as when the new heat pump equipment is installed yet some of the single pane glazed buildings have not yet been upgraded.

There are already heat exchangers in buildings W20, W34, and W35 for getting heat input from the campus steam distribution system which will be repurposed for this use. For the chilled water interface, we recommend assembling a Heat Exchanger Pallet that can be used first in this building complex and then moved elsewhere for use as sections of the campus are further converted to ambient loop-based distributed heat pumps. A typical pallet is shown in this graphic, with the exact exchangers employed chosen to balance capacity and space considering where the pallet is projected to be used in the future. There are no such space considerations in these buildings which all have ample free mechanical room space.

Figure 27: Typical Heat Exchanger Pallet

5.3 New Mechanical Equipment

Pursuant to a detailed consideration, space modeling, and 3D scans of specific spaces where equipment will be placed, the following table depicts how the above-identified equipment is used to "fit" the needed and available spaces within the 6 building Test Fit cluster. Preference is given to unitary W-2-A WSHPs where usable due to their excellent efficiencies, but 4-pie building interior approaches are used where needed or practical because sufficient space is obviously not available for unitary equipment. To simplify the approach, W-2-A units are limited to one larger unit (AAON SA-23 ~23 tons) and one small unit (ClimateMaster TEHxxx 3–6-ton horizontal units in W32 only due to limited space). There are ample other options available that require further consideration once architectural and engineering preferability are understood. Also, we made trade-offs regarding the approach used in W34 to avoid needing an electric power upgrade that should be revisited in a further refinement.

Table 5: Overview Proposed New Mechanical Equipment

Technology/Method	**W31**	**W32**	**W33**	**W34**	**W35**	**W20**	**Notes**
Glazing:							
Glazing Double Pane Upgrade		■		■		■	These buildings all single pane glass
Glazing to KalWall or equiv.			■				Translucent, light weight wall panels
Inter/Intra-Bldg Loop:							
Ambient Loop Conversion				■	■	■	
Ambient Loop Extension	■	■	■			■	W20 must be isolated from CW loop
Heat Pump Equipment:							
Unitary WSHP w/hot gas reheat	RTUs	■	■	■	Alt.		AAON/others, chosen for efficiency
4-Pipe Intra Building		Alt.		■	Alt.	New coils	MultiStack MR020 (for efficiency)
PoolPak					■		Built-in energy recovery/pool heat
W-2-R VRF/Terminal Dev. WSHP	Floor 0-2						e.g. Daikin splits, small unitary WSHPs
3-way W-2-W-2-A Heat Pumps						■	Multistack
Exhaust Energy Recovery:							
W-2-A or W-2-W-2-A Heat Pumps	Old flues	■	■	■	■	■	Each exhausts not with ERV already
ERVs	Alt.	Alt.	Alt.	Alt.	Alt.	Alt.	
Electricity Upgrade:							
New/added Xfmr Required			Yes				

Below are the first pass detailed equipment selections for each building in the Test Fit cluster, together with the specific issues for conversion identified for that building. Elements of this workup are still work-in-progress, especially to determine the expected adjusted loads that will result from glazing upgrades in the worst buildings like W20 which is over 50% glazing on the perimeter walls. Some peak capacity figures are nominal thus not precise, and electric kW values are all via simple conversion from Total RLA for 460/480V versions of the equipment regardless of the individual building's voltage (variations of all equipment are available for all voltage mixes).

In reviewing the below tables for each building, note that there are multiple parts except for W33 which is very simple. The top bar provides the existing peak loads from the available data and an estimate of the reduced load after exhaust energy recovery and building glazing and lighting/LED upgrades. The next section shows how existing equipment will be upgraded with a rough matching of equipment capacities and air flows. Following sections show how exhaust recovery affects the net loads and the power demand, and how "hybrid" and other source/sink resources result in a "Net Load to Ground" being an early estimator for the effective peak load to use for GHEX and Thermal Storage sizing.

It should be noted that the total capacity of equipment proposed in some buildings in this first pass is well above the capacities that our initial analysis says are needed. This is in part because fulfilling the CFM needs at high efficiency operation was the priority. Further iterations will refine this approach to reach a more optimal suggested equipment selection based on the balance of CapEx, OpEx, and difficulty of installation. However, this first pass with excess capacity still does not exceed the electric capacity available in all buildings except the minimally powered W33 Rockwell Cage, thus proving "fit" and demonstrating feasibility of distributed heat pump solutions across campus.

5.3.1 Building W20

As mentioned earlier, the chilled water loop to W20 must be reconfigured to isolate the selected 6 building cluster from the rest of the buildings on that west campus chilled loop which continues to Kresge and a few more buildings. On review, it appears the best location for the necessary new piping to enter W20 is about the midpoint of the basement NW corner mechanical room then to the main basement mechanical room.

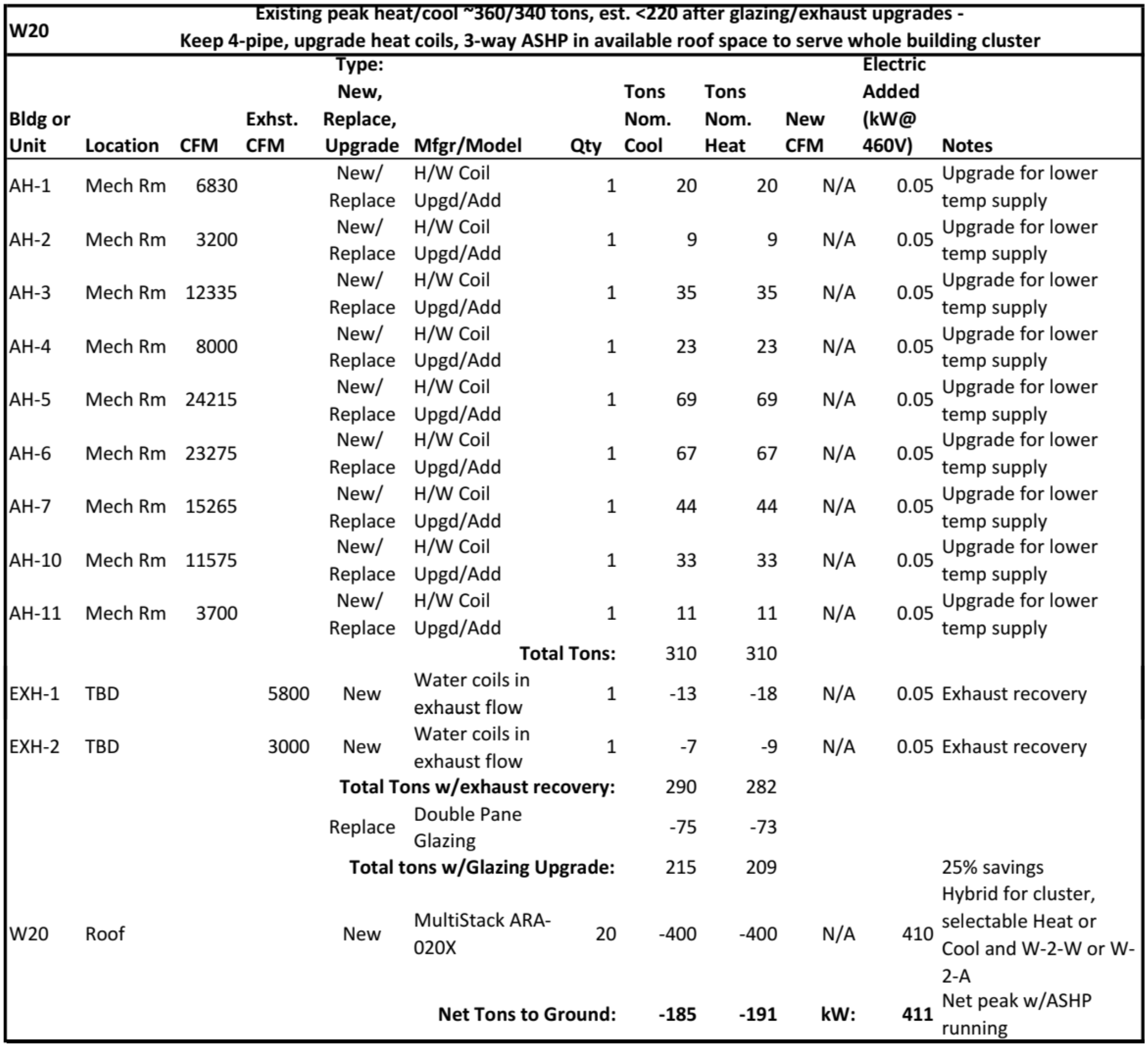
W20 is unique among the 6-building cluster in two key other ways. First, the mechanical rooms in W20 are very tight, especially vertically, making upgrading equipment with larger unitary systems proposed elsewhere more difficult in this building. Second, W20 was originally equipped with its own chillers in a roof nook that is still present including structural mounting rails. Using a new class of W-2-W-2-A rooftop units (MultiStack ARA), this 4-pipe building can be readily upgraded with the sole exception of needing to scope a path for the pipe connection from that roof area to the ambient loop in the basement – the original pipes appear to have been removed.

These roof nook units work both in W-2-W mode to serve the building hot and cold loops from the ambient loop, and in W-2-A mode to exchange energy between any loop including the ambient loop and the atmosphere. In such systems involving GHEX, this capability is called "Hybrid" where ASHP assets work together with the ground loop and thermal storage resources. In the uncommonly mild weather at MIT where it rarely gets under 10°F, these modern heat pumps are still efficient even near the peak load times and they are exceptionally efficient at all other times. These optionally air source units will supplement all of the test fit cluster ambient loop, run W20, and provide off peak additional energy source and sink to store thermal energy in the ground elements when power costs are low to use later when the power cost is high.

It appears that the piping to the roof nook has been obsoleted. Thus, new piping will need to be run from the upper mechanical room to the roof nook area. The details of this pipe routing have not been considered; however, the plans say that a 10” pipe loop was originally present.

As mentioned, the one large flaw of W20 is that it has large amounts of single pane glazing. This glass will need to be upgraded for a cost-effective decarbonized HVAC system. However, the equipment proposed will meet the existing load and some CUP provided energy can make the difference until the glazing is upgraded. That said, it is recommended that the opportunity of the tax credits and rebates available now be taken advantage of and to upgrade W20 as needed for an optimally decarbonized building.

Table 6: HVAC Capacities



W20	Existing peak heat/cool ~360/340 tons, est. <220 after glazing/exhaust upgrades - Keep 4-pipe, upgrade heat coils, 3-way ASHP in available roof space to serve whole building cluster										
Bldg or Unit	**Location**	**CFM**	**Exhst. CFM**	**Type: New, Replace, Upgrade**	**Mfgr/Model**	**Qty**	**Tons Nom. Cool**	**Tons Nom. Heat**	**New CFM**	**Electric Added (kW@ 460V)**	**Notes**
AH-1	Mech Rm	6830		New/ Replace	H/W Coil Upgd/Add	1	20	20	N/A	0.05	Upgrade for lower temp supply
AH-2	Mech Rm	3200		New/ Replace	H/W Coil Upgd/Add	1	9	9	N/A	0.05	Upgrade for lower temp supply
AH-3	Mech Rm	12335		New/ Replace	H/W Coil Upgd/Add	1	35	35	N/A	0.05	Upgrade for lower temp supply
AH-4	Mech Rm	8000		New/ Replace	H/W Coil Upgd/Add	1	23	23	N/A	0.05	Upgrade for lower temp supply
AH-5	Mech Rm	24215		New/ Replace	H/W Coil Upgd/Add	1	69	69	N/A	0.05	Upgrade for lower temp supply
AH-6	Mech Rm	23275		New/ Replace	H/W Coil Upgd/Add	1	67	67	N/A	0.05	Upgrade for lower temp supply
AH-7	Mech Rm	15265		New/ Replace	H/W Coil Upgd/Add	1	44	44	N/A	0.05	Upgrade for lower temp supply
AH-10	Mech Rm	11575		New/ Replace	H/W Coil Upgd/Add	1	33	33	N/A	0.05	Upgrade for lower temp supply
AH-11	Mech Rm	3700		New/ Replace	H/W Coil Upgd/Add	1	11	11	N/A	0.05	Upgrade for lower temp supply
						Total Tons:	310	310			
EXH-1	TBD		5800	New	Water coils in exhaust flow	1	-13	-18	N/A	0.05	Exhaust recovery
EXH-2	TBD		3000	New	Water coils in exhaust flow	1	-7	-9	N/A	0.05	Exhaust recovery
				Total Tons w/exhaust recovery:			290	282			
				Replace	Double Pane Glazing		-75	-73			
				Total tons w/Glazing Upgrade:			215	209			25% savings
W20	Roof			New	MultiStack ARA-020X	20	-400	-400	N/A	410	Hybrid for cluster, selectable Heat or Cool and W-2-W or W-2-A
					Net Tons to Ground:		**-185**	**-191**	**kW:**	**411**	Net peak w/ASHP running

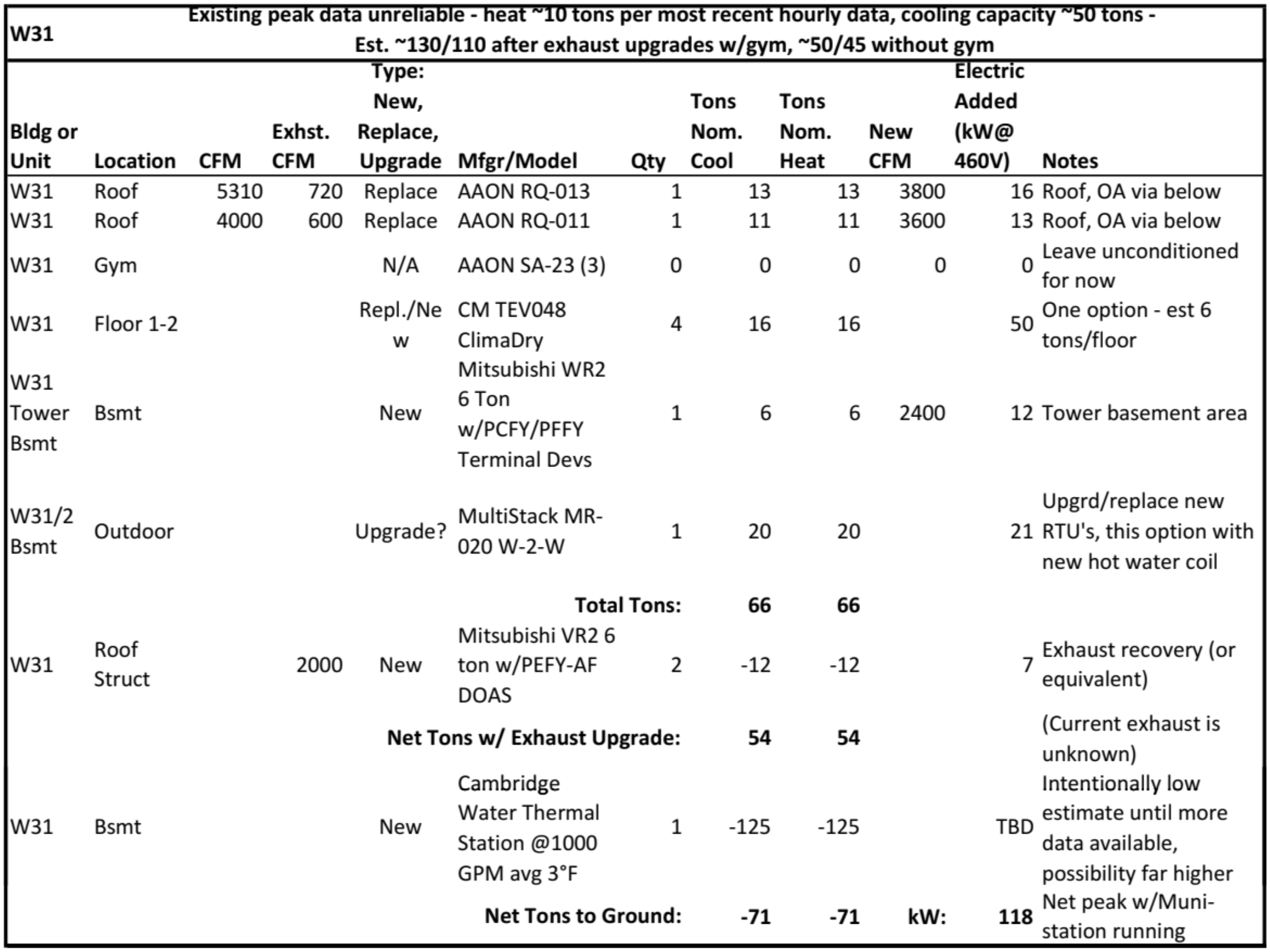
5.3.2 Building W31

Building W31 is unique in the cluster in several ways. First, it is very old and parts of the building are not conditioned which will remain unconditioned as requested. The “tower” section has some

RTU's that will be upgraded to WSHPs, and the tower has a roof structure at the top of the stairwell perfect for installing a WSHP DOAS for the whole building to eliminate the current direct exhaust to vent stacks present in the original unconditioned structure. Lower tower floors are currently under served with HVAC which will be upgraded using unitary WSHPs which can be readily placed in any available closet or nook area. An alternative approach is available using a WSHP-VRF split system which has numerous terminal unit options and can be easily installed in any existing building – the WSHP base could be several locations including the roof enclosure. Such a VRF solution could, for example, use the available VRF "radiator" terminal devices to directly replace existing radiators. The basement exercise area HVAC has recently been upgraded however it appears the units, which are RTUs at ground level on the Vassar St. side of the building, were given steam heat coils. These units will either be upgraded to full heat pumps and/or, as specified here will receive supplemental conditioning with a WSHP and heat exchange coils in the air distribution trunks inside the building.

One preferred 6-building cluster thermal source/sink option is the Cambridge Water Thermal Transfer Station being worked out with them now. Once W31-W33 are upgraded to heat pumps, the boiler in W31 will no longer be needed and can be removed. That space is identified for the Thermal Transfer Station, although it could also be placed outside the buildings in a vault if necessary.

Table 7: W31 HVAC Capacities



W31	Existing peak data unreliable - heat ~10 tons per most recent hourly data, cooling capacity ~50 tons - Est. ~130/110 after exhaust upgrades w/gym, ~50/45 without gym										
Bldg or Unit	Location	CFM	Exhst. CFM	Type: New, Replace, Upgrade	Mfgr/Model	Qty	Tons Nom. Cool	Tons Nom. Heat	New CFM	Electric Added (kW@ 460V)	Notes
W31	Roof	5310	720	Replace	AAON RQ-013	1	13	13	3800	16	Roof, OA via below
W31	Roof	4000	600	Replace	AAON RQ-011	1	11	11	3600	13	Roof, OA via below
W31	Gym			N/A	AAON SA-23 (3)	0	0	0	0	0	Leave unconditioned for now
W31	Floor 1-2			Repl./New	CM TEV048 ClimaDry	4	16	16		50	One option - est 6 tons/floor
W31 Tower Bsmt	Bsmt			New	Mitsubishi WR2 6 Ton w/PCFY/PFFY Terminal Devs	1	6	6	2400	12	Tower basement area
W31/2 Bsmt	Outdoor			Upgrade?	MultiStack MR-020 W-2-W	1	20	20		21	Upgrd/replace new RTU's, this option with new hot water coil
						Total Tons:	**66**	**66**			
W31	Roof Struct		2000	New	Mitsubishi VR2 6 ton w/PEFY-AF DOAS	2	-12	-12		7	Exhaust recovery (or equivalent)
						Net Tons w/ Exhaust Upgrade:	**54**	**54**			(Current exhaust is unknown)
W31	Bsmt			New	Cambridge Water Thermal Station @1000 GPM avg 3°F	1	-125	-125		TBD	Intentionally low estimate until more data available, possibility far higher
						Net Tons to Ground:	**-71**	**-71**	**kW:**	**118**	Net peak w/Muni-station running

5.3.3 Building W32

W32 has a typical penthouse mechanical room driven HVAC system with sufficient space for either a 4-pipe solution or smaller unitary WSHP upgrades. To ensure an example building solution of all small unitary unit upgrades and since this mechanical room space is a bit tight, the proposed AHU units are all horizontal mode small packaged systems that are the most commonly used GSHP form in modern decarbonized buildings. They prove "fit," but further iterations can consider other approaches.

The hidden from ground view W32 roof provides a perfect location for solar gain. Since this building and the 6-building cluster have significant DHW needs for locker room showers, this space is mostly dedicated to a tracking parabolic solar thermal array for year-round gain which will serve a number of DHW special WSHPs in W32. These heat pumps use refrigerants tuned for higher temperature commercial DHW loads, currently R134a in most cases, and contain double wall heat exchangers certified for domestic water use. They also efficiently achieve the hot water temperatures needed in commercial systems to counter legionella. Multiple DHW dedicated heat pumps are available, with ones selected for their small size which can flexibly fit in the available space. It is expected that additional DHW tanks may be needed to ensure all solar gain is efficiently utilized, and the whole DHW sizing is still an unfinished/draft effort since we do not yet have any good predictor of hot water use volume (can be read with clamp-on recording ultrasonic meter). Even with tracking solar installed, there will be available roof space along its south edge where W-2-W-2-A units such as on W20 could be placed as needed to serve W32 as a 4-pipe building, and/or for W-2-A units to serve the whole cluster as desired to reduce the amount of GHEX needed. The below workup schedules as many of those units as the available power budget would support, with the number being higher or lower as further iterations of the design occur – there is space for up to 600 tons, although that would require additional power supply. The flat roof of the W32 mechanical room and squash courts provides additional space for PV solar which is specified to help offset the power needs of the heat pumps.

Table 8: W32 HVAC Capacities

W32	Existing peak heat/cool ~100/43 tons but almost 100% exhaust/recovery - Est. ~30/30 (air) after glazing/exhaust upgrades w/ DHW, remove existing dry chiller										
Bldg or Unit	**Location**	**CFM**	**Exhst. CFM**	**Type: New, Replace, Upgrade**	**Mfgr/Model**	**Qty**	**Tons Nom. Cool**	**Tons Nom. Heat**	**New CFM**	**Electric Added (kW@ 460V)**	**Notes**
S-1	Mech Rm	3960		Replace	ClimateMaster TEH064	2	9	9	4600	15	One solution shown w/ unitary GSHP's and hot gas reheat
S-2	Mech Rm	1115		Replace	ClimateMaster TEH038	1	3	3	1500	5	
S-3	Mech Rm	10700		Replace	ClimateMaster TEH072	4	24	24	9200	32	
S-4/ ACCU-1	Mech Rm	3400		Replace	ClimateMaster TEH064	2	10	10	4600	15	
S-5	Mech Rm	10000		Replace	ClimateMaster TEH072	4	23	23	9200	32	part return/part makeup
S-6	Mech Rm	2970		Replace	ClimateMaster TEH038	2	6	6	3000	9	
S-7	Mech Rm	6300		Replace	ClimateMaster TEH038 & 049	3.5	12	12	6125	22	
FCU-1	Mech Rm	1020		Replace	ClimateMaster TEH038	1	3	3	1500	5	Heating is new, unit is an unknown
					Net Tons:		**89**	**89**			
	Mech Rm or Roof			New	MultiStack MR-020 W-2-W	3	61	61		84	For exhaust recovery below, may be on roof and could be W-2-W-2-A
E-1	Mech Rm		1195	Upgrade	Water coils added	1	-3	-4		0.05	Peak exhaust cool/heat 62/99
E-2	Mech Rm		7400	Upgrade	Water coils added	1	-17	-27		0.05	
E-3	Mech Rm		4340	Upgrade	Water coils added	1	-10	-16		0.05	
ER-1	Mech Rm		8200	Upgrade	Water coils added	1	-18	-30		0.05	
ER-2	Mech Rm		6000	Upgrade	Water coils added	1	-14	-22		0.05	
					Net Tons w/ Exhaust Upgrade:		**28**	**-8**			
W32	Mech Rm			New	Nordic WH-85	4	0	38		43	Nyle/Nordic/ColMac (capacity estimated)
CS-Thrml	Roof			New	TBD		0	-39			Star/others
W32	Roof			New	MultiStack ARA-020X	6	-120	-120	N/A	123	Space for up to 640 tons available heat/cool/ASHP
					Net Tons to Ground:		**-92**	**-130**	**kW:**	**385**	Net peak w/ASHP running

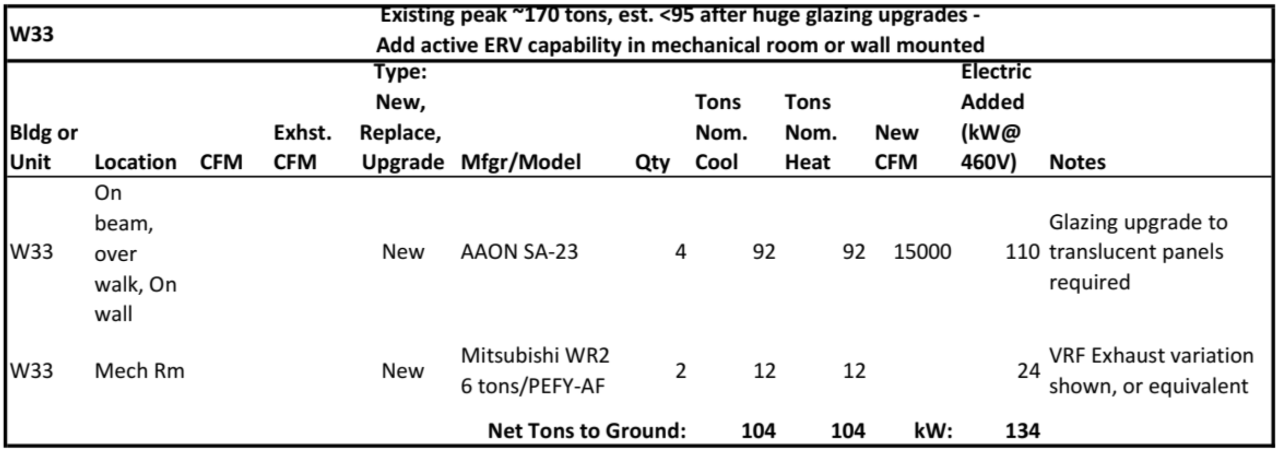
5.3.4 Building W33

W33 is a very leaky and marginally space conditioned gym that cannot be decarbonized without upgrading the envelope. Experience and the fact that the curtains are typically covering the existing steel frame single pane windows at all times suggest that the easiest way to upgrade this envelope is to replace the window upper walls with very lightweight translucent panel walls such as KalWall or equivalent. This is an essential upgrade that would significantly enhance the "look" of the space as well. With that upgrade and a plan to increase the roof insulation next re-roofing, a code variance should be possible to at least partially condition this space especially for when it is used for exams.

To decarbonize W33's HVAC, which is now overhead steam, a set of unitary WSHP units will be installed. The likely locations include A) behind bleachers, B) above the caged-off walkway adjacent to W35, C) along the upper part of the central support columns which appear to have ample strength and could be high out of view, and/or D) mounted a similar height along the other outer walls blocking small parts of the upper glazing walls. These are all fine options with ready paths for ambient loop connections and power conduits. Also recommended are new light weight destratification fans mounted high on the central beam or walkway cage to ensure heat is not lost in this voluminous space during the winter, especially from the likely under insulated roof.

We also recommend a DOAS be implemented in the available upper mechanical room space which could be one of many forms, with one flexible WSHP approach shown for power sizing.

Table 9: W33 HVAC Capacities



W33				**Existing peak ~170 tons, est. <95 after huge glazing upgrades - Add active ERV capability in mechanical room or wall mounted**							
Bldg or Unit	**Location**	**CFM**	**Exhst. CFM**	**Type: New, Replace, Upgrade**	**Mfgr/Model**	**Qty**	**Tons Nom. Cool**	**Tons Nom. Heat**	**New CFM**	**Electric Added (kW@ 460V)**	**Notes**
W33	On beam, over walk, On wall			New	AAON SA-23	4	92	92	15000	110	Glazing upgrade to translucent panels required
W33	Mech Rm			New	Mitsubishi WR2 6 tons/PEFY-AF	2	12	12		24	VRF Exhaust variation shown, or equivalent
					Net Tons to Ground:		**104**	**104**	**kW:**	**134**	

5.3.5 Building W34

W34 is a unique building because it has an Ice Rink that requires special environmental support, and an upper floor indoor track which is less space conditioned. The ice system provides an opportunity for thermal gain all winter to the 6-building cluster integrated thermal system and thermal storage elements by redirecting the ice heat pump's heat rejection from the existing outdoor fan coil unit instead to a plate heat exchanger with the ambient loop. During all times when the ice system is not at full capacity and when it is off, the heat exchanger with the ambient loop can enable the existing outdoor fan coil to become an additional thermal source/sink as needed throughout the year under the system's AI Supervisor control. This use of the existing outdoor W-2-A heat exchanger is one of the tools used to limit the amount of GHEX required to meet peak loads, and to add resiliency to the system.

This building has two primary approaches possible for HVAC decarbonization. The first is to leave the building as 4-pipe for the primary HVAC elements driven by W-2-W heat pumps such as MultiStack. Ample room for the needed equipment has been identified and confirmed via 3D scans. Heating coil improvements would be needed for the ideal ≤120°F heating loop water temperature. This might require a bit more fan energy which has been nominally added. This solution also serves all exhaust energy recovery needs with the addition of a few coils in select ducts. There is plenty of space for this solution, especially in the north W34 mechanical room. The other solution is to replace all AHUs with unitary WSHPs, but that solution would be more complex.

The Ambient Loop upgrade will involve modifications to the chiller loop in W34 so the run continuing to Kresge and beyond is not interrupted. Also, the run going to W33 and beyond will begin in either W34 or W35 mechanical rooms, wherever it is most convenient. More in-depth on-site analysis is required to determine the exact modifications, isolations, and path of this upgrade.

Table 10: W34 HVAC Capacities

W34	**Existing peak heat/cool ~200/105 tons - Est. <160/80 tons after glazing/exhaust upgrades, upgrade includes ice system heat capture**										
Bldg or Unit	**Location**	**CFM**	**Exhst. CFM**	**Type: New, Replace, Upgrade**	**Mfgr/Model**	**Qty**	**Tons Nom. Cool**	**Tons Nom. Heat**	**New CFM**	**Electric Added (kW@ 460V)**	**Notes**
AC-2	Mech Rm	13000	3200	New/ Replace	Water coils added	1				0.05	Replacement shown, but can be 4-pipe upgrade solution as well for all these, adding for exhaust recovery -- existing unit 38 tons
AC-3	Mech Rm	15000	7500	New/ Replace	Water coils added	1				0.05	Existing: 51 tons
AC-4	Mech Rm	18000		New/ Replace	Water coils added	1				0.05	Existing: 62 tons
AC-5	Mech Rm	18000		New/ Replace	Water coils added	1				0.05	Existing: 62 tons
HV-6	Mech Rm	10000	3700	New/ Replace	Water coils added	1				0.05	Oversized, but left for now
W34	Mech Rm			New	MultiStack MR-020 W-2-W	8	160	160		164	For above coils and unit heaters
W34	Track			New	AAON SA-23	2	46	46	7500	55	3rd floor track
					Total Tons:		**206**	**206**			Heating significantly oversized
AC-1	Ice HP Rm			New	Hear Exahanger, heat to ambient loop winter, ambient to FC summer @ ~120 ton waste ability	1	-120	-26	(more validation needed)		Heat based on ~90kW average @COP=3 all winter - note peak ~840kW-420kW=420kW @COP=3 => ~120 tons capacity for cooling
					Net Tons to Ground:		**86**	**180**	**kW:**	**219**	

5.3.6 Building W35

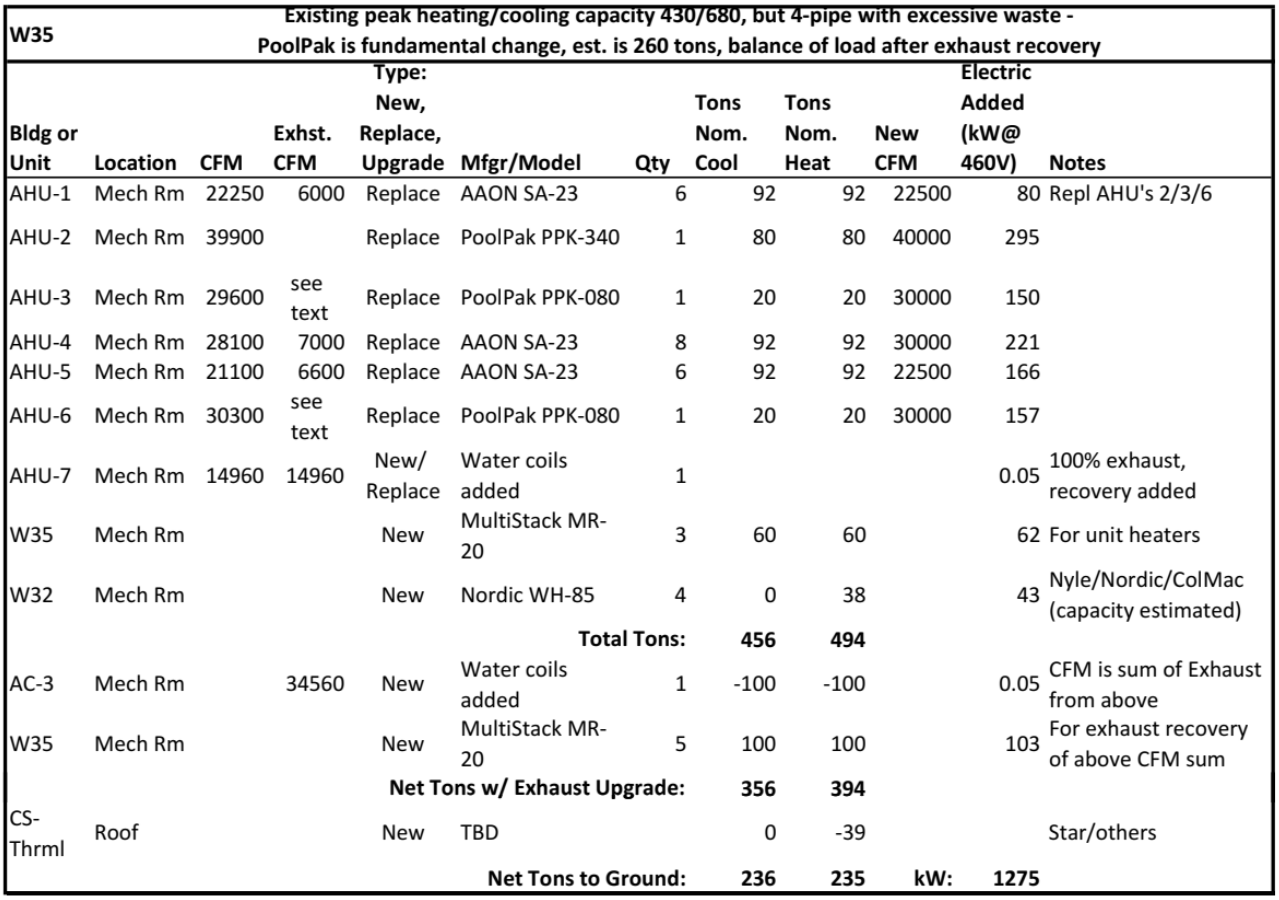
Building W35 is unique because it is principally two pools with spectator space. The upper floors of the perimeter have other more typical functions. The pool space requires special conditioning which, without active exhaust energy recovery, results in very large HVAC loads that are generally like the high exhaust volume laboratories. Likewise for the locker rooms which are 100% exhaust/make-up. A cost-effective decarbonization of the HVAC and exhaust in all such buildings must be undertaken to limit the amount of added electric power needed.

The simplest solution for pools and spectator HVAC operations is to use a pre-packed solution such as PoolPak which includes all of A) dehumidified HVAC, B) regulated make-up air to meet the needs of the space including whether in normal or swim meet mode with a larger audience, C) energy recovery from the dehumidified air returned directly to the pool water, and D) periodic need for larger volume exhaust such as after chlorine shock treatments for the pools. This packaged solution is the simplest for this building provided a path to installation of the PoolPak units is available (e.g., temporary large louver removal). If needed, the same functional solution is possible with individual WSHP and/or W-2-W equipment.

For the purpose of showing diversity of application and because of special issues in W35, we propose a mix of solutions beyond the pool area. Two of the other AHUs are “typical” and we propose small clusters of high efficiency WSHPs that 3D analysis suggests can readily fit. There is also a local 4-pipe solution potentially upgrading the existing AHUs that will be considered in subsequent iterations for comparison purposes.

The locker room AHU however is 100% exhaust and 100% make-up air exactly like the laboratory exhaust systems all across MIT’s campus that waste the majority of HVAC energy today. The W35 locker room system is an opportunity to demonstrate active lab exhaust 100% energy recovery that would be a total game changer for the energy loads all across MIT. With this one solution campus-wide, decarbonization would be vastly simplified. The penthouse mechanical rooms studied suggest there is ample space for at least one of the equipment solutions for exhaust decarbonization everywhere. To facilitate the “lab exhaust energy recovery” approach, we initially propose a W-2-W solution with multi-stage air coils for cascade energy recovery at high COP. Another solution involving smaller compressor units with DX coils for greater efficiency and flexible enough to fit in any mechanical penthouse campus-wide is also available and will be analyzed for comparison in a further iteration. This opportunity to demonstrate advanced exhaust energy recovery should be seriously considered.

Table 11: W35 HVAC Capacities



W35	Existing peak heating/cooling capacity 430/680, but 4-pipe with excessive waste - PoolPak is fundamental change, est. is 260 tons, balance of load after exhaust recovery										
Bldg or Unit	**Location**	**CFM**	**Exhst. CFM**	**Type: New, Replace, Upgrade**	**Mfgr/Model**	**Qty**	**Tons Nom. Cool**	**Tons Nom. Heat**	**New CFM**	**Electric Added (kW@ 460V)**	**Notes**
AHU-1	Mech Rm	22250	6000	Replace	AAON SA-23	6	92	92	22500	80	Repl AHU's 2/3/6
AHU-2	Mech Rm	39900		Replace	PoolPak PPK-340	1	80	80	40000	295	
AHU-3	Mech Rm	29600	see text	Replace	PoolPak PPK-080	1	20	20	30000	150	
AHU-4	Mech Rm	28100	7000	Replace	AAON SA-23	8	92	92	30000	221	
AHU-5	Mech Rm	21100	6600	Replace	AAON SA-23	6	92	92	22500	166	
AHU-6	Mech Rm	30300	see text	Replace	PoolPak PPK-080	1	20	20	30000	157	
AHU-7	Mech Rm	14960	14960	New/ Replace	Water coils added	1				0.05	100% exhaust, recovery added
W35	Mech Rm			New	MultiStack MR-20	3	60	60		62	For unit heaters
W32	Mech Rm			New	Nordic WH-85	4	0	38		43	Nyle/Nordic/ColMac (capacity estimated)
					Total Tons:		**456**	**494**			
AC-3	Mech Rm		34560	New	Water coils added	1	-100	-100		0.05	CFM is sum of Exhaust from above
W35	Mech Rm			New	MultiStack MR-20	5	100	100		103	For exhaust recovery of above CFM sum
					Net Tons w/ Exhaust Upgrade:		**356**	**394**			
CS-Thrml	Roof			New	TBD		0	-39			Star/others
					Net Tons to Ground:		**236**	**235**	**kW:**	**1275**	

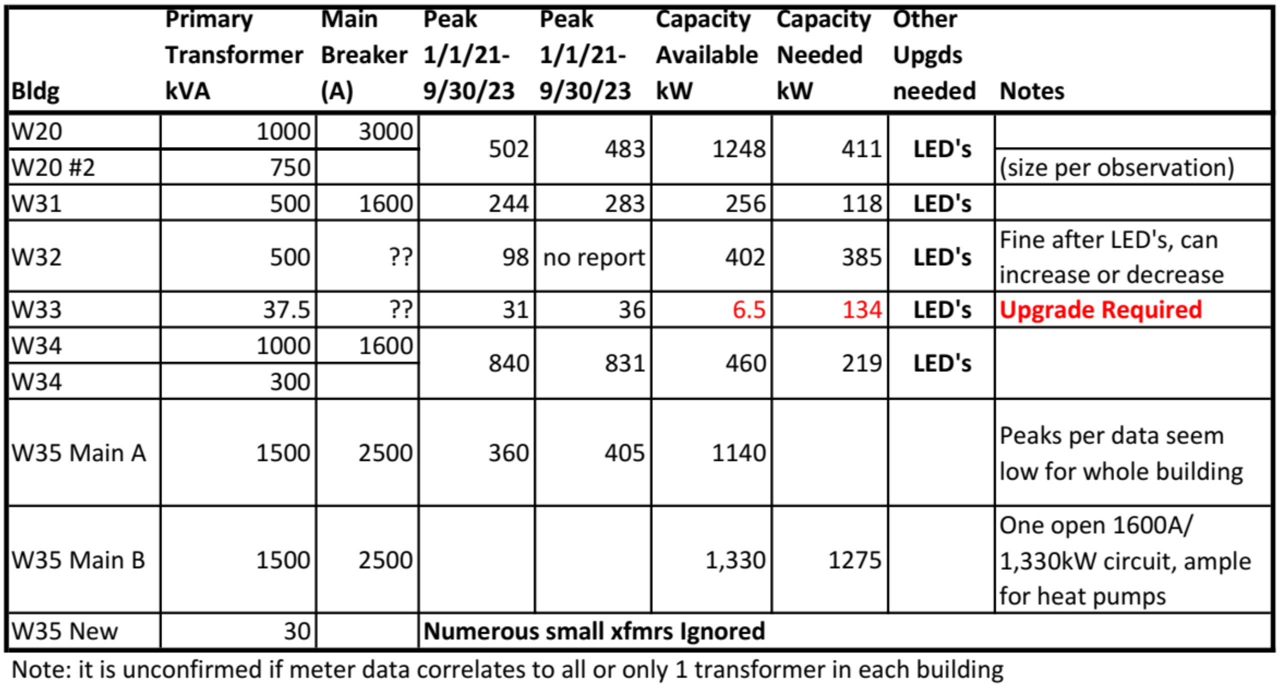
5.4 Electrical System Requirements

A fundamental aspect of decarbonization with heat pumps is that electric consumption will increase when upgrading from fossil based central plant utilities to electric distributed heat pumps. The process of designing such a system is a multi-step process where one first determines a base solution then iterates to find a more optimal solution for decarbonization while balancing all of the variable factors involved including equipment efficiencies, building envelope upgrades, thermal sources and sinks, and thermal storage.

The Test Fit first pass electric load solution is shown in Table 12 below. This initial assessment based on plans, schedules, and some direct equipment observations concludes that Buildings W20, W31, W32, W34, and W35 have ample power available for the solution shown. Further detailed review is needed to confirm this conclusion.

Building W33 will need electric upgrades for decarbonization via distributed heat pumps. This is not a surprise as W33 has sufficient power only for lighting. An approximate 200kW service is needed for W33.

Table 12: Electrical Overview



Bldg	Primary Transformer kVA	Main Breaker (A)	Peak 1/1/21-9/30/23	Peak 1/1/21-9/30/23	Capacity Available kW	Capacity Needed kW	Other Upgds needed	Notes
W20	1000	3000	502	483	1248	411	**LED's**	
W20 #2	750							(size per observation)
W31	500	1600	244	283	256	118	**LED's**	
W32	500	??	98	no report	402	385	**LED's**	Fine after LED's, can increase or decrease
W33	37.5	??	31	36	6.5	134	**LED's**	**Upgrade Required**
W34	1000	1600	840	831	460	219	**LED's**	
W34	300							
W35 Main A	1500	2500	360	405	1140			Peaks per data seem low for whole building
W35 Main B	1500	2500			1,330	1275		One open 1600A/ 1,330kW circuit, ample for heat pumps
W35 New	30		**Numerous small xfmrs Ignored**					

Note: it is unconfirmed if meter data correlates to all or only 1 transformer in each building

5.5 Ground Heat Exchanger and Ground Thermal Storage

The above six building level heat pump fit analyses included multiple thermal sources such as air source assets on W20 and W32 (as space and power would allow), and a minimally capable Cambridge Water System Thermal Exchange that could likely be larger after further work with the water department. With those external thermal inputs plus the included heat pumps for exhaust energy recovery, the net load to ground on an annual basis is only ~125 tons out of a total load calculation of over 1200 tons. This both reflects the initially stated approach of specifying more equipment tonnage in this first pass that is ultimately expected after some iteration, and the fact that tonnage in energy recovery is not the same as Ground Load. Further iterations will consider both more air-to-water heat pumps on W32 where there is space, but which would likely require additional power, and will consider less ASHP assets and thus more GHEX resources. Also please remember that real determination of the amount of ground heat exchanger and thermal storage needed for a decarbonization system requires an hourly model and simulation which is still forthcoming because the needed data was received too recently for completion of this portion of the Test Fit.

For a basic rough order of magnitude consideration, one could “guess” that about 230 bore-ft/ton are needed at MIT with a balanced load in the combined saturated overburden and underlying Argillite “bedrock”. We see that MIT has received other “geothermal” assessments with very large bore-ft/ton estimates, but they were for non-balanced loads and thus have little value for comparison – one works in design of these advanced systems to create a balanced load before one can accurately estimate actual GHEX required. Also, proper GHEX estimation requires completion of a test bore and Thermal Response Test, hopefully also a separate 120’ overburden test bore for separate testing. As communicated earlier, it is critical when this test happens to also obtain all the data from the test so a more advanced numerical method computation can be completed to obtain information about the ground “Heat Capacity.” The older conventional testing approach computes only the average ground

Thermal Conductivity and key other parameters are estimated solely from unreliable well logs without any data-based determination. The more thorough numerical method ground testing analysis determines both parameters as well as the thermal characteristics of the grouting job to confirm the test is high quality.

At 125 tons Ground Load and 230 bore-ft/ton, which suggests approximately 28750 bore feet, or about 48 bores at a modest 600'. We have identified 5-6 locations immediately adjacent to the 6-building cluster where angle drilling can occur. At 48 total bores, which would be 8-10 bores per cluster. This solution fits the site and would entail very limited drilling time at each site to limit impact. Further clarity and layout of the tradeoffs and options will be ready after the now available data is fully analyzed and a digital twin model and simulation built.

5.6 Proposed Solar Photovoltaic and Thermal Collectors

Impressed during walk-throughs of the 6-building cluster and seeing the vast expanse of open space on rooftops of W31 – 35, our plan has been expanded from earlier versions to propose adding renewable energy from solar on some of these six buildings. We examined both solar concentrating collectors for thermal energy and solar photovoltaics for electricity. Solar collectors would reduce the thermal load on the geothermal system, and solar PV would supply some electricity to equipment generation. Initial layouts for rooftop solar thermal collectors and solar photovoltaic panels have been created. Output varies based on weather, time of year and pointing angle of the panels. Excess generation could be stored in batteries and used to help manage peak-load demand. In order to improve our proposal, we have created a model in Excel and validated its estimates against a real-world photovoltaic system. The model output includes 5-min increments of energy output estimates, for further analysis and comparison with time-dependent peak loads of buildings.

5.6.1 Summary

Table 13: Rooftop Solar Energy Assessment (annual)

Rooftop	Number of Devices	% Building Electricity (2022 data)	Collector Energy (kBTU)	Solar PV Electricity	Avoided ($mtCO_2e$)
W20	471 PV	10%		872,647 kBTU =255,748 kWh	77
W32	107 PV 105 Col.	5% (PV-only)	1,133,051	198,245 kBTU =58,100 kWh	84
W34	1280 PV	16%		2,182,410 kBTU =639,601 kWh	192
W35	350 PV 77 Col.	8% (PV-only)	830,904	648,464 kBTU 190,046 kWh	106

Our recommendation includes photovoltaics only on W20 and W34, and both solar thermal collectors and photovoltaics on W32 and W35.

We are aware there is already a commitment to putting solar PV on W20 underway, independent of this proposal. Thus, we are not recommending any collectors on this rooftop.

5.6.2 Assumptions

[Please note that this section is a work in progress]

5.6.2.1 Size, Weight, and Power

We assumed certain dimensions for thermal collectors, and photovoltaic panels, based on web research for typical sizes and weights. Actual panels and collectors' dimensions and spacing may be slightly different. Our assumptions around hardware specifications are shown in the table below.

Table 14: Solar Energy Component Specifications

	Height x Width x Length	Device Spacing	Orientation	Weight	Energy Efficiency
Solar Thermal Collector	4.8’x3.5’x10’	12-21 inches (see figure)	1-axis rotation (around length)		~75%
Photovoltaic Panels	0.2’x3.8’x7.6’	5 inches	5° tilt for W20, W32 and W35; 10 or 15 deg tilt for W34	~5lbs/sq-ft	20%

In order to determine fit, we created a spacing arrangement to reduce shadow between devices at prime solar hours. The figure below shows the spacing assumptions for the solar thermal collectors. For improved performance, it may be possible to make the collectors in the back row taller than the ones in the front so they can collect more energy by remaining sunlit.

Figure 28: Solar Thermal Collector Spacing Assumptions

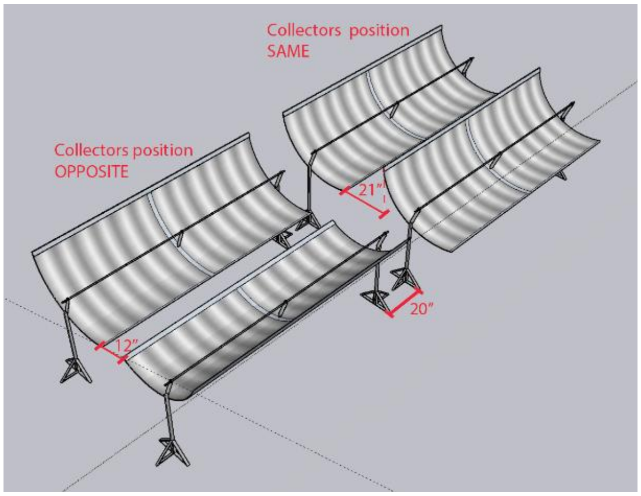


Table 15: Considerations for Solar Installations

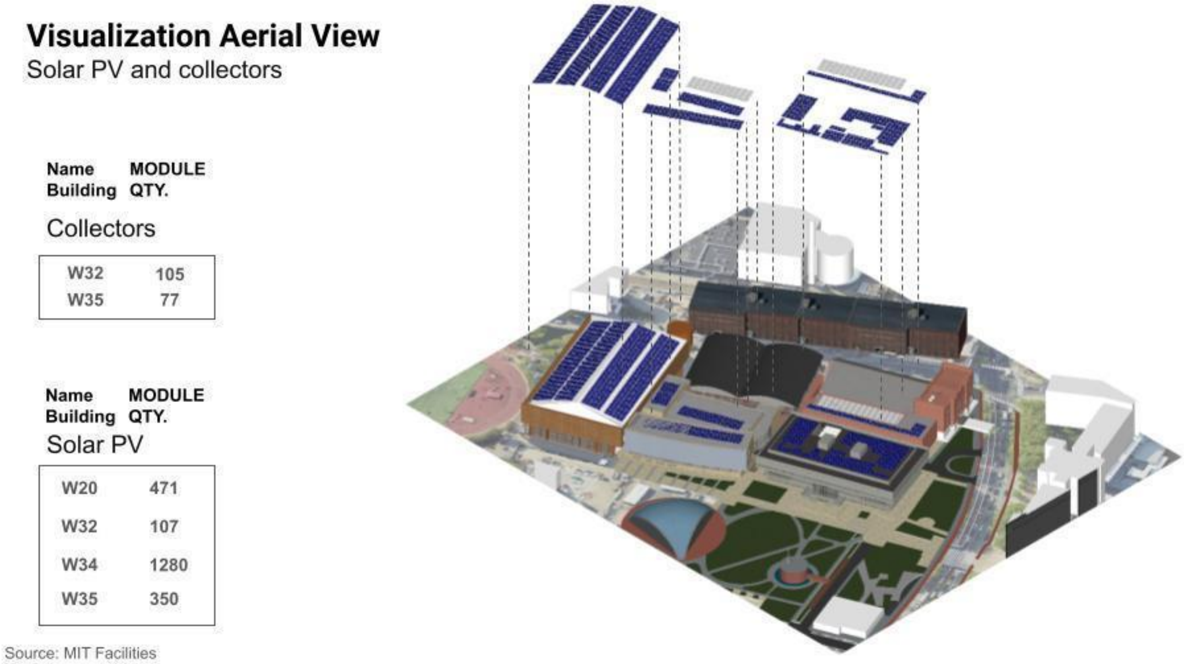
Solar Thermal Concentrating Collectors	**Solar Photovoltaic Panels**
- Collectors - Piping for fluid lines - Electrical hookups and control equipment for pointing collectors - Local-expert: https://parabolicsolartrough.com/	- Solar panels - Mounting stands and weights - Inverters and electrical hookups
Considerations: Two types of solar-thermal collection systems were considered: flat, and parabolic troughs. We selected parabolic troughs due to higher efficiency, however they have higher complexity as they rotate to optimize solar direction. Flat systems could be used alternatively.	Considerations: Orientation, and tilt angle greatly contribute to power generation of panels. Cooler panels (but not too cold) also are more efficient. Thermal aspects were not modeled in this exercise.

5.6.3 Placement Options

Considerations for placement include:

- Roof angle, direction
- Ability to securely adhere panels or collectors to rooftop
- Ease of access for installation and repair
- Weight tolerance (not yet evaluated)
- Sun/shadow conditions (determined via keep-out zones from 3D model)
- Ease of plumbing or electrical hookup

Figure 29: Locations and Quantity Photovoltaics, Thermal Collectors Test Fit Bldgs



Visualization Aerial View

Solar PV and collectors

Collectors

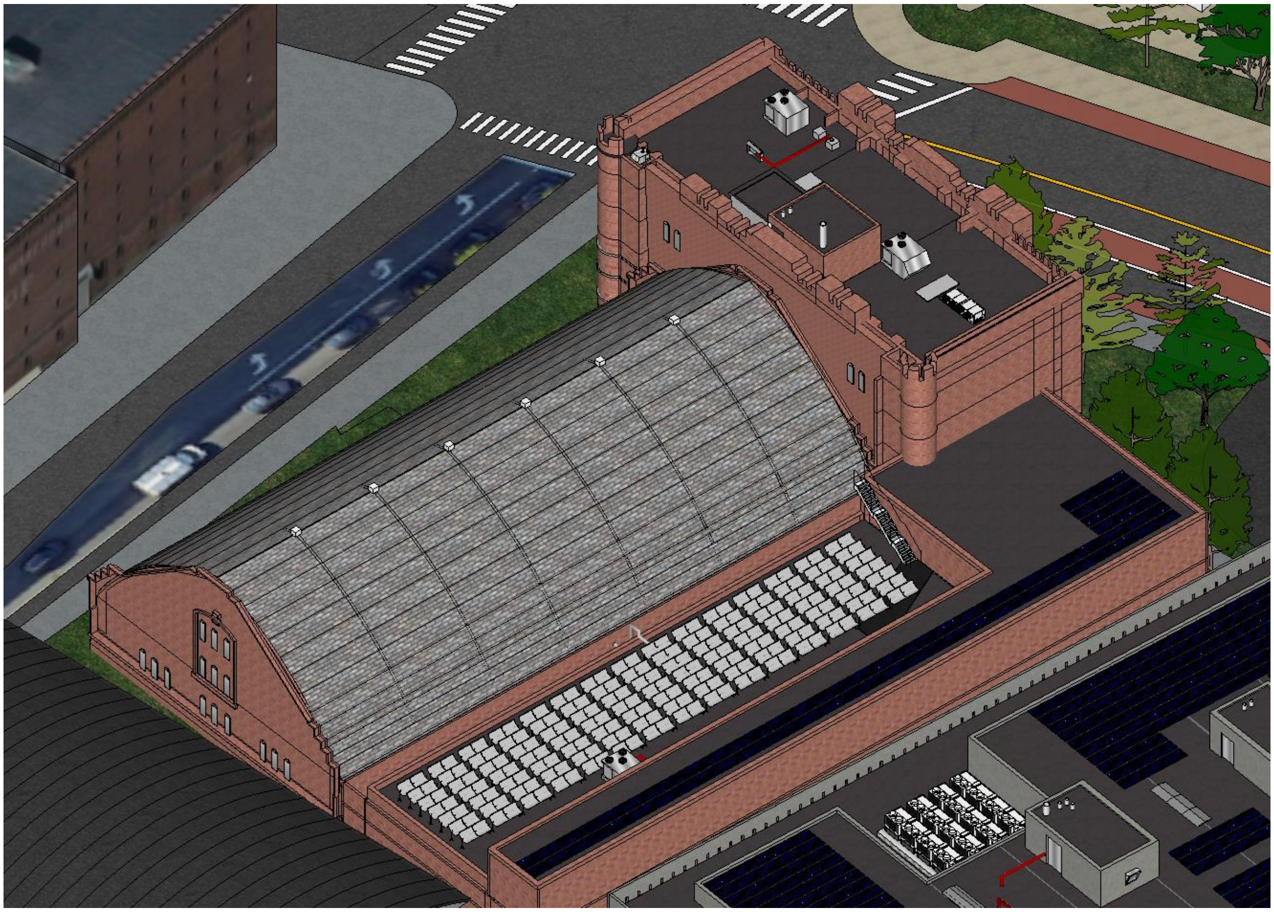
Name Building	MODULE QTY.
W32	105
W35	77

Solar PV

Name Building	MODULE QTY.
W20	471
W32	107
W34	1280
W35	350

Source: MIT Facilities

Figure 30: Building W32 Aerial View Proposed Orientation Thermal Collectors, PVs



Select Solar Thermal Collector Location Photos

On our walkthroughs to examine roof space for equipment, we noticed ample space for solar photovoltaic and thermal collectors. Here is our assessment of potential spaces.

Figure 31: W32 Roof

Figure 32: W35 Roof

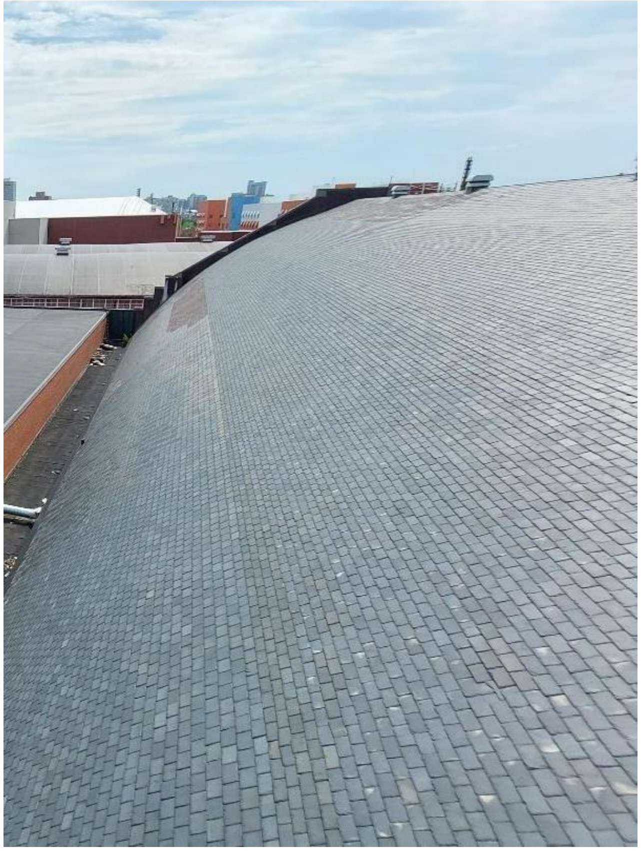
W20 has rooftop space as well available for solar panels, though there are shaded regions to avoid.

Figure 33: W20 Roof

Non-Optimal Rooftops

Some roofs do not lend themselves to solar installations, such as W31 and W33 pictured next.

Figure 34: W31 Roof



There is a portion of W31 (where the photographer is standing) that is flat, sunlit, and could hold some equipment. The area was significantly smaller than W32 however, and there are some structures that would create shade.

Figure 35: W33 Roof (No Photo)

We did not walk on the W33 roof – the surface is curved, and it would be difficult to install anything here.

Figure 36: W34 Roof

The W34 roof is angled, with ±10°, and ±15° for the upper and lower sections. One would have to get creative to create a proper mounting scheme for getting good sunlight angles, considering the more east-west orientation. Benefits, however, include that even if overall the energy will be reduced for this design, the times when power is supplied will be distributed during the day. For our modeling, we assumed roof-flush panels, keeping the contour of the roof rather than creating a fixed mount, which might require special processes to affix to the roof.

Figure 37: Aerial View of W34 and W35

Note slope of roof W34.

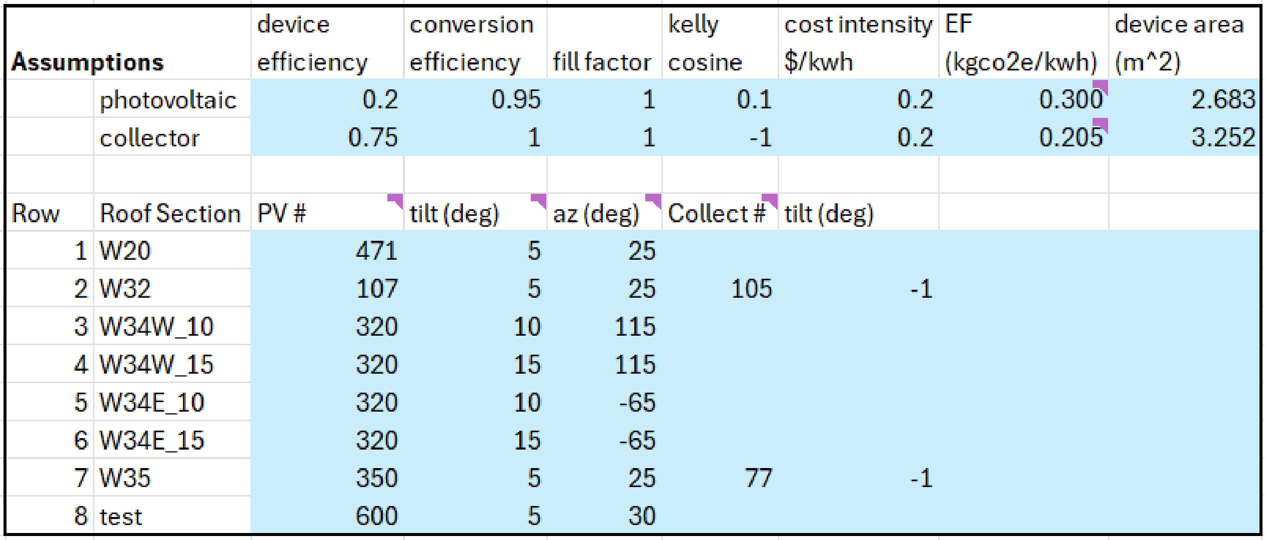
5.6.4 Solar System Modeling

Specific assumptions were made for the system and roof sections for input into our model, and for sensitivity analysis. The number of panels or collectors that fit on the roof, and the orientation of those rooftops was determined via our 3D modeling and may be modified and input as a parameter to the model. The tilt of the panels is also a model input variable. For modeling purposes, “-1” represents 1-degree of freedom for sun elevation tracking available on the thermal collectors. The timestep and coverage period can be varied for higher accuracy or speed as needed.

The model does not directly account for insufficient panel spacing which may shade other panels at low solar angles. It is assumed that between the “sun horizon threshold” and the spacing design that those are already accounted for. This is only a consideration for panels on mounts, rather than flush with roof. To approximate this consideration, one can increase the “sun horizon threshold” above the “no shadow threshold” computed value in the model from panel width and spacing geometry. For our modeling purposes, we used a 5-degree tilt, with a 10-degree sun horizon threshold, which would still create some small amount of shadow at low angles on the behind panels but is not deemed substantial. For certain roofs we may be able to accommodate more than 5 inches of spacing as well, these are simply approximations.

Table 16: Solar Modeling Assumptions

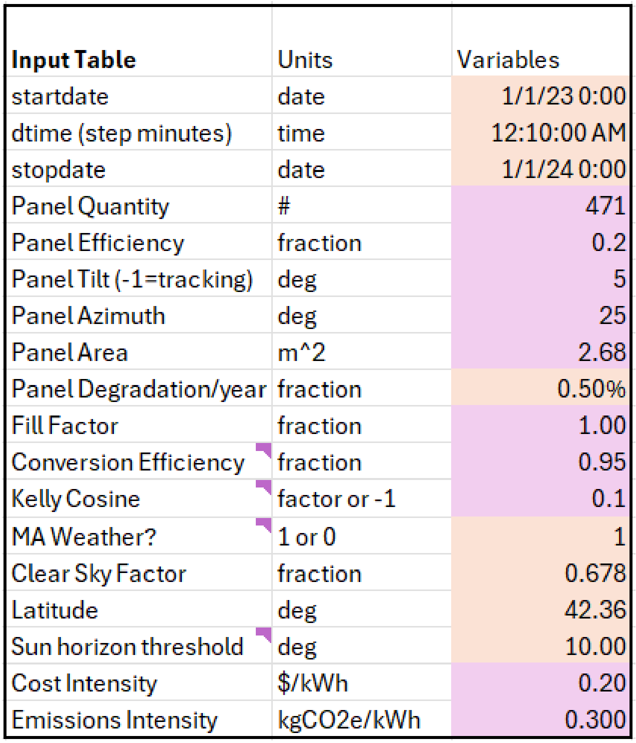
Modeling assumption inputs for building rooftops, photovoltaics, and thermal concentrating-collectors.



Assumptions		device efficiency	conversion efficiency	fill factor	kelly cosine	cost intensity $/kwh	EF (kgco2e/kwh)	device area (m^2)
	photovoltaic	0.2	0.95	1	0.1	0.2	0.300	2.683
	collector	0.75	1	1	-1	0.2	0.205	3.252
Row	Roof Section	PV #	tilt (deg)	az (deg)	Collect #	tilt (deg)		
1	W20	471	5	25				
2	W32	107	5	25	105	-1		
3	W34W_10	320	10	115				
4	W34W_15	320	15	115				
5	W34E_10	320	10	-65				
6	W34E_15	320	15	-65				
7	W35	350	5	25	77	-1		
8	test	600	5	30				

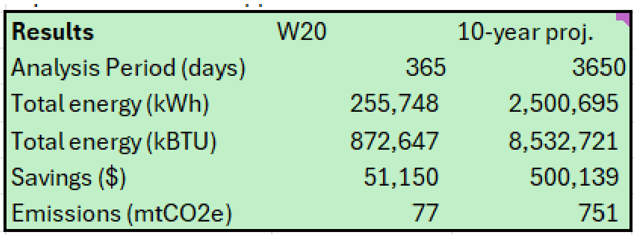
Table 17: Solar Modeling Parameters

(W20 Photovoltaic Example)



Input Table	Units	Variables
startdate	date	1/1/23 0:00
dtime (step minutes)	time	12:10:00 AM
stopdate	date	1/1/24 0:00
Panel Quantity	#	471
Panel Efficiency	fraction	0.2
Panel Tilt (-1=tracking)	deg	5
Panel Azimuth	deg	25
Panel Area	m^2	2.68
Panel Degradation/year	fraction	0.50%
Fill Factor	fraction	1.00
Conversion Efficiency	fraction	0.95
Kelly Cosine	factor or -1	0.1
MA Weather?	1 or 0	1
Clear Sky Factor	fraction	0.678
Latitude	deg	42.36
Sun horizon threshold	deg	10.00
Cost Intensity	$/kWh	0.20
Emissions Intensity	kgCO2e/kWh	0.300

Table 18: System Model Results for Individual Rooftop Section (W20 Example)



Results	W20	10-year proj.
Analysis Period (days)	365	3650
Total energy (kWh)	255,748	2,500,695
Total energy (kBTU)	872,647	8,532,721
Savings ($)	51,150	500,139
Emissions (mtCO2e)	77	751

The timestep ("dtime") may be adjusted down to 5 minutes while still covering a full year, for extracting tabulated energy data, or increased (and number of rows decreased) for faster runs.

Inside the model, various environmental conditions are modeled, and certain parameters are calculated. For example, it is modeled that when the sun is below the "sun horizon threshold" the panels/collectors do not function due to shadows, and dense atmosphere. The panel degradation per year parameter is only used for the 10-year projection calculation, not the short-term calculations which assume beginning of life equipment. Both cost of energy and emissions per unit of energy are considered constants for the model. Kelly-cosine losses seen by low-incidence angles on the photovoltaics are also included in the model for angles above cos(theta)=0.64 which is about 50 degrees. The "clear sky factor" is an atmospheric parameter determining how much light entering through the atmosphere reaches the surface.

When activated, “MA weather” is factored in as a monthly percentage of clear sky. The following chart shows the weather curve, derived from historic weather patterns. Alternative patterns (or perfect weather) may be implemented in the model instead as desired.

Figure 38: Solar Flux Transmittance MA Weather

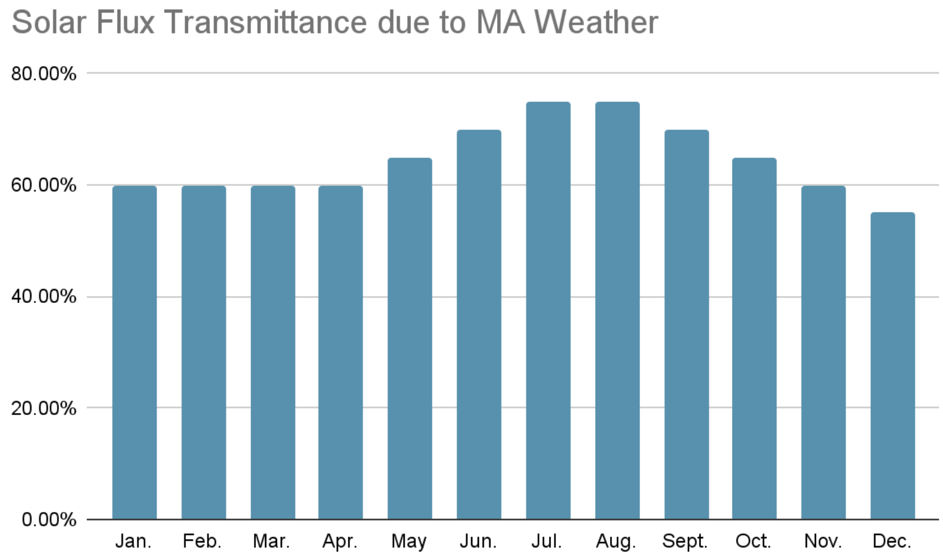


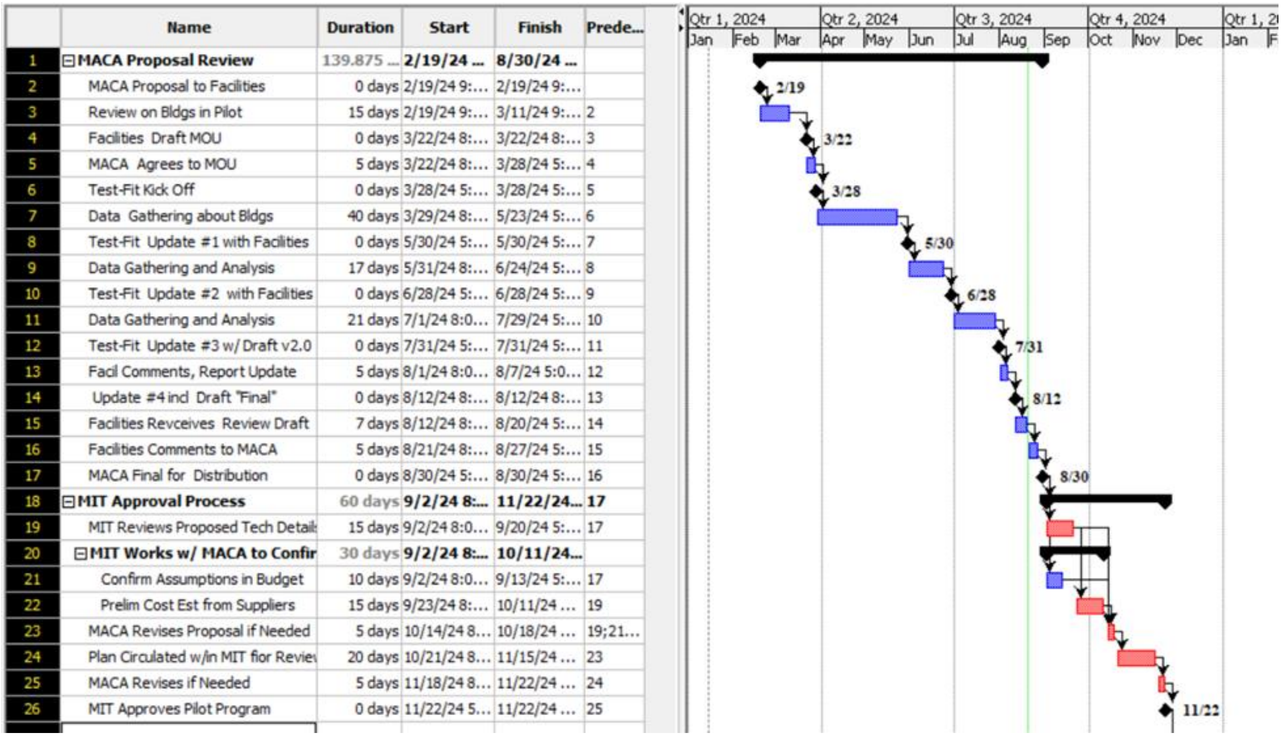
Table 19: Parameters and Equations for Excel Model

Model Background	**Parameters Calculated**
Time Weather influence in MA Kelly Cosine for PV Atmospheric attenuation due to angle Earth distance from sun impacting solar flux Latitude location of site Device and hookup efficiencies Tilt and tracking	declination (deg) hour angle (deg) solar elevation (deg) space solar flux (W/m^2) clear sky ground solar flux (W/m^2) clear sky ground horizon. solar flux (W/m^2) weather % solar azimuth (deg) cos(theta) kelly factor panel flux (W/m^2) total W

6 Logistics Plan/Sequence of Construction

6.1 Pilot Program: Working Timeline for MIT Approval

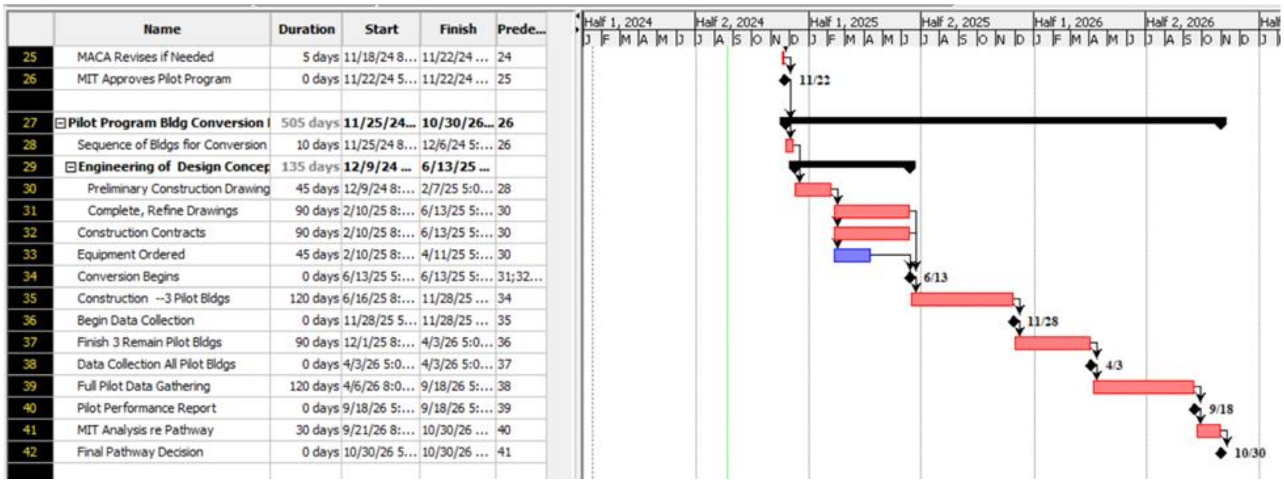
Figure 39: Gantt Chart MIT Decision re Pilot Program



	Name	Duration	Start	Finish	Prede...
1	⊟ **MACA Proposal Review**	139.875 ...	**2/19/24 ...**	**8/30/24 ...**	
2	MACA Proposal to Facilities	0 days	2/19/24 9:...	2/19/24 9:...	
3	Review on Bldgs in Pilot	15 days	2/19/24 9:...	3/11/24 9:...	2
4	Facilities Draft MOU	0 days	3/22/24 8:...	3/22/24 8:...	3
5	MACA Agrees to MOU	5 days	3/22/24 8:...	3/28/24 5:...	4
6	Test-Fit Kick Off	0 days	3/28/24 5:...	3/28/24 5:...	5
7	Data Gathering about Bldgs	40 days	3/29/24 8:...	5/23/24 5:...	6
8	Test-Fit Update #1 with Facilities	0 days	5/30/24 5:...	5/30/24 5:...	7
9	Data Gathering and Analysis	17 days	5/31/24 8:...	6/24/24 5:...	8
10	Test-Fit Update #2 with Facilities	0 days	6/28/24 5:...	6/28/24 5:...	9
11	Data Gathering and Analysis	21 days	7/1/24 8:0...	7/29/24 5:...	10
12	Test-Fit Update #3 w/ Draft v2.0	0 days	7/31/24 5:...	7/31/24 5:...	11
13	Facil Comments, Report Update	5 days	8/1/24 8:0...	8/7/24 5:0...	12
14	Update #4 incl Draft "Final"	0 days	8/12/24 8:...	8/12/24 8:...	13
15	Facilities Revceives Review Draft	7 days	8/12/24 8:...	8/20/24 5:...	14
16	Facilities Comments to MACA	5 days	8/21/24 8:...	8/27/24 5:...	15
17	MACA Final for Distribution	0 days	8/30/24 5:...	8/30/24 5:...	16
18	⊟ **MIT Approval Process**	60 days	**9/2/24 8:...**	**11/22/24...**	**17**
19	MIT Reviews Proposed Tech Detail	15 days	9/2/24 8:0...	9/20/24 5:...	17
20	⊟ **MIT Works w/ MACA to Confir**	30 days	**9/2/24 8:...**	**10/11/24...**	
21	Confirm Assumptions in Budget	10 days	9/2/24 8:0...	9/13/24 5:...	17
22	Prelim Cost Est from Suppliers	15 days	9/23/24 8:...	10/11/24 ...	19
23	MACA Revises Proposal if Needed	5 days	10/14/24 8...	10/18/24 ...	19;21...
24	Plan Circulated w/in MIT fior Review	20 days	10/21/24 8...	11/15/24 ...	23
25	MACA Revises if Needed	5 days	11/18/24 8...	11/22/24 ...	24
26	MIT Approves Pilot Program	0 days	11/22/24 5...	11/22/24 ...	25

6.2 Pilot Program: Building Conversion, Performance Data

Figure 40: Building Conversion, Performance, Final Pilot Report



	Name	Duration	Start	Finish	Prede...
25	MACA Revises if Needed	5 days	11/18/24 8...	11/22/24 ...	24
26	MIT Approves Pilot Program	0 days	11/22/24 5...	11/22/24 ...	25
27	⊟ **Pilot Program Bldg Conversion I**	505 days	**11/25/24...**	**10/30/26...**	**26**
28	Sequence of Bldgs fior Conversion	10 days	11/25/24 8...	12/6/24 5:...	26
29	⊟ **Engineering of Design Concep**	135 days	**12/9/24 ...**	**6/13/25 ...**	
30	Preliminary Construction Drawing	45 days	12/9/24 8:...	2/7/25 5:0...	28
31	Complete, Refine Drawings	90 days	2/10/25 8:...	6/13/25 5:...	30
32	Construction Contracts	90 days	2/10/25 8:...	6/13/25 5:...	30
33	Equipment Ordered	45 days	2/10/25 8:...	4/11/25 5:...	30
34	Conversion Begins	0 days	6/13/25 5:...	6/13/25 5:...	31;32...
35	Construction --3 Pilot Bldgs	120 days	6/16/25 8:...	11/28/25 ...	34
36	Begin Data Collection	0 days	11/28/25 5...	11/28/25 ...	35
37	Finish 3 Remain Pilot Bldgs	90 days	12/1/25 8:...	4/3/26 5:0...	36
38	Data Collection All Pilot Bldgs	0 days	4/3/26 5:0...	4/3/26 5:0...	37
39	Full Pilot Data Gathering	120 days	4/6/26 8:0...	9/18/26 5:...	38
40	Pilot Performance Report	0 days	9/18/26 5:...	9/18/26 5:...	39
41	MIT Analysis re Pathway	30 days	9/21/26 8:...	10/30/26 ...	40
42	Final Pathway Decision	0 days	10/30/26 5...	10/30/26 ...	41

7 Impacts

7.1 Cost

The Pilot Program we propose is a low-cost and low-risk approach to:

- Generate performance data for the HVAC system design and components
- Resolve concerns about perceived complexity of the proposed approach, both for installation and maintenance
- Provide in-use data about system operating cost
- Provide guidance about electrical loads during peak-use periods
- Provide guidance about possible disruption to campus activities if a unit fails

In addition, the pilot would help build a broader understanding of the cost of:

- Converting the entire campus to the proposed distributed thermal energy heat pump system.
- Converting the chilled water loop to an ambient water loop. Converting the existing CW loop is a major component of CapEx savings between this proposal and the four top-rated AEI pathways. Converting the CW loop would also reduce disruption to campus activities compared to having to install extensive new piping as with other pathways.

Other cost-related benefits of the Pilot Program include:

- Demonstrating a “custom-fit” HVAC solution for a building or even single floor results in little or no cost penalty.
- How a staged rollout can reduce operational and financial risks.
- Opportunity to demonstrate and measure performance of optional thermal management systems.

Pilot Program Cost – While more analysis is needed, the preliminary cost for the pilot is ~$12-15 million gross (~$8-10 million with IRA funds). We have formally requested assistance from MIT staff, Facilities and/or Financial, to help refine the estimates. (See Annex 2)

We are also awaiting updated life-cycle cost estimates from AEI to reflect more objective assumptions requested by MIT. Having the revised AEI estimates will enable us to refine our cost comparisons to other pathways.

Pilot Will Not Result in Additional CapEx: Importantly, regardless of which decarbonization pathway is adopted, virtually all the equipment in the Pilot could remain in the buildings or installed elsewhere on campus. Thus, the Pilot Program would not increase overall project CapEx.

Pilot Program Operational Cost. To operate the six (6) buildings in the Pilot Program, the incremental energy costs should be minimal, if any. All HVAC equipment for the buildings in the Pilot will be operated by electricity generated by CUP.

Electricity usage during the Pilot Program will be a good guide for estimating usage for much of the rest of the campus. The EUI in W35 is comparable to an energy-intensive lab. Electricity usage in administrative and classroom buildings should be less than other buildings in the Pilot Program.

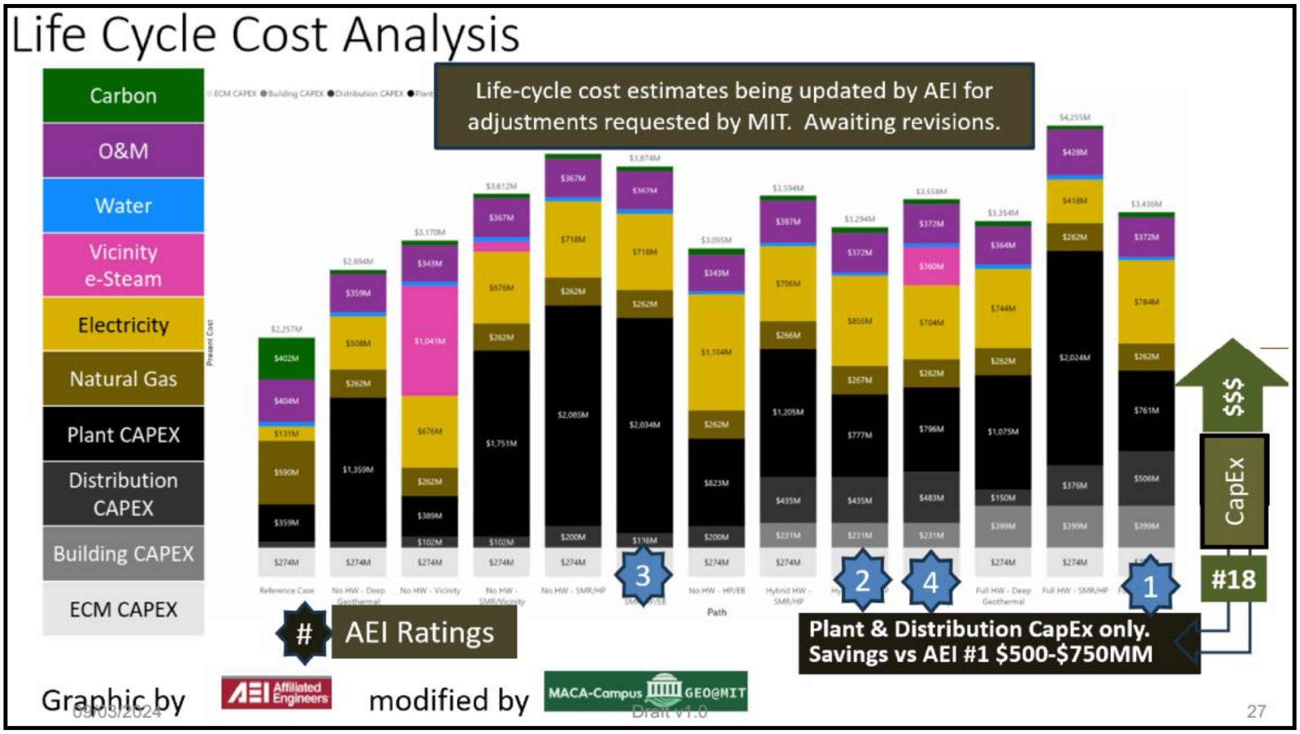
Compared to decarbonization pathways using steam or a centralized system to help manage ambient water temperature, the MACA/Geo@MIT distributed design reduces electricity usage by:

- Operating a heat pump at the point of use only when heating or cooling is needed
- Eliminating energy transmission losses between the CUP and campus building
- Capturing and recycling waste heat from exhaust
- Leveraging high WSHP operating efficiency
- Capturing free energy in the ambient loop when there is concurrent heating and cooling

Combined we believe total electricity usage with the MACA/Geo proposal will be significantly lower than any of the AEI pathways. Assuming a savings of just 15% -- several in our group estimate savings of 25+% -- life-cycle electricity cost with our proposal would be reduced by $100+MM from the $784MM cost of AEI's highest-rated proposal.

The relative savings would apply to most, if not all the AEI proposals. Total dollar savings will vary by proposal. The proposed Pilot Program will provide operational data to help refine the estimate.

Figure 41: Reduced CapEx Pathway 18


Life Cycle Cost Analysis

Life-cycle cost estimates being updated by AEI for adjustments requested by MIT. Awaiting revisions.

Plant & Distribution CapEx only. Savings vs AEI #1 $500-$750MM

Graphic by modified by

7.2 Carbon Emissions Reductions

The Pilot Program eliminates emissions from steam and chilled water, which are generated at the CUP. The table below shows emissions from FY2022 for the buildings, and the projected post-Pilot Program once emissions from steam and chilled water are eliminated. The vast majority of the remaining emissions are from electricity assuming MIT continues depending on the CUP for all power (a very tiny proportion goes to natural gas for appliances which may be replaced separately).

Table 20 below is a preliminary assessment of the CO2 effect if MIT continues to use existing CUP generated electricity.

NOTE: This Pilot Project proposal instead calls for MIT to purchase Clean Energy from the power utility which is now available from most utilities for a slightly higher rate to cover the associated RECS and their administration. Then the Pilot Project six buildings will be 100% decarbonized except for the gas cooking in W20.

Table 20: Annual Carbon Reductions

Building	**FY2022 ($mtCO_2e$)**	**Pilot ($mtCO_2e$)**	**Reduced ($mtCO_2e$)**	**Reduction**	**Solar addtl. ($mtCO_2e$)**
W20	1,865	778	1,087	58%	77
W31	1,562	359	1,203	77%	
W32	454	363	92	20%	84
W33	125	29	96	77%	
W34	1,560	1,247	314	20%	192
W35	3,129	745	2,384	76%	106
Total	**8,695**	**3,521**	**5,176**	**60%**	**459 (5%)**

Assumptions:

- No more steam or chilled water
- Natural gas still used for appliances
- Electricity consumption change due to replacing equipment not yet quantified
- Solar photovoltaic and concentrating collector contribution kept separate (Based on constant emissions intensity from 2022/2023 Sustainability datapool set.)

As the electric grid gets cleaner, and as MIT switches from using CUP electricity to the grid, the emissions of the buildings will trend towards zero. The above emissions reduction numbers assume 2023 emissions factor values shown in the table below and are considered constant. In reality these will change as emissions from electricity decrease, which provide electricity to the CUP. Currently electricity grid emissions for New England are around 250 gCO2e/kwh, and is expected to decrease as more wind and solar is added to the mix.

Table 21: 2023 Emissions Factors to Calc Solar Offsets

Emissions Factors utilized in emissions factors calculations for solar PV and collector offsets.

	$gCO_2e/kBTU$	gCO_2e/kWh
Steam	60	
Gas	53.18	
Chilled Water	32.96	
Electricity	88	300

The 2022 emissions factors are identical to the significant digits shown. These were calculated from MIT Sustainability Datapool datasets.

This Pilot Project proposal instead calls for MIT to purchase Clean Energy from the power utility which is now available from most utilities for a slightly higher rate to cover the associated RECS and their administration. With such purchases, the Pilot Project six buildings will be 100% decarbonized except for cooking with gas in W20.

7.3 Low Levels of Campus Disruption

While the exact amount of proposed GHEX and Thermal Batteries is not yet complete, the process is to select both volume, location, and an installation technique that results in the least campus site impact possible. Such installations are being installed in all sorts of locations nationwide daily, thus the level of disruption is generally tolerated. However, some of the GHEX installation techniques are locally loud which requires planning. In general, each such location will experience an about 2-week sound level disruption with multiple avoidance techniques available including remoting and sound wall enclosing the loud air compressors. Further attention would be given to avoiding immediate staging to an adjacent bore site installation, instead opting for staggered site selection to control the duration of sound disruption at any one site. Further, an innovation to vastly reduce drilling compressor noise is available which could be pursued by anyone interested at MIT.

8 Summary and Recommendation

General Findings re Equipment Proposed

- All equipment associated with the proposed distributed water-source heat-pump system will fit in existing spaces allocated to HVAC equipment.
- Extending the chilled-water loop to the three (3) buildings not currently in the loop can be achieved with minimal effort.
- All proposed equipment supports the goal of 100% decarbonization provided green power is used.
- All proposed equipment is currently available from HVAC manufacturers as a regular production model.

Pilot Program

The Pilot Program will help address concerns expressed:

- Whether the necessary equipment will fit in available non-programmed spaces.
- Whether peak-load electricity demand using WSHPs will exceed capacity of the building or the "campus grid."
- Potential issues of installing and managing distributed, multiple, smaller HVAC units in separate buildings.

Significant Cost Savings

Pilot Program will demonstrate how a distributed heat pump thermal energy system can reduce required capital expenditures over other decarbonization approaches. Based on preliminary estimates, the proposed approach, if installed on the entire campus, would reduce CapEx $500-$750 million compared to the AEI highest-rated pathway. The projected increased operating efficiency of the distributed system would reduce operating expenditures by at least $100 million compared to the highest-rated AEI pathway.

Technical and Performance Findings

This Test-Fit analysis for a Pilot Program indicates that a distributed heat-pump thermal energy system should be the most energy efficient solution for decarbonizing the MIT campus. For the buildings in the Pilot Program for campus-wide installation:

- WSHPs will provide both heating and cooling, eliminating the need to invest in, operate and maintain parallel heating and cooling systems.
- WSHPs attached to the repurposed ambient loop are highly efficient with an annual average Coefficient of Performance of 5.0 and higher.
- Commercially available WSHPs are less expensive per unit with higher end-point output than a centralized system, and easier to maintain or swap out if needed

Benefits of the Ambient Loop

- The ambient loop eliminates transmission losses from the CUP to the six-building Pilot cluster, especially heat energy losses.
- A single "ambient loop" eliminates half the pumping power used in a 4-pipe system
- A bi-directional ambient loop improves heat-pump efficiency at all times and lowers total pumping power required.
- Repurposing the existing chilled-water loop to an ambient loop eliminates most excavation for new piping, thereby reducing disruption to campus activities and significantly reducing required capital expenditures.

Benefits of Concurrent Systems and Exhaust Recovery

- Concurrent system-wide heating and cooling will significantly reduce total HVAC energy usage and costs compared to other proposed pathways. Savings are especially enhanced with active exhaust-energy recovery in large ventilation volume buildings such as W35.

- Point of application exhaust energy recovery with heat pumps in DX mode is significantly more efficient than any central energy recovery approach.

Recommendation – Approve Pilot Program. We strongly recommend that MIT approve expenditures for HVAC decarbonization in the proposed six-building Pilot Program on west campus. This Test-Fit analysis has shown that the proposed HVAC decarbonization pathway based on distributed heat pumps can achieve zero emissions from campus buildings by 2035 through electrification. Industry experience shows this is likely the most efficient decarbonization to operate and maintain, thus having the lowest CapEx and long-term OpEx of any proposed decarbonization approach. Once the buildings are converted and the Pilot system is operational, the data gathered will provide highly credible guidance about the benefits of the proposed pathway for the balance of MIT's campus.

In addition to the Pilot Program, we strongly encourage MIT to include the distributed WSHP design in any list of decarbonization pathways being evaluated by consultants and other campus decarbonization groups. We believe the design proposed by the MACA/Geo@MIT team could help MIT demonstrate to the world an affordable, practical approach to rapid decarbonization.

Project Team Members, Advisors

Susan Murcott / MACA

’90, ‘92 Civil and Environmental Engineering

Susan is an environmental engineer specializing in sustainable water, wastewater, energy, and earth systems. For over 3 decades at MIT, she has held research and teaching/senior lecturer positions in the Civil and Environmental Engineering Department, the Department of Urban Studies and Planning, and as a Lecturer at D-Lab.

Rick Clemenzi / MACA, ’81, Computer Engineering

Judy Siglin / MACA Affiliate

Rick Clemenzi is a Systems Engineer specializing in Advanced Thermal Systems. He is a Certified GeoExchange Designer (CGD) and principal engineer at Geothermal Design Center a licensed geothermal specialty engineering firm, and co-founder of Net Zero Foundation along with Judy Siglin who are working to advance rapid and cost-effective decarbonization.

John Dabels / MACA, SM ’79 Sloan

A major portion of John’s career has been split between: (i) helping guide the development and launch of a range of products, mostly transportation related; (ii) conducting financial analysis and/or operating as a senior financial executive in several larger and smaller companies.

Shiladitya DasSarma/MACA, ’84, PhD, Available Advisor

Biochemistry. Professor, University of Maryland School of Medicine and Institute of Marine and Environmental Technology, Baltimore. Research concerns impacts of climate change on society and the mechanisms of cell survival after environmental stress. Founded MIT Alumni for Climate Action received the Margaret MacVicar Award for his leadership on climate action by MIT.

David T. Williams / MACA, MIT ’82, Mechanical Engineering Dept.

David attended MIT from 1977-1982 pursuing a course in Mechanical Engineering with a strong interest in building systems. His 40+ year professional career is in Architecture/Engineering consulting for the premier firm in this area of design in MN, LHB Corp where he is a Principal, Senior Mechanical Engineer, and Sustainability Specialist.

Herb Zien / MACA

’73, Management

Herb Zien (Sloan SM ’73) co-founded a firm that became the largest owner and operator of District Energy Systems in the US, with 21 Central Utility Plants serving 11 cities including Boston.

Tunca Alikaya / Geo@MIT / MACA

’24 E-MBA, Sloan

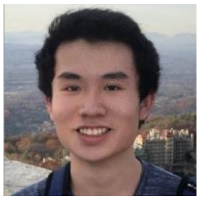
Expanding Celsius Energy, a Schlumberger New Energy start-up that provides geo-energy technology for zero-carbon heating and cooling of buildings, to the US market.

Kevin Johnson /

Harvard GSD ’24, Architect, **Geo@MIT / MACA**

Kevin is an architect and current Master in Design Studies student at Harvard GSD, with a background in Urban Design and Landscape. He has significant experience in urban planning, decarbonization, and emergency management. In Chile, Kevin leads a design studio focused on climate change and urban growth, and serves as Chair of Latin GSD. He is also engaged in exploring advanced energy systems at Harvard SEAS and participating in global design competitions.

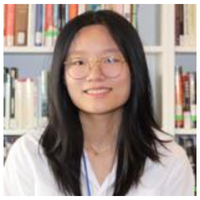
Jillian James /MACA. Jillian has a S.B. Aerospace Engineering ‘10 and a SM in Aero Astro Engineering ‘16. She is an En-ROADS ambassador, and the director of Sustainability of NetScout. Jillian also manages the MIT Climate Clock website and has been a key technical player in making the MIT Climate Clock projection on the Green Building (#54) possible.



Jason Chen / Geo@MIT

’25 Mechanical Engineering & Literature

Jason Chen is an undergraduate senior at MIT double majoring in mechanical engineering and literature and minoring in computer science, and member of student Geo@MIT team that won two DOE Geothermal Technologies Office awards. He is passionate about accelerating energy transition through research and commercialization of technologies.



Olivia Chen / Geo@MIT

’26, Mechanical Engineering

Olivia Chen is an undergraduate junior at MIT majoring in Mechanical Engineering, and member of student Geo@MIT team that won two DOE Geothermal Technologies Office awards. She is passionate about energy, sustainability, and entrepreneurship.

Megan Lim / Geo@MIT / MACA, ’24, Business Management

Megan is an MIT business management graduate as of May 2024, and member of student Geo@MIT team that won two DOE Geothermal Technologies Office awards. She has spent the past 4 years involved with the Undergraduate Association, where she served as chair of the Committee on Innovation, helped run a 24/7 student space named Banana Lounge, served on the Presidential Advisory Cabinet, and worked on a wide range of student issues. She interned at the MIT Office of Sustainability during the summer and is working at MIT’s Environmental Solutions Initiative.

10 References

Oak Ridge National Laboratory. Grid Cost and Total Emissions Reductions through Mass Deployment of Geothermal Heat Pumps for Building Heating and Cooling Electrification in the United States. Nov. 2023

Oak Ridge National Laboratory. Evaluation of the Impacts of Heat Exchanger Operation on the Quality of Water Used as Heat Source and Sink. June 10, 2018.

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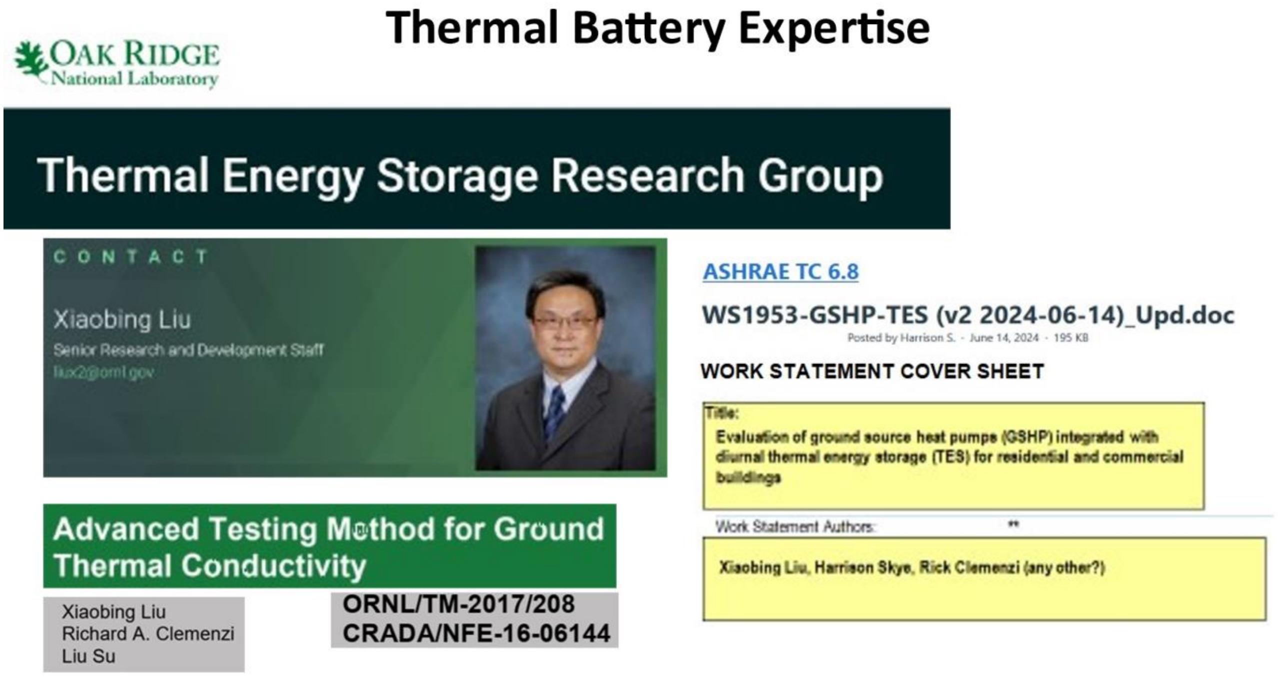

Thermal Battery Expertise

OAK RIDGE
National Laboratory

Thermal Energy Storage Research Group

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Advanced Testing Method for Ground Thermal Conductivity

Xiaobing Liu
Richard A. Clemenzi
Liu Su

ORNL/TM-2017/208
CRADA/NFE-16-06144

ASHRAE TC 6.8

WS1953-GSHP-TES (v2 2024-06-14)_Upd.doc

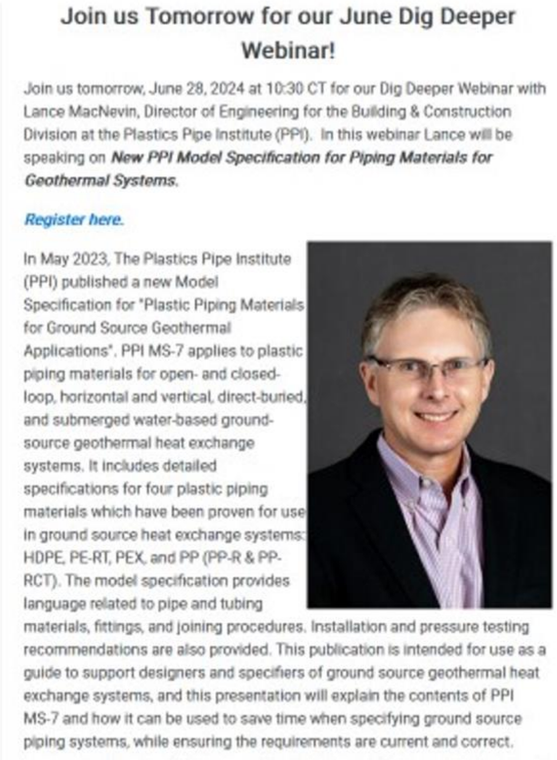
Posted by Harrison S. · June 14, 2024 · 195 KB

WORK STATEMENT COVER SHEET

Title:
Evaluation of ground source heat pumps (GSHP) integrated with diurnal thermal energy storage (TES) for residential and commercial buildings

Work Statement Authors: **
Xiaobing Liu, Harrison Skye, Rick Clemenzi (any other?)

PE/PP Pipe Expertise



Join us Tomorrow for our June Dig Deeper Webinar!

Join us tomorrow, June 28, 2024 at 10:30 CT for our Dig Deeper Webinar with Lance MacNevin, Director of Engineering for the Building & Construction Division at the Plastics Pipe Institute (PPI). In this webinar Lance will be speaking on ***New PPI Model Specification for Piping Materials for Geothermal Systems.***

Register here.

In May 2023, The Plastics Pipe Institute (PPI) published a new Model Specification for "Plastic Piping Materials for Ground Source Geothermal Applications". PPI MS-7 applies to plastic piping materials for open- and closed-loop, horizontal and vertical, direct-buried, and submerged water-based ground-source geothermal heat exchange systems. It includes detailed specifications for four plastic piping materials which have been proven for use in ground source heat exchange systems: HDPE, PE-RT, PEX, and PP (PP-R & PP-RCT). The model specification provides language related to pipe and tubing materials, fittings, and joining procedures. Installation and pressure testing recommendations are also provided. This publication is intended for use as a guide to support designers and specifiers of ground source geothermal heat exchange systems, and this presentation will explain the contents of PPI MS-7 and how it can be used to save time when specifying ground source piping systems, while ensuring the requirements are current and correct.

Certified GeoExchange Designer (CGD) Course:

Training course for advanced thermal system designers and engineers that should be considered a prerequisite for designing any system involving GHEX. Course teaches how to design and install the GHEX involving low-maintenance, economical and green alternatives for space conditioning needs. The course spans the full spectrum from an introduction to the technology through a complete review of the design process.

CGD Course Topics:

- Ground Source Heat Pump Design – Residential & Commercial
- Designing Closed Loop, Ground Heat Exchanger, Configurations & Layouts
- Soil/Rock Classification and Conductivity
- Borehole Grouting
- Thermal Conductivity in-situ testing
- Ground Loop Heat Exchanger Software
- Ground Source Heat Pump in System Performance

Other sources of Thermal Energy Network information:

- ORNL Thermal Energy Storage Research Group
- DOE Geothermal Technologies Office: Geothermal Heat Pumps
- Trane Thermal Energy Storage
- NY State NYSERDA Thermal Energy Networks

Annex 1 Abbreviations and Key Concepts

Abbreviations

ASHP - Air Source Heat Pumps where energy is transferred between air both inside and outside for heating or cooling, or between air in the exhaust stream and the make-up air stream for energy recovery.

A-2-A-2-W transfer of energy between air and air and water (A-2-A-2-W). Used both for exhaust energy recovery and for dehumidification which are both primary functions of HVAC systems in commercial and laboratory use.

AHU – air handling unit

CAPEX – capital expenses

CGD – Certified GeoExchange Designer

CO2e – carbon dioxide equivalent

CFM – cubic feet per minute (typically an air flow measure in HVAC)

CHP – Combined Heat and Power plant

COP – Coefficient of Performance (COP), the unitless comparison of heat output (COPh) or cold output (COPc) to the amount of electricity used.

CSP – concentrating solar power

CUP – Central Utility Plant

CW – chilled water

DHW – domestic hot water

ERV – energy recovery ventilators

EUI – energy use intensity

GHEX – ground heat exchange

GHG – greenhouse gas

GSHP – ground source heat pump (aka GHP – geothermal heat pump)

HDPE – high density polyethylene pipe

HVAC – heating, ventilation, and air conditioning

HX – heat exchange

OPEX – operating expenses

O&M – operation and maintenance

PPA – power purchase agreement

PCM – phase change materials

PP – polypropylene pipe

PV – photovoltaic

REC – renewable energy certificate

W-2-A & W-2-W – heat pumps that transfer thermal energy between water and either air or water

W-2-A-2-A – 3-way heat pumps that transfer thermal energy flexibly between water and two air streams which are particularly useful in exhaust energy recovery

W-2-W-2-A – 3-way heat pumps that transfer thermal energy flexibly between two water loops and air

WSHP – Water Source Heat Pump, heat pumps that transfer thermal energy between water and various secondary thermal loads generally for space conditioning or domestic hot water (DHW)

Key Concepts

Building Load -- the thermal heating and cooling loads of the building

Electric Load -- in this case, the electric demand (kW) and energy (kWh) loads placed on the electric supply by the combination of heat pumps and pumping required by the overall system

Ground Load -- the combination of thermal rejection and extraction to and from the ground

Thermal Energy Networks - A network of pipes to connect multiple buildings together and thermal sources and sinks, such as GHEX, air, waste heat, surface water, municipal water network and/or sewer, to provide space heating, and building cooling, heating, and domestic hot water.***[1]***

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[1] NYSERDA: https://www.nyserda.ny.gov/All-Programs/Clean-Energy-Communities/High-Impact-Actions/Toolkits/Thermal-Energy-Networks

Annex 2 Questions Raised about Consultant Pathway Costs

Letter sent to MIT Facilities Group requesting clarification on Decarbonization Pathway costing assumptions – the results of this request are pending and required before the cost model can be completed:

17 July 2024

To: MIT Facilities Group
Re: AEI Presentation – Some Clarifications, Please

Based on your explanation of roles during the recent "Test-Fit" analysis update with MACA Decarbonization Workgroup, I thought you might be able to help clarify a couple of questions about the AEI presentation. My role in the Workgroup is primarily financial. Experience includes a wide range of project management and financial assignments, including developing forecasts, business plans, and pro formas.

One of the goals of the MACA team is to help MIT achieve zero emissions from buildings. While much conversation with our group has focused on a particular approach, the group's "Mission Statement" is much broader. As noted at the beginning of our Business Plan, we believe the mission is consistent with presenting a pathway option to MIT that apparently has not been explored by AEI – campus-wide distributed heat pumps. Implementing one or more key components of the distributed design could result in increased energy efficiency and generate financial benefits compared to the 13 pathways evaluated in the AEI presentation.

Time available to present and review our financial analysis is short. Based on the 06/04/2024 AEI presentation, the final AEI report is due 09/02/2024 – less than 35 workdays from now. We believe participants reviewing our financial analysis should feel confident that the approach to calculating the estimates is consistent with the approach used by AEI.

The AEI presentation, like virtually all PowerPoint presentations with myriad material, includes the inevitable ambiguities that need to be clarified. The requests for clarification of AEI material focus more on how assumptions were applied in the model to calculate life-cycle costs rather than the assumptions themselves.

There was a question during the workshop whether inflation was applied when calculating life-cycle costs. After reading the transcript several times of the discussion surrounding the question, it is not clear whether life-cycle costs are in nominal or constant dollars – i.e., with inflation or adjusted for inflation.

More information about several items will help ensure more consistency with AEI's approach.

- Life-Cycle Period – based on slides, 30 years.
- In AEI's analysis we assume Life-Cycle costs are in 2024 dollars (US$ 2024), aka "Constant Dollars," "Present Value." On AEI slides (#38, #39), LCCA seems to include an inflation rate of 3.0%/yr. At 3.0%/year, an item costing $100.00 Year 01 would cost $235.66 in Year 30.

The same slides note a "discount rate "of 5.0%/year being applied to the "inflated cost" to calculate "present cost," or "present value." Even after the Q&A, we're not clear if a 5.0% discount rate was applied to the same costs that were adjusted for inflation at 3.0% or a different set of costs.

If a discount rate of 5.0% were applied to costs subject to 3.0% inflation, the $235.66 cost in Year 30 would have a 2024 cost of $57.25, <u>$42.75 less</u> than the $100.00 base cost not adjusted for inflation.

Our concern – if the discount rate were applied as noted on the slides, calculated LCCA "present cost" – US$2024 – would be grossly underestimated. Clarification of how the discount was applied, please. (See p.3 for a table with impact over 30 years of the inflation/discount assumptions.)

- Scope of Costs in CapEx Buckets. We want to make sure our CapEx "buckets" are as comparable as possible to AEI's.

  - Distribution CapEx – we are assuming Distribution CapEx includes all construction-and-equipment costs to purchase and install piping, pumps, etc., needed for transporting water or steam. Included would be any costs for drilling and piping associated with managing the water temperature, whether for heat pumps or steam.

  - Plant CapEx – we are assuming Plant CapEx includes all "plant and equipment" other than for infrastructure. Included would be costs for direct equipment and installation of HVAC, exhaust energy recovery, etc. Equipment could be located at CUP or individual buildings.

    New "building-like" construction – thermal storage towers, e.g. – would be included in "Plant CapEx" and not part of "Building CapEx."

  - Excluded from MACA CapEx –We did not attempt to estimate "<u>ECM CapEx</u>" and "<u>Building CapEx</u>." We assume "Building CapEx" incorporates all scheduled upgrades to buildings – windows, insulation, etc. – required to improve efficiency for any HVAC proposal but <u>excludes</u> any HVAC-related equipment.

    <u>Electrical service</u> requirements also were excluded. With completion of the "Test-Fit" analysis, a reasonable estimate can be made whether electricity usage from equipment for the six buildings in the Pilot Program exceeds existing capacity of one or more of the buildings or affects the campus "grid." We share the concern about overtaxing the campus grid as more systems are electrified. Projected operational data from the Test Fit will provide better guidance.

    <u>OpEx</u> is also excluded. LCCA for electricity for 3 of 4 AEI top-rated options was reasonably comparable and likely to approximate our OpEx for electricity. Only #9 was significantly higher.

- Risk to MIT. Slide #45 displays MIT evaluation criteria. Is there a more detailed explanation available for "Environmental and financial reward outweighs risk to MIT"? It would be helpful to view the variables and weights in the risk assessment.

Apparently not addressed in the AEI presentation, but we assume of considerable interest to MIT, is the range of incentives at the Federal, state, and local utility level. For example, the Inflation Reduction Act (IRA) enables organizations, including not-for-profits, to receive payments up to 40.0% of certain CapEx. In our budget, we believe MIT could qualify for ~$75 million.

Any clarification of issues would be greatly appreciated. We're available and anxious to help the Facilities Group where possible.

<u>Information Clarification Checklist</u>

- LCCA – 30 years?
- Discount rate of 5.0% for costs
  - How calculated by year
  - Applied to what costs
- Risk evaluation methodology
- MIT's interest in incentives to reduce CapEx
- Facilities' request for clarification of any MACA proposal assumptions
- Facilities' interest in how MACA members might help analyze other pathway options
- Other

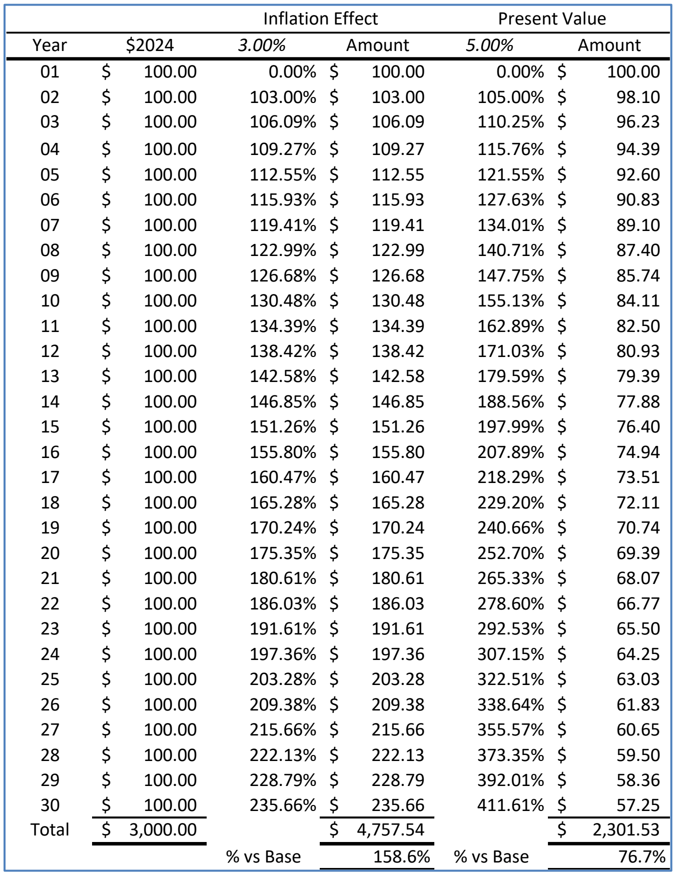
Clarification information as soon as practical, please. Thanks very much.

[Signature redacted]

ATTACHMENT:

HOW INFLATION, "DISCOUNTS" IMPACT LIFE-CYCLE COST

The table attempts to simplify the effects of inflation and "discounts" on life-cycle cost estimates. In the AEI review of options, Inflation is assumed to be 3.0%. Thus, costs in Year 02 are 3.00% higher than in Year 01. Costs in Year 03 are 3.00% higher than Year 02 and 6.09% higher than Year 01, the base year, etc.



		Inflation Effect		Present Value	
Year	$2024	*3.00%*	Amount	*5.00%*	Amount
01	$ 100.00	0.00%	$ 100.00	0.00%	$ 100.00
02	$ 100.00	103.00%	$ 103.00	105.00%	$ 98.10
03	$ 100.00	106.09%	$ 106.09	110.25%	$ 96.23
04	$ 100.00	109.27%	$ 109.27	115.76%	$ 94.39
05	$ 100.00	112.55%	$ 112.55	121.55%	$ 92.60
06	$ 100.00	115.93%	$ 115.93	127.63%	$ 90.83
07	$ 100.00	119.41%	$ 119.41	134.01%	$ 89.10
08	$ 100.00	122.99%	$ 122.99	140.71%	$ 87.40
09	$ 100.00	126.68%	$ 126.68	147.75%	$ 85.74
10	$ 100.00	130.48%	$ 130.48	155.13%	$ 84.11
11	$ 100.00	134.39%	$ 134.39	162.89%	$ 82.50
12	$ 100.00	138.42%	$ 138.42	171.03%	$ 80.93
13	$ 100.00	142.58%	$ 142.58	179.59%	$ 79.39
14	$ 100.00	146.85%	$ 146.85	188.56%	$ 77.88
15	$ 100.00	151.26%	$ 151.26	197.99%	$ 76.40
16	$ 100.00	155.80%	$ 155.80	207.89%	$ 74.94
17	$ 100.00	160.47%	$ 160.47	218.29%	$ 73.51
18	$ 100.00	165.28%	$ 165.28	229.20%	$ 72.11
19	$ 100.00	170.24%	$ 170.24	240.66%	$ 70.74
20	$ 100.00	175.35%	$ 175.35	252.70%	$ 69.39
21	$ 100.00	180.61%	$ 180.61	265.33%	$ 68.07
22	$ 100.00	186.03%	$ 186.03	278.60%	$ 66.77
23	$ 100.00	191.61%	$ 191.61	292.53%	$ 65.50
24	$ 100.00	197.36%	$ 197.36	307.15%	$ 64.25
25	$ 100.00	203.28%	$ 203.28	322.51%	$ 63.03
26	$ 100.00	209.38%	$ 209.38	338.64%	$ 61.83
27	$ 100.00	215.66%	$ 215.66	355.57%	$ 60.65
28	$ 100.00	222.13%	$ 222.13	373.35%	$ 59.50
29	$ 100.00	228.79%	$ 228.79	392.01%	$ 58.36
30	$ 100.00	235.66%	$ 235.66	411.61%	$ 57.25
Total	$ 3,000.00		$ 4,757.54		$ 2,301.53
		% vs Base	158.6%	% vs Base	76.7%

For the 30-year life cycle, the "compounding" effect of inflation increases the price of what cost $100.00 in Year 01 to $235.66 in Year 30.

Over each of the 30 years, if someone spent the equivalent of what cost $100.00 in Year 01, with inflation, expenditures would total $4,757.54, an increase of 58.6% vs the base.

When reviewing projections over a multi-year period, it is common to calculate a "present value." Present value is an estimate of what the "inflated" dollars of the future would be in today's dollars.

Most "present value" calculations are applied to revenue or cash flow. The "discount rate" applied to future cash flow can be a combination of anticipated inflation, perceived risk, contingency, ROI on alternative investments, etc.

"Present value" for costs is less affected by the aforementioned factors. While there is clearly uncertainty about inflation, the estimate of future costs can recognize this uncertainty by adjusting the assumption for inflation. The first 10 years could assume inflation of 3.0%, the next 10 years, 3.5%, etc. Different inflation rates could apply to different categories of cost as well.

In the AEI charts (starting slide #39) a sidebar notes "discount rate" of 5.0% has been applied to determine "present value" of costs. Our Confusion is why 5.0% was used to 'discount" costs when the inflation rate was assumed to be 3.0%.

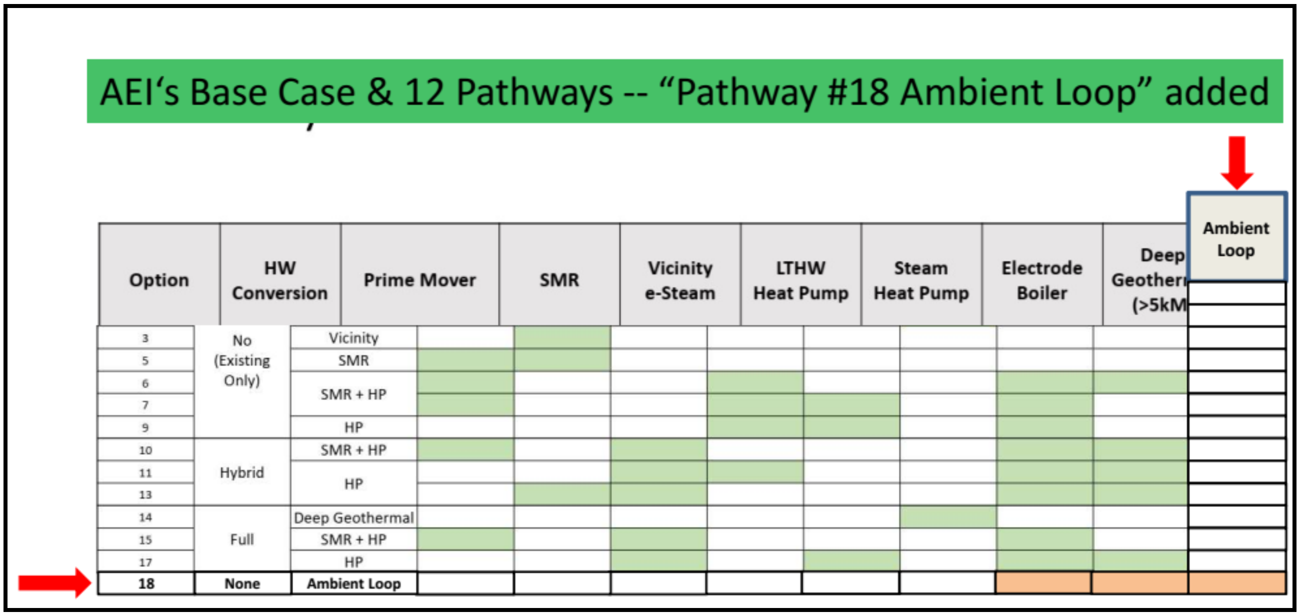
The table notes the effect of the higher-than-inflation 5.0% discount rate. Beginning in Year 02 and in each year thereafter, the "present" cost is less than $100.00, the amount not adjusted for inflation. Thus, when the discount rate is greater than the inflation rate, "present" cost/year declines over time.

The net effect of the decline on life-cycle costs is significant. Over 30 years, rather than a total "present" life-cycle cost of $3,000.00, the life-cycle cost estimate declines to $2,301.53, 23.7% less than cost without inflation.

As noted in the memo, we would appreciate clarification of what costs were "discounted" and method used to discount the costs. Thank you.

Annex 3 Comparison: MACA/Geo@MIT Plan with AEI's Pathways

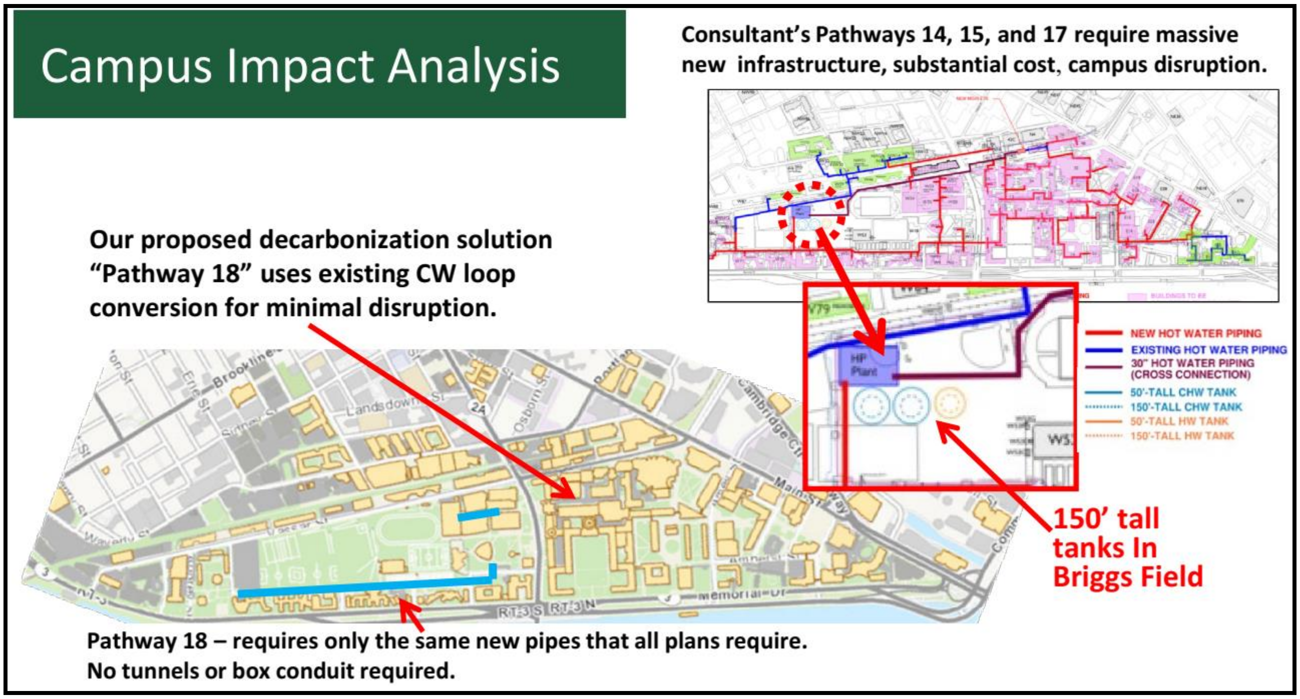
Figure 42: Pathways: Comparison of Key Components



AEI's Base Case & 12 Pathways -- "Pathway #18 Ambient Loop" added

Option	HW Conversion	Prime Mover		SMR	Vicinity e-Steam	LTHW Heat Pump		Steam Heat Pump	Electrode Boiler	Deep Geotherm (>5kM	Ambient Loop
3	No (Existing Only)	Vicinity		🟩							
5		SMR	🟩	🟩							
6		SMR + HP	🟩			🟩			🟩	🟩	
7			🟩			🟩	🟩		🟩		
9		HP				🟩	🟩		🟩		
10	Hybrid	SMR + HP	🟩		🟩				🟩	🟩	
11		HP			🟩	🟩			🟩	🟩	
13				🟩	🟩				🟩	🟩	
14	Full	Deep Geothermal						🟩			
15		SMR + HP	🟩		🟩				🟩		
17		HP			🟩		🟩		🟩	🟩	
18	**None**	**Ambient Loop**							🟧	🟧	🟧

Figure 43: Campus Map -- Impact Analysis



Campus Impact Analysis

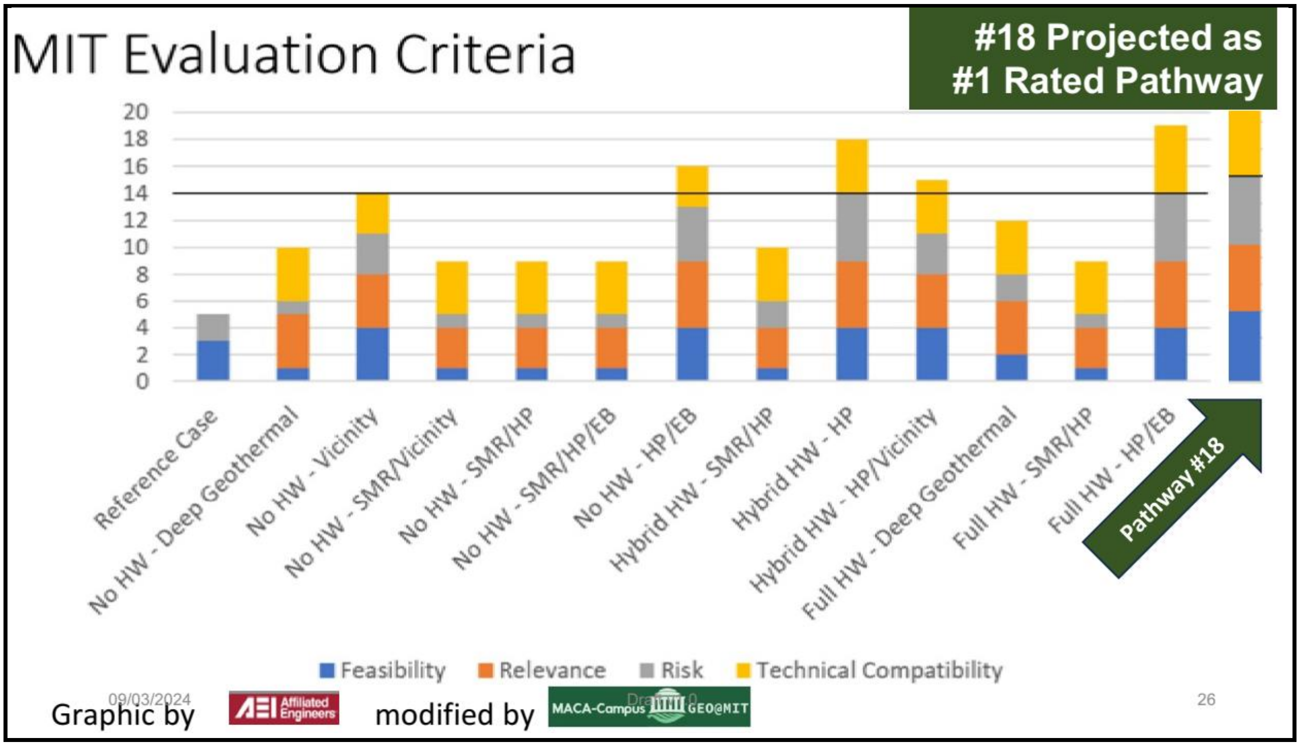
Consultant's Pathways 14, 15, and 17 require massive new infrastructure, substantial cost, campus disruption.

Our proposed decarbonization solution "Pathway 18" uses existing CW loop conversion for minimal disruption.

150' tall tanks In Briggs Field

Pathway 18 – requires only the same new pipes that all plans require.
No tunnels or box conduit required.

Figure 44: Evaluation Score Estimates by Pathway



MIT Evaluation Criteria

#18 Projected as #1 Rated Pathway

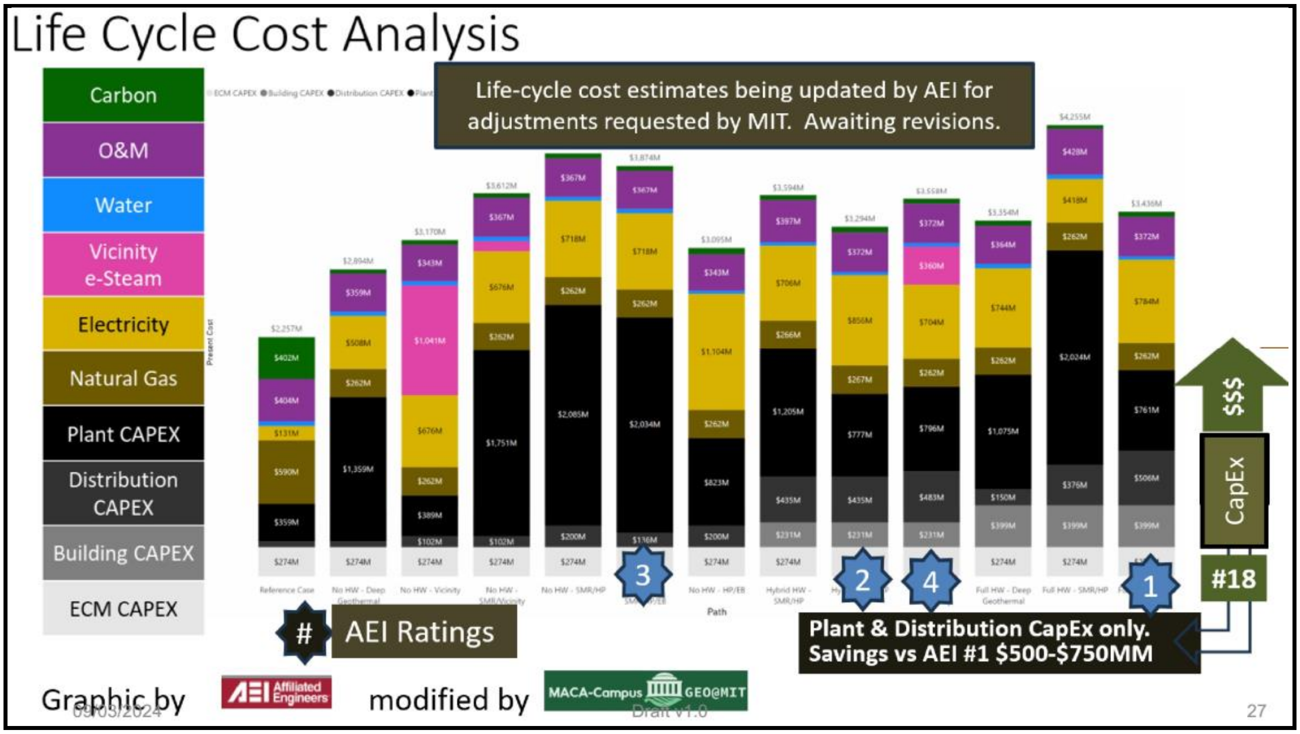
09/03/2024

Graphic by AEI Affiliated Engineers modified by MACA-Campus GEO@MIT

Draft v1.0

26

Figure 45: Life Cycle Cost Estimates by Pathway



Life Cycle Cost Analysis

Life-cycle cost estimates being updated by AEI for adjustments requested by MIT. Awaiting revisions.

AEI Ratings

Plant & Distribution CapEx only. Savings vs AEI #1 $500-$750MM

09/03/2024

Graphic by AEI Affiliated Engineers modified by MACA-Campus GEO@MIT

Draft v1.0

27

Annex 4 Further Considerations

Tangential Benefit – Reinforcing MIT's Reputation for Innovation and Practical Solutions. One of MIT's primary goals is to design an approach to decarbonization that can be adapted to many locations throughout the US and worldwide. The MACA/Geo@MIT distributed approach is easily scalable, both for larger applications as well as smaller applications. Some components of the design could help increase use of and reduce the installation cost of WSHPs for many single-family homes.

Whereas an ambient loop can increase the efficiency of WSHPs, an ambient loop does not need to be complex or costly. Nor does an ambient loop need to be underground or require bore holes or wells. An ambient loop for a small cluster of buildings or even a single building can be designed using a combination of existing "equipment" – in-bound water, water heaters, storage tanks, sewer lines, etc. While the COP of such a system would be reduced somewhat compared to a more complex system, the COP using a simplified ambient loop would still likely far exceed the COP of ASHPs and certainly an HVAC system fueled by natural gas.

A mini-ambient loop operating with support from the CUP would reduce the cost of installing WSHPs and expand the use of WSHPs. Rather than having to drill bore holes, many clusters of buildings, single buildings and individual homes could install WSHPs with a low-cost, simplified ambient loop design.

Designing and testing such a mini-ambient loop would seem to be an ideal project for D-Lab and other interested students. MIT could then begin promoting the design as an approach to reduce GHG emissions through the increased use of WSHPs.

List of Figures/Renderings

Figure 1: Mission Statement 7
Figure 2: 3D Model Example View 9
Figure 3: Lidar Scan W34-228 Mechanical 10
Figure 4: Test Fit Heat Pump Equipment 10
Figure 5: Building EUI 11
Figure 6: W20 Monthly Load Distribution for Chilled Water (CW) and Steam Usage 16
Figure 7: W20 Building Monthly CW Load Parameters 17
Figure 8: W20 Building Monthly Steam Load Parameters 18
Figure 9: W35 Monthly Load Distribution for Chilled Water (CW) and Steam Usage 18
Figure 10: W35 Building Chilled Water Hourly Data Load Parameters 19
Figure 11: W35 Building Monthly Data Steam Load Parameters 20
Figure 12: W34 Monthly Load Distribution for Chilled Water (CW) and Steam Usage 20
Figure 13: W34 Building Monthly Data Chilled Water Load Parameters 21
Figure 14; W34 Building Monthly Data Steam Load Parameters 21
Figure 15: Monthly Chilled Water, Steam, Electricity, and Natural Gas Consumption 22
Figure 16: W20, W34, and W35 2023 - 2024 Hourly Chilled Water Analysis 23
Figure 17: Six-Building 2023 - 2024 Hourly Steam Analysis 24
Figure 18: W34 2022 Daily Peak Chilled Water Loads 25
Figure 19: W35 2022 Daily Peak Chilled Water Loads 25
Figure 20: W35 Hourly Steam/CW Load Reduction from Overlap and Exhaust Recovery 26
Figure 21: MIT Ambient Loop 31
Figure 22: Decarbonization with Distributed Heat Pump Design Considerations 35
Figure 23: Control Systems Methodologies 37
Figure 24: Line Drawing of Test Fit Proposal 39
Figure 25: Recommended Path for New Ambient Loop Piping through Rockwell Cage 40
Figure 26: Alternate Path Ambient Loop 41
Figure 27: Typical Heat Exchanger Pallet 42
Figure 28: Solar Thermal Collector Spacing Assumptions 55
Figure 29: Locations and Quantity Photovoltaics, Thermal Collectors Test Fit Bldgs 57
Figure 30: Building W32 Aerial View Proposed Orientation Thermal Collectors, PVs 57
Figure 31: W32 Roof Figure 32: W35 Roof 58
Figure 33: W20 Roof 58
Figure 34: W31 Roof 59
Figure 35: W33 Roof (No Photo) 59
Figure 36: W34 Roof 60

Figure 37: Aerial View of W34 and W35 60
Figure 38: Solar Flux Transmittance MA Weather 63
Figure 39: Gantt Chart MIT Decision re Pilot Program 64
Figure 40: Building Conversion, Performance, Final Pilot Report 64
Figure 41: Reduced CapEx Pathway 18 66
Figure 42: Pathways: Comparison of Key Components 81
Figure 43: Campus Map -- Impact Analysis 81
Figure 44: Evaluation Score Estimates by Pathway 82
Figure 45: Life Cycle Cost Estimates by Pathway 82

Return to Table of Contents

List of Tables

Table 1: Summary of Existing Buildings Energy Sources 12
Table 2: 2022 Monthly and Total Heating 6 Bldgs 13
Table 3: 2022 Monthly and Total Chilled Water Usage for MIT W20, W34, W35 14
Table 4: Monthly Average Outdoor Air Temperature 2021-2023 (degrees F) 15
Table 5: Overview Proposed New Mechanical Equipment 42
Table 6: HVAC Capacities 44
Table 7: W31 HVAC Capacities 45
Table 8: W32 HVAC Capacities 47
Table 9: W33 HVAC Capacities 48
Table 10: W34 HVAC Capacities 49
Table 11: W35 HVAC Capacities 51
Table 12: Electrical Overview 52
Table 13: Rooftop Solar Energy Assessment (annual) 54
Table 14: Solar Energy Component Specifications 55
Table 15: Considerations for Solar Installations 56
Table 16: Solar Modeling Assumptions 61
Table 17: Solar Modeling Parameters 62
Table 18: System Model Results for Individual Rooftop Section (W20 Example) 62
Table 19: Parameters and Equations for Excel Model 63
Table 20: Annual Carbon Reductions 67
Table 21: 2023 Emissions Factors to Calc Solar Offsets 68

Return to Table of Contents