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Solving for Carbon Neutrality at MIT

OPTIMAL TECHNOLOGY SELECTION TO MEET MIT'S CARBON NEUTRALITY GOALS

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Introduction

Context

The Earth's climate is changing, and the preponderance of present-day change is associated with human activity, specifically the emission of greenhouse gas (GHG). Our planet is currently about 0.8°C warmer than it was in the pre-industrial age. The amount of CO_2 in the atmosphere now is greater than at any point in the last 800,000 years according to polar ice core data, and continues to rise. The CO_2 persists in the atmosphere for a very long time and the climate system responds relatively slowly, accumulated GHG emissions will result in climate changes that will last more than a thousand years. The warming climate will produce rising sea levels, coastal flooding, droughts and changes in precipitation intensity and distribution, ocean acidification, loss of sea ice, increased wildfires, and impacts on animal and plant populations.

In order to avert the worst outcomes of climate change, MIT has pledged to find affordable, equitable ways to bring every aspect of the global economy to net-zero carbon emissions no later than 2050. As the MIT community works to pioneer technologies and policies to help society combat climate change, there is a keen sense of responsibility to improve the sustainability of our campus and use it as test bed for change. For this purpose, MIT has set a tangible goal of achieving net-zero direct emissions (scope 1 and scope 2) by 2050. Our project objective is to identify a viable way forward that meets MIT's carbon goals while minimizing cost and accounting for social disruptions.

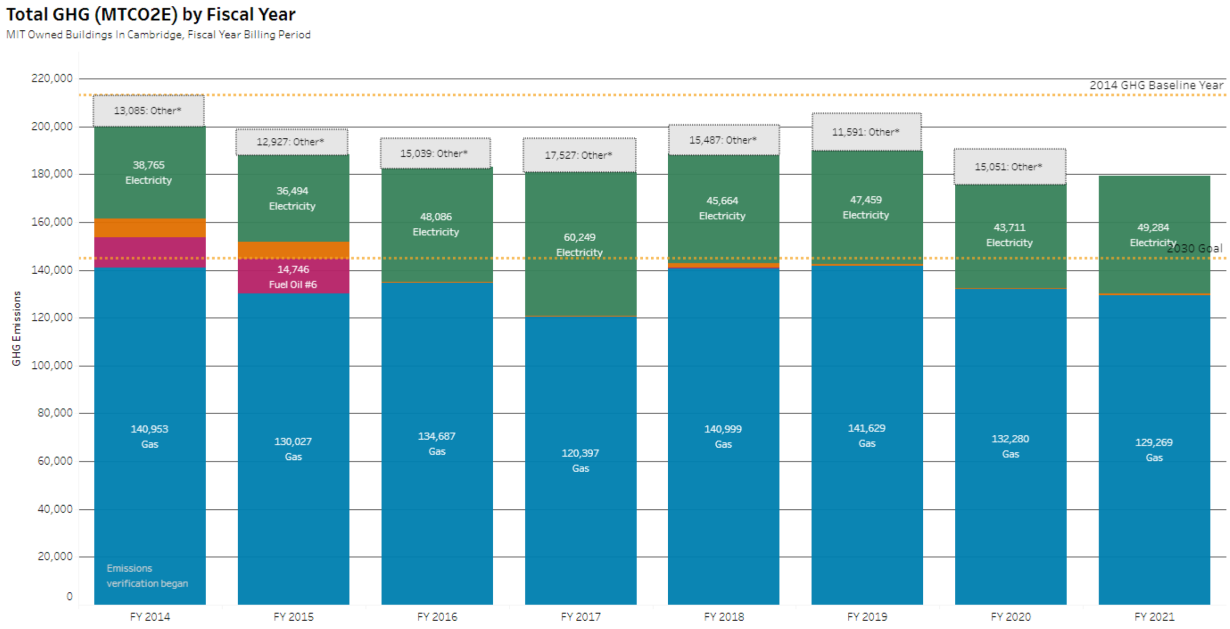


Figure 1: MIT's Total GHG (MTCO2E) by Fiscal Year [1]

Despite the best intentions and extensive efforts thus far, the road to carbon neutrality is far from easy. As Figure 1 showed, MIT has achieved around 10% of total GHG reduction in 2021 compared to 2014. However, positioned at the leading edge of technology, MIT's energy demand is not likely to reduce significantly, and the need to replace Central Utility Plant (CUP)'s natural gas consumption system with reliable and sizable clean energy sources poses the biggest challenge ahead. Our team's approach is to build an optimization model with reasonable estimates of the emissions reduction potential and the estimated cost curves for each technology to minimize the overall cost in achieving carbon neutrality by 2050.

Technologies Available

To conduct an analysis of which technologies to use to meet MIT's carbon neutrality goals, we first define the set of technologies under consideration. These technologies include:

(1) **Building Efficiency Improvements:** enhancements to existing buildings, similar to those conducted on Building 46, reduce the energy needs of the building.

(2) **Ground Source Heat Pump (GSHP):** installed heat pumps take advantage of the difference between below-ground and above ground temperatures for more efficient heating.

(3) **Air Source Heath Pump (ASHP):** installed outside of buildings to electrify and increase efficiency of heating or cooling based on exchanging hear with outside air.

(4) **Electric Heating:** electrified heating sources, such as water boilers, that have low efficiency but can be used anywhere for low cost and easy to install.

(5) **Nuclear Batteries:** fission based Small Modular Reactors (SMRs).

(6) **ISO-NE:** electricity purchased from the local New England grid.

(7) **Carbon Capture:** implemented at the CUP, this technology captures carbon emitted by the combustion of fuel.

(8) **Biofuel:** biogas burned in MIT CUP. Our model considers this as the only viable bio-based fuel for MIT needs.

(9) **Rooftop Solar:** fixed-axis solar PV panels on MIT-owned buildings.

(10) **Renewable PPAs:** direct Power Purchasing Agreements (PPAs) with renewable energy generation plants around New-England. The locality of the plant is important so that the energy could be transmitted to MIT. If this is not the case, this energy would be considered as carbon offset, a form of decarbonization that we are not interested in for the 2050 solution. The energy sources will most likely be wind resources (either inland or offshore), but may also be other renewables such as utility scale solar.

Approach

To determine the optimal mix of technologies that would allow MIT to meet their carbon neutrality goals by 2050 while minimizing costs, an integer programming model can be used to solve for the quantity of energy supplied by each technology that will minimize these costs. A linear programming model is a mathematical optimization model that minimizes or maximizes a linear function when subjected to various constraints. The model outputs the set of variables that enable this optimal outcome, also called "decision variables". This technique can be used when complex trade-offs must be modeled mathematically in order to determine the optimal solution.

Because of the complexity of selecting the right technologies to meet MIT's goals, we chose to model this decision as a linear program. This allows us to input the costs and constraints of each technology into the mathematical model and it will output the solution that best meets these needs at the lowest possible cost. It also allows us to change these constraints, i.e. to remove nuclear or another technology that has uncertain outcomes, in order to conduct scenario planning in the case that a single technology is unavailable. In this moel, the objective is to minimize costs under the constraint of zero emissions in 2050. Additional constraints include the maximum capacity of each technology and the requirements of MIT's energy consumption needs. The costs are defined by the levelized cost of energy for each type of technology, which includes the cost per kWh over the lifetime of the given technology. The details of this model, and the relevant assumptions, are outlined in the sections below.

Optimization Framework

Sets

$\mathcal{I}$: set of available technologies i

$\mathcal{I}_1$: building efficiency improvements
$\mathcal{I}_2$: ground source heat pumps
$\mathcal{I}_3$: air source heat pumps
$\mathcal{I}_4$: nuclear batteries
$\mathcal{I}_5$: ISO-NE
$\mathcal{I}_6$: carbon capture
$\mathcal{I}_7$: bio-fuel
$\mathcal{I}_8$: electric heating
$\mathcal{I}_9$: rooftop solar
$\mathcal{I}_{10}$: renewable PPAs

Parameters

$\mathcal{D}_h$: total energy demand for heat
$\mathcal{D}_e$: total energy demand for electric
m_i : emissions per kWh for each technology
$c_i(k_i)$: LCOE for each technology as a function of total energy consumed

Decision variables

k_{ih} : energy used for heat from technology i
k_{ie} : energy used for electricity from technology i

Formulation

$$
\begin{aligned}
\min \quad & C \\
\text{s.t.} \quad & C = \sum_i c_i(k_i) \times k_i && \text{cost function} \\
& D_h = \sum_i k_{ih} && \text{heat supply and demand balance} \\
& D_e = \sum_i k_{ie} && \text{electricity supply and demand balance} \\
& \sum_i m_i(k_{ih} + k_{ie}) \leq 0 && \text{sets emissions equal to zero in 2050} \\
& k_i h \leq h_i \forall i && \text{heat capacity} \\
& k_i e \leq e_i \forall i && \text{electricity capacity}
\end{aligned}
$$

Assumptions

For each technology, we included practical considerations for implementation. In the optimization framework, these practical considerations translate into constraints that prevent the model from identifying a solution that can not be implemented in practice. In this section, we outline the assumptions that underlie these constraints.

(1) **Building Efficiency Improvements:** We set a hard limit for heat efficiency projects to 34.4% of estimated demand and electricity efficiency projects to 30.4% of estimated demand. We have also assumed a rising cost for increasing efficiency levels.

(2) **Ground Source Heat Pump (GSHP):** Based on the work done for the research project, it is assumed that GSHPs can only comprise 35.9% of the total heating needs. This reflects a coefficient of performance of 5, which is on the higher end of GSHPs, but will reflect the absolute maximum possible with GSHP systems.

(3) **Air Source Heat Pump (ASHP):** For air source heat pumps, the constraints on space are much less of a problem. However, there are still challenges in designing for peak load. A hybrid system, as Mike Gevelber discussed, can alleviate these concerns by using a boiler to help address these peak load amounts while transitioning most of the system to heat pumps. We use the constraint of 90% ASHPs for heating load based on this analysis, in which there is a careful balance between heating capacity, emissions reduction, and upfront cost.

(4) **Electric Heating:** For electric heating we assumed a low LCOE that could make it an option in case of heating needs where GSHP and ASHP is not an option.

(5) **Nuclear Batteries:** Assumed to provide combined heat and power generation in similar ratio to CUP - 40% electricity and 60% heat. We expect the technology to be commercially available by 2035, and the building project to take 1 year.

(6) **ISO-NE:** Our base model considers the grid to reach net-zero by 2050. In secondary models we run calculations for scenarios in which the grid does not reach their goal.

(7) **Carbon Capture:** We assume that it is possible to capture all carbon emitted by the CUP by consuming 30% of the produced energy.

(8) **Bio-fuel:** Bio-gas requires fixed cost in adaptation of the CUP equipment to use it as a fuel source. In addition, sourcing of bio-gas would be challenging at scale, reflected in price rising with energy generation from bio-gas.

(9) **Rooftop Solar:** Total roof space of MIT was evaluated in two methods. The first method was to divide the total on-campus floor area owned by MIT (13,348,265 ft^2) by the total floor numbers (1005) to get the average rooftop area (13,282 ft^2, then multiply the average rooftop area with the MIT owned building count (184), to arrive at an estimated total rooftop area of 2,443,862 ft^2. The second method was to look at the floor areas of each building[2] and guess the rooftop area of that building by the layout, then summarize the total guess rooftop area (2,558,331 ft^2). We chose to use the first method result of 2,443,862 ft^2 for our calculation since we do not know which buildings were not MIT-owned and thus the second method has a larger potential for error. Based on data from EnergySage[3], we evaluated annual energy production per square foot of rooftop for Massachusetts to be 26.5kWh. In addition, we assumed 50% of total roof space at MIT is available for PV rooftop solar installations. Based on these assumptions, maximum annual electricity generation from rooftop solar in MIT is 32,445,225kWh.

(10) **Renewable PPAs:** Since rooftop solar has a lower LCOE than the evaluated cost of PPAs, we assumed all PPAs will require a cost premium to install storage capacity either on campus or as part of the generation site. This storage capacity is required to maintain continuous operations at MIT while using above 17% of renewable electricity. In addition, since renewable energy is intermittent, renewable energy resources (PPAs and rooftop solar) will be capped at 70% of total energy generation in order to maintain grid stability.

(11) **Energy Demand:** We assume demand for energy on campus will increase at a rate of 1% per year until 2050. Initial demand in 2022 is 1,754,730,000 kWh of heating and cooling and 190,798,923 kWh of electricity.

Cost Modeling

For each technology, we developed a model of cost as a function of the quantity of energy supplied. This reflects the reality that each technology scales differently, and there may be social or political costs to implementation. For example, for a technology with large regulatory hurdles, the incremental cost for one unit of electricity is much higher than the incremental cost for the 100th unit of electricity. The details of each of these cost curves is outlined below.

(1) **Building Efficiency Improvements:** Using current cost estimate of building 46 project ($10,965,700 total cost for 5,921,621 kWh annual electricity savings and 31,769,068 lbs annual steam savings), with energy benefits from 2023 to 2050, we assumed a base LCOE for energy efficiency projects to be 0.07 [$/kWh]. Based on that, "low hanging fruit" efficiency projects, for example, LED lighting, were estimated to deliver the first 10% reduction in energy consumption in a lowered cost of 0.06 [$/kWh]. Upon reaching 10%, the cost per kWh rises linearly as efficiency projects become more costly, to the point of 0.19 [$/kWh] in case of 30% energy demand reduction. Solely for the sake of modeling, the cost keeps growing at the same rate. However, since the model is designed to pick lower cost alternatives, it practically caps efficiency projects before 30% is reached.

(2) **Ground Source Heat Pump (GSHP):** First, we calculate the basic levelized cost of energy based on the capital and maintenance costs as well as the energy provided. The formula for the simplified levelized cost of energy is as follows:

$$\frac{(K \cdot C)}{(8760 \cdot F)} + V$$

In this formula, K represents the total capital cost per kw installed; C is the capital recovery factor calculated as $\frac{i(1+i)^n}{(1+i)^n-1}$, where i is the discount rate; F is the capacity factor that represents the portion of time that the source is generating power (between 0 and 1); and V are the variable costs, which in this case is primarily maintenance. The 8760 in the denominator is the number of hours in a year [4]. To calculate the levelized cost of energy, we use the approximate cost per ton from Mike Gevelber's presentation (see appendix for cost chart). For low-temp GSHPs, this is \$9,500 per ton. A yearly maintenance cost of \$0.005 per kWh is used for the variable cost V. This is based on variable cost representing about 1% of the capital costs. The discount rate is 3% based on similar LCOE calculations. We use a capacity factor F of .45 based on Mike Gevelber's presentation. The resulting LCOE is \$0.083 per kWh.

There are two additional considerations for costs for ground source heat pumps. First, there is a disruption when the holes are dug and any initial pilots that may be required to get more accurate cost estimates. Second, with more buildings added to the system, the system efficiency as a whole will improve based on our conversations with GSHP experts. Therefore, the resulting costs can be modeled as:

$$\mathrm{LCOE}_{\mathrm{GSHP}} = 0.102 - 1.19 \cdot 10^{-09}x + 7.3 \cdot 10^{-18}x^2$$

(3) **Air Source Heat Pump (ASHP):** Similar to the above analysis, the LCOE formula was used to calculate the cost curve for air source heat pumps. The same numbers were used for the above replaced by the relevant numbers from Mike Gevelber's analysis. The costs were modeled using the low-temp air source heat pumps, which are described to be more efficient. Additionally, maintenance costs are generally twice as much as ground-source heat pumps; a cost of \$.01 per kWh was therefore used for the variable cost. The remaining assumptions were the same. This resulted in an LCOE of \$.034 per kWh. Because air-source heat pumps do not have the same efficiency gains that ground source heat pumps have, this number was held constant across all energy level usage. [5]

(4) **Electric Heating:** We assumed a low and fixed LCOE of \$.03 per kWh.

(5) **Nuclear Batteries:** As a base LCOE we used the higher-range estimation provided by the OECD-NEA for SMRs, which is 0.11 [\$/kWhe][6]. On top of that, we assumed \$550K (annually) for PR efforts incurred to build a nuclear power plant on campus and keeping it working. In addition, at a certain point, the area now owned by MIT for a nuclear reactor will not be enough, and therefore MIT will need to acquire or alternate the purpose of additional land to put the nuclear batteries on. This cost grows as MIT adds more nuclear energy, but since it is divided by the total energy generated by these nuclear reactors, the actual LCOE varies up and down with total energy generated. For the purpose of modeling, we fitted a 4-degree polynomial to the estimated data points. The result, shown below, is the cost equation used to model nuclear energy LCOE as a function of total electric energy produced by nuclear in the year 2050. Appendix 2 shows the calculations and model fitting.

$$LCOE_{\mathrm{Nuclear,electricity}} = 0.403 - 1.52 \cdot 10^{-08}x + 2.58 \cdot 10^{-16}x^2 - 1.69 \cdot 10^{-24}x^3 + 3.79 \cdot 10^{-33}x^4$$

(6) **ISO-NE:** ISO-NE cost estimation is 0.13 [\$/kWh] flat-rate.

(7) **Carbon Capture:** we estimate the LCOE for carbon capture to be \$50 per ton of CO2 captured [7]. This cost is included to account for capital investments on top of the energy consumption of 30% of produced energy [8].

(8) **Biofuel:** As a base LCOE we used 0.09 [\$/kWhe] provided by EIA for biomass fuels[9]. We added a \$500K (annually) as the portion of the capital cost and maintenance costs incurred for CUP operations with using bio-gas. For 20% of electricity demand and above, MIT is expected to pay a premium for

sourcing the fuel at a cost rising with demand. For the purpose of modeling, we fitted a 2-degree polynomial to the estimated data points. The result, shown below, is the cost equation used to model bio-fuel LCOE as a function of total electric energy produced in 2050. Appendix 3 shows the calculation and model fitting.

$$LCOE_{\text{Bio-fuels,electricity}} = 0.377 - 1.01 \cdot 10^{-08}x + 7.73 \cdot 10^{-17}x^2$$

(9) **Rooftop Solar:** Based on additional data from EnergySage[3], and under the assumption of a 25 years lifetime of the system, we evaluated LCOE for rooftop solar at MIT to be 0.085 [$/kWhe]. Appendix 4 shows the data and calculations done to get this number.

(10) **Renewable PPAs:** Baseline for PPAs is assumed to be 0.1 [$/kWhe], storage premium is 0.02 [$/kWhe].

Incorporating Social Cost

For nuclear energy, we incorporated a cost that will be incurred by MIT in case it decides to pursue this path. As nuclear energy suffers from bad reputation, the city of Cambridge, and its residents are likely to resist the offer by MIT to install nuclear batteries on campus. MIT will need to allocate budget for lobbying and PR in order to be able to proceed and maintain the nuclear plant running. This cost is projected to be more heavily incurred before the project starts and during the build. However, it is possible that MIT will need to keep the effort going at some level. Our model incorporate an estimation of $2.25M for initial campaign and another $400-500K per year starting 2035.

Additionally, a multiplier for ground source heat pumps was applied to account for disruption to campus by drilling wells to install the heat pump system. A 20% premium on cost was added for initiating a heat pump project to account for this disruption.

Optimization Results

We solved the above optimization problem under thee potential scenarios:

(1) The base case: including all technologies that are likely to be available by 2050.

(2) Nuclear contingency: if nuclear is unavailable due to regulation or zoning restrictions, we ran the model excluding the possibility of nuclear.

(3) ISO-NE and nuclear unavailable: if ISO-NE does not meet its net zero goals, we ran a sensitivity that excluded ISO-NE from being used. In this scenario, nuclear was also unavailable

Each of these scenarios would allow us to understand the optimal mix of technologies in 2050 and develop a strategy backwards from there on how to best roll out these technologies.

2050: Solving for net zero

The first scenario relies on a diversity of sources, with nearly all technologies included in the solution. This can be seen in Table 1. Natural gas in this scenario still accounts for a portion of the electricity and heat needs, and is offset by carbon capture. Air-Source Heat Pumps are the primary source of heat, while nuclear batteries fill the gap left by what natural gas cannot fulfill. The total cost in this scenario is $154M annually (this number includes accounting for the capital expenses portion allocated to the energy generated that year).

Table 1: Results considering the optimal scenario for 2050

Technology	Share of Heat	Share of Electricity	Cost in 2050
Efficiency	7%	9%	$15.5M
GSHP	3%	-	$4M
ASHP	51%	-	$40M
Elect Heating	-	-	-
Nuclear Batteries	11%	18%	$24M
ISO-NE	-	12%	$15.5M
PPAs	-	13%	$15.5M
Solar	-	3%	$2.8M
Bio-fuels	5%	7%	$3.6M
Natural Gas	23%	36%	$30M
Carbon Capture	-	-	$3.6M
Total Annual Cost			$154M

2050: Contingency for No Nuclear

The second scenario considers that Nuclear energy will not be a possibility, being it from legislative ban or technological barriers. The results from this model can be seen in Table 2. Natural gas in this scenario still accounts for a portion of the electricity and heat needs, and is offset by carbon capture. Air-Source Heat Pumps are the primary source of heat, with ISO-NE being responsible for another big part of the electricity needs. The total cost in this scenario is $180M annually.

Table 2: Results considering nuclear will not be possible for 2050

Technology	Share of Heat	Share of Electricity	Cost in 2050
Efficiency	7%	8%	$15.5M
GSHP	-	-	-
ASHP	65%	-	$51.3M
Elect Heating	-	-	-
Nuclear Batteries	-	-	-
ISO-NE	-	38%	$55.5M
PPAs	-	13%	$17.3M
Solar	-	3%	$2.8M
Biofuels	5%	7%	$4.3M
Natural Gas	22%	31%	$29.4M
Carbon Capture	-	-	$4.3M
Total Annual Cost			$180M

2050: Contingency for ISO-NE not reaching net zero and no nuclear

The third scenario additionally considers that the ISO-NE grid will not reach carbon neutrality by the year 2050. As such, we completely remove it from the model, as there is no means of offsetting this carbon from within campus. Atmospheric carbon capture is considered too expensive and inefficient here. The results, further discussed below, can be seen in Table 3. Cost is astronomical in this case, with immense needs for efficiency and GSHPs. The total cost is $800M annually.

Table 3: Results considering no ISO-NE and no nuclear for 2050

Technology	Share of Heat	Share of Electricity	Cost in 2050
Efficiency	30%	13%	$150M
GSHP	19%	-	$450M
ASHP	23%	-	$18M
Elect Heating	-	-	-
Nuclear Batteries	-	-	-
ISO-NE	-	-	-
PPAs	-	21%	$17.3M
Solar	-	5%	$2.8M
Bio-fuels	17%	24%	138M
Natural Gas	37%	17%	$21.7M
Carbon Capture	-	-	$2.7M
Total Annual Cost			$799M

Discussion

Implications of Model Results

Taking into account that all our assumptions hold, the optimization models has shown that a mix of the proposed technologies will be the best way forward for MIT to achieve decarbonization. Nuclear is an important part of the plan, providing almost 1/5 of the electricity needs and 10% of the heating. Efficiency projects need to be conducted throughout the years, representing a reduction of 7% and 9% in heat and electricity demand on campus, respectively. The CUP continues to be run, up to its capacity, but with a mix of 20% of bio-gas, and capital investments of carbon capture technologies must be implemented to account for the carbon emitted during combustion. The rest of the electricity need is obtained from a mix of rooftop solar, local PPAs and buying from the ISO-NE grid.

To provide all heating needs, Ground Source Heat Pumps and Air Source Heat Pumps should be installed. 50% of the heating is provided by ASHPs, while only 3% by GSHPs. We acknowledge that the model has not recommended any electric heating, such as boilers, but that they are important as a backup source, so we recommend investing some amount in implementing electric heating sources in the buildings.

Finally, it is noticeable that almost all increase in energy demand has been absorbed by increase in building efficiency, and that the CUP continues to be run due to its very cost-effective nature and no need for capital investments other than the installation of a carbon capture system.

Our team also understand the need for contingency plans, and as such has run a scenario disregarding Nuclear technology, in the case that legislation prohibits its use in the city of Cambridge, and one in which the ISO-NE grid has not become carbon neutral by 2050.

For the first contingency case we observe an increase in cost mostly due to the missing heat energy provided 'for free' from the nuclear power generation, having to be supplemented by ASHPs, and the need to increase the purchase of electricity from ISO-NE.

For the second contingency case results become even more interesting. Cost rises astronomically, as we can no longer purchase electricity from ISO-NE – we have no way of offsetting this carbon on campus. Instead, we have to build an enormous amount of efficiency on campus, reaching 30% for heat and 13% for electricity, install a lot of GSHPs to provide additional heating, and use a lot of bio-gas, as the CUP is our only electricity generation source.

Working Backwards from 2050

Under the assumptions of the first scenario, in order to achieve net zero carbon emission by 2050, MIT needs to start the following technology implementations shown in Figure 2 per the implementation timeline. The black bars indicate testing period required for the technologies and the gray bars indicate the technology implementation period (the time required to put that technology in place). Although ISO-NE and Natural Gas provide heat and electricity in this scenario, they are not listed in the timeline since there is no implementation required.

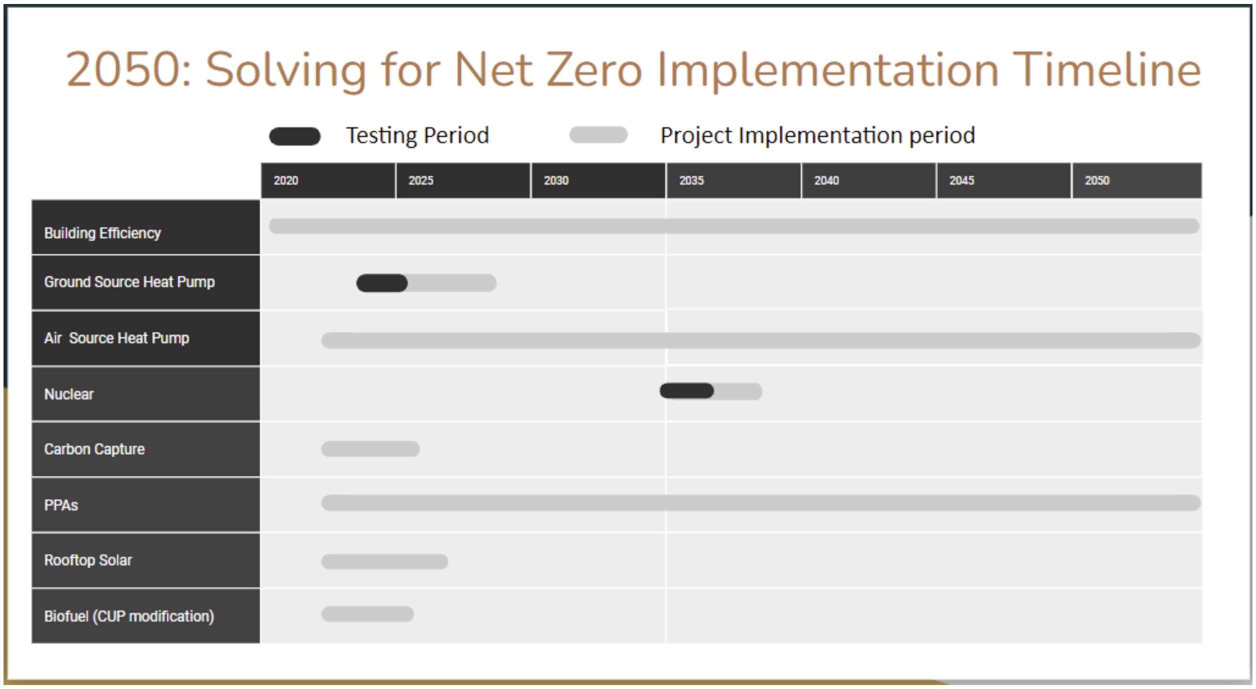


Figure 2: Implementation Timeline for First Scenario

For the first scenario, timeline for each of the technologies implementation is explained as follows:

- **Efficiency:** building efficiency projects are already underway, and the implementations for each buildings will continue until 2050 due to the nature of these renovation projects.
- **GSHP:** the GSHP projects will likely take a year to plan out and acquire necessary buy-ins from stakeholders. Once the necessary approval is acquired, a test site could be identified to facilitate feasibility study, which we currently estimate the testing period as between 12 - 18 months. If the testing project proves that GSHPs are feasible at MIT, we estimate that six buildings (3% of the total 184 MIT owned buildings) will need to be modified for achieving the 3% heat reduction in first scenario. Based on our previous interview with GSHP expert, each building modification would take an average of three months to complete, granting another 12 months as buffer, which would have the GSHPs implemented by 2028.
- **ASHP:** the ASHP projects could be started as soon as possible since they are relatively easy to implement, but the implementation will last from now until 2050 due to the sheet amount of MIT owned buildings that could benefit from ASHPs.

- **Nuclear:** we assume that small unclear batteries will be available on 2035 (all necessary permissions and citizen supports would be acquired prior to 2035) and the initial testing period will be around 12 months to make sure a smooth power source transition, after the 12 months testing period, another 12 months would be required for the full implementation.
- **Carbon Capture:** in this scenario, carbon capture capability should be installed as soon as possible in CUP. We estimate the implementation period to be approximately three years.
- **PPAs:** we should start acquiring appropriate PPAs as soon as possible and continue purchasing them as needed.
- **Rooftop Solar:** rooftop solar projects should start immediately per this timeline with a dedicated focus team. We estimated five years from start to finish for installing rooftop solar systems across the entire campus on MIT owned buildings.
- **Bio-fuel (CUP modifications):** we assume any necessary infrastructural modification CUP required to consume bio-fuel should be completed in three years as indicated in the timeline.

Cost Estimation

We performed an estimation of the total capital investment costs to achieve the energy production mix we are suggesting for the optimal case, that is, including Nuclear reactors and considering ISO-NE has achieved carbon neutrality by 2050.

The following assumptions and calculations have been used for the cost estimation:

- **Efficiency:** the LCOE is the perpetuity cost of the capital investment. As such, having an LCOE of $15.5M in 2050 roughly translates in a yearly investment of that amount.
- **GSHP, ASHP, Nuclear Batteries and Solar:** for these sources we start with the amount of energy we determined needs to produced, calculate power requirements based on capacity factors and use installed costs to reach a capital investment need. For GSHP, we assume a capacity factor of .45 to get to an energy requirement of about 20MW. This translates to 5687 tons of energy needed. At a cost per ton of $15,600, which includes both the thermal loop and the boreholes, this translates to $89M in capital costs. If different well sizes were used, the costs may be lower, but more space would be needed to install shallow wells. For ASHP, the energy requirement of 134MW requires installed capacity of 84,671 tons. According to professor Gevelber's presentation, air source heat pumps cost about $2,700. To run the wires between buildings, we assume and additional 20% cost per ton to bring the cost per ton to $3,240. The total capital cost is therefore $274M. For Nuclear we estimate the need for around 22MW of electricity power, which would require a capital investment of $111M. For rooftop solar, we used EnergySage's example system to determine the cost of $69M for the entire MIT PV-solar system.
- **Bio-fuels:** Since we need to use only 20% mix (with Natural Gas), we assume no adaptation is required for the CUP turbine and CUP systems other than installation of a bio-gas tank and a pre-treatment system for the bio-gas inlet to CUP turbine. We asses a project to install this infrastructure to cost up to $10M.
- **Carbon Capture:** We assume a system to be sized for the entire power capacity of the CUP, 48MW. We used installed cost for a commercial carbon capture system, 576.4 $/kW [10]. In addition, we added a 10% premium due to the relatively small size of the CUP compared to utility power plants. As a result, we evaluate the capital cost of the carbon capture system to be $30.4M.
- **Electric Heating:** Although the model did not recommend the use of electric heating as a source we recognize the need for backups being in effect and so have estimated the use of $10M dollars in electrification efforts such as boilers.

- **Natural Gas, ISO-NE and PPAs:** we assume no capital investments are needed to use any of these technologies.

Table 4 summarizes the capital cost assessment for the various energy sources we presented in our main model.

Table 4: Capital Investment Cost Estimation

Technology	Power capacity need	Capital Investment (until 2050)
Efficiency	-	\$420M
GSHP	9MW	\$89M
ASHP	134MW	\$274M
Elect Heating	-	\$10M
Nuclear Batteries	22MW	\$111M
ISO-NE	14MW	-
PPAs	15MW	-
Solar	3.7MW	\$69M
Bio-fuels	8MW	\$10M
Natural Gas	40MW	-
Carbon Capture	-	\$30.4M
Total Estimated Capital Investment	-	\$1.013B

Future Work

We built this model in order to come up with an analytics-based solution to a complex problem. The optimization for cost approach is meant to help planners build a map to achieve carbon neutrality for MIT in the least costly way overall, thus using LCOE as the main decision metric. Our team performed robustness tests on the model to ensure it would supply appropriate results upon adjusting the inputs. These tests showed satisfactory results, as the model reacts to change in LCOE modelings as well as changing constraints, such as disabling the use of a certain resource. However, the model's outputs are only as good as the inputs it gets. In this work, we modeled the different technologies' LCOE based on a series of assumptions that enabled us to come up with a plan for MIT to achieve carbon neutrality by 2050. In order to achieve more accurate results using this model in the future, these assumptions need to be validated or altered via additional research and as more information becomes available. Our suggestion for future work, or research, is to build accurate LCOE models for each technology, then run the model again based on the formulation presented in this paper.

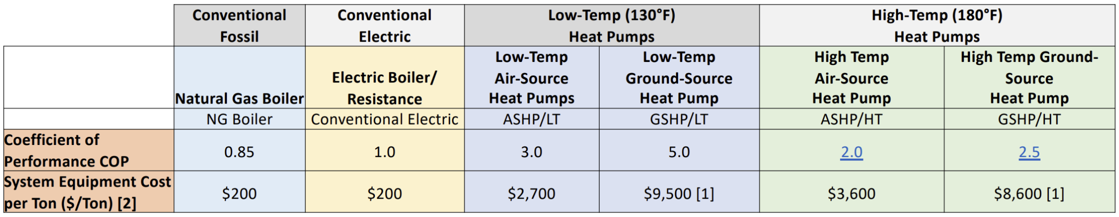
Conclusion

This paper presents, as requested, a plan to achieve carbon neutrality in scopes 1 and 2 carbon emissions by 2050 for MIT. Our team presented a scenario, including estimated budget and timeline for implementation, that is set to achieve this goal with an effective use of the resources and assets MIT has. Our method to develop the plan, was through an optimization model, that minimizes the Levelized Cost Of Energy (LCOE), under a zero carbon constraint. The LCOE metric incorporates all costs associated with energy use, including capital expenses and operating expenses. Using a series of assumptions, we evaluated the LCOE for MIT, for each technology under consideration. For future work, our team suggested revaluations of these LCOE numbers based on deeper research.

The results of our model show that for MIT to achieve the set goal, it needs to utilize different energy generation, conservation, and conversion technologies, such as nuclear, rooftop solar, efficiency projects, and heat pumps installations. Our base model projects $154M of annual cost, for the year 2050. We also acknowledge the possibility of some technologies, such as nuclear, to not be available or some assumptions to be wrong, for example, ISO-NE not achieving net-zero by 2050. Our optimization model design enables us to easily change our assumptions and develop contingency plans for such scenarios. We show a couple of these alternative scenarios in our paper. We can learn from these the addition in expected annual costs if a technology is not available, as can be seen in both scenarios. The scenario in which both nuclear and ISO-NE are not available, is more than four times more expensive than the others, with an estimated 2050 cost of $799M. This result is valuable for decision makers considering different scenarios and trying to decide where to direct MITs efforts.

We hope our work will be useful to inform MIT leadership in its effort to decarbonize MIT's operations. By offering this optimization tool and several examples of output scenarios, we demonstrated the power of an analytics-based approach to inform the solution development for achieving the goal of net-zero MIT by the year 2050. Upon completion of this work, we believe this is possible. We also believe that this approach suits MIT's goal and mission, and that MIT can set an example for institutions, companies, and other entities around the world, for developing science and analytic based solutions for solving climate-change problems.

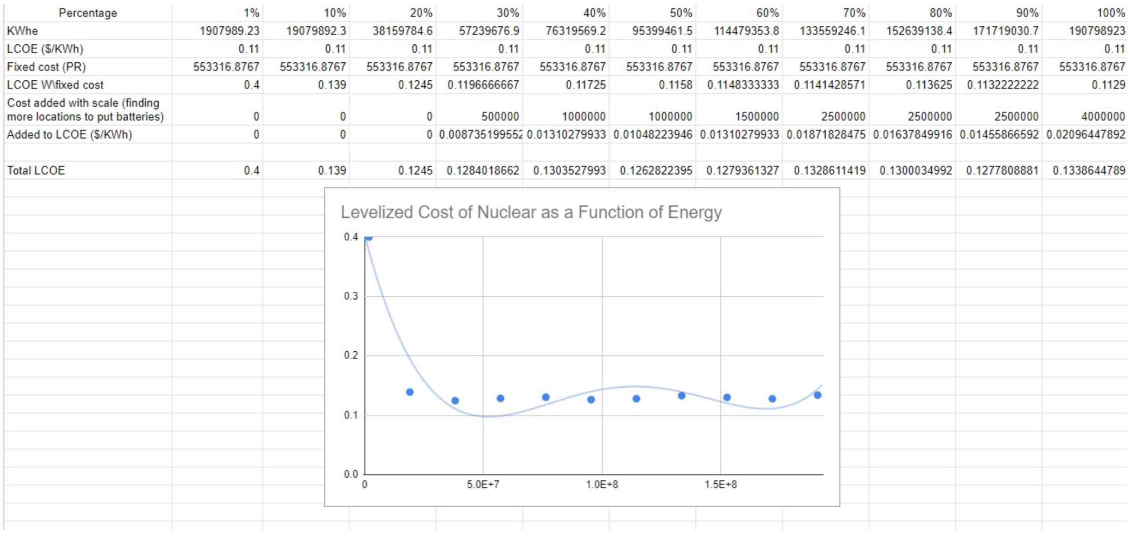
Appendix 1 - Heat pumps cost analysis



	Conventional Fossil	**Conventional Electric**	**Low-Temp (130°F) Heat Pumps**		**High-Temp (180°F) Heat Pumps**	
	Natural Gas Boiler	**Electric Boiler/ Resistance**	**Low-Temp Air-Source Heat Pumps**	**Low-Temp Ground-Source Heat Pump**	**High Temp Air-Source Heat Pump**	**High Temp Ground-Source Heat Pump**
	NG Boiler	Conventional Electric	ASHP/LT	GSHP/LT	ASHP/HT	GSHP/HT
Coefficient of Performance COP	0.85	1.0	3.0	5.0	2.0	2.5
System Equipment Cost per Ton ($/Ton) [2]	$200	$200	$2,700	$9,500 [1]	$3,600	$8,600 [1]

Figure 3: Costs from BU analysis of heat pumps

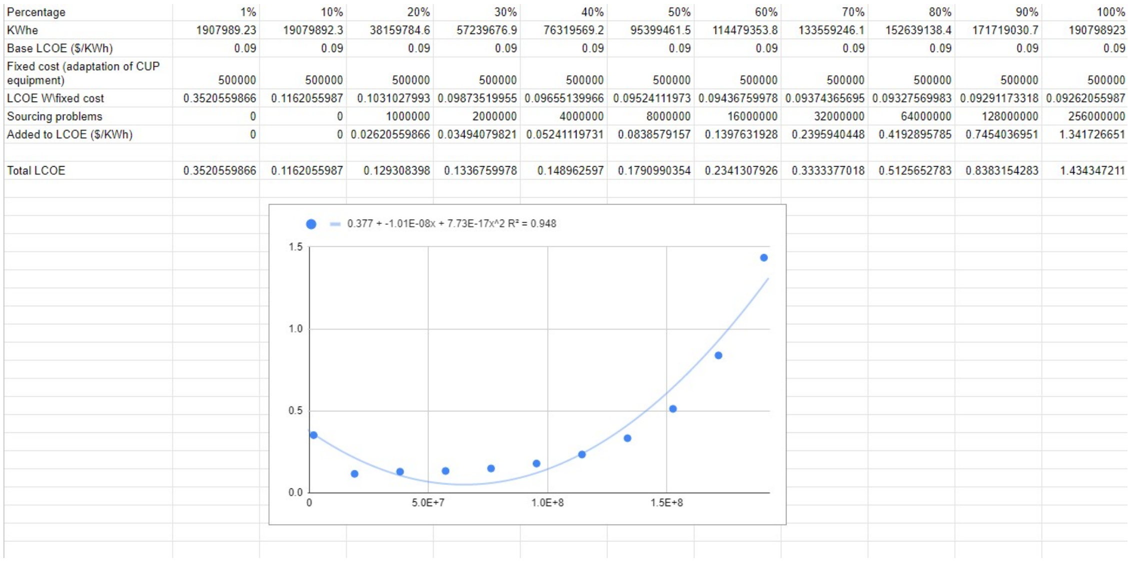
Appendix 2 - Nuclear LCOE modelilng calculations



Percentage	1%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
KWhe	1907989.23	19079892.3	38159784.6	57239676.9	76319569.2	95399461.5	114479353.8	133559246.1	152639138.4	171719030.7	190798923
LCOE ($/KWh)	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Fixed cost (PR)	553316.8767	553316.8767	553316.8767	553316.8767	553316.8767	553316.8767	553316.8767	553316.8767	553316.8767	553316.8767	553316.8767
LCOE W\fixed cost	0.4	0.139	0.1245	0.1196666667	0.11725	0.1158	0.1148333333	0.1141428571	0.113625	0.1132222222	0.1129
Cost added with scale (finding more locations to put batteries)	0	0	0	500000	1000000	1000000	1500000	2500000	2500000	2500000	4000000
Added to LCOE ($/KWh)	0	0	0	0.008735199552	0.01310279933	0.01048223946	0.01310279933	0.01871828475	0.01637849916	0.01455866592	0.02096447892
Total LCOE	0.4	0.139	0.1245	0.1284018662	0.1303527993	0.1262822395	0.1279361327	0.1328611419	0.1300034992	0.1277808881	0.1338644789

Figure 4: Calculations to model nuclear batteries LCOE as a function of electricity generation

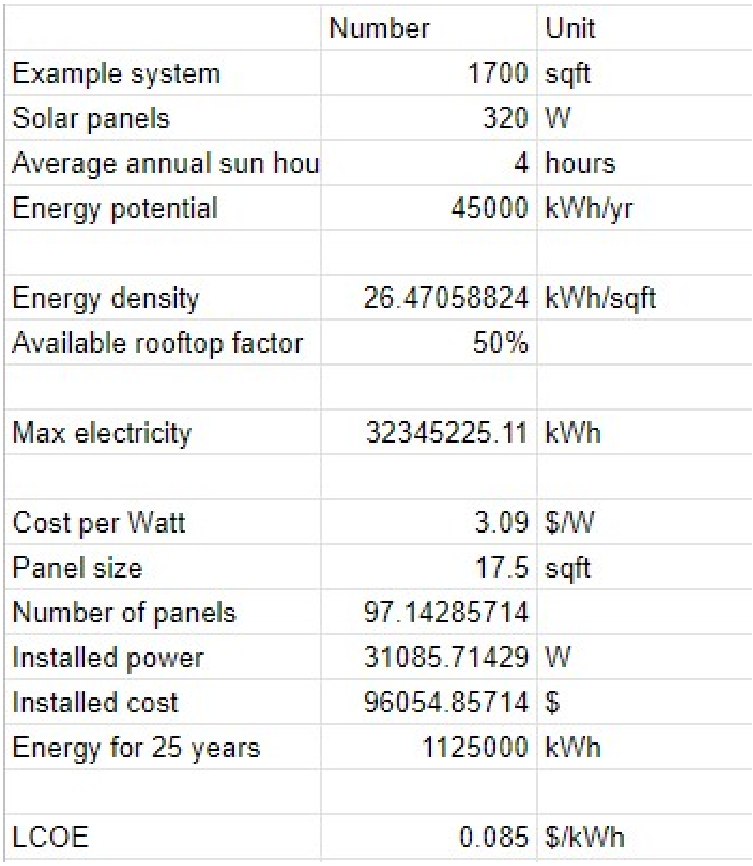
Appendix 3 - Biofuel LCOE modelilng calculations



Percentage	1%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
KWhe	1907989.23	19079892.3	38159784.6	57239676.9	76319569.2	95399461.5	114479353.8	133559246.1	152639138.4	171719030.7	190798923
Base LCOE ($/KWh)	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Fixed cost (adaptation of CUP equipment)	500000	500000	500000	500000	500000	500000	500000	500000	500000	500000	500000
LCOE W\fixed cost	0.3520559866	0.1162055987	0.1031027993	0.09873519955	0.09655139966	0.09524111973	0.09436759978	0.09374365695	0.09327569983	0.09291173318	0.09262055987
Sourcing problems	0	0	1000000	2000000	4000000	8000000	16000000	32000000	64000000	128000000	256000000
Added to LCOE ($/KWh)	0	0	0.02620559866	0.03494079821	0.05241119731	0.0838579157	0.1397631928	0.2395940448	0.4192895785	0.7454036951	1.341726651
Total LCOE	0.3520559866	0.1162055987	0.129308398	0.1336759978	0.148962597	0.1790990354	0.2341307926	0.3333377018	0.5125652783	0.8383154283	1.434347211

Figure 5: Calculations to model biofuel LCOE as a function of electricity generation

Appendix 4 - Solar LCOE calculations



	Number	Unit
Example system	1700	sqft
Solar panels	320	W
Average annual sun hou	4	hours
Energy potential	45000	kWh/yr
Energy density	26.47058824	kWh/sqft
Available rooftop factor	50%	
Max electricity	32345225.11	kWh
Cost per Watt	3.09	$/W
Panel size	17.5	sqft
Number of panels	97.14285714	
Installed power	31085.71429	W
Installed cost	96054.85714	$
Energy for 25 years	1125000	kWh
LCOE	0.085	$/kWh

Figure 6: Calculations to model Soalr-PV LCOE

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