Scalability of Carbon-Neutral Cooling System

by

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Abstract

The scalability of a carbon neutral cooling system to provide the MIT campus its annual cooling needs was assessed. The cooling system under observation requires 400 W of electricity mainly to power unidirectional fans that propel air through the chambers and 1423.88 W of hot water to raise the temperature of the airflow in the regenerative cycle.

The results of the theoretical energy calculations, based on the annual cooling needs and energy consumption of MIT in the 2017 fiscal year, determined that there is not enough excess hot water supplied by the natural gas utilized by the power plant on campus in order to fully operate enough system units to contribute adequate cooling. MIT requires 207,679,950.191 kWh of energy of cooling annually with an excess of 211 kWh of excess hot water, which is not enough to power the required 101,839 system units necessary to provide total campus cooling, which is 8.45×10^7 kWh of energy.

Evacuated tube solar collectors across an area of 181 m^2 may be able to bridge the thermal energy gap assuming 800 W/m^2 at 65% efficiency.

Thesis Supervisor: Douglas Hart
Title: Professor of Mechanical Engineering

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Chapter 1

Introduction

1.1 Motivation

World-wide demand for cooling homes, offices and other interior spaces claims billions of dollars annually and with the low efficiency of current appliances coupled with the global warming crisis, the wave of need for cooling shows no signs of receding. According to the International Energy Agency, 10 air conditioners will be sold every second over the next 30 years.[5] In 2013, China was solely responsible for the purchase and installation of 64 million air conditioning units, eight times that of the United States.[7] Global consumption of power for air conditioning exclusively is projected to grow 33 fold by the year 2100, multiplying faster than the urgency of heating.[9] In the U.S. alone, air conditioning units in residential spaces capture 6% of electricity usage, estimated to cost nearly $9 billion each year.[4]

The main technology behind cooling smaller living areas and commercial spaces relies heavily on the usage of refrigerants. The coolants are pumped into an evaporator and a maze of metallic fins that transfer the heat inside a space to the refrigerant by allowing it to reach a gaseous state. The refrigerant then condenses back into a liquid in its external circuit where the heat is released into the environment. Up to present day, refrigerants such as halogenated chlorofluorocarbons have been used, which emit harmful greenhouse gases during the refrigeration cycle along with the heat extracted from the airstream.

Gases like these negatively affect the ozone layer more than the commonly blamed toxin, carbon dioxide.[4] Emission of these lethal gases ultimately expedite global warming and fuel the ongoing cycle between rising temperatures and global cooling needs. Numerous publications estimate the Earth has already heated up between 0.9°C and 1.2°C since the start of the Industrial Revolution and with present day rates of industrial, residential and commercial practices scientists do not anticipate a decline in emissions.[11]

The Carbon-Neutral Cooling System Team has therefore sought to present an alternative evaporative cooling appliance for smaller dwelling spaces that is carbon-neutral and affordable.

1.2 System Requirements

In order to facilitate comfortable living conditions in a eco-friendly manner, the system needs to meet several criteria outlined below in Table 1.1.

Table 1.1: Full Cooling System Requirements

Requirement	Specification	Reasoning
Temperature	22°C	Maintain air within average range of comfort
Humidity	RH$<$ 60% (max)	Maintain air within average range of comfort
Carbon-Neutral	GWP$<$ 0.1 (max)	No emit substances with high GWP
Reliability	4380 runtime (min)	Practical system implementation
Power	9.2 kWh	Maximum power consumed by average household
Volume	$1.8\mathrm{m}\times0.75m \times 1.2m(max)$	Portable and installable indoors
Weight	45 kg (max)	Weight below OSHA limit for two-person lifting

System requirements have been calculated based on the following assumptions regarding the cooled environment: 50m^2 enclosed space, two externally exposed walls of length 14m each, and two moderately active individuals. Full details of energy calculations that fit the system requirements along with the assumptions can be found in Appendix C of White Paper. It is also vital to note the full definition of carbon-neutral and climate-neutral processes. Carbon-neutral denotes the emission of carbon dioxide into the environment while climate-neutral specifies the ejection of all greenhouse gases, including carbon dioxide. From this point on, the paper will continue to utilize the term carbon-neutral but insinuate the definition of climate-neutral based on the following equation.

$$\text{Carbon}_{\text{Produced}} - \text{Carbon}_{\text{Sequestered}} - \text{Carbon}_{\text{Offset}} = 0$$

1.3 Existing Solutions

Modern cooling systems fall into several categories, first of which uses refrigerants such as HCFC-22 or R-22. Central air conditioners cool larger living spaces such as houses with a central compressing unit and propels the air into other rooms using a fan and the existing duct system. Heat pumps are nearly identical to central air conditioners in that the procedure is reversible for necessary heating needs during colder times. Other variations of these techniques manifest in the form of ductless mini-split and room air conditioners which are less robust and frequently less efficient. Refrigerants are an indispensable aspect of this operation as it provides the main source of heat transfer between the internal and external environments. However the production of GWPs are intrinsically tied to their usage in current methods of cooling and thus only exacerbate the existing environmental crisis. Furthermore, the efficiency of current models range merely between 30% to 50% and even lower for older, less adequate prototypes, only perpetuating their usage to compensate for the lack of efficient power usage.

The second group of systems relies on simpler technology but makes much more use of the surrounding climate. Evaporative coolers exploit the evaporation of water as the primary mechanism of cooling. The vaporized water cools the internal air that is blown across it and consequently adds moisture to it as well. Indirect evaporative coolers alternatively eliminate the addition of moisture through the strategic placement of the evaporation process. These are not as frequent in modern homes but function well in drier climates and flaunt a much higher efficiency ratio.

Other, less common methods include the collection of heat during the day, cool air at night and the storage of energy until absolutely required by residents. Still other mechanism cycle through a similar storage process between hotter and colder seasons.[3]

Besides these approaches, current mitigation procedures include visitations to larger builds such as malls during business hours, amending policies to hold air conditioning manufacturers to higher efficiency standards and alternative cooling methods which on average tend to be more expensive and less efficient.

1.3.1 LORACS Solution

The Carbon-Neutral Cooling System Team has combined the efficiency of a direct evaporative cooler with a desiccant wheel in order to provide a system that can adequate cool an enclosed living space with reasonable amounts of power and no negative environmental consequences. The system consists of three modules: The Desiccant Wheel Module, Cascade Heat Exchanger Module and Cooling Module. The first is concerned with the production of extremely dry and hot air. Several passes through the desiccant wheel will effectively dry out and heat up the air in preparation for the evaporative cooler. The second changes the temperature of the air at constant specific humidity to output the correct temperature of air via the direct evaporative cooler before it enters the cooling module where the air is finally chilled to the correct temperature to cool a room.

Chapter 2

Design of System

2.1 Theory

Air temperature and humidity in this system is tracked by a psychrometric plot which records the humidity on the vertical axis and dry bulb temperature on the horizontal axis. Dry bulb temperature refers to the temperature of the air without accounting for moisture, which is taken care of by the humidity scale. An example chart can be found below in Figure 2.1.

Two distinct paths of airflow are exhibited in the system. First, the general process flow is the path in which ambient air is cooled and pumped into the room. Stages 1 to 2 represents the initial intake of ambient air into the desiccant wheel which adds heat and removes moisture. The temperature of the air is then lowered from stage 2 to 3 at a constant specific humidity through the cascade heat exchanger. The process is repeated once more in stages 3 to 5. The target cooling temperature is reached when the air is passed through the direct evaporative cooler in which moisture is also added back into the air stream. This completes the first large airflow path.

A counter airstream is cycled back through the system from stages 6 to 10, called the regenerative process flow. After cool air is introduced to the target cooling space, it will warm up after a period of time due to the higher average temperature of the room, depicted in stages 6 to 7. In stages 7 to 8, the slightly heated air is pulled back into the system through the cascade heatexchanger that initially cooled the ambient air in order to heat the air that has now entered. The air is further heated in stages 8 to 9 using a heat source which is in this case a steady supply of excess water. Stages 9 to 10 completes this cycle by using the desiccant wheel to transfer heat and the water pulled from the ambient air to this counter stream. Figure 2.1 and Table 2.1 exhibits the specific heats and temperatures as well as the hardware involved in each respective stage.

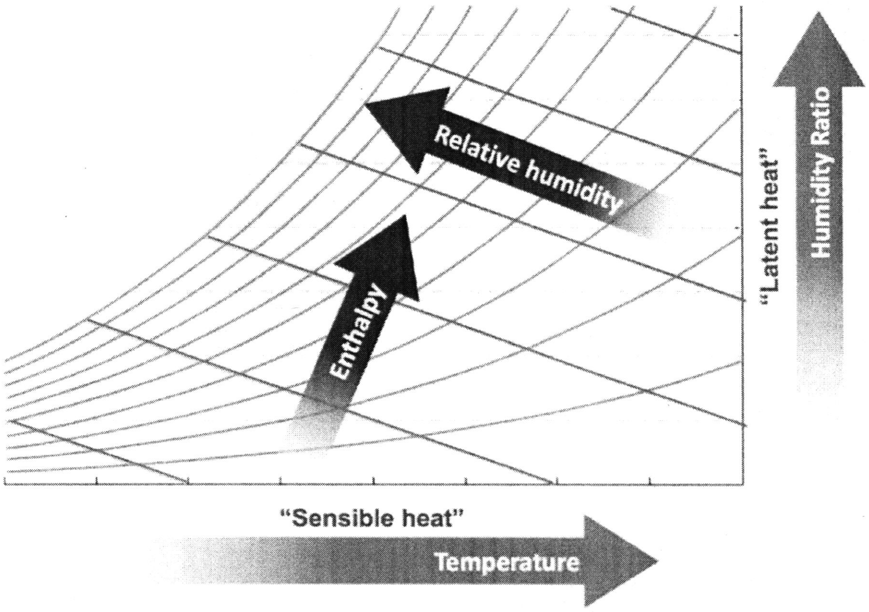


Figure 2-1: An example psychrometric chart that depicts air temperature and humidity at specific points of airflow path

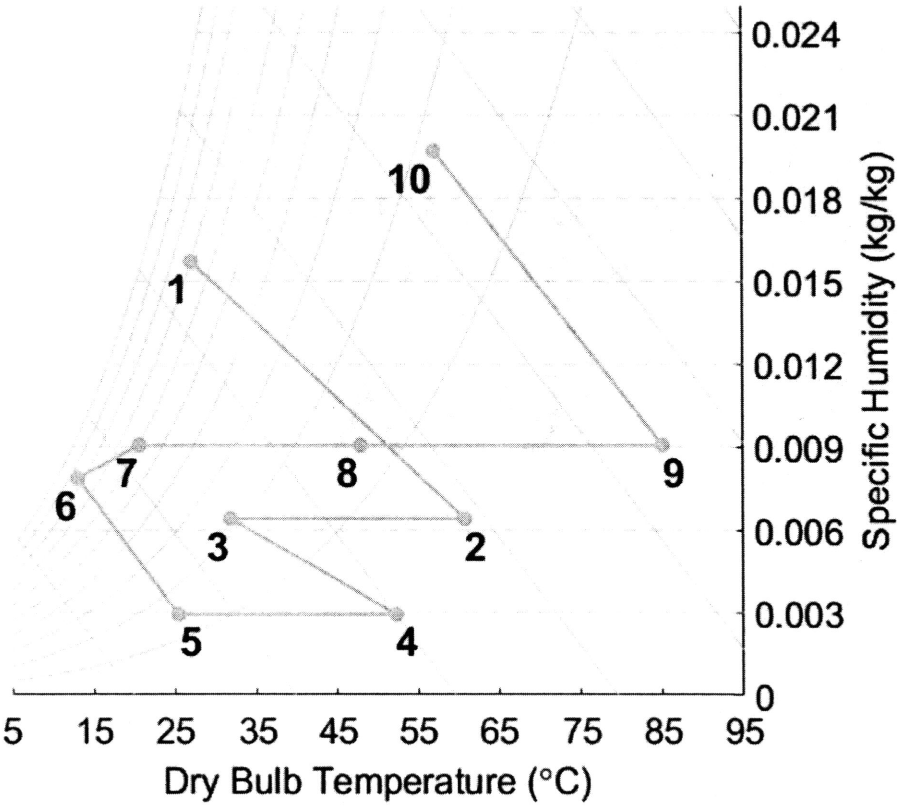
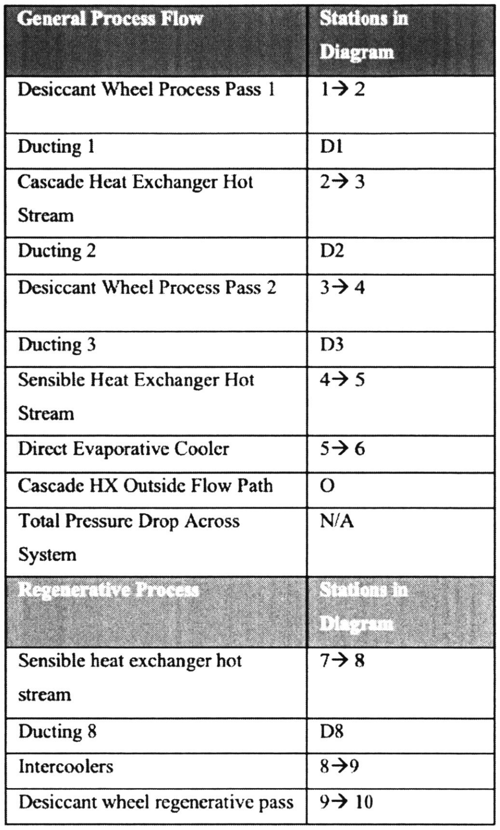


Figure 2-2: LORACS specific psychrometric chart that specifies target air temperature and humidity within the system at certain stages of airflow path. Stages 1 to 6 denote the general process flow for cooling while Stages 6 to 10 illustrate the regenerative process flow used to prepare the system for continued cooling capacities.

Table 2.1: General and Regenerative Process Flows



General Process Flow	Stations in Diagram
Desiccant Wheel Process Pass 1	1→2
Ducting 1	D1
Cascade Heat Exchanger Hot Stream	2→3
Ducting 2	D2
Desiccant Wheel Process Pass 2	3→4
Ducting 3	D3
Sensible Heat Exchanger Hot Stream	4→5
Direct Evaporative Cooler	5→6
Cascade HX Outside Flow Path	O
Total Pressure Drop Across System	N/A
Regenerative Process	**Stations in Diagram**
Sensible heat exchanger hot stream	7→8
Ducting 8	D8
Intercoolers	8→9
Desiccant wheel regenerative pass	9→10

2.2 Architecture

2.2.1 General Layout

Construction of the physical cooling system can be broken down into three main modules: the desiccant wheel, the cascade heat exchanger and the evaporative cooler. Each module interacts with steps from both the general and regenerative process flow due to the efficient heat recycling nature of this system. A spatial diagram of the system can be found below in Figure 2.2.1. which labels the general process, regenerative and the ambient flow streams.

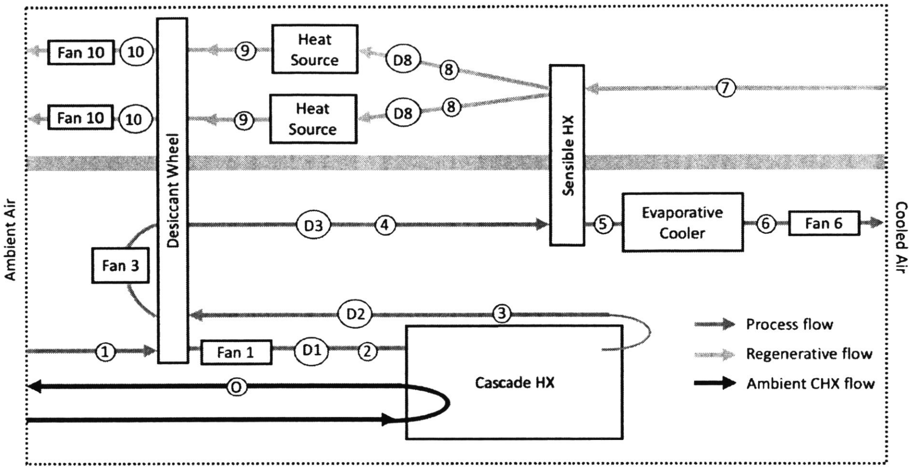


Figure 2-3: A spatial representation of the system relating specific stages of various flow paths to major hardware appliances they interact with in a dimensionally accurate diagram.

2.2.2 Physical Construction

Each module is constructed of plywood boards that house each of the three main hardware appliances. Sealed ducts connect the airstreams between each module while a combination of compressive foam strips and foil tape seal the edges and interior compartments of each module. Fans throughout the system propel the airstreams through each heating and cooling compartment which can be plugged into any outlets available in a modern home. Sensors controlled by arduinos track the inlet and outlet airspeeds, humidities and temperatures of the air streams in order to observe and analyze the performance and efficiency of the system at every stage. A CAD model of the final system is depicted below in Figure 2.2.2.

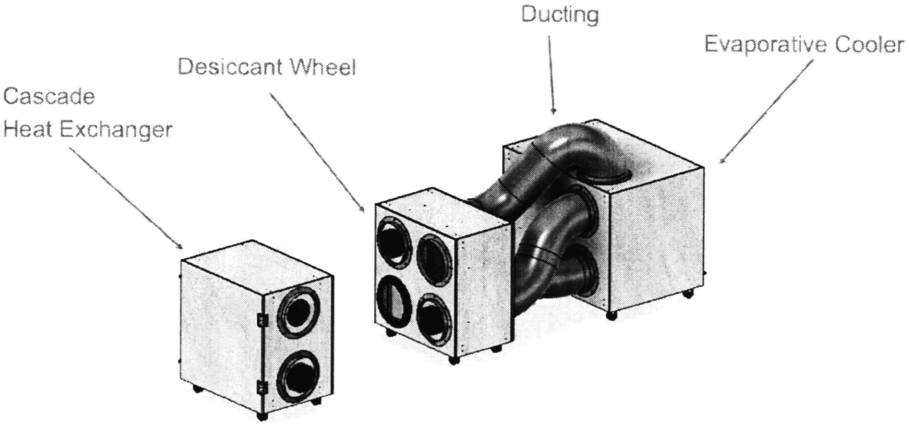


Figure 2-4: CAD model of cooling system broken down into three main modules: desiccant wheel, cascade heat exchanger and evaporative cooler.

Chapter 3

System Energy Consumption

Electricity and hot water are the two dominant energy sources for the full cooling system. Sensors connected to multiplexer boards and controlled by Arduino boards along with the fans draw upon roughly 400 W of power. Compared to the power required for the fans, the power needed to operate the three Arduino boards is less than 0.125 W each, totaling up to less than 1 W for all the sensors. Air is cycled through the system mainly through the use of five fans that draw 50-80 Watts of power each. In total, this adds up to a maximum of 400 W. These are accessed through widely available power 120VAC outlets found in interior office and residential spaces.

The required power requirement of hot water is dictated by the flow rate and efficiency of the air after exchanging heat with the hot water. By equating the change in thermal energy of the air divided by the efficiency of the respective heat exchanger, the change in thermal energy, and consequently the power of the hot water can be deduced. Based on a flow rate of $0.026\text{m}^3/\text{s}$ and at 85% efficiency for the gas-liquid heat exchanger described in equation 1, the system requires 1423.88 W of power provided by the excess hot water.

Chapter 4

Scalability to MIT

4.1 MIT Energy Consumption and Potential

Annually, MIT requires roughly 207,680,950.191 kWh of energy to provide cooling for its facilities as of the 2017 fiscal year. Several energy sources currently fuel the production of this energy including natural gas, oil, and electricity. This process is responsible for 20.5 kMT of greenhouse gases.[10]

During colder seasons, MIT efficiently cycles the excess heat generated from the used of natural gas through buildings on campus to heat rooms. However during the summer, this thermal energy is unused. Hot water is pumped along long stretches of pipelines until it cools to a reasonable temperature for other potential use. This system taps into the lost thermal energy to heat up the regenerative airstream from stages 8 to 9. MIT consumes up to 608.1 kWh of natural gas annually and directs its energy to two subpaths. One entails the process of producing 67.3 kWh of electricity from the turbines while the other produces 329.8 kWh of steam from the boilers. This leaves 211 kWh of hot water that is untapped during the warmer days of summer.

4.2 Scalabiltiy

For the purposes of calculating total energy consumed and required by the system, estimations regarding average runtimes have been made. This paper will assume there are 3 months out of the calendar year in which MIT uses cooling. We also assume an average of 30 days per month, 10 hours of regular operation of the cooling system each day. This yields 900 hours. However, based on the calculations of the required runtime to provide 3.5 kW of cooling power during different ambient temperatures in Appendix C of the "White Paper on a Carbon-Neutral Cooling System", the percentage of actual runtime can be determined.[8] Previous estimations recorded a 30% of operational runtime when ambient conditions are at 27°C and 85% of the time at 46°C ambient temperature. Assuming the worst case scenario of the hottest average recorded temperature in Cambridge, MA history as 39°C, simple linear estimation returns a 64.74% runtime. In turn, the actual required runtime is 582.66 hours.[1] When the runtime is multiplied by the power provided by one cooling system, the total cooling energy potential given by one cooling system annually can be observed, at 2039.3 kWh. Given the total cooling energy MIT requires annually, 101,839 cooling system units must be in place to fully supply campus with enough cooling. As the system utilizes two sources of energy, electricity and waste hot water, and waste hot water is scarcer in quantity, the question of whether or not this technology can feasibly be scaled to produce all of MITs cooling needs will depend on the availability of waste hot water on campus. With 101,839 required cooling system units, each requiring 1,423.88 W of hot water for a complete runtime of 582.66 hour, the comprehensive

Table 4.1: Relevant Energy Quantities

Annual Energy	Power [kWh]
MIT Cooling	207,680,950.191
MIT Excess Hot Water Supply	211
Total Cooling System Hot Water Need	8.45×10^{7}

amount of energy required solely as a form of waste hot water tallies to 8.45×10^7 kWh.

This required thermal energy is much greater than the observed amount of usable waste heat of 211 kWh, by 5 orders of magnitude. Therefore at the current efficiency of the cooling system and its required power restraints, this technology at present cannot be scaled to comprehensively provide MIT cooling power for hotter seasons.

Chapter 5

Other Heat Sources

To bridge the gap in thermal energy need and requirement to scale this technology, solar collectors can prove to be viable options. Assuming the 211 kWh of energy untapped waste hot water unused by MIT is negligible in comparison to the required thermal energy needed by the 101839 system units, the target energy to provide is still 8.45×10^7 kWh.

Evacuated tube are the more efficient type of solar collectors. Two glass surfaces on either side of an evacuated space redirects the suns heat to warm up an internal fluid.[2] The power specification is estimated at worst case to be 800 $\mathrm{W/m^2}$ at 65% efficiency.[6] Dividing total energy by the the number of hours of operation and the power draw of the solar collector, 181 m^2 of open space is required. For perspective, the area covered by half of a professional football fields endzone would be sufficient to house this amount of solar collectors.

Chapter 6

Future Modifications

6.0.1 Potential Modifications

In order to increase cooling performance, there are a few modifications that can aid this process. First is the implemented sealing methods. All housing material is wood which is porous in nature and not ideal for airtight or thermally insulating compartments. Cheaper materials that are less porous and more insulating can greatly increase the heat transfer efficiency of each critical stage. Sealants around openings for sensors and doors is currently fulfilled by compressive foam and foil tape. However, caulking and other substances that start out as viscous fluids can more effectively cover small holes and pores in the system. Another point of improvement stems from the media used by the evaporative cooler. Cardboard and aspen fiber have been tested in the direct evaporative cooler used in the current system. However there are more effective mediums such as cellulose, spongy pads that are generally more expensive than wood but harness the accessible evaporative potential better.

6.0.2 Future Goals

Goals for future iterations of this cooling system revolve around the adoption of this technology and those similar in residential and commercial settings. There are three avenues to this objective: increased efficiency and marketability. Through the aforementioned modifications to the sealing methods; individual hardware efficiencies such as the heat exchanger, desiccant wheel and direct evaporative cooler; and more efficient energy sources can pave the way for increased power efficiency which can lower the barrier to those who are unfamiliar with this mechanism. Each physical component of the devices implemented in the system have intrinsic inefficiencies that can be avoided or bypassed through the use of higher quality parts.

Currently, heating is facilitated by an external hot water supply driven by the fact that MIT possess a cogeneration plant that utilizes this source effectively in the summer but wastes its potential during warmer seasons. However not all facilities or environments in need of this cooling system have such readily available supplies in amounts as large as those provided by the MIT power plant. Therefore, allowing the system to be more compatible with energy sources that are already inherent to various environments can promote the use of this system.

Furthermore, the system at its current state is modular in technical design but not maneuverable, easily installable or aesthetic. Each module is relatively large and requires additional time to connect to another heating source such as hot water. Additionally, it is loud and can benefit from a visual revamping. Factors such as this can greatly increase the market appeal as well convince consumers of its functionality as well.

Chapter 7

Conclusion

Climate change and its consequences will soon and may well be irreversible. However, the accumulation of several seemingly small steps can prevent such an inevitability. The Carbon-Neutral Cooling Team has taken this initial step to seek out alternative methods to meet immediate local cooling needs using excess or untapped energy, specifically thermal heat in this case to provide as a heat source for the regenerative airstream cycle.

Although the hot water leftover from the consumption of natural gas on the MIT campus is not sufficient enough to satisfy annual cooling demands, there are other avenues of extracting thermal heat for this system such as solar collectors. Through further efforts to increase energy transfer efficiency and implement other carbon-neutral techniques, the goal of this project is to first make the cooling process on campus carbon-neutral and potentially all global cooling.

Bibliography

[1] Average Weather in Boston. WeatherSpark.com.

[2] How does a Solar Vacuum Tubes Work. SolarTubs.com.

[3] Types of Cooling Systems. smarterhouse.org.

[4] Air Conditioning, October 2015. Energy.gov.

[5] Cooling in buildings, March 2019.

[6] Boaz Soifer Bristol Stickney. Solar Thermal Hydronics: Collector Comparison and Selection, November 2009.

[7] Lucas Davis. Air Conditioning and Global Energy Demand, April 2015.

[8] Wasay Anwer et. al. White Paper on a Carbon-Neutral Cooling System. Technical report, Massachusetts Institute of Technology, 2018.

[9] Jon Henley. World set to use more energy for cooling than heating, October 2015.

[10] MIT. Plant GHG Metrics, 2017.

[11] Earl J. Ritchie. Exactly How Much Has the Earth Warmed? And Does It Matter?, September 2017. Forbes.com.