The Future is Electric

2.832 Solving for Carbon Neutrality at MIT
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Introduction

In late 2021 COP26 was held in Glasgow, where nations from around the world gathered to lay the framework for accelerating the push towards global, net-zero carbon emissions. The overarching goal of this conference to curb global warming to less than 1.5C will require significant culture shifts and unified efforts. Fortunately, MIT had already committed to reducing its carbon footprint with the "Fast Forward MIT: Climate Action Plan". These commitments include net-zero carbon emissions by 2026 and the elimination of direct emissions by 2050. To achieve these goals, MIT has begun to offset emissions through PPA's, increasing solar energy installations, and plans to convert transportation to zero-emission. Although these seem like strong initial efforts, much more aggressive measures are required to fully decarbonize campus operations. The goal of this report is to lay out a plan for reaching a 100% reduction in scope 1 and scope 2 MIT campus carbon emissions by 2050. Based on data from *Energize_MIT* [8], this equates to a reduction in approximately 200,000 metric tons of CO_2. To reach this goal, the proposed decarbonization plan relies on a combination of building efficiency improvements, heat pumps, and airflow optimization to reduce HVAC demands, a large-scale heat recovery system, and an eventual retiring of the CUP turbines which will be replaced with the carbon-free power source of nuclear batteries or reliance on the ISO-NE grid with electric boilers.

We have chosen these technologies due to their scalable nature and feasibility in the short and long term. Due to this approach, technologies like biofuels were not considered due to their low energy density not being feasible for this large-scale implementation. Based on our research into the ISO-NE Grid, we have also used the assumption that the grid will not be fully carbon neutral by 2050, which forces MIT to aim for the integration of nuclear without dependence on the grid. It is important to note these assumptions when assessing the recommendations provided for MIT's path to carbon neutrality. As suggested, this report will outline two paths that both focus on the implementation of building electrification, building efficiency upgrades, and a retrofit of the CUP. The divergence of the two paths comes with the determination of the feasibility of the integration of nuclear technology in Cambridge. One path will focus on the integration of nuclear technology to achieve carbon neutrality at MIT, while another path will focus on the electrification and retrofitting of the CUP with electric boilers as a contingency plan to achieve, or at least approach, carbon neutrality at MIT.

Building Efficiency

Regardless of assumptions about external entities or MIT's potential source of energy in 2050, the goal is to reduce the total carbon that MIT emits across all years. Making improvements to building efficiency is something that MIT can start doing now to see a reduction in greenhouse gas emissions in a relatively short time frame. There are many ways to improve efficiency in MIT's buildings, including optimizing airflow in the many laboratories on campus and occupancy monitoring. The various options should be researched and evaluated on a building-by-building basis to determine where MIT can see the greatest improvement in carbon emissions.

As a research institute, MIT contains hundreds of laboratories spread throughout its 190 buildings. Laboratories make up a large source of emissions due to their outside air and air turnover requirements. In 2019 an investment-grade energy audit, as well as a Lab Ventilation Risk Assessment (LVRA), was conducted on building 46, the Brain and Cognitive Science

Complex. Building 46 is MIT’s largest greenhouse gas emitter by roughly 68%. The conclusions of the study on building 46 show that many of MIT’s laboratories are being over-ventilated, causing unnecessary energy losses.[20] According to Michael Gevelber, buildings were often designed in a time when there was no consideration for energy conservation, so a higher than necessary airflow was utilized to ensure other building needs were met. Additionally, he calls out that fans account for 40% of HVAC costs so reducing airflow can have a large impact on energy savings.[1] The building 46 study proposed disruptive solutions involving an overhaul of the existing ventilation systems which claim to make drastic improvements in energy consumption (49% for building 46) and alternate less disruptive solutions involving modification to the current ventilation system that still claim significant improvements (36% for building 46).[20] The study conducted on building 46 was a great start, but MIT needs to expand this type of study to include more buildings as well as create a plan for periodic review of buildings to prevent excess greenhouse gas emissions in the future.

Present to 2030

The first step in expanding the scope of MIT’s building efficiency progress is identifying the buildings where efficiency improvement will have the greatest impact and thus should be accomplished first. A logical starting point would be to conduct similar studies on buildings in order of carbon emissions, however, *Energize_MIT* only offers estimates for some buildings’ emissions because not all buildings are individually metered. According to *Energize_MIT* “when buildings are metered as a group, estimates are found using the individual building's proportion of square feet as compared to the group total”.[8] These estimates provide a good starting point for moving forward with conducting the additional energy audits, but MIT should simultaneously invest in the least disruptive way to monitor all buildings individually. Figure 1 shows the 10 buildings with the highest emission levels.

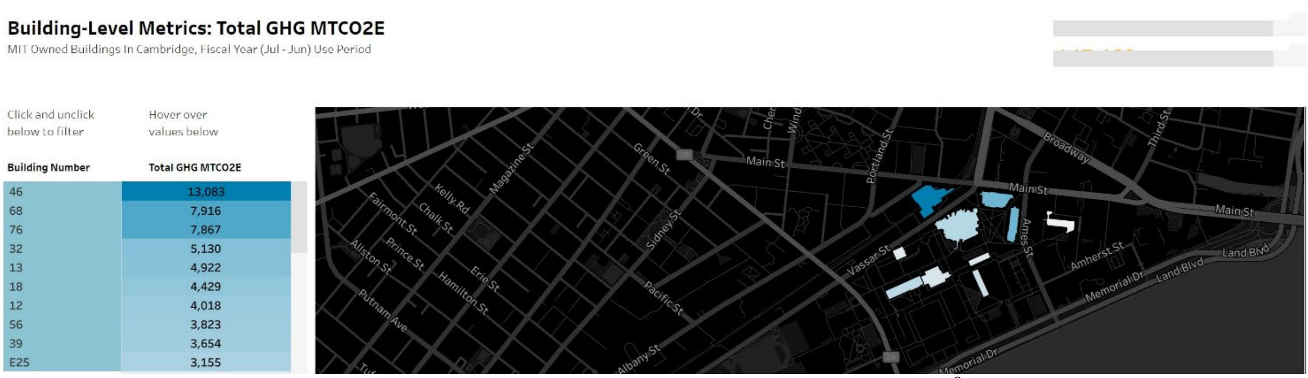


Figure 1: *Highest 10 GHG Emissions per Building* [8]

Starting in 2023, MIT should aim to hire an outside company similar to CHA Consulting, the company that conducted the audit on building 46 in 2019, to complete energy audits on two buildings per year. These audits will begin with buildings 68 and 76 in 2023 and conclude with building E25 in 2028. Like the audit for building 46, the company will also provide options for improving efficiency in that building and its associated energy savings. Plans for enacting the decided upon improvement option should be implemented within a year of each audit completion.

As mentioned previously, MIT must move toward metering each building individually to accurately understand the source and distribution of its emissions. According to the *Energize_MIT's* 2021 metering status report [8], the table below lists the metrics for where MIT currently stands regarding its building metering.

Status	**# of Buildings**
Fully Metered	24
CW and Electric	5
CW and Steam	9
CW only	13
Steam and Electric	4
Steam only	5
No Metering	44
Not Applicable	16

Table 1: *Building Metering Status*

Table 1 shows that there is a great deal of metering that needs to be added to achieve the necessary goal of 100% fully metered buildings. Non-Intrusive Load Monitoring (NILM) offers a viable, low disruption, and low-cost solution to achieving this goal. According to Enetics, a company specializing in NILM, this technology consists of "a single recording meter installed at the electrical service entrance that captures the energy consumption and time of use for each major appliance in the home or business. Hardware installation is quick and easy and re-wiring of appliances is never required".[17] Data is tracked and can be viewed on associated software devices. Although used primarily in residential settings in the past, this technology is beginning to emerge in the commercial sector. A study performed in India compared NILM in commercial settings with its installation in the Institute of Information Technology of Dehli to residential use and the results were promising.[2] To understand how this technology can be installed and utilized at MIT, we recommend doing a trial install in building E25 in 2023. Building E25 is the unmetered building with the highest emissions so would offer a useful test platform. To conduct the trial, MIT could consider using research groups consisting of graduate and doctorate students. The trial period for building E25 will begin after installation in 2023 and will consist of 6 months of monitoring and data collection. If the trial period is successful and NILM proves to be a useful method for individually metering buildings, MIT can move forward with hiring a company such as Enetics to install NILM technology on the remainder of the unmetered buildings. The goal is to have all buildings individually metered by the year 2030.

Occupancy monitoring is another technology that will better allow MIT to limit excess energy consumed and thus help to reduce carbon emissions. As Mr. Michael Gevelber showed with Boston University, universities have vastly different occupancy patterns during working hours throughout the weekdays, in the evenings, on weekends, and during the summer months when many students are no longer on campus. His studies show that in many buildings there is no adjustment in airflow rates, heating and cooling needs, and electricity needs in these times of inoccupancy. In their St. Mary's street office and research space, reducing nighttime air exhaust to 10% resulted in an estimated savings of 21% of total oil or $12,522 and 13% of total electric or $20,000 over a year time frame.[1] These savings are significant, and we recommend that MIT invest in occupancy monitoring and the associated implementation of "inoccupancy modes of operation" in those time periods where applicable. There are a plethora of Advanced Research Projects Agency-Energy (ARPA-E) projects that other universities and companies have received grants for such as BU's Computational Occupancy Sensing System (COSSY) or Cornell's Indoor Occupant Counting Based on RF Backscattering.[14] Starting in 2023, MIT should implement occupancy monitoring technology similar to the aforementioned projects either by developing its own technology or teaming with another university or outside company to implement one that has already been developed. Like the process of individually metering buildings, implementation of this project will also depend on a team of graduate students and PhD students. The first phase will involve research and development and selection of an occupancy monitoring program and should be completed by 2025. The next phase will involve installation and trial operation and should be up and running in all applicable buildings by 2030.

2030 to 2040 & 2040 to 2050

By the year 2030, we plan to have completed the energy audits on the 10 highest emitting buildings, enabled individual metering on all buildings on campus, and installed an occupancy monitoring system in applicable buildings. The previous decade included a significant amount of efficiency research and improvement that will start reducing emissions shortly after implementation. Throughout these following decades, we must continue to invest in periodic efficiency checks so that we do not fall back into inefficient energy habits. These periodic checks will involve a randomized "spot check" type system for buildings that have not undergone significant changes and a more in-depth audit on buildings that have undergone major renovation or reallocation of spaces. In the next decade, we anticipate a BERDO tax will be implemented, further emphasizing the need for the entire MIT community to fully commit to energy efficiency. MIT should make a constant effort to encourage the MIT community to adjust their habits to eliminate excess energy consumption. These actions include turning off the lights when there is sufficient natural light or when leaving the room, leaving windows closed when the heat or cooling systems are activated, and turning off electronics that are not in use. Although difficult to formally measure the carbon emission reduction associated with these behaviors, every ton of carbon emitted counts, and the buy-in from the community will be important as we move toward more drastic changes throughout these decades to reach carbon neutrality.

Efficiency Challenges and Campus Disruption

Many of the efficiency improvements mentioned involve improvement or modification to HVAC systems. Laboratories often offer the greatest opportunity for efficiency improvement due to overventilation. A challenge that will arise with our plans to implement the proposed efficiency improvements is the conflict between our priorities and the priorities of the faculty members who own and operate the labs due to the potential disruption the improvements will cause. The efficiency surveys on the buildings will not be as disruptive but the recommended modifications that result from these surveys will likely displace labs for a period of time. After the building 46 audit, the least disruptive of the two proposed options was selected even though it resulted in less emission reduction. Similarly, the additional audits will likely result in the selection of the least disruptive improvements despite lower savings. Even with the least disruptive option selected, MIT will need support from faculty members and will have to try to show them the benefit that these improvements will bring to (or at least that these improvements will in no way hinder) their labs and research capabilities. Our occupancy monitoring plan may also receive pushback since lab directors' number one priority is their research and they will be apprehensive about the effect that changes to the lab conditions (heating, cooling, lighting, ventilation) when the building is unoccupied, will have on their ongoing research and associated lab equipment. There will be live labs where occupancy monitoring will not be feasible, and we acknowledge that we may not be able to obtain buy-in from all buildings where occupancy monitoring would be technically feasible, due to concerns about the effect on research. For this reason, we conservatively estimate that we will be able to install occupancy monitoring in 30% of MIT buildings.

Efficiency Estimated Savings and Financials

To approximate the energy savings of the continuation of the building 46 surveys to the 10 buildings with the highest emissions, we first observe that the completed building 46 survey and selection of option B resulted in a 36% savings in emissions for that building. Building 46 contains 398 laboratories and produces the highest emissions so we anticipate that this 36% saving for building 46 is higher than average. Using a range of 20% to 30% savings for each of the remaining 9 buildings, we were able to determine the total savings for the 10-building project to be 13,770 to 18,261 metric tons of CO_2. We scaled the cost from the building 46 audit by square footage to approximate the cost for each building. The total cost is estimated to be $64,032,112. Translating these numbers into investment per metric ton of CO_2 saved, we calculate the range to be $3,506 to $4,650 per metric ton of CO_2. These calculations are shown in Appendix A.

The proposed NILM installation project will not result in any direct energy savings but will be crucial to tracking and understanding the origin of our emissions.

To approximate the energy savings and cost of the occupancy monitoring project, we utilized Michael Gevelber's study on BU's St. Mary St. Building. We selected this building for reference because it offered a mixed-use building with offices, classes, and research. His study showed that reducing nighttime airflow down to 10% resulted in savings of 21% of oil and 13% of electricity, with an implementation cost of $50,000. We utilized 2021 *Energize_MIT* data, along with the conservative assumption that we will be able to install occupancy monitoring in 30% of MIT's 190 buildings, to estimate an energy savings of 10,066 metric tons of CO_2, a cost of $2,850,000. This translates to $283 per metric ton of CO_2e. These calculations are shown in Appendix A.

Heat Recovery System

Although efficiency improvements can provide important reductions in campus energy demands, they are not aggressive enough to serve as a solution for MIT's lofty carbon neutrality goals. One proposed approach to achieve efficiency improvements on campus is to implement a large-scale heat recovery system. These systems store energy through hot or cold storage, and during temperate weather conditions can deliver the appropriate heating or cooling needs throughout campus with this stored energy. Stanford implemented a heat recovery system on their campus called SESI (Stanford Energy System Innovations project), which has been operating over the past several years with remarkable success.[25] One of the advantages Stanford has is a significant overlap in its heating and cooling demands throughout the year, as seen portrayed in Figure 2 below.

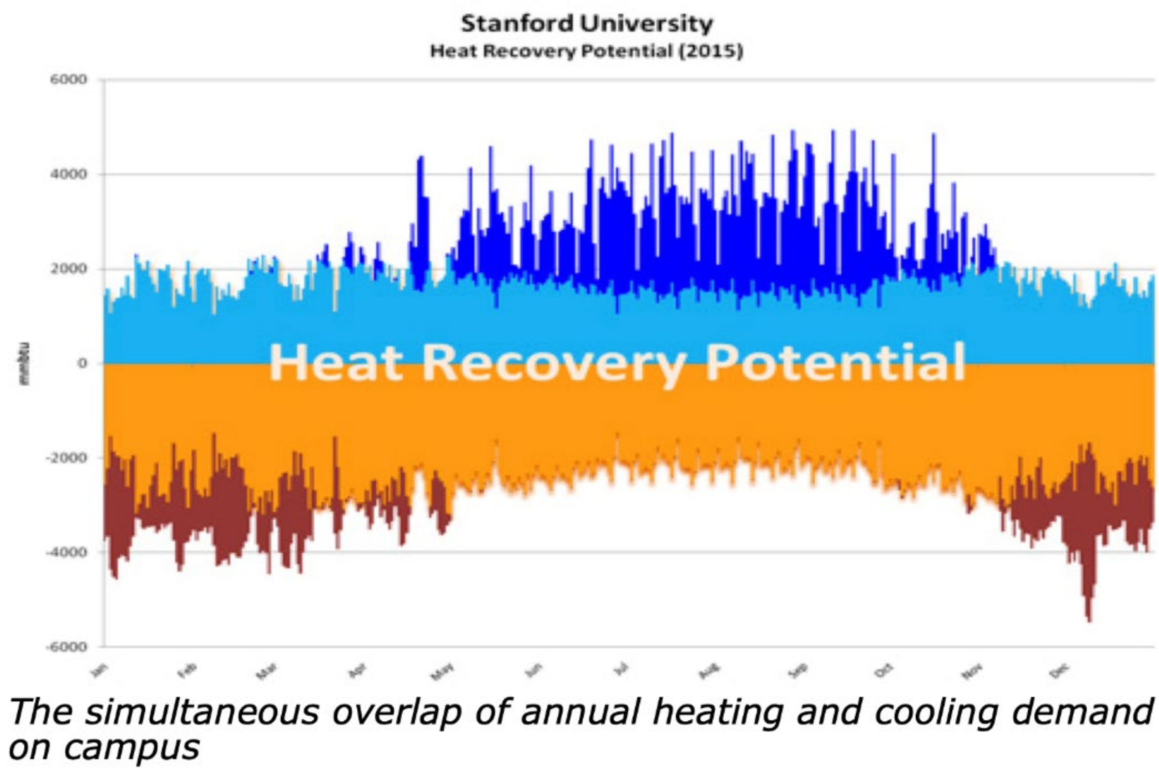


Figure 2: *Stanford Heating and Cooling Demand*

For comparison, Stanford has 701 degree days of heating and 934 degree days of cooling, while MIT has 2187 degree days of heating and 843 degree days of cooling.[11] The significant heating demands of MIT suggest that, although still feasible, the heat recovery potential is much lower when compared to Stanford. SESI is a 2015 project that presently captures 53% of waste heat from cooling and provides 88% of the annual heating load. [25] On campus, 315MWh of cold-water storage and 175MWh of hot water storage are installed for load leveling and shifting. This $438M project has reduced Stanford campus carbon emissions by 68%. [25]

It is recommended that a full feasibility study be conducted to determine the exact heat recovery potential of MIT. Without this data, a conservative estimate is to assume that MIT would likely only realize half the efficiency benefits when compared to Stanford, meaning only a 40% reduction in heating/cooling demands. This amount of savings would translate to a 40,000 metric ton reduction of GHG emissions, which equates to a 20% reduction. Unfortunately, if a similar system were installed at MIT for an estimated $450M with these carbon savings, it would translate to a rather costly $11,000 per metric ton of CO_2e. Due to the significant challenges with implementing a large-scale heat recovery system, an alternate large-scale efficiency contingency plan should be available for MIT to fall back on. For this reason, an extensive campus-wide heat pump pathway will be investigated, which shall be labeled “Building Electrification”.

Building Electrification

From an MIT institution and campus standpoint, transitioning to buildings that are fully electrified poses a challenge given the region’s climate and the school’s technical requirements. From a climate standpoint, the MIT campus area is challenged with cold winters and humid summers. As discussed, Boston requires significant heating and reliable cooling sources to maintain its facilities. From a technical standpoint, MIT's focus on cutting-edge research requires the use and maintenance of energy-intensive labs with substantial ventilation requirements. An additional challenge is the emissions tied to the generation of electricity consumed by the electrified buildings. The following approach indicates a potential, albeit expensive, scenario to neutralize a portion of the CO_2 emissions through building electrification. As a reminder, this option is an alternative to the Heat Recovery system.

Present to 2030

Multiple actions can be taken throughout the following decade to improve building electrification efforts across MIT. As mentioned earlier in this paper, MIT does not currently have a full profile of all its building's emissions due to its current level of metering, thus an initial step in this decade is to create, collect, and understand the emissions profiles of all 190 buildings in MIT's portfolio.

Part of the electrification efforts at MIT will rely on a combination of ground and air-sourced heat pumps. A pilot building for building electrification would be the W20, the Stratton Student Center, which produced 1860 metric tons of CO_2e of GHG emissions in Calendar Year (CY) 2021 from a mixture of steam, electricity, and gas. For geothermal or ground sourced heat pumps (GSHPs), test boreholes for piping and ducting can be implanted underneath the outdoor recreational fields (Briggs, Tennis Courts, Jack Barry Field, Steinbrenner Stadium). Given the current construction going on next to the softball fields, initial costs for excavation can be significantly reduced and the economic burden lessened for a pilot project. This pilot project can serve to provide a true measure of performance for GSHPs to understand soil, silt, and the heat pump's true coefficient of performance on MIT land. Another important pilot project to take on during this decade would focus on the electrification of a Sloan Campus building. E51 provides a good candidate to test out a water source heat pump technology due to the nearby Charles River. Figure 3 shows the Charles River temperature readings through 2021.

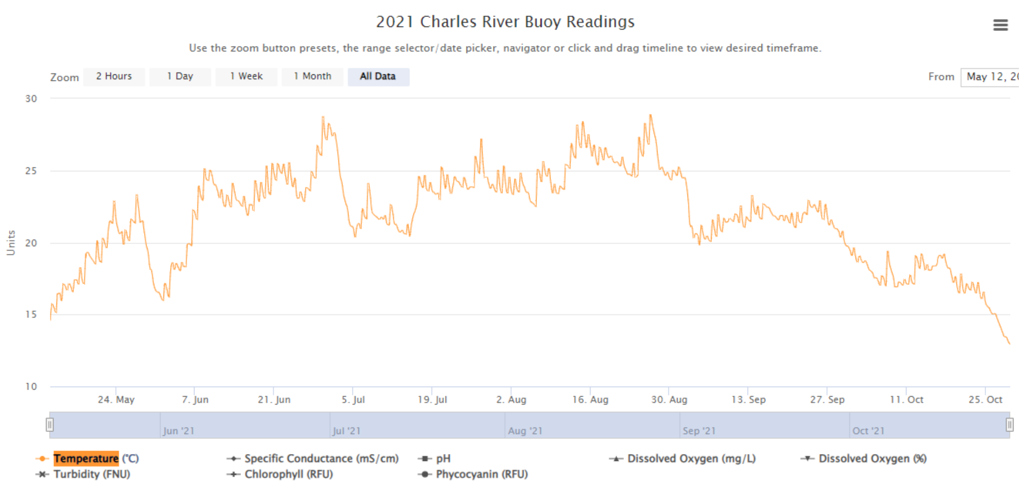


Figure 3: *Charles River Temperature Readings*

A pilot water-sourced heat pump here would provide data on the performance of this type of heat pump in a body of water with relatively large fluctuations (Low: 12C / High: 28C) in temperature throughout the year. This data will be especially insightful during the winter months as heating requirements increase and the heat source (water) temperature decreases.

Assuming positive confirmation of efficiencies, an electrification rate of approximately 7 buildings per year needs to be attained to achieve total electrification by 2050. For this decade, this is a target of 55 buildings throughout the campus. To mitigate the large real estate requirement for the ducting and piping required in GSHPs, a project involving excavation and installation of the necessary infrastructure can be performed underneath the remainder outdoor fields of the MIT Recreation center.[22] This outdoor area includes Briggs Field, MIT Outdoor Tennis Courts, Jack Barry Field, and Steinbrenner Stadium and represents a relatively low cost of installation and disruption for a large amount of real estate, 100,514 square meters. This area, highlighted in Figure 4, equates to approximately 15% of MIT's total campus size.

Figure 4: *MIT Outdoor Recreational Space Footprint*

Obvious resistance to this would come from MIT Recreational, MIT Athletics, and the Student Body yet could be mitigated through a phased approach of closures and excavations. Sharing and dual-use of fields are not uncommon among other institutions and further disruptions can be mitigated through construction during the summer months.

The buildings targeted for electrification during this period should be non-lab buildings to gain social, economic, and political momentum for the electrification effort.

A critical component to the next decade's electrification effort comes in planning and a strategic roadmap for more research and laboratory-intensive buildings.

2030 to 2040

Continued electrification throughout the 2030 to 2040 decade poses a significant risk for disruption in the buildings with laboratories and research facilities. While the electrification effort is faced with significant headwinds, the need for decarbonization of buildings outweighs the temporary discomforts of a few laboratories. Strategic plans regarding lab displacements and experiments made during the past decade should be put into place during this timeframe. A combination of shared laboratory space and building usage while buildings are retrofitted for electrification efforts will be difficult to garner support but is not an impossible effort. Similar plans when buildings require maintenance can be implemented here to minimize the impact on any research group.

2040 to 2050

During this decade, the remainder of buildings with the largest energy footprint need to be addressed. These are the labs with the largest energy and ventilation requirements. Heat pumps (air or ground) may be infeasible due to the physical size of the heat pump required and the available land area of MIT's campus.

In the next section, we will discuss the plan for the installation of a clean energy source in the CUP, but if this is not feasible it is important to consider the impact of upstream carbon emissions. While the installed heat pumps generate no direct emissions, energy from the CUP and the ISO-NE grid will still have an emissions footprint. While we believe that the carbon emissions from the ISO-NE grid will be reduced through decarbonization efforts, full clean emissions will not be obtained in this timeframe[23]. We approximate that in 2050 the ISO-NE grid will be 10% of today's emissions, thus 30kg CO2e/MWh.

Additional Electrification Challenges

Building electrification will pose some new challenges. Conversion to electricity will create increased overall demand on the CUP and ISO-NE grid. Furthermore, conversion to heat pump technology for heating and cooling needs will increase the peak load during specific months of the year. Figure 5 represents the monthly energy demand in GJ for Fiscal Year (FY) 2014 to FY2021[8].

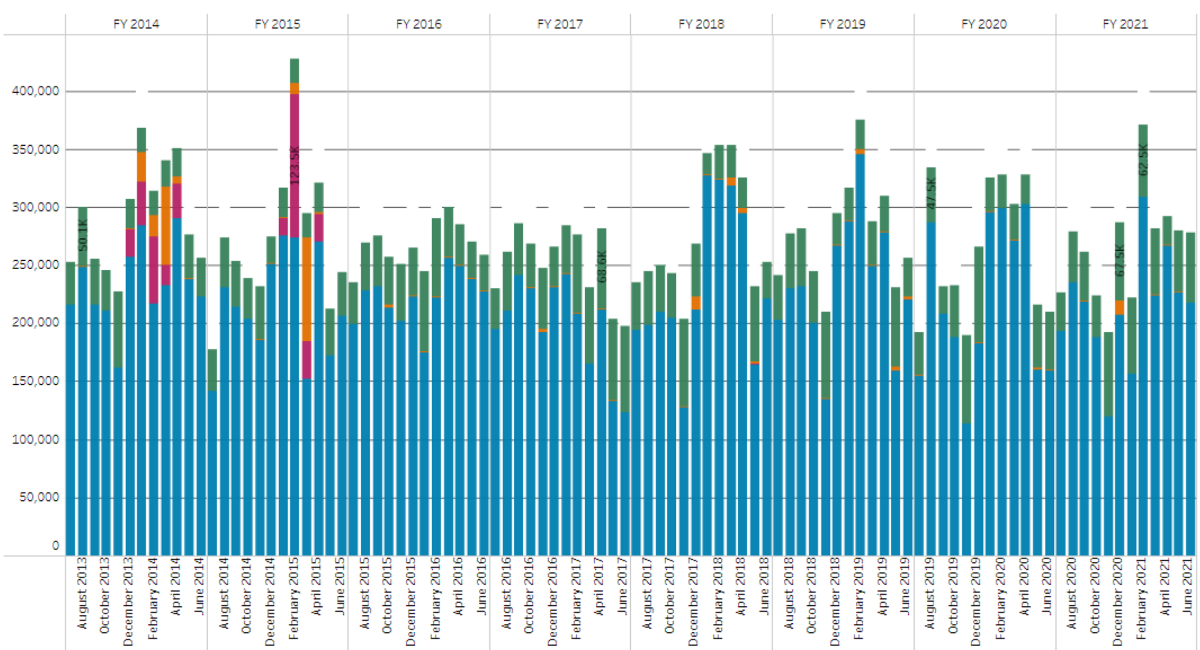


Figure 5: *MIT Total Monthly GJ Demand by Fiscal Year*

Figure 5 shows that total energy demand peaks in the winter months. The green represents electricity demand and the blue represents natural gas. Currently, electric energy consumption peaks in the summer months; however, as building electrification becomes ubiquitous across campus, we expect a shift in the peak demand that moves towards the winter months thanks to the New England climate and its heating requirements. Given this transition to electricity, there is a risk of resiliency during these months as peak demand may surpass load supply and capacity. Additionally, while heat pumps can result in a 20% to 25% energy reduction in energy consumption due to their high COP and efficiency, electrification of the buildings will raise the overall electricity consumption as heating and cooking elements shift away from gas-powered sources[13]. Mitigations to this peak demand and bolstering of resiliency are discussed later in this paper. Another significant challenge associated with ground source heat pumps is the potential disruption to MIT's campus and activities. As mentioned previously, there would likely be opposition from MIT Recreational, MIT Athletics, and the Student Body if we were to utilize the athletic fields and these disruptions would need to be mitigated with a carefully thought out, detailed installation plan.

Electrification Estimated Savings and Financials

As a small case study, electrification of the Sloan buildings E40, E51, E52, E53, E62, and E60 would require heat pumps that can service a total of 715,153 square feet of building space.[8] Costs will vary depending on the type of heat pump chosen and its efficiency. Assuming GSHP installation, it is estimated that conversion of the Sloan buildings within the next decade would cost between $12M and $22M. This cost breakdown assumes that one heating ton is required per 500 square feet of building space, residential GSHP installation costs range from $7,000 to $13,000 per heating ton, and a 20% premium on residential to commercial installation rates.[13] The variation in installation costs stems from the variability in the number of boreholes and piping configuration (horizontal, slinky, vertical) required.

For the remaining 12.2M square feet of campus building space, an estimated cost of $206M to $383M is required for full electrification over the course of 20 years. This calculation was derived from online research supplemented with calculations completed by our classmates[10]. From these calculations, it was determined that ground source heat pumps can account for approximately 14% of MIT's heating and cooling needs. This translates to a 14% reduction of total CUP heating and cooling emissions. In FY2021, MIT's emissions profile totaled 178,553 metric tons of CO_2e with an estimated 40% to 60% of these emissions comprised of heating and cooling requirements.[21] Assuming heating and cooling requirements are 50% of building emissions, this results in a target impact of 12,500 metric tons of CO_2e. From an investment cost standpoint, this results in a range of $16K per metric ton of CO_2e to $30K per metric ton of CO_2e. Given that the electrification of buildings will result in a mix of GSHPs and ASHPs, this cost estimate is a useful upper limit. Considering the ASHP price discount of approximately 40% to 50% compared to GSHPs, the investment cost can be reduced through a selective product mix.[24] Furthermore, these estimates do not factor in MIT's planned growth and future construction.

Central Utilities Plant Retrofit

It is clear that there is a significant need for onsite electricity generation on MIT's campus. This is a hurdle that MIT will have to overcome with renewable energy in order to decarbonize by 2050. The CUP at MIT is an on-site combined heat and power plant that relies on natural gas combustion for steam, electricity, and chilled water. Using the existing infrastructure of the CUP provides multiple paths forward. From 2022 to 2030, the CUP is expected to operate more efficiently than the ISO-NE Grid. With that in mind, we must use this time to effectively plan out the transition of the technology currently used at the CUP to a renewable energy source, especially as the CUP turbines reach their end of life in 2040. This leads to the divergence of the two paths to achieve carbon neutrality at MIT that was previously introduced, with the primary choice being the integration of nuclear batteries into the CUP or retrofitting of the CUP with electric boilers to achieve, or at least approach, carbon neutrality at MIT.

Integration of Nuclear at MIT

MIT is an institution known for leading the way in technological innovation. The commitment to a 2050 carbon-neutral campus can give the institution another platform to lead in an innovative, groundbreaking, and controversial, while necessary way. When evaluating technologies that will support MIT and the world in fighting climate change, there is an old answer to this new problem. This answer is nuclear. However, it is not the nuclear plants being shut down across the world that is the answer; instead, it is the evolution of this technology into micro-reactors. We recognize there are significant hurdles to its integration due to perception and policy; however, we believe that these perceptions are changing, and MIT can play an instrumental role in scientifically backing and supporting this change. In April 2022, a bipartisan bill was brought to the Senate floor called the International Nuclear Energy Act of 2022. This bill will "promote the safe, secure and peaceful use of civil nuclear energy by reducing China and Russia's influence on other nations' civil nuclear energy programs".[15] The legislation "establishes an Executive Office for Nuclear Energy Policy".[15] Although this legislation is focused on reducing foreign dependence on Chinese and Russian nuclear energy, we believe it is important in understanding the changing sentiment toward nuclear in the United States. Legislation like this and the Biden infrastructure bill demonstrate the need for understanding present-day nuclear technology and how we can integrate it into society for our benefit. With respect to MIT, nuclear batteries would curb carbon emissions and provide a solution to climate change. We also believe that these micro-reactors, or nuclear batteries, have the potential to shake the public stigma around nuclear safety and environmental impacts. MIT has led the way in the past and normalized controversial technologies, it is our duty as an institution to lead the way again as we face our largest threat, climate change. Below is a plan explaining why the integration of nuclear batteries on campus is necessary and outlining the steps to achieve this goal.

Present to 2030

As the technology and regulations for nuclear batteries continue to progress, MIT must use this decade to focus on the hurdle of policy and public opinion around nuclear in Cambridge. This work can only be successful through significant knowledge transfer to the public through partnerships with Cambridge City Council and other Cambridge institutions. Our first recommended step is to partner with the Advanced Nuclear and Production Experts Group (ANPEG) and two divisions within the Harvard Kennedy School of Public Policy (HKS), the Belfer Center for Science and International Affairs and the Nuclear Energy Department. This partnership should be focused on creating a Carbon-Free Energy Policy Board focused on understanding the hurdles around nuclear battery integration in Cambridge, as well as creating marketing and information campaigns to shift public opinion on this new technology. From the analysis performed, the most important will be the success of the information campaign focused on the clear differences between nuclear plants and nuclear batteries. The council must highlight that the nuclear battery "is a fundamental energy advance in both form and function, shifting the way nuclear is perceived by the pubic and stakeholders and differentiating it from all other energy sources in its capability to address adaptation to climate change".[6] They will have to differentiate nuclear batteries by highlighting the "intrinsic safety features that ensure safe shutdown and prevent overheating without any operator intervention"[6], the significantly reduced exclusion zones, the reduced energy to size constraints, the reduced environmental and community impacts, the increased resilience to extreme weather conditions, the increased local control of energy, and the significant benefits of these micro-reactors. The marketing campaign will likely determine that a name change is required to ensure individuals disassociate the old technology from the new. In addition to these campaigns, the Carbon-Free Energy Policy Board should host informational town halls with Cambridge City Council to ensure public opinion aligns with our policy goals.

In parallel, MIT should begin an operational strategy for the implementation of nuclear batteries on campus. MIT must identify areas for the installation of nuclear batteries, determine the required energy usage on campus by 2035, and therefore estimate the number of batteries required to reach carbon neutrality. Due to the compact size of nuclear batteries, this technology is superior to renewable alternatives for MIT's campus. For scale, see Figure 6.

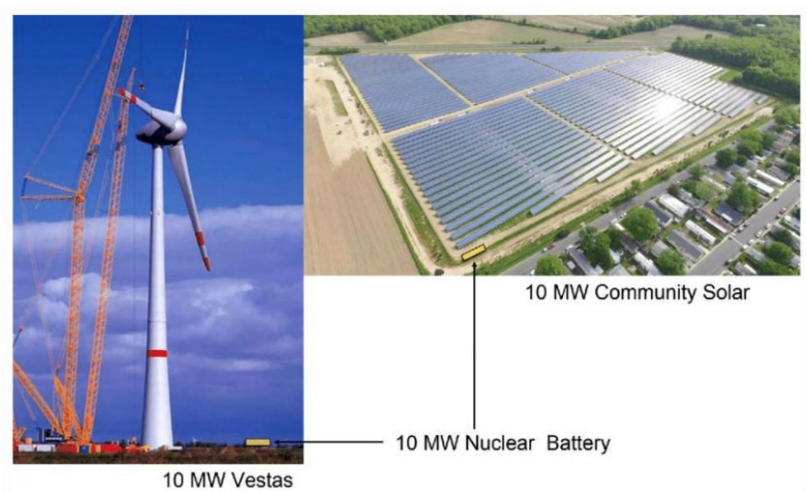
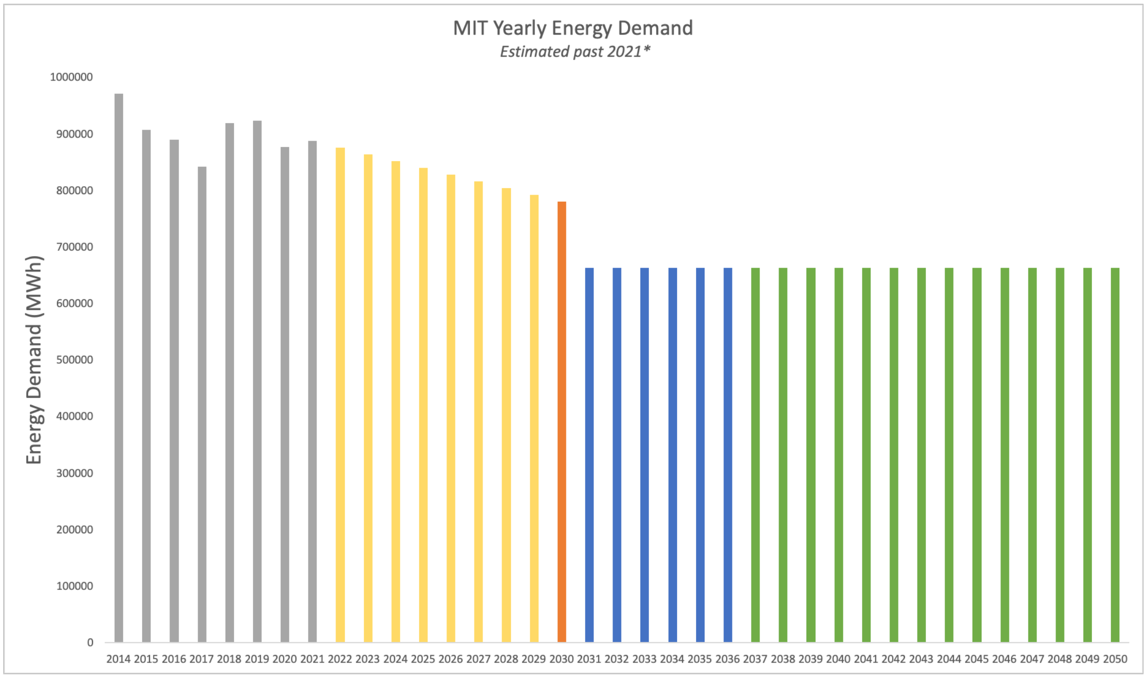


Figure 6: *Size of Nuclear Batteries Relative to Other Renewable Energy* [6]

The size of these 10MW nuclear batteries and the required containment would "fit into a standard twenty foot (6 meter) ISO shipping container"[4&6]. At this size, the batteries would have the ability to generate 10MW of energy at approximately 95% capacity factor without significant impact on the campus' footprint[4]. This means that implementation at MIT's campus would not be constrained by size.

To determine the number of nuclear batteries necessary, a comparative analysis was done across the quarterly energy usage data from 2014 to 2021 provided in *Energize MIT* [8]. This analysis allowed us to understand peak demands and average energy usage by quarter. Figure 7 demonstrates the yearly energy demand at MIT from 2014 to 2050. Note that from 2022 to 2050 are estimates based on reductions from the implementation of the technologies discussed in this paper.



*Estimated using building efficiency upgrades, SESI implementation, and building electrification

Figure 7: *Estimated MIT Yearly Energy Demand*

As seen in Figure 7, the prior year's energy demand is colored grey. The implementation of building efficiency upgrades was used to determine the trend in energy usage seen in yellow from 2022 to 2030. From 2030 to 2031, the SESI implementation or largescale heat pump retrofit would lead to a significant drop in energy demand seen between orange and blue. From 2031 to 2036, MIT will remain constant in energy usage due to the campus' 1% growth and continued building electrification seen in blue. After 2036, with the implementation of nuclear batteries in 2035, the energy demand will remain constant but will now be met by a carbon-free energy source seen in green. Based on this trend analysis, the energy demand for the year at MIT in 2035 will be 663,016 MWh, with the estimated quarterly demand seen in Table 2.

Year	Quarter	Energy Demand (MW*h)
2035	Q1	168,365
2035	Q2	142,252
2035	Q3	161,693
2035	Q4	190,706
2035	**All**	**663,016**

Table 2: *MIT Estimated Energy Demand for 2035*

Based on this forecasted energy demand, 9 nuclear batteries will need to be installed on MIT's campus. The number of nuclear batteries necessary was determined using the following assumptions from Jacopo Buongiorno's "Can Nuclear Batteries Be Economically Competitive in Large Markets" [4] and standard conversion calculations.

Assumptions:

- 1 nuclear battery generates 10MW [4]
- 95% capacity factor [4]
- 24-hour run-time [4]
- 2 weeks of maintenance down-time per year (optional)

Calculations:

1) Energy Generation per Nuclear Battery:

$$1\,nuclear\ battery \cdot \frac{10\,MW\ energy}{1\,nuclear\ battery} \cdot \frac{351\,days}{1\,yr} \cdot \frac{24\,hrs}{1\,day} \cdot 0.95\,CF = \frac{80{,}028\,MWh}{1\,nuclear\ battery}$$

2) Required Nuclear Batteries to meet 2035 MIT Energy Demand:

$$663{,}016\,MWh \cdot \frac{1\,nuclear\ battery}{80{,}028\,MWh} = 9\,nuclear\ batteries$$

2030 to 2040

After over a decade of the Carbon-Free Energy Policy Board's integration into the Cambridge community, MIT should be set up for success to implement nuclear batteries on campus by 2035. This date is estimated by experts to be when nuclear batteries will be approved by the Nuclear Regulatory Commission (NRC) for commercial use in urban areas[18]. In 2030, MIT should revisit the energy demand calculations and ensure that the approximation of 2035 energy demand being 663,016 MWh is realistic. If energy consumption for 2035 remains consistent with historical trends and our emissions savings adjustments are realized, then MIT should begin the installation of 9 nuclear batteries it is not consistent, MIT should adjust the number of nuclear batteries required to meet energy demands based on the "Energy Generation per Nuclear Battery" calculation above. After the installation of the nuclear batteries on campus, MIT should use the next five years to monitor the impacts on emissions and document this success in emissions reductions formally.

2040 to 2050

In 2040, 5 years after the installation of the nuclear batteries, MIT should work with Carbon-Free Energy Policy Board to hold a public hearing on the findings of the emissions monitoring and share the insights from the implementation and use of this novel technology.

Nuclear Batteries Financials

When assessing the financial cost of implementation on campus, nuclear is an expensive but necessary solution. Each nuclear battery is estimated to be \$30M to \$100M per battery for implementation [4]. By 2035, this means that the total estimated implementation cost for 9 nuclear batteries would range from \$270M to \$900M, equating to \$2,040 per metric ton of CO_2e to \$6,801 per metric ton of CO_2e. Once implemented there are negligible operating and maintenance costs. We also recommend allocating \$2.7M to the Carbon-Free Energy Policy Board to start the strategic marketing and information campaign. Although this cost is seen to be high in comparison to other technologies that can support carbon neutrality, we believe that in order to ensure that MIT's campus is carbon neutral by 2050 it is necessary to implement these nuclear batteries. This implementation will give us freedom from the ISO-NE grid's energy and ensure that we meet our goals.

Retrofitting the CUP with Electric Boilers

Due to the aversion to nuclear in Cambridge and within the public, a contingency plan has been outlined in the event nuclear is not a viable political option. Although this path may not lead to carbon neutrality by 2050, it must still aim to minimize carbon emissions to the maximum extent possible. In this scenario, we feel the only remaining viable solution is to depend primarily on the ISO-NE grid for electrical needs, while the steam demands are met by electric boilers.

By 2035, several years of efficiency improvements, campus growth, and electrification will have theoretically occurred on campus. It is also assumed that MIT will have a clearer picture of whether to embark on this contingency plan or not, thus, 2035 estimates will be used for this analysis. By this time, the grid will be cleaner than the CUP turbine and as previously discussed, the anticipated annual energy demands are 663,016 MWh.

The chilled water system will remain the primary source of campus cooling and will be an all-electric refrigeration plant, like the majority of the present-day system. This assumes that the waste heat chill-water turbine that exists today will be retired and replaced by another electrical refrigeration plant. [7] As previously discussed, the heating and cooling needs on campus will be augmented by ground source or air source heat pumps on newer buildings, and retrofit on older buildings where appropriate. With these conditions, the central steam plant remains the only significant power requirement that requires electrification. To minimize costs and impact on campus operations, the simplest solution is to retire the CUP turbines, import electrical power from the ISO-NE grid, and retrofit the steam plant with electric boilers. Electric boilers are already a commercially available technology that can produce steam through resistive heating elements, or by passing current through water via immersed electrodes; the latter of the two typically have a higher maximum capacity. [26] Electric boilers do have some advantages over fossil fuel, including extremely high efficiencies and are typically more compact than fossil fuel boilers. A second advantage is that they have no minimum operating condition, whereas gas boilers do; meaning any load less than the minimum requires all excess steam to be exhausted as waste heat through the stacks. [26]

To understand current campus demands, today's CUP configuration must be fully understood. The CUP is comprised of two Titan 250 gas turbines which can generate 22MWe.[12] Each turbine can exhaust heat to a Hamon Deltak Heat Recovery Steam Generator (HRSG), which is each capable of outputting steam at 74,000lbs/hr. [16] This combination of turbine and HRSG makes up the "Cogeneration plant" that boasts efficiencies of up to 85% according to the Solar Turbines brochure.[12] Although, this efficiency is during ideal conditions where all exhaust heat is being utilized for steam production, which is rarely the case; the turbines when solely producing electricity are only 39% efficient. [12] In addition to the COGEN plant HRSG's, the CUP has five natural gas capable boilers for supplemental steam capacity.[9] Appendix B portrays the full CUP steam and electrical generation layout. Table 3 summarizes the steam capacity of the CUP assuming 80% efficiency in the natural gas boilers and converts it to an equivalent electric boiler assuming 99% efficiency. [26]

Boiler Number	Design Capacity (Natural Gas input, MMBTU/hr)	Steam capacity at 80% efficiency (lbs/hr)	Electric boiler equivalent (MW)
3	116.2	93,000	27.5
4	116.2	93,000	27.5
5	145.2	116,000	34.4
7	99.7	80,000	23.6
9	125.8 (or 119.2 on ULSD)	101,00	29.8
HRSG1	134	74,000 (known)	22.0
HRSG2	134	74,000 (known)	22.0

Table 3: *Steam Capacity of CUP*

Capacity Calculations

The 2016 CUP upgrade proposal calculations suggest that campus steam demands can be met by the HRSG alone, and none of the additional boiler capacity is required during normal operation. Furthermore, peak steam demands are reported at 365kpph. [7] Provided with this data, we determine it is unlikely that installed electric boilers would need to exceed 44MW to meet today's capacity needs. Factoring in a conservative 15% to 30% savings from efficiency improvements, heat pumps or a heat recovery system, and 10% campus growth leads to a 5% to 20% reduction in capacity needs by 2035. Michael Gelveber provided studies showing that 80% of heating capacity serves 95% of heating season duration, thus 28MW to 34MW of steam capacity would be sufficient in all scenarios. Although, it is recommended a natural gas boiler be retained for additional steam capacity in emergency situations.

Capital costs for high voltage electric boilers are estimated at $100,000 per MW, leading to the acquisition of electric boilers priced between $3M to $4M, with total installation cost estimated to be less than $7M. [26] Peak electrical demands on campus are presently 38MWe capacity. [7] Using a similar discussion regarding HVAC efficiency savings leads to an estimated 30MW to 37MW required to handle peak capacity demands. Electrical needs and steam demands combined, disregarding chilled water capacity since peak load will be in winter, could lead to peak campus power demands at 70MWe to 75MWe. Putnam station is a 6 cable 62.9MVA substation, thus it requires an upgrade to handle these anticipated peak power demands. Using the PEguru Substation Cost estimating model[19], a Putnam substation upgrade will cost between $6M to $8M. The assumptions for this estimation are listed below:

- Large Power transformer (50MVA to 100MVA)
- 6 cables
- 13.8KV transformer, surge arrester, and insulators
- 2000 Amp wavetrap and tuner
- Various connectors and cabling
- Assume minimal building alterations or new trenches required.

Electric Boilers Financials

From 2014 to 2021 38% to 41% of energy use was for steam generation alone. Based on these percentages and the 2035 energy demand estimates of 663,016MWh, the portion of the energy required for heating needs is estimated to be a 265,000MWh annual demand for steam. Operational costs for electric boilers at $0.13 per kWh translates to $34M for steam production alone. When compared to natural gas, at 70% efficiency during steam generation (estimated average COGEN and boiler efficiencies) leads to 1,407,200MMBtu of required natural gas energy, which is approximately $1.4x10^7$therms (1therm per 10,000BTU), $1 per therm leads to $14M of annual natural gas costs. These estimates suggest that heating operational expenses will more than double when electrified.

ISO-NE grid in 2050 will be assumed to be 10% of today's emissions, thus 30kg of CO_2e per MWh. Heating demands will shift from 80,000 metric tons to 8,000 metric tons, representing a 72,000 metric tons reduction in 2050. At a total cost of $15M for electric boiler installation and Putnam substation upgrade, this results in a cost of $208 per metric ton of CO_2e. Although it is by far the cheapest long-term solution, as a reminder, this pathway is not expected to lead to carbon neutrality by 2050 and is fully dependent on how the ISO-NE grid develops with respect to renewable energy.

Conclusion

MIT made a commitment to reach carbon neutrality by 2050 and we must serve as an example and fulfill our promises in order to uphold our reputation. Meeting this goal is no simple task. Almost all the potential paths forward are surrounded by uncertainty and challenges to implementation. Efficiency upgrades pose challenges to research labs as the implementation and change cause disruption to labs and may not be welcomed by lab directors. Heat pump installations will cause disruption to campus resources. Nuclear batteries face policy hurdles within the MIT community and in the surrounding Cambridge area, as well as regulatory hurdles from the NRC. Electric boilers rely on the ISO-NE grid which we do not have confidence will be carbon neutral by 2050. Despite these challenges, based on our research we have made assumptions and formulated a multi-pronged approach that contains the technologies that we believe would lead to a viable path for MIT to become carbon neutral by 2050.

Our approach provides multiple paths we believe could be viable for MIT to become carbon neutral by 2050, see Table 4.

Path	Technology Implemented
Path 1	Efficiency Upgrades, Occupancy Monitoring, Heat Pumps, Nuclear Batteries
Path 2	Efficiency Upgrades, Occupancy Monitoring, Heat Recovery System, Nuclear Batteries
Path 3*	Efficiency Upgrades, Occupancy Monitoring, Heat Pumps, Electric Boilers
Path 4*	Efficiency Upgrades, Occupancy Monitoring, Heat Recovery System, Electric Boilers

**Due to dependence on the ISO-NE Grid, there is a significant possibility that MIT does not get to carbon neutral with this plan.*

Table 4: *Paths to Carbon Neutrality*

We have rolled up the cost associated with each path in Table 5, to see the financial summary of each independent technology see Appendix C. Although we understand that the associated cost with becoming carbon neutral is high, we believe that this cost is necessary to become carbon neutral, uphold our reputation, protect future generations and lead the way for the country and world in approaching our climate emergency.

Path	Installation time frame	Capital Cost	GHG reductions (MT)	Cost ($) per metric ton of $CO_{2}e$
Path 1	Present - 2045	$542.85M - $1349.85M	168.3K MT - 172.8K MT	$21,789 - $41,933/MT
Path 2	Present - 2045	$786.85M - $1416.85M	195.8K MT - 200.3K MT	$16,789 - $22,933/MT
Path 3*	Present - 2050	$287.85M - $464.85M	108.3K MT - 112.8K MT	$19,997 - $35,141/MT
Path 4*	Present - 2050	$531.85M	135.8K MT - 140.3K MT	$14,997 - $16,141/MT

**Due to dependence on the ISO-NE Grid, there is a significant possibility that MIT does not get to carbon neutral with this plan.*

Table 5: *The Cost of Carbon Neutrality by Path*

Our comprehensive approach to reach carbon neutrality involves various efficiency improvements that will allow us to start observing savings within the decade across all paths, research and trial studies to determine a campus-wide solution to heating and cooling of either heat pump installations (path 1 and path 3) or a heat recovery system (path 2 or path 4), and a retrofit of the CUP that would ideally include nuclear batteries (path 1 and path 2), but also considers the use of electric boilers (path 3 and path 4) if nuclear batteries prove to not be feasible. To reach the 2050 goal, we must recognize that there will be cost associated with any path to get there and start moving forward by conducting the necessary research and making the necessary changes, while understanding that there may be additional challenges and changes our future depends on action.

Appendices

Appendix A: Efficiency Improvement Calculations

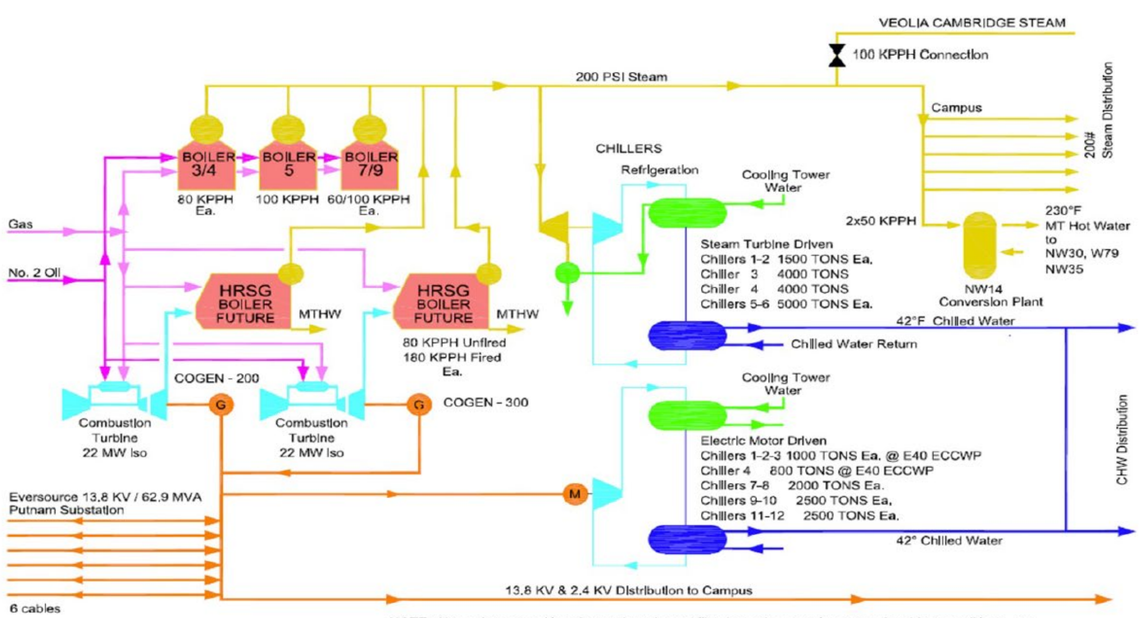
Energy Surveys:

BLDG	GHG MTCO2 FY21	Square Footage	KBTU/ft^2	GHG Savings (MTCO2)-low limit (20%)	GHG Savings (MTCO2)-high limit (30%)	% GHG Savings-low limit	% GHG Savings-high lim	Square Footage Ratio	Implementation Cost $
46	13083	418300	541.2	4787	4787	0.365894672	0.365894672	1	10965700
68	7916	260390	516.6	1583.2	2374.8	0.2	0.3	0.622495816	6826102
76	7867	367698	380.3	1573.4	2360.1	0.2	0.3	0.879029405	9639173
32	5130	463890	189	1026	1539	0.2	0.3	1.108988764	12160838
13	4922	183540	446.7	984.4	1476.6	0.2	0.3	0.438775998	4811486
18	4429	133732	553.6	885.8	1328.7	0.2	0.3	0.319703562	3505773
12	4018	237777	303.4	803.6	1205.4	0.2	0.3	0.568436529	6233304
56	3823	143940	460.2	764.6	1146.9	0.2	0.3	0.3441071	3773375
39	3654	76640	772.8	730.8	1096.2	0.2	0.3	0.183217786	2009111
E25	3155	156676	341	631	946.5	0.2	0.3	0.374554148	4107248
		Total:		**13770**	**18261**				**64032112**
			$ investment/GHG Savings (MTCO2)	**4650.184599**	**3506**				

Occupancy Monitoring:

	Estimated Savings	Estimated Implementation Cost				Electricity (MTCO2)	Gas(MTCO2)	Total
BU Example-St. Mary S	21% of oil & 13% of electric	50,000		**MIT 2021 Numbers**		49284	129,269	178,553
MIT Savings & Cost-30% of buildings	10066.023	2850000						
			$ investment/GHG Savings (MTCO2)	**283**				

Appendix B: CUP layout with steam, electric, and chill water capacities



Appendix C: Financial Summaries of Technologies Evaluated for Paths to Carbon Neutrality

Technology	**Installation time frame**	**Capital Cost**	**GHG reductions**	**Cost ($) per metric ton of CO_2*e***
Efficiency Upgrades - Audits & Improvement (HVAC and labs)	Present-2028	$64M	13.8k-18.3k MT	$3,506-4,650/MT
Occupancy Monitoring	Present- 2030	$2.85M	10k MT	$283/MT
Heat Pumps Full Integration	Present-2032	$206-383M	12.5k MT	$16,000-$30,000/MT
Heat Recovery System	2030-2035	$450M	40k MT	$11,000/MT
Nuclear Batteries	2035 -2045	$270-900M	132k MT	$2,000-7,000/MT
Electric Boilers	2035 -2050	$15M	72k MT	$208/MT

References

[1] “Achieving Significant GHG Reduction in Commercial Buildings: Options, Analysis & Tools.” 2.832 Michael Gevelber 2022.

[2] Batra, Nipun, et al. “A Comparison of Non-Intrusive Load Monitoring Methods for Commercial and Residential Buildings.” ResearchGate, 27 Aug. 2014, https://www.researchgate.net/publication/265169205_A_comparison_of_non-intrusive_load_monitoring_methods_for_commercial_and_residential_buildings .

[3] Bonacorda, Patricia. “HVAC Efficiency: What It Is, Why It Matters and How to Get Started | Alliance to Save Energy.” Alliance to Save Energy, 24 Nov. 2015, https://www.ase.org/blog/hvac-efficiency-what-it-why-it-matters-and-how-get-started#:~:text=Energy%20consumption%20through%20heating%2C%20ventilation,energy%20usage%20in%20commercial%20buildings.

[4] Buongiorno, Jacopo, et al. “Can Nuclear Batteries Be Economically Competitive in Large Markets?” Energies, no. 14, MDPI AG, July 2021, p. 4385. Crossref, doi:10.3390/en14144385.

[5] Chandler, David. “3Q: Why ‘Nuclear Batteries’ Offer a New Approach to Carbon-Free Energy | MIT News | Massachusetts Institute of Technology.” MIT News | Massachusetts Institute of Technology, MIT News, 25 June 2021, https://news.mit.edu/2021/nuclear-batteries-decarbon-0625.

[6] Conca, James. “What Would Nuclear Batteries Do For Us?” Forbes, Forbes, 25 Jan. 2021, https://www.forbes.com/sites/jamesconca/2021/01/25/what-would-nuclear-batteries-do-for-us/?sh=29220a7ee9dd.

[7] “CUP Operations presentation” 2.832 Jon Sepich 2022

[8] “Energy and GHG Campus Totals.” Energize MIT, Office of Sustainability, https://tableau.mit.edu/views/Energize_MIT/Energize_MIT?:embed=y&:showShareOptions=true&:display_count=no&:showVizHome=no#1. Accessed 2 May 2022.

[9] Epsilon Associates, Inc. “New Nominal 44 MW Cogeneration Project.” Powering MIT, Epsilon Associates, Inc., Dec. 2016,

https://powering.mit.edu/sites/default/files/documents/1-26-2017%20MIT%20PSD%20PDF%20downsized.pdf.

[10] “Ground vs Air-Source Heat Pumps: Benefits & Drawbacks | WM Henderson.” WM Henderson, 5 Feb. 2021, https://www.wmhendersoninc.com/blog/ground-vs-air-source-heat-pumps-benefits-drawbacks/#:~:text=Ground%2Dsource%20heat%20pumps%20consume,helping%20to%20decrease%20fuel%20emissions

[11] “Heating & Cooling Degree Days.” Heating & Cooling Degree Days – Free Worldwide Data Calculation, https://www.degreedays.net/#. Accessed 8 May 2022.

[12] Hodge, B. K. Alternative Energy Systems and Applications. John Wiley & Sons, 2017, https://www.solarturbines.com/en_US/products/gas-compressor-packages/titan-250.html.

[13] “Incentives For Ground-Source Heat Pumps | MassCEC.” Mass CEC, 17 Dec. 2015, https://www.masscec.com/incentives-ground-source-heat-pumps#:~:text=The%20costs%20for%20residential%20GSHP,the%20site%20and%20project%20type.

[14] Kan, Edwin. “Indoor Occupant Counting Based on RF Backscattering.” Cornell University | Arpa-e.Energy.Gov, 26 Apr. 2018, https://arpa-e.energy.gov/technologies/projects/indoor-occupant-counting-based-rf-backscattering.

[15] “Manchin, Risch Introduce The International Nuclear Energy Act Of 2022 - U.S. Sen...” U.S. Senate Committee on Energy and Natural Resources, 8 Apr. 2022, https://www.energy.senate.gov/2022/4/manchin-risch-introduce-the-international-nuclear-energy-act-of-2022.

[16] “MIT Central Utility Plant Combustion Turbine Expansion Project” Department of Environmental Protection, https://www.mass.gov/doc/draft-psd-permit-fact-sheet-mit-central-utilities-plant/download

[17] “Non-Intrusive Load Monitoring (NILM).” Enetics, Inc., https://www.enetics.com/Products/Software/Non-Intrusive-Load-Monitoring-NILM.

Accessed 2 May 2022.

[18] Buongiorno, Jacopo. "Nuclear Batteries presentation" 2.832 Solving for Carbon Neutrality at MIT. 30 Mar. 2022, Massachusetts Institute of Technology, Cambridge. Lecture.

[19] "Substation Cost Estimator | PEguru." PEguru Substation Design | Power System Analysis, PEguru, 6 Mar. 2020, https://peguru.com/substation-cost-estimator/.

[20] Higgins, Luke and Huang, Yu. "Building 46 Research Project" 2.832 Solving for Carbon Neutrality at MIT. 27 Apr. 2022, Massachusetts Institute of Technology, Cambridge. Lecture.

[21] "So, What Exactly Is Building Electrification?" Green Tech Media, 05 Jun. 2020, https://www.greentechmedia.com/articles/read/so-what-exactly-is-building-electrification

[22] Borchik, Daniel and Higgins, Luke and Jiang, Wren and Stehr, Connor, Connor's Carbon Crushing Crew. 2.832 Solving for Carbon Neutrality at MIT. 27 Apr. 2022, Massachusetts Institute of Technology, Cambridge. Lecture.

[23] Pfeifenberger, Johannes. "The Electricity Grid's Role in Achieving Carbon Neutrality in the U.S. and New England." 2.832 Solving for Carbon Neutrality at MIT. 28 Feb. 2022, Massachusetts Institute of Technology, Cambridge. Lecture.

[24] "Air Source Heat Pumps vs Ground Source Heat Pumps." *Energy Saving Trust*, 1 Apr. 2022, https://energysavingtrust.org.uk/air-source-heat-pumps-vs-ground-source-heat-pumps/.

[25] "Stanford Energy System Innovations (SESI) Project | Stanford." *Sustainable Stanford*, https://sustainable.stanford.edu/sites/.

[26] "Boiler Plant Optimization | Cleaver Brooks" | *Cleaver Brooks Solutions* https://cleaverbrooks.com/.