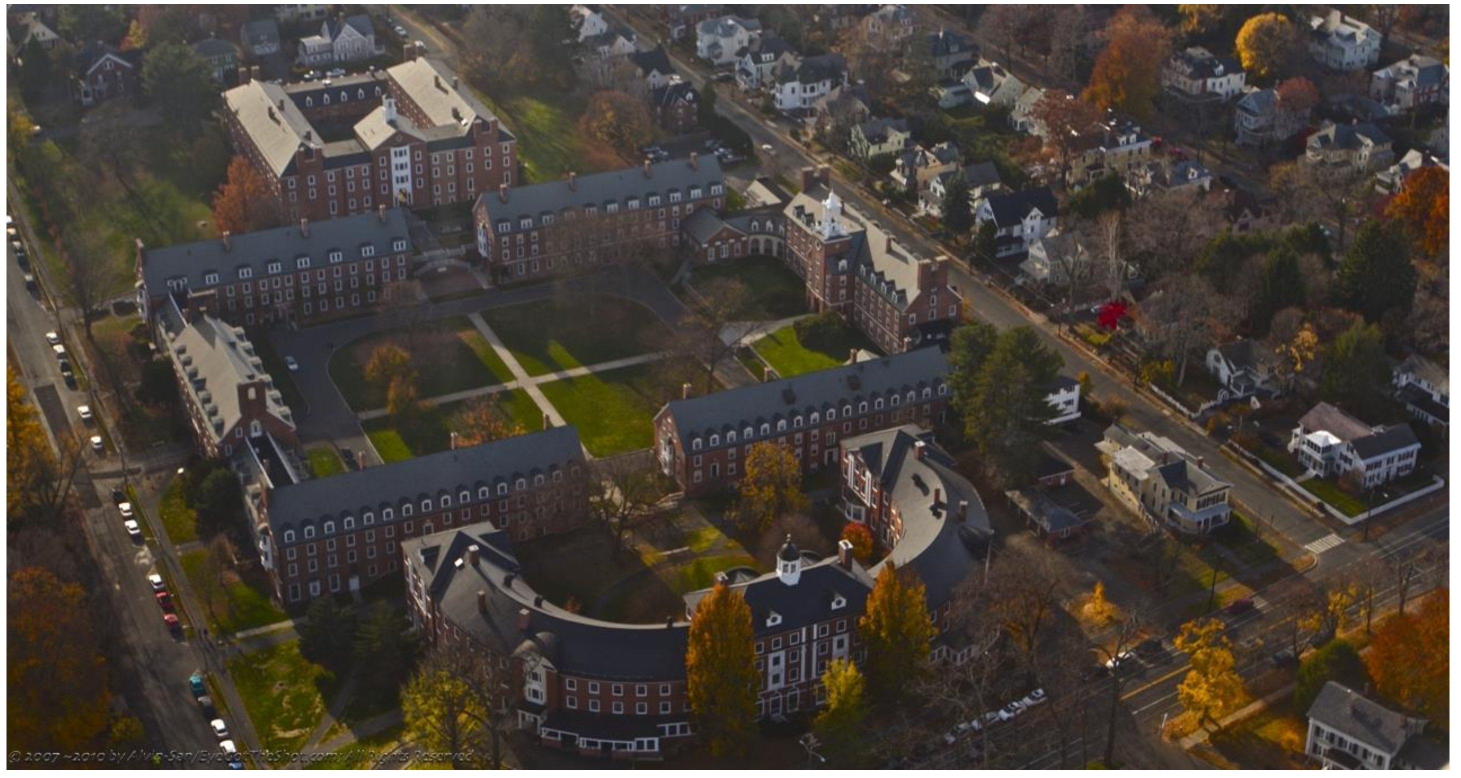

Smith College
Campus Energy Decarbonization Study

(Revision 3)

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EXECUTIVE SUMMARY

The purpose of this report is to explore a variety of strategic options and recommend a direction that would enable Smith College to achieve its 2030 Climate Targets. Currently Smith College has committed to being a Zero Emissions campus by 2030. This study was specifically to look at what would be required to achieve this target in campus buildings.

The main objective of the study is to develop and evaluate possible approaches and options for deep carbon emission reductions and, provide recommendations for the best overall Smith College campus decarbonization strategy. This recommended strategy outlines a specific path and key steps that will lead towards eliminating carbon emissions from the campus building energy use by 2030.

This will include the following elements:

- Be cost effective from long-term, life cycle cost perspective
- Must be technically sound and reliable in providing long-term low-carbon energy supply
- Be resilient to a multitude of external risks, such as risks related to climate change, availability and affordability of low-carbon fuels and energy sources, and variable economic conditions
- Provide opportunities to engage students and researchers on campus in energy use and energy efficiency research.

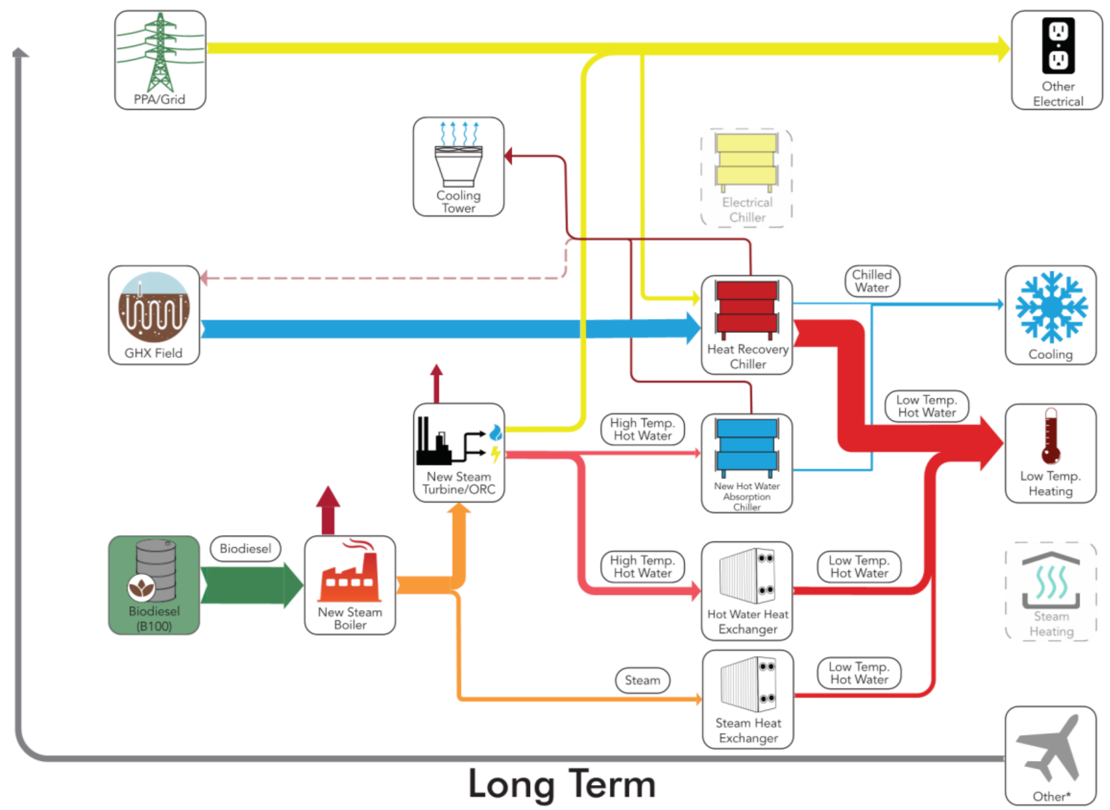
Based on our analysis that involved comprehensive evaluation of the existing campus energy infrastructure and energy demand profiles, all available low-carbon fuel/ energy sources and complementary technologies, and the development and evaluation of five potential broad decarbonization strategies, we have developed, analysed and recommended the following Short, Medium and Long term steps to begin the transition of Smith College campus to carbon neutral performance:

1. **Short Term strategy**: Fuel switch for the existing steam boilers from natural gas to renewable biodiesel.
2. **Medium Term strategy**: Initial stage of design and implementation of a new low temperature heating system operating in parallel with the existing Steam heating plant and steam heating distribution network.
3. **Long Term strategy**: Final stage of design and implementation of the new low temperature heating system, Tri-generation system based on renewable biodiesel and decommissioning of the existing steam heating and CHP plants and steam heating distribution network

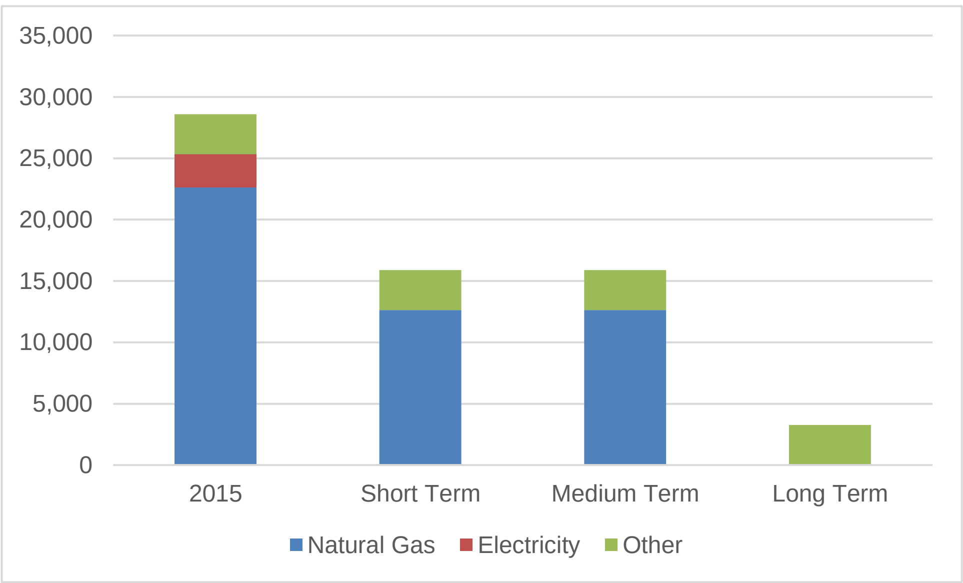
While the implementation of the recommended Short Term, Medium Term and Long Term steps will allow Smith College to achieve carbon neutral performance, it is important to remember that, at this initial stage of the project, there are still a number of details that require further investigation. Details such as the final source of renewable fuel (whether this is B100 from Northeastern Biodiesel or another renewable fuel from a different supplier), for example, or which buildings will be connected to the low temperature heating water network still need to be decided.

These details, however, will not ultimately change the overarching recommended strategy outlined in this report, or prevent the College from achieving its goal of carbon neutral performance. The fundamental principles that the Short Term, Medium Term and Long Term strategies are based on (switching to a low carbon fuel in the short term, then progressively installing and switching the campus to a low temperature heating water system) have the flexibility to be adapted to suit any challenges as they arise.

In order to achieve this ambitious goal the College will need to make a number of critical decisions in the next few years, all of which will have long term implications on its energy infrastructure. The approach developed and recommended as part of this study will allow the College to make significant reductions to its GHG emission in the short term, thereby buying it more time to properly investigate and implement more substantial decisions regarding its key existing energy infrastructure components and the existing building stock. By following the recommended approach Smith College will not only be able to meet its carbon neutral target, but also modernize its building energy infrastructure to be compatible with any renewable energy technologies that are currently available as well with those that might become available in the future.



Energy and Emissions Flow (Recommended Approach, Long Term)



Smith College Campus GHG Reductions

LIMITING CONDITIONS

LIST OF ABBREVIATIONS

BAU	Business as Usual
CED	Campus Energy Decarbonization
CHP	Combined Heat & Power
CHW	Chilled Water
DES	District Energy System
EDI	Energy Demand Intensity
GHG	Greenhouse Gas
HW	Heating Water
LTHW	Low Temperature Heating Water
MMBTU	Million BTU/hr
PV	Solar Photovoltaic
PPA	Power Purchase Agreement

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1. INTRODUCTION

1.1 Smith College Climate Targets

The purpose of this report is to explore a variety of strategic options that would enable Smith College to achieve its 2030 Climate Targets. Currently Smith College has committed to being a Zero Emissions campus by 2030. This study was specifically to look at what would be required to achieve this target in campus buildings. This study comes at an important time in the evolution of climate planning as a community of practice where two important changes have happened.

The first is related to time, planning and investment. With less than 15 years to go until 2030 we have collectively entered the time horizon that matches with budget cycles for major planned infrastructure. The expected lifespan of HVAC equipment or building envelope components for example can exceed 15 years. This means that the building and infrastructure decisions that we make in 2016 and 2017 can either enable or prevent achievement of emissions reductions targets.

The second change, is given our limited time to act, and the magnitude of the changes needed to achieve 2030 climate reduction targets, institutions need to look at energy supply first and energy efficiency second. Traditionally climate and energy efficiency planning has approached this problem in the opposite order. Energy efficiency now is generally viewed in climate planning as a secondary tool employed to increase affordability, resilience and optimize renewable energy infrastructure investments.

In the original scope of the request for proposal for this study it identified three streams of inquiry. They were to look at a centralized approach, a decentralized approach, and an approach based on building energy efficiency. We have with approval of the Smith College staff adapted this approach to focus instead on centralization versus decentralization as the primary organizing principle of our research and employed energy efficiency as a tool in each exploration.

In summary, what you will read in this report are timely recommendations that focus on what infrastructure decisions need to be made in the short, medium, and long term, in order to meet Smith College's existing ambitious climate targets. The recommendations will be the result of detailed explorations that include looking at a range of energy sources and improvements to efficiency, but focus mainly on how to switch Smith College buildings entirely off of fossil fuels while also meeting other secondary objectives.

1.2 Scope and Objectives of Study

As noted above the focus of this study is on reducing carbon emissions from the operation of buildings on Smith College campus and the energy infrastructures that supports them. Addressing the carbon emissions related to other aspects of the Smith College campus, such as transportation, and waste etc., is outside the scope of this study.

The main objective of the study is to develop and evaluate possible approaches and options for deep carbon emission reductions and, provide recommendations for the best overall decarbonization strategy. This strategy will outline a specific path and key steps that will lead towards eliminating carbon emissions from the campus building energy use by 2030.

This will include the following elements:

- Be cost effective from long-term, life cycle cost perspective
- Must be technically sound and reliable in providing long-term low-carbon energy supply
- Be resilient to a multitude of external risks, such as risks related to climate change, availability and affordability of low-carbon fuels and energy sources, and variable economic conditions
- Provide opportunities to engage students and researchers on campus in energy use and energy efficiency research.

1.3 Approach and Methodology

Identifying an optimal strategy and recommended solution for decarbonization of a large urban development such as Smith College campus represents a complex endeavour. It involves developing a sound resolution to a multitude of elements while carefully considering their interrelationships. Some of them can interact in a synergistic and complimentary manner, while some can be in direct contradiction with each other. Therefore, it is crucial to establish not only a clear set of objectives, but also a clear set of drivers, constraints and opportunities, as well as their respective hierarchy right at the onset of the analysis.

The following key drivers and constraints and their impact on developing the recommended strategy have to be considered:

- The existing energy infrastructure components on campus, their capacities, operational characteristics, reliability, fuel and energy sources, technologies, type and extent of their distribution networks, operation and maintenance conditions and the remaining service life for the individual systems and their components
- The mix of the existing campus buildings, their mechanical systems type, performance and compatibility with low-carbon energy technologies or distribution networks
- The existing aggregate annual heating, cooling and electricity demand profile of the campus
- The planned upcoming upgrades to existing buildings and the planned new buildings
- The current and anticipated future cost and availability of various energy and fuel inputs
- The potential synergies and incompatibilities between the broad strategies of fuel switching, changing campus energy distribution infrastructure and implementing building energy efficiency measures
- The availability and technical and economically feasibility of various alternative low-carbon fuels and energy sources, technologies and distribution networks, as well as their compatibility with the existing systems
- Rational, and technically seamless implementation of the transition from the current energy infrastructure reliant on fossil fuels to the eventual low-carbon energy infrastructure while maintaining the existing campus buildings, energy plants and distribution networks in operation
- Cost effective deployment of capital for implementing the transition from the current energy infrastructure reliant on fossil fuels to the eventual low-carbon energy infrastructure
- Relatively short time frame to implement this transition by 2030

Given this context, our broad approach and methodology that we have used to develop the optimal decarbonization strategy for Smith College campus is as shown in Figure 1:

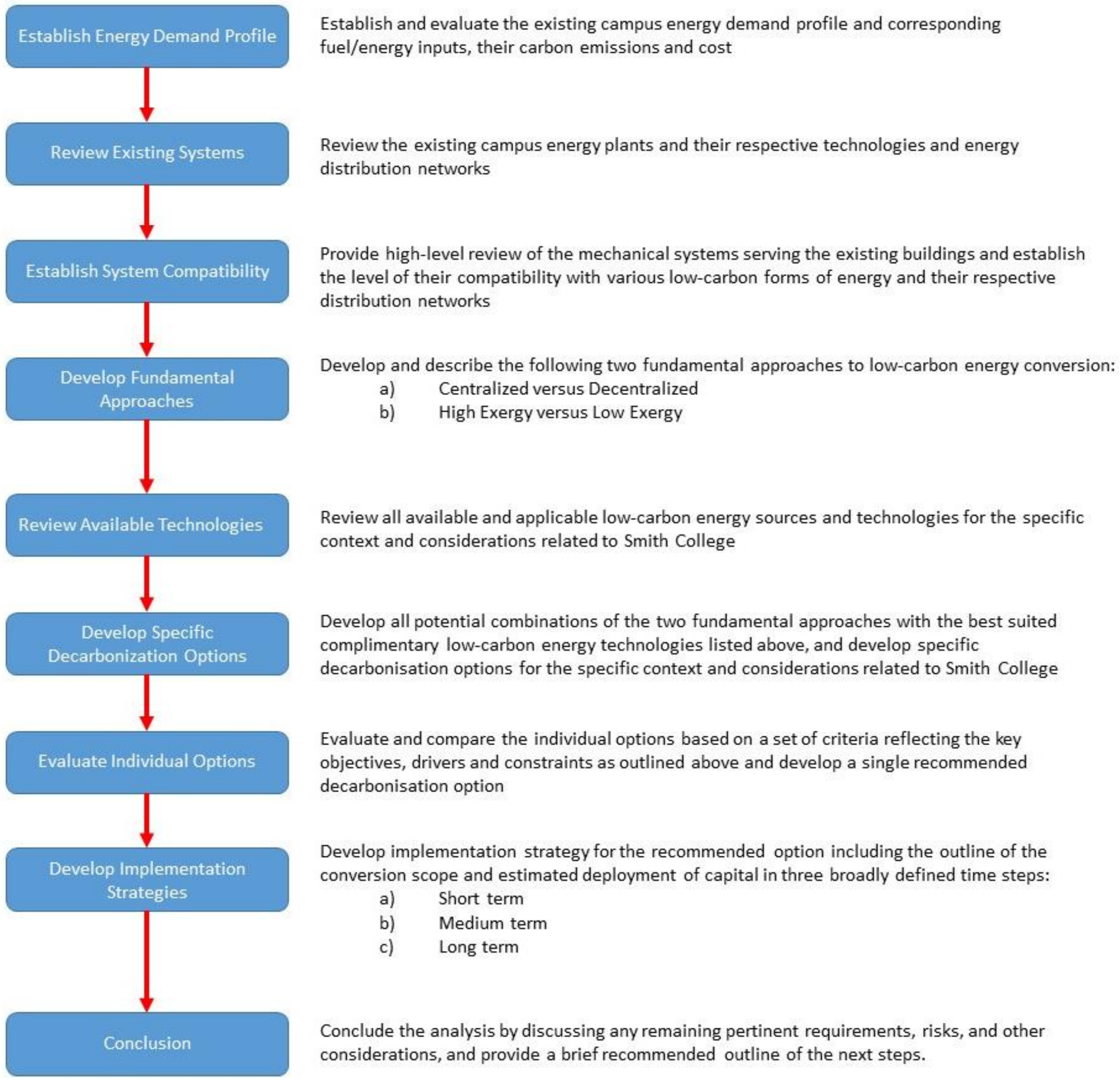

Figure 1: Methodology Flow Chart

2. <u>CURRENT STATE</u>

2.1 Existing Campus Building Stock

Smith College was founded in 1875, and as a result, the campus comprises a broad range of building types ranging from the historical early 18th century all the way to new recently completed modern buildings. The core of the campus includes academic buildings; mainly lecture halls, life science, bioscience and engineering labs, libraries, museum of performance arts, faculty offices and administration offices, with only a relatively small extent of student residence buildings. The majority, and the remaining student residence buildings are located on the Northern end and Northeast corner of the campus. Two gymnasiums, with one of them including indoor pool, and an indoor track and tennis facility are located at the southern end of the campus. The campus facilities management office and the campus central energy plant are both located at the most southern tip of the campus.

From the energy demand perspective, the buildings housing life science, bioscience and engineering labs, libraries and museum of performance arts, as well as the three sports facilities, are all located within the campus core, and likely represent the highest energy demand density within the campus. They all have high demand for heating, cooling as well as electricity. From these, Ford Hall, housing science and engineering programs, Burton Hall and Sabin-Reed Hall, housing bioscience, chemistry and geoscience programs are reported to have the highest energy demand, possibly representing 20% of the campus demand, mainly due to their lab function, that includes operation of fume hoods with large volume of constant flow air exhaust with corresponding volume of outdoor make-up air. In addition, Sabin-Reed Hall has only single pane windows, which further contributes to its especially large energy demand.

The student residence buildings are heavily heating dominated and the majority of them do not have any mechanical cooling.

Many of the older buildings on campus have been retrofitted to some degree over the years. Some of the retrofits included energy efficiency measures, mainly replacing the original single pane windows with newer double pane windows. To the extent possible, the original heritage architecture of the majority of the older buildings has been maintained.

Overall, given the building typology mix, their age and quality of the construction in combination with the local Northeast US climate, the Smith College campus is heavily heating dominated as elaborated in more detail in the following sections below.

2.2 Campus Existing Energy Infrastructure

Smith College campus has an extensive energy infrastructure in place. It includes central heating plant generating steam and the associated steam distribution network, and central cooling plant and the associate chilled water distribution network. A central CHP plant with gas-fired turbine generating electricity and steam has been added in 2008. It is used as a parallel heat source for the steam heating network as well as it was originally intended to serve as a heat source powering the cooling plant's two absorption chillers. The individual plants and their associated infrastructures are described below.

2.2.1 Campus Heating Plant

The campus heating plant consists of three dual-fuel (natural gas and No. 6 fuel oil) boilers generating steam at 125 psi that is distributed through the existing steam distribution network throughout the campus. Two of the boilers are relatively old, but very well maintained, and can generate up to 20,000 #/hr of steam at 125 psi and 80% efficiency. The third, newer boiler with more sophisticated and complex controls is rated for up to 65,000 #/hr of steam at 125 psi and an estimated efficiency in high 80%'s. However, as noted by the chief plant engineer, the boiler was only able to generate #50,000 #/hr of steam in actual operation. Given that the highest reported campus heating demand was at 65,000 #/hr of steam, the combined output capacity of the three boilers and the CHP turbine is more than sufficient to meet this peak demand. All boilers, and especially the two older ones have been well maintained and appear to be in excellent working condition.

The plant contains 90,000 gal of No. 6 fuel oil storage comprised of three 30,000 gal fuel oil storage tanks.

The existing campus steam distribution network is installed in 7ft by 7ft walk able underground tunnels and extends to and supplies steam to a large number of buildings on campus (refer to steam distribution network site plan). Given the heating plant is located at the most southern tip of the campus, which is also the lowest elevation point of the campus; all steam condensate (at 190F) is returned by gravity back to the central plant.

Most of the buildings on campus connected to the steam network have hydronic based heating systems and interface with the steam via a steam to hot water heat exchanger. However, there are still number of student residence buildings that use steam directly inside the building to heat individual room with steam radiators.

Over the years, and due to the aging steam distribution network, the system has been experiencing numerous leaks mainly due to the corrosion from the pipe exterior. Any significant leaks have all been repaired on individual occurrence basis. In addition, the college has a more comprehensive steam piping replacement plan in place that is being implemented section by section during the summertime when the steam system is turned off.

2.2.2 Campus Cooling Plant

The campus cooling plant, located just across the road from the heating plant, consists of three centrifugal chillers of 700 ton capacity each, one screw chiller of 1,000 ton capacity, and two steam absorption chillers; one 210 ton and one 800 ton capacity, respectively. All chillers are water cooled with a set of cooling towers located on the roof of the cooling plant. The highest reported campus cooling demand is about 2,500 tons. The minimum cooling demand required to operate the absorption chillers with the CHP unit is 800 tons.

Similar to steam distribution network, the existing chilled water supply and distribution network (sized for 4,000 gpm flow) extends throughout a large portion of the campus. However, there are many buildings on campus that are not connected to the central chilled water system, and instead, have their own building-level cooling system. Many of the smaller building have a number of split window-mounted AC units.

One of the chillers, the 1,000 ton York screw chiller has reached the end of its service life and is scheduled to be replaced before the next cooling season.

The two absorption chillers are intended to complement the summertime operation of the CHP plant and their steam demand of 20,000 #/hr is matched with the steam generation capacity of the CHP plant. However, due to the fact that minimum cooling demand of 1,100 tons cannot be adequately sustained for sufficiently long periods, and the CHP turbine has only a limited output turn-down ability, both the CHP plant and the absorption chillers are off during the summertime.

2.2.3 Campus CHP Plant

The relatively new campus CHP plant was completed in 2008 and is directly adjacent to the steam boiler plant. The plant includes single dual-fuel (natural gas and No.2 fuel oil) gas turbine with 3.5 MW of electrical and 20,000 #/hr of steam (thermal) output. It requires natural gas inlet pressure at 195 psi, which is much larger pressure than the pressure available from the natural gas utility's distribution network. Therefore, a separate natural gas compressor station was included as an integral part of the CHP plant. A recently added new diesel powered generator of 750 kW capacity was added to the system to enable "black start" of the turbine and CHP operation during the public utility's grid power failure. Also, the CHP plant controls have recently been upgraded with automatic load shedding controls.

The CHPs power generation output of 3.5 MW matches the average campus electrical demand that stays relatively steady whole year around. The campus peak electricity demand does significantly exceed CHP plant capacity. During heating season, with steam system operational, the waste heat output from the CHP turbine is fully utilized by the steam system. However, as mentioned above, there is inadequate demand for the CHP turbine steam output to power the absorption chillers during the cooling season. Therefore, to protect the turbine from short cycling, the CHP plant is off during the summer time while the steam heating system is off.

In addition to power generated by the CHP plant, the campus power distribution system is also supplied from two public utility's sources, one source is standby. The utility grid is used to export power generated by the CHP plant when campus demand is lower than plant output, and to supply additional power when campus demand is higher than CHP plant output.

Campus electrical power distribution system is via buried 13.8 kV and 2.4 kV cables. Approximately 15% of the college buildings are not served from the campus distribution system. These buildings are on separate utility company meters.

Smith College has been exporting power since December 2013. The CHP plant electricity net production for 2015 was 16,977,200 kWh. CHP electricity net use for 2015 was 15,845,477 kWh. CHP electricity net exported for 2015 was 1,111,723 kWh. Purchased electricity net for 2015 was 8,219,412 kWh. As of April 2016, Northampton's average electricity rate of 20.64¢/kWh is about 66% higher than the U.S. average of 12.43¢/kWh.

2.2.4 Campus Solar Photovoltaic Array

Smith College also has a number of solar photovoltaic installations on its campus. The Indoor Track & Tennis (ITT) facility and Ford Hall building have a 1,500 panel installation which together is expected to generate approximately 550,000 kWhs of electricity a year. The college's Campus Center also has a 130 panel, 29kW installation is expected to generate approximately 30,000kWhs of electricity a year.

2.3 Existing Campus Energy Use

This section examines the existing energy demand of the Smith college campus based on the natural gas and electricity use, as well as steam generation records. First, it is useful to show the combined energy demand profile of the campus that includes all forms of energy displayed in a single graph using the same energy units for each individual energy demand profile. This combined energy demand profile of Smith College campus in MWh is shown in Table 1 2 below. It clearly indicates that the campus is heavily heating dominated. From that if follows that the primary focus of our analysis to identify an optimal decarbonization strategy will be put on replacing current fossil fuel dependent heating with an alternate low-carbon heating fuel/energy source and technology.

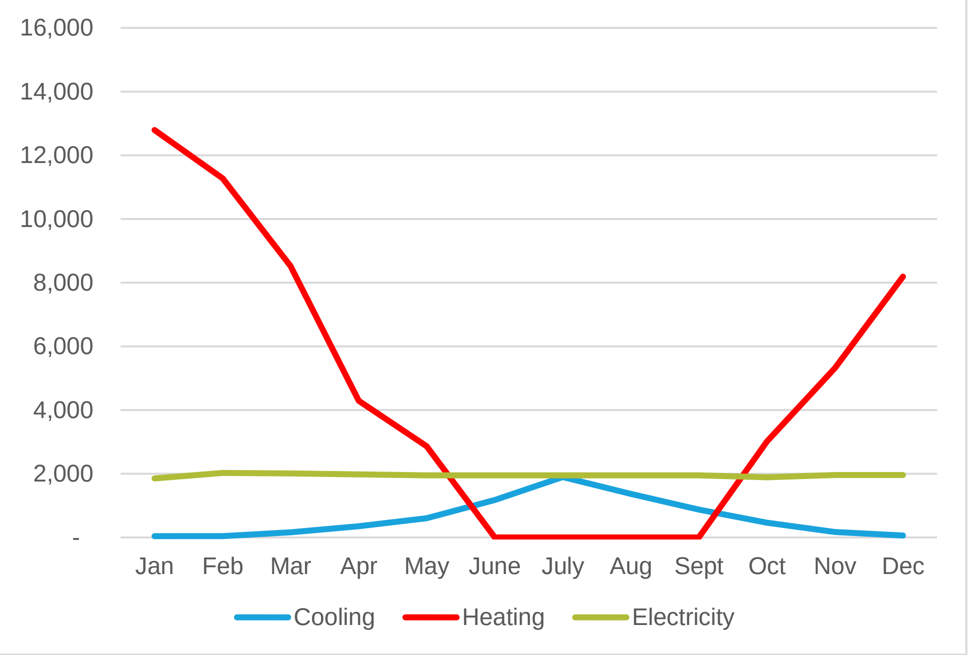

Figure 2: Existing Campus Thermal Energy & Electricity Demand (MWh)

In order to develop relevant and effective energy strategies for the Smith College Campus, a forecasted heating and cooling energy demand model was created. The goal of this energy model was to develop an overarching picture of what the Smith College's energy demand will look like. As the monthly energy use data of the existing buildings was not available an Energy Use Intensity (EUI) for that building type was taken from the Commercial Reference Library and used to calculate a predicted annual energy demand and then using a percentage distribution the monthly demand was found. This data was used to create monthly demand profiles of the various building types and these profiles were then compiled together to create a single profile for the Smith College campus as a whole.

The heating and cooling demand is analysed first in the sections below. First, it is broken down and compared by building type, classifying the buildings on campus by their typology (academic, residential, etc.) then using Energy Demand Intensities (EDI's) to estimate their annual heating and cooling demand. A seasonal heating/cooling profile is then used to break this annual consumption into monthly demand, then combined to form the total thermal demand profiles for Smith College. The findings of campus energy efficiency reports and metered fuel consumption were incorporated to verify these results.

2.3.1 Existing Heating Demand Profile

Figure 3 shows that the expansion of the steam heating network to include the buildings currently without central steam would increase the demand on the steam heating network by a relatively small amount compared to the overall system load.

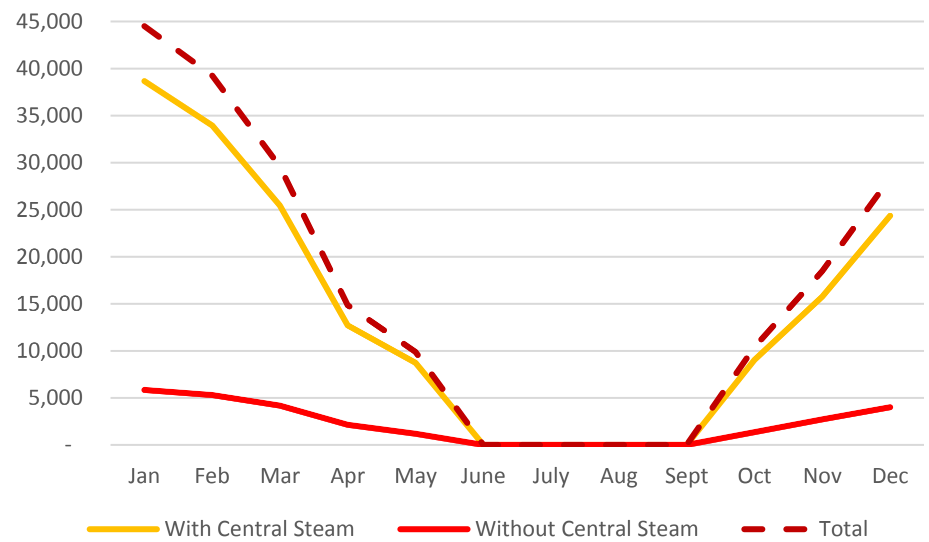

Figure 3: Smith College Heating Demand Profile (MMBTU)

Figure 4 compares the annual heating demand of the different buildings on the Smith College Campus. Similarly to Figure 3 the classrooms represent a large part of the campus load with the classrooms representing almost 55% of the campus' annual heating requirements. As expected, the total heating demand profile follows a seasonal profile and peaks in January with the heating systems being turned off during the summer months.

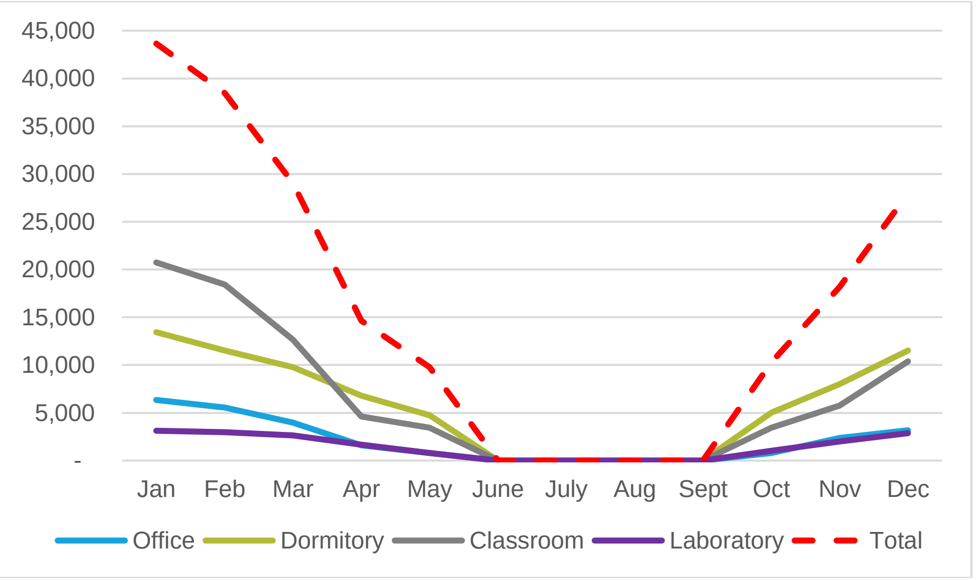

Figure 4: Smith College Annual Heating Demand Profile (MMBTU)

Table 1 lists the forecasted annual space heating and DHW loads and EDIs for each Smith College building type.

	Area (ft^2)	Annual Heating Load (MMBTU)	Heating EDI ($MMBTU/ft^2$)
Offices	312,842	27,767	.089
Dormitory	1,136,604	89,581	.079
Classroom	1,185,009	93,322	.079
Laboratory	265,277	17,795	.067
Total:	2,899,732	228,466	.079

Table 1: Forecasted Heating Demand and EDI by Facility

2.3.2 Existing Cooling Demand Profile

The cooling demand shown in Figure 5 demonstrates the current campus demand on the chilled water network as well as the potential demand if additional buildings are added. This figure shows that the campus chilled water network could support a significantly larger cooling demand relative to its current demand, if all buildings were connected.

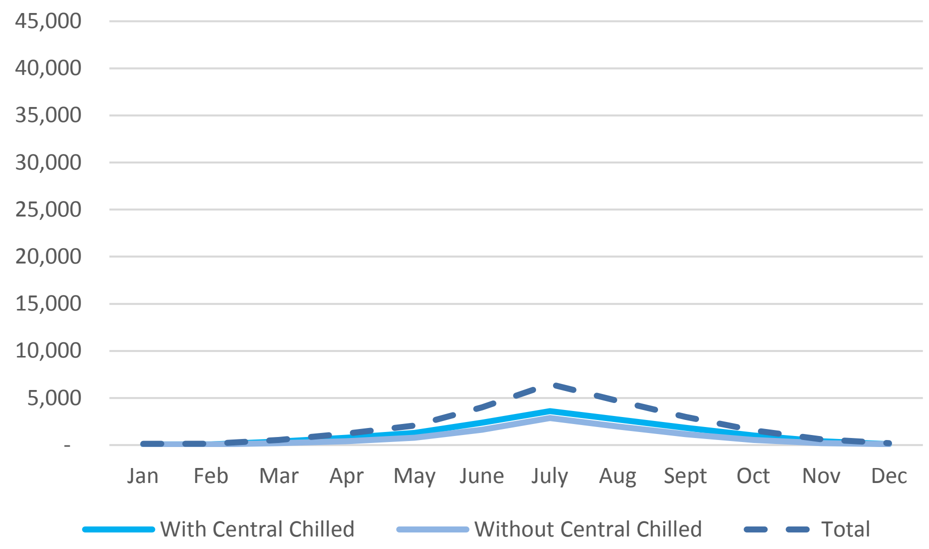

Figure 5: Smith College Chilled Water Demand Profile (MMBTU)

Figure 6 compares the overall combined annual cooling demand for the College's office, dormitory, classroom and laboratory facilities. Overall, the total cooling demand profile of the facilities follows the expected seasonal patterns. The City of Northampton is in ASHRAE climate zone 5 and has a heating dominated climate, with significant cooling only required during peak summer months which is also confirmed by the actual campus demand.

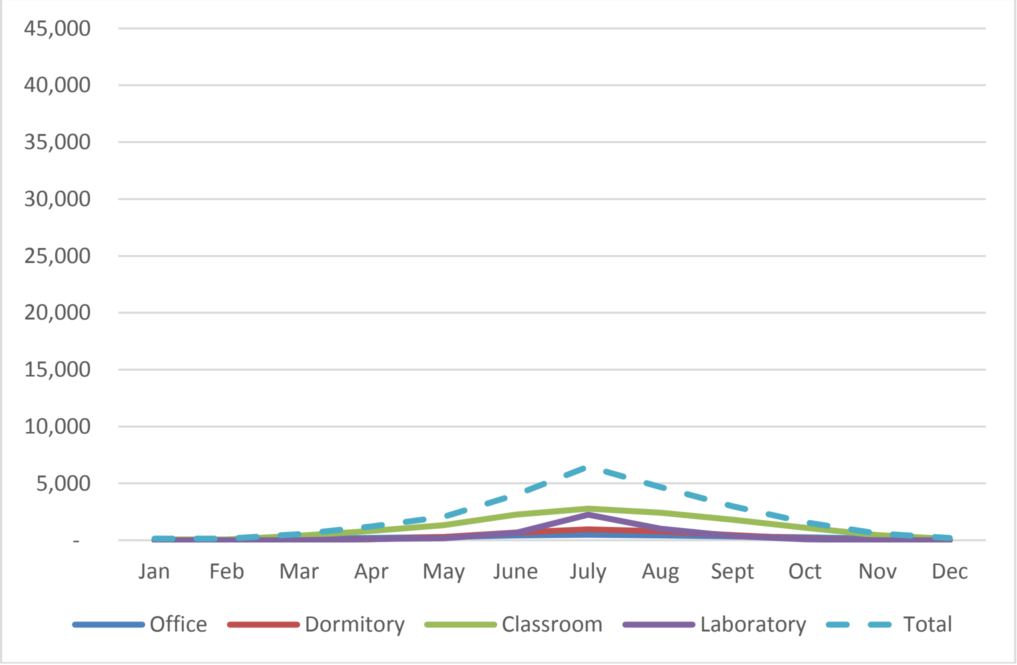

Figure 6: Smith College Annual Cooling Demand Profile (MMBTU)

Figure 6 also shows that the laboratory and classroom facilities representing the majority of the site's cooling load. At nearly 75% of the annual cooling demand, classrooms and laboratories shape the cooling demand profile for the whole campus. It is important to note that the cooling demand from the laboratories is split among only a few buildings so on a per building basis the laboratories have the highest cooling demand. Table 2 lists the forecasted annual cooling loads and cooling EDIs of the different Smith College building types.

	Area (ft^2)	Annual Cooling Load (MMBTU)	Cooling EDI (MMBTU/ft^2)
Offices	312,845	2975	.01
Dormitory	1,136,605	3445	.003
Classroom	1,185,009	13,345	.011
Laboratory	265,276	4640	.018
Total:	2,899,735	24,405	.008

Table 2: Forecasted Cooling Demand and EDI by Facility Type

2.3.3 Existing Combined Thermal Demand Profile

Figure 7 shows the total heating and cooling demand of the Smith College Campus assuming that all buildings would be connected to the chilled water network. The total thermal energy demand profile is important because it highlights times when the campus is simultaneously in heating and cooling mode as well as the relative magnitudes of the heating and cooling demand. This helps to identify times and quantities of heat rejected within the campus that could potentially be captured and utilized elsewhere.

The significant difference in scale of the heating and cooling demand profiles can also be seen in Figure 7. The heating demand profile is an order of magnitude larger than the cooling demand profile for the majority of the year. During the summer months however the existing steam heating plant is off and does not provide any heat. The demand profile indicates that is some amount of rejected heat that could potentially be recovered from the cooling plant operation during the shoulder season, provided the two systems would be thermally compatible.

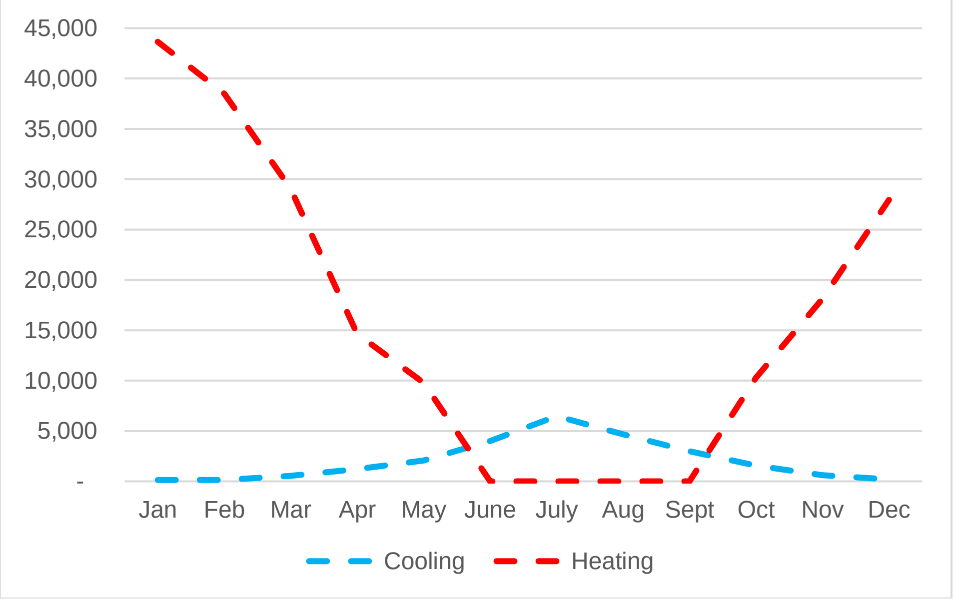

Figure 7: Smith College Thermal Demand Profile (MMBTU)

2.3.4 Summary

The thermal energy demand analysis of the Smith College Campus has confirmed that the campus does have a heating dominated energy demand profile with a high baseline heating demand. The heating baseline is primarily due to the requirements of the classrooms as they are the only building type requiring heat during the summer months. Although a heating dominated system, Figure 7 shows that the amount of potentially recoverable waste heat from the campus cooling plant heat rejection during the summer months will have a significant impact on reducing the overall heating energy demand of Smith College during the summer

2.4 Existing Electricity Consumption

At Smith College there are a number of energy end uses that require electricity including lighting, plug loads, mechanical systems within building as well as the central plant itself. As described in section 2.2.3 above, Smith College has two sources of electricity; from the electrical grid owned by the public utility and from the campus owned CHP plant. Figure 8 shows the historical electricity demand at Smith College from 1990 to 2015, as well as the different sources that have been used to meet it. In 2015 approximately two thirds of the College's annual electricity consumption has been met by the natural gas CHP unit.

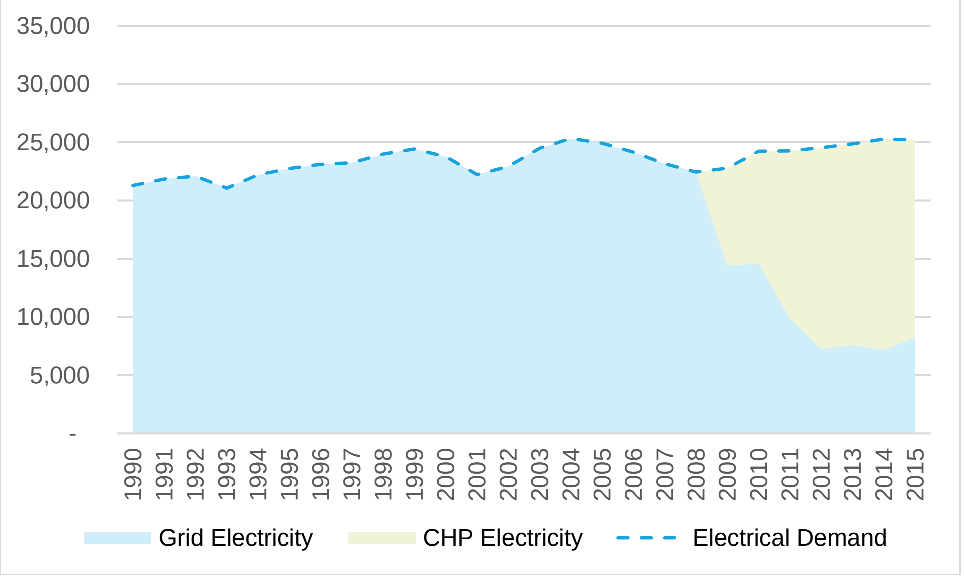

Figure 8: Smith College Historical Electricity Consumption (MWh)

2.5 GHG Emissions

Figure 9 shows the breakdown of Smith College's 2015 GHG emissions by source. It shows that the vast majority of GHG emissions at Smith College come from natural gas consumption (i.e. the CHP plant and central boilers). The 'Other' sources, which represent approximately 10% of the campus's total emissions, refers to a number of small end uses including:

- Fleet gasoline consumption,
- Fertilizer consumption,
- Faculty/Staff commuting,
- Directly financed air travel, and
- Refrigerant/Chemical consumption.

These emissions are outside the scope of this report and would need to be separate addressed in order for Smith College to be carbon neutral by 2030. GHG emissions coefficient of 0.331 tons/MWh and 0.181 tons/MWh for electricity and natural gas respectively have been used throughout this report. These coefficients were taken from the latest Smith College Master GHG Inventory.

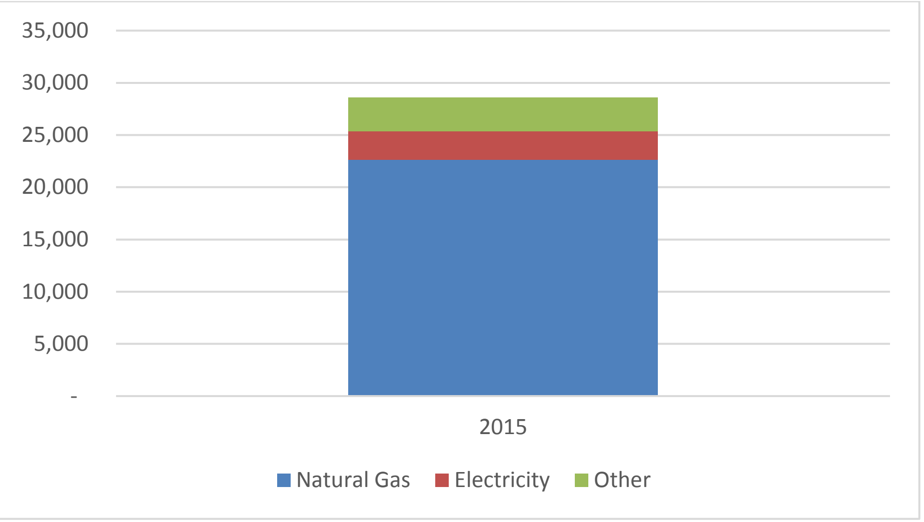

Figure 9: Smith College GHG Emissions (MTons)

2.6 Summary

While Smith College's natural gas steam CHP unit allows it to generate electricity at roughly half the GHG emissions intensity as the local electricity grid, it also locks the College into heavily relying on a single fuel source. The high exergy nature of the campus's steam heating supply network also limits the extent to which low carbon energy sources or technologies can be integrated into the campus's mechanical systems (refer to sections 3, 4 and 5 for a more detailed review of decarbonization strategies, energy sources and technologies).

A diagram illustrating the existing Smith College energy infrastructure components and their relationships is shown in Figure 10 below.

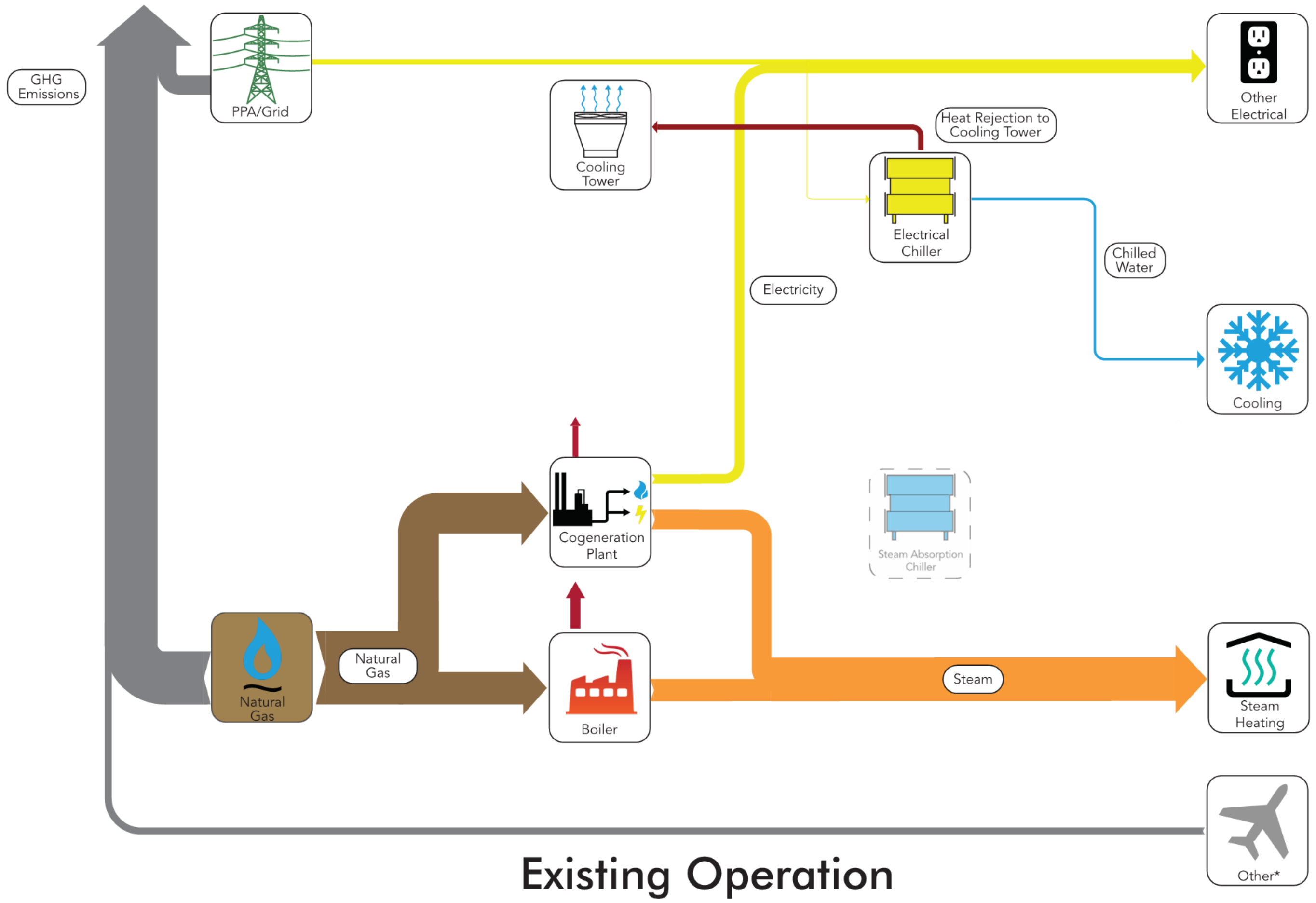

Figure 10: Existing Campus GHG Emissions Summary

3. CAMPUS ENERGY DECARBONIZATION STRATEGIES

3.1 Introduction

As outlined in the Approach and Methodology Section 1.3 above, developing an optimal strategy and recommended solution for decarbonization of Smith College campus represents a complex endeavour. It involves developing a sound resolution to a multitude of elements while carefully considering their interrelationships. Some of them can interact in a synergistic and complimentary manner, while some can be incompatible with each other.

The approach to identifying available decarbonization options foe Smith College has to consider and conform to the fact that the campus has essentially been fully built out, with only relatively few upcoming new buildings or major building renovations being planned in the near future. Another key consideration is the fact that the campus already has three existing centralized energy plants and associated distribution networks.

Before we proceed into identifying and evaluating various low-carbon energy sources and technologies and their potential combinations, our first step focuses on evaluation of the fundamental direction based on the following two broad low-carbon campus energy conversion strategies:

1. Centralized versus Decentralized
2. High Exergy versus Low Exergy

3.2 Centralized Energy Supply Strategy

Centralized energy supply strategy is ideally suited for sufficiently large densely developed urban areas, such as towns, neighbourhood districts, academic campuses, etc. with a large variety of building typologies and diverse energy demands. It typically includes a single, large capacity central energy plant and associated energy distribution network extending outwards and supplying the required forms of end-use energy to the buildings within the entire development area. Given the high density and relatively close proximity of the end-use buildings, the implementation of the energy distribution network is typically cost effective. The end-use buildings obtain all of their thermal energy needs from the centralized system via an "energy transfer station" (i.e. a heat exchanger) and typically do not include any building level energy generation technology.

The key advantage of the centralized energy supply strategy is that the output capacity of the central energy plant can be better optimized and is typically smaller than the sum total of individual peak end-use building demands due to the diversified demand. The central energy plant also provides better opportunity for larger extent of energy recovery across all buildings served by the centralized energy system. Another key benefit of a centralized energy system is that it easy to configure with higher levels of equipment redundancy and resiliency, as well as, it is able to more cost effectively include multiple complimentary larger scale systems such as cogeneration, tri-generation, geo-exchange, and heat recovery systems. The centralized energy plant and energy distribution network is also more cost effective to operate and maintain. And finally, it is more flexible to accommodate future potential switch to alternate fuel/energy sources and technologies.

The downside of the centralized energy supply strategy is that, in order to achieve all of its advantages described above, it needs to be carefully planned well ahead, and it typically requires a large deployment of capital at the early stages of the development it is intended to serve, typically long before the build out of the development it is intended to serve is completed.

The fact that Smith College has three existing centralized energy plants and distribution networks (steam heating plant, CHP plant, and chilled water plant) in operation and good working order will certainly play a significant role in developing optimal energy supply decarbonization solution for the campus.

3.3 Decentralized Energy Supply Strategy

The decentralized energy supply strategy is ideally suited for less densely developed urban areas and for areas where build-out progress tends to be relatively slow extending over a long period of time. It always includes a building-level energy plant that provides heating/cooling separately for each building it serves. This strategy is well suited for new, well designed and highly energy efficient buildings that require only a relatively small external energy inputs. For such buildings the required building energy plant capacity is relatively small, simple and cost effective to install and operate. In this context, it also lends itself to a simple and cost effective addition of small-scale on-site renewable energy technologies. The advantage of this strategy in the context of new building is that the required relatively small amount of capital required to install a building-level energy plant can be more efficiently deployed on a building-by-building basis.

From a larger development size perspective of Smith College campus, comprised primarily of existing, older and less energy efficient buildings; the decentralized energy supply strategy would be more costly since it would essentially require brand new energy plant based on low-carbon technologies, as well as energy efficiency upgrades for each of the buildings. Also, the sum total of the individual building-level energy plant capacities would exceed the comparable centralized energy plant capacity.

And lastly, the decentralized energy supply strategy lacks the ability to benefit from diverse energy demand among different buildings and the associated potential energy recovery.

3.4 Exergy – Energy Quality

In order to identify the optimal energy strategy option, it is also important to understand the qualitative aspects of energy defined as exergy.

The term "exergy" describes the quality of energy in any given energy form. It directly relates to practical usability of different forms of energy by different technologies and end uses. In broad practical terms, it is important to make a clear distinction between high and low exergy energy sources and end-use forms of energy.

Consistent with the 2nd law of thermodynamics, all high exergy forms of energy can be downgraded and utilized with any low exergy end-use technologies and systems, but not the other way around.

Given all forms of energy eventually end up as thermal energy at various temperature levels, a simplified visualization of the distinction between the high and low exergy energy sources and end use energy forms can be illustrated as a temperature scale as shown in Figure 11 below.

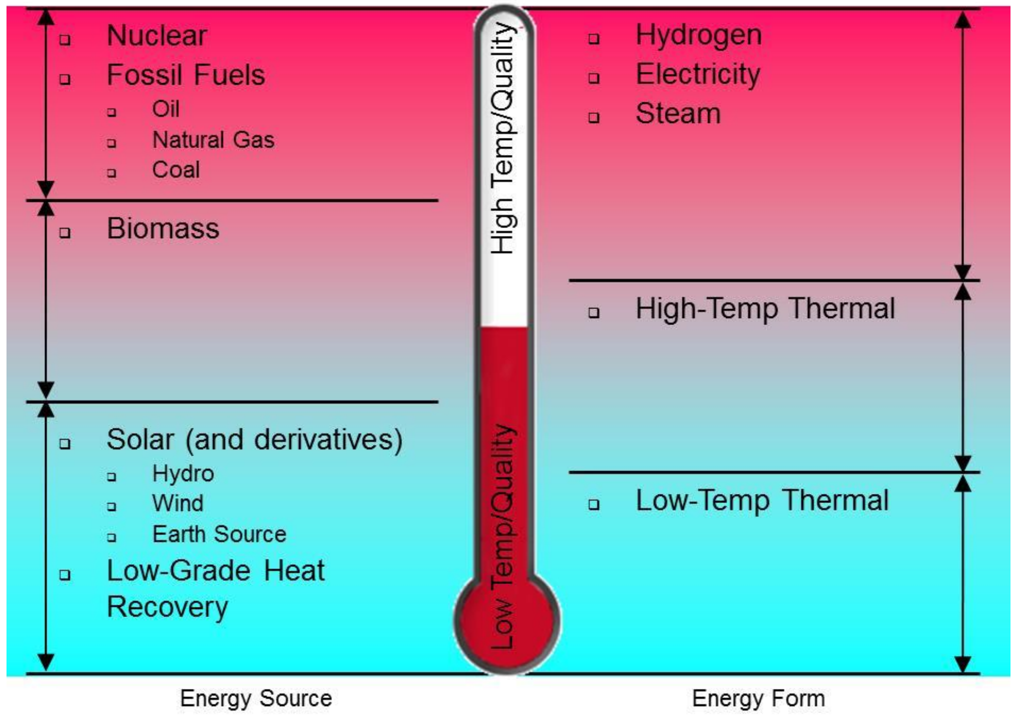

Figure 11: High Exergy versus. Low Exergy

3.5 High Exergy Energy Supply Strategy

High exergy, or high-grade forms of energy, can only be derived from high-grade energy sources such as fossil fuels, nuclear and solar in combination with corresponding specific types of compatible energy conversion technologies (i.e. combustion, nuclear fission, solar PV), and include high-grade end-use forms of energy such as electricity, steam or high temperature heating water. These high exergy energy forms represent the most valuable and usable, and therefore most commonly used, forms of energy within our society. All conventional end-use energy systems such as building heating systems have been designed to require high exergy form of energy such as steam or high temperature heating water.

All existing buildings on Smith College campus require steam or high temperature heating water for space heating. Also, the existing central steam heating plant as well as the CHP plant require high exergy fuel input; natural gas to generate the high exergy output in the form of high pressure steam or electricity.

3.6 Low Exergy Energy Supply Strategy

Low exergy or low-grade forms of energy, are typically derived from lower energy density and more diffused energy sources, and in practical terms represent low-temperature thermal energy. Most common examples of low exergy energy sources and energy conversion technologies include low-temperature solar thermal collectors, recovered low temperature waste heat from cooling systems heat rejection, thermal energy extracted from the ambient temperature, geo-exchange using heat pumps, etc. As such, the practical usability of the low exergy forms of energy is limited and it requires complementary and compatible energy conversion technologies as well as end-use systems capable of operating with low-temperature heating water.

None of the low exergy forms of energy are compatible and useable with conventional building heating systems that have been designed to require high exergy form of energy such as steam or high temperature heating water.

3.7 Summary

In the context of identifying the optimal and recommended decarbonization strategy for Smith College Campus, there are four fundamental strategy options available. These options represent the four possible combinations of the two key strategies described and discussed above.

Figure 12: Broad Strategy Options

The process of defining the specific details within each strategy option and narrowing them down to a single recommended option will need to give careful consideration to the following facts:

1. Smith College has three existing centralized energy plants and distribution networks (steam heating plant, CHP plant, and chilled water plant) in operation and good working order
2. Smith College campus is comprised primarily of existing, older and less energy efficient buildings with all of them having conventional high exergy building heating systems and a majority of them tied to their existing centralized energy distribution network

All of the potential campus energy decarbonization strategy options are described, analysed and discussed in the Section 4.

4. LOW-CARBON ENERGY SOURCES & FUELS

4.1 Introduction

All energy forms available to our society (other than nuclear energy derived from radio-active elements) originate from a single primary energy source, the sun. This includes fossil fuels, such as coal, oil, and natural gas, which represent different variations of solar energy stored in a highly concentrated form accumulated over millions of years.

All forms of renewable and low-carbon energy are also derivatives of solar energy. Solar radiation that reaches our planet is a relatively low-grade and 'dilute' form of energy available intermittently when compared with the high energy densities of readily available fossil fuels. To capture this energy in the form of solar thermal energy, wind, water, or various versions of biofuels derived from a variety organic waste streams in useful concentrations and quantities, requires the use of specific energy conversion technologies.

Two important metrics to consider when reviewing energy sources and fuel types, is the energy density and GHG emissions intensity of the sources. The energy density of a fuel refers to the quantity of energy contained in a specific type of fuel by volume or by weight (i.e. how much energy a specific fuel can carry). Figure 13 compares the energy densities of various types of types. The higher the energy density of a fuel, the smaller the quantity needs to be consumed in order to meet the same end use demand. Liquefied natural gas, for example, has a lower energy density than biodiesel or conventional diesel. A larger volume of natural gas would therefore need to be consumed in order to meet the same end use demand.

- Oil/gasoline — 9.0 kWh/l (13.5 kWh/kg)
- Coal — 6.24 kWh/l (6.6 kWh/kg)
- Biomass (Wood) — 2.1 kWh/l (5.0 kWh/kg)
- Propane Gas* — 0.025 kWh/l (13.9 kWh/kg)
- Natural Gas* — 0.010 kWh/l (12.1 kWh/kg)
- Hydrogen H_2 — 0.002 kWh/l (39.0 kWh/kg)

(* at STP)

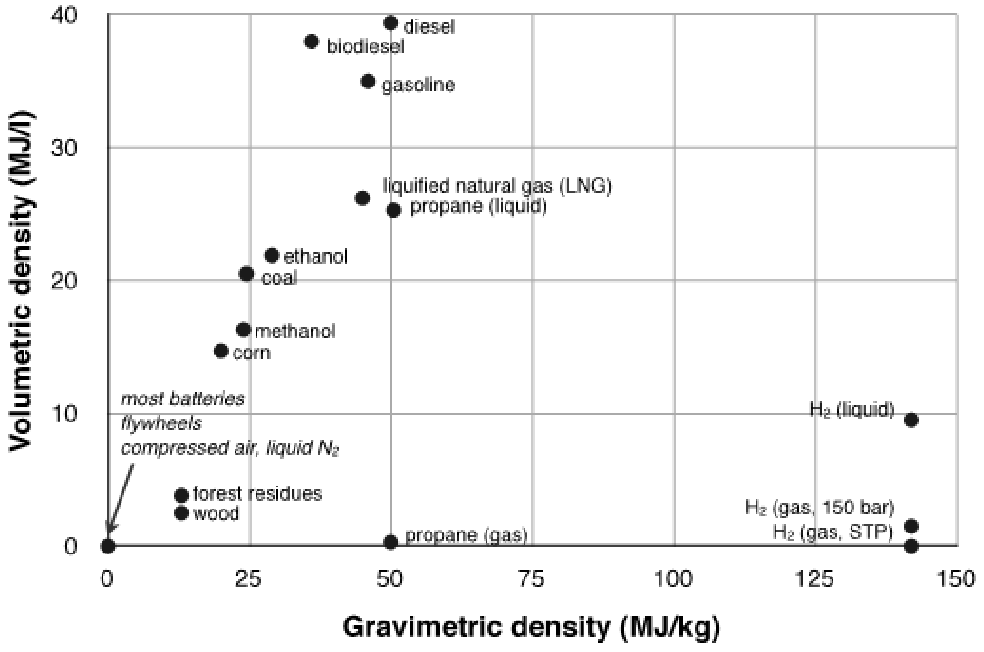

Figure 13: Energy Density of Various Fuels

The GHG emissions intensity of a fuel refers to the amount of GHGs emitted by a fuel source per unit of energy produced. Figure 14 compares the GHG emissions intensity of a number of different fuel sources. It shows that coal, for example, emits significantly more GHG emissions than natural gas. A given amount electricity generated by coal fire power plant would therefore emit more GHG emissions than the same amount of electricity generated by a natural gas powered CHP unit.

It should be noted that various forms of biofuels (i.e. biomass wood waste or biodiesel) are generally considered as being carbon neutral only if they are 100% derived from a variety of waste streams of organic materials from construction, forestry, agriculture and food industries that would have otherwise been disposed of and ended up in landfills. Crop based biofuels derived from purposely grown crops (i.e. corn for manufacturing of ethanol, or fast growing trees grown for firewood, or wood pellets) are more controversial and are generally not considered as carbon neutral. Therefore, all of the biofuels considered for Smith College and discussed in sections below are derived from waste streams of organic materials. Crop based biofuels are not being considered.

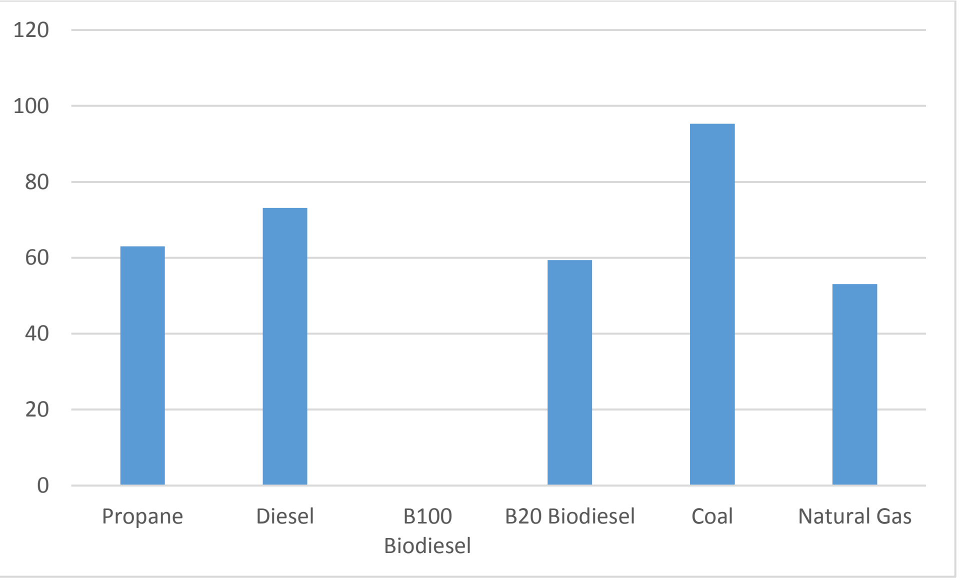

Figure 14: GHG Intensity of Various Fuels (kg CO2/MMBTU)

In order for Smith College to meet its goal of being carbon neutral, it will need to transition from using GHG intensive sources of energy (primarily natural gas and grid electricity generated by coal fire power plants) to low carbon energy sources and fuels. This section will outline the five most readily available renewable low carbon energy sources/fuels available to Smith College, identify their benefits and limitations, and review their application at Smith College.

4.2 Biomass (Wood Waste)

Biomass fuel utilizes waste wood products from the construction, forestry and agriculture industries. While the definition of 'waste wood' and whether it is carbon neutral are sometimes contended[1], in general waste wood products (wood destined for landfills) are considered a carbon neutral energy source. Using wood waste biomass as a fuel would require importing large amounts of biomass to the campus, as there are no readily available sources nearby. This may require shipping the biomass over long distances which could diminish the carbon neutral nature of the fuel as well as make it difficult to procure fuel on short notice. As shown in Figure 13, biomass has one of the lowest energy density per volume from solid the fuels category, which is why such large amounts will be required. In order to satisfy 100% of the Campus' heating demand approximately 30,000ft3 or 17 truckloads of biomass would need to be delivered each week.

4.3 Biodiesel (Waste Product)

Biodiesel, generated from waste cooking oil products, is generally considered as a carbon neutral alternative to liquid petroleum fuel. It is produced from a mixture of cooking waste vegetable and animal oils that would otherwise be disposed of. Most

[1] Source Cornwall, W., 2016. Proposal to define wood-burning as 'carbon neutral' fuels debate. http://www.sciencemag.org/news/2016/03/proposal-define-wood-burning-carbon-neutral-fuels-debate

commonly, biodiesel is often used as a relatively small additive by volume to petroleum diesel. The term 'B20' refers to the concentration of biodiesel in a petroleum blend (i.e. 20% biodiesel). Pure biodiesel is therefore called 'B100' refers to biodiesel in its pure form.

When used as a fuel for a cogeneration/tri-generation system biodiesel can be used to generate both electricity and steam or high temperature heating water.

Another benefit of using biodiesel is that it is cleaner to burn; it produces less sulphates, particulate matter and carbon monoxide than conventional diesel[2]. However, due to its slightly lower heating value and higher oxygen content when compared to petroleum diesel, biodiesel combustion produces higher NOx emissions[3]. The main disadvantage of using biodiesel is its limited supply. As an alternate fuel there are often only a few biodiesel producers in a local market, if there is more than one at all. This means reduced competition, as well as risk of the potential for future supply shortages or price increases if the alternate fuel becomes more popular.

Biodiesel has a lower cloud point (the point at which crystals begin to form in the fuel as it is cooled) and pour point (the lowest temperature at which the fuel will begin to flow) than petroleum diesel (refer to Table 2) as well as slightly less energy content. As biodiesel begins to gel, its viscosity increases at a higher rate than petroleum diesel. Heated fuel lines and below ground storage tanks may be required in order to effectively handle biodiesel in colder climates.

	Cloud Point, F (C)	Pour Point, F (C)
Petroleum Diesel	-31 to 41 (-35 to 5)	-31 to 5 (-35 to -15)
Biodiesel (B100)	26 to 59 (-3 to 15)	23 to 50 (-5 to 10)

Table 3: Properties of Petroleum Diesel and Biodiesel at Low Temperatures

Biodiesel is also an effective solvent and this needs to be considered before integrating it into an existing system. While most tanks designed to store petroleum diesel can store B100 biodiesel, as a solvent it has been known to loosen or dissolve sediments in fuelling systems left by conventional diesel over time. Loosened sediment can clog filters and even interfere with fuel injection. Existing storage tanks should be thoroughly cleaned before being used with biodiesel.

If biodiesel is in contact with some metals such as copper or copper containing metals (such as brass or bronze), or with lead, tin or zinc it will degrade and form high sediment levels that can also pass through the system. Biodiesel is also not compatible with some hoses and gaskets, as it can soften and degrade certain types of rubber compounds, and it has been known to permeate through some plastics (polyethylene and polypropylene). If biodiesel is being integrated into an existing fuel handling system, the compatibility of all materials in the system need to be reviewed.

Biodiesel is also more susceptible to microbial degradation than petroleum diesel when stored for long periods of time. This can result in the development of sediments in the fuel. Additional monitoring is therefore recommended if storing biodiesel, as well as minimising its contact with water, heat and sunlight.

An alternative to the B100 biodiesel fuel would be to use the B20 instead which is 80% traditional diesel fuel. By reducing the concentration of biodiesel being used the issues relating to excessive material degradation of certain metals and synthetic materials is negated. The B20 biofuel does not need the system modifications that B100 requires and most boilers and engines which use diesel can freely switch between B20 and regular diesel. The downside of using B20 is that the majority of the fuel still consists of fossil fuels which release large amounts of carbon and noxious chemicals. Since the current systems at Smith College use natural gas, which burns cleaner than diesel, switching over to B20 would actual produce more GHG's than not switching over at all for a similar or worse price point.

A local producer of biodiesel for Smith College, located less than 25 miles away from the campus, is Northeast Biodiesel. Northeast Biodiesel uses vegetable and animal oils from local restaurants to produce biodiesel, generating an estimated 1.75 million gallons each year[4].

Figure 15: Northeast Biodiesel's First Delivery of Recycled Vegetable Oil[5]

Discussions between Smith College and Northeast Biodiesel indicate that their production could be scaled up to meet the demands of a large institutional facility. While this would reduce the unit cost of the biodiesel produced, it's should be noted that the price of biodiesel can vary in a similar manner to any other commodity. Figure 16 below compares the average cost of electricity, petroleum diesel and biodiesel (B99/B100) from 2010 to 2016 (using a $/gasoline gallon equivalent price to allow each fuel to be compared). It shows that, in general, the price of biodiesel tracks the price of conventional diesel. This volatility means that it would be difficult to either predict the long term cost of biodiesel, or enter into long term supply contracts with biodiesel suppliers.

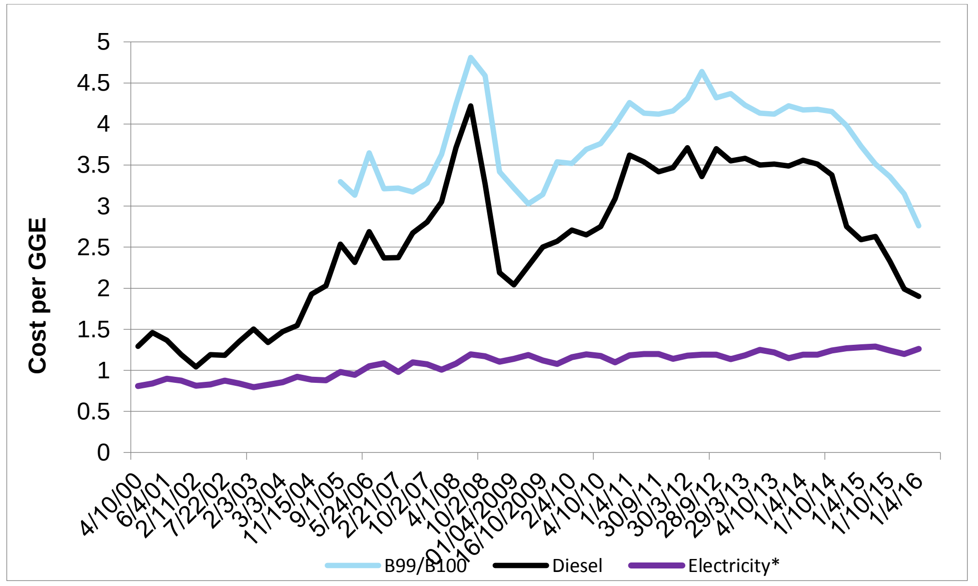

Figure 16: Average US Retail Fuel Price (per Gasoline Gallon Equivalent)[6]

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[2] Source EPA: https://www3.epa.gov/region9/waste/biodiesel/questions.html
[3] Source EPA, 2011. Biofuels and the Environment: First Triennial Report to Congress.
[4] Source Northeast Biodiesel: http://www.northeastbiodiesel.com/about/
[5] Source Northeast Biodiesel: http://www.northeastbiodiesel.com

[6] Source: US Department of Energy (http://www.afdc.energy.gov/fuels/prices.html),
Electricity prices are reduced by a factor of 3.4 because electric motors are approximately 3.4 times as efficient as internal combustion engines

4.4 Biomass and Biodiesel Emissions

A common concern with burning either biomass or biodiesel is the potential for increased air pollution over conventional natural gas systems. While the emissions and localised impacts of any type of fuel combustion have to be carefully considered, there are a number of technological options that can effectively mitigate the various types of emissions. Staged combustion, water emulsification of the injected fuel, or selective catalytic reduction technology can be used to significantly reduce NOx emissions, while various other technologies are used to capture and scrub particulate emissions and sulphur dioxide. These technologies allow such facilities to operate in urban areas, as shown in countries such as Sweden which rely heavily on biomass combustion for their energy generation. The specific type of emission control equipment for the selected biofuel type for Smith College would be determined during detailed design.

4.5 Solar Energy

Solar energy technologies utilize the primary, fully renewable and free energy source on our planet: the sun. There are two primary technologies for converting solar energy into useable form: photovoltaic (PV) systems and solar thermal systems. PV systems use the energy in the suns light to produce electricity in PV Cells (see section 6.3) and solar thermal uses the solar radiation to produce hot water. The largest issue with any solar system is the intermittent availability of solar radiation which makes it difficult to depend on for steady electricity or heated water generation.

4.6 Deep High Temperature Geothermal

Earth temperatures tend to naturally increase with greater depth. The geological formations beyond several km below the surface can reach sufficiently high temperatures that, if reachable, can be utilized as a useful geothermal energy source. .Deep high temperature geothermal resources are commonly categorized according to available source temperatures as follows:

- *High-grade* geothermal resources - source temperature (T > 212°F)
- *Mid-grade* geothermal resources - source temperature (212 > T > 180°F)
- *Low-grade* geothermal resources (T < 180°F)

The temperature to depth ratio is referred to as the geothermal gradient. Typically, the geothermal gradient ranges from about 30 to 60°F/km, though the gradient can be lower in areas of very stable earth structure and considerably higher (up to 200°F/km) at tectonic plate boundaries or in areas affected by unusual local hydrothermal conditions. The magnitude of the geothermal gradient is the most important determining factor affecting the feasibility for developing geothermal resources because it dictates the depth at which the more useful mid-grade and high-grade geothermal resources occur. Drilling costs, which are typically the most expensive element of a geothermal energy system, escalate disproportionately with greater depth.

Geothermal energy can be harnessed in several different ways depending on site-specific geological and hydrothermal characteristics and the particular requirements of the end-use application. Geological formations hosting geothermal resources may be highly permeable with plentiful water/brine/steam fluids within the formation or the rock may have very low permeability and host very little fluid. The presence/absence of formation fluids and the mobility of these fluids within the rock formations strongly influences the development potential of the geothermal resource and dictates suitable options for harnessing the resource, and accompanying costs.

If adequate formation fluids (i.e. water or steam) are present then the formation fluids may be directly extracted with geothermal production wells, then passed through a heat exchanger to transfer heat from the fluid before the fluids are re-injected into separate injection wells at a cooler temperature back to the formation. If formation fluids are not adequate or sufficiently mobile for direct extraction, then options are more limited and the development potential of the resource is significantly diminished. In these circumstances, there are various ways in which fluids may be introduced into geothermal wells and circulated back to the surface at an elevated temperature before passing through a heat exchanger to harness the heat, but the efficiency is typically less and the cost per unit of output capacity is usually higher than direct extraction systems.

According to a 2011 report published by the Oregon Institute of Technology, useful, direct-use temperatures (of at least 180F + range) did not occur in areas near Smith College (Central Massachusetts) until depths of 11,500 ft. Drilling to this depth would be very expensive (on the order of +$10M). Additionally in order to utilize these temperatures ground water must also be found at these depths. Central Massachusetts is largely igneous and metamorphic rock and less likely to contain productive aquifers. Therefore, to realize deep geothermal in this region, the reservoir would probably need some type of fracture stimulation

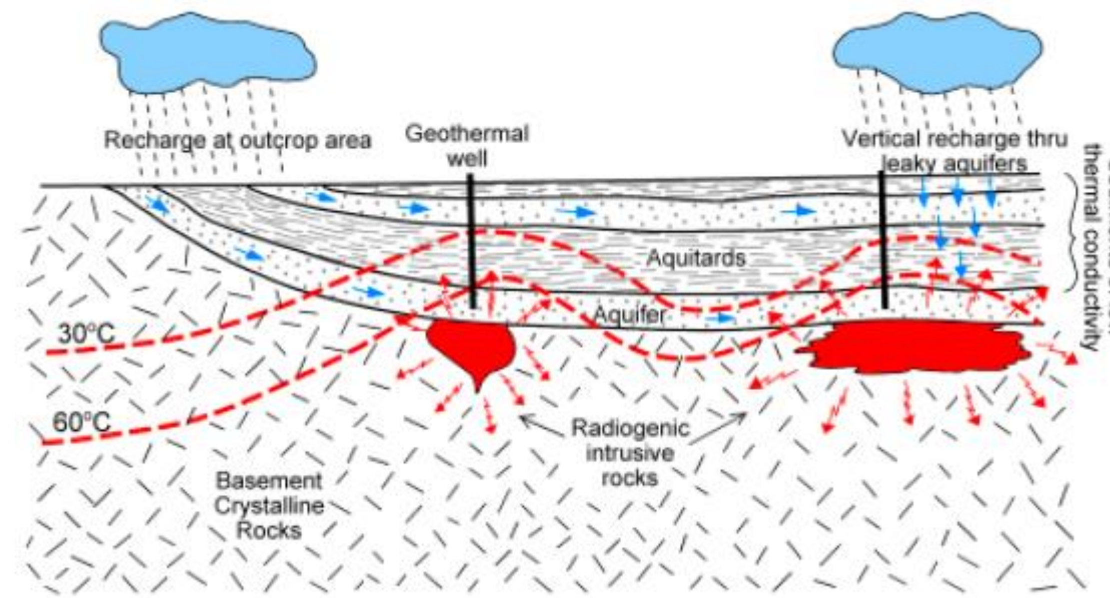

Figure 17: Conceptual diagram of Geothermal System[7]

4.7 Geo-Exchange

Unlike deep, high temperature geothermal, the geo-exchange uses the natural ambient temperature of the ground which retains substantial amounts of low grade heat from the absorbed solar radiation and represents a free carbon heat energy source. Its relatively low temperature, which is normally equal to annual average air temperature of the region, means that it can be used as either a heat sink (to reject heat into) or as a low grade heat source. Geo-exchange can only be used as a low-grade thermal sink or source in combination with heat pump technology. It cannot generate electricity.

Geo-exchange ground heat exchanger configurations are numerous and range from open loop ground water wells to vertical closed loop boreholes or horizontal loops constructed of plastic high-density polyethylene (HDPE) piping. All systems use heat pumps and a circulating fluid (water, or a water-glycol mixture) as a heat transfer medium. The configuration and size of a geo-exchange system depends on the underlying geology of the site and the annual heating and cooling energy demand requirements of the building(s) that it will serve. Water to water heat exchange is also feasible in large bodies of water (i.e. oceans, lakes), depending on local regulations

Geo-exchange systems require large extent of land with vertical closed loop configurations being the most compact with typical borehole spacing of a 15ft grid. In general a system sized to meet 30% of a systems peak thermal demand is able to meet 80% of its annual demand. A geo-exchange system sized to meet 30% of Smith College's peak heating demand would require 12 acres of land. Additionally some of the existing buildings at Smith College still require steam for heating. Without appropriate building heating systems retrofit to hydronic low-temperature heating a geo-exchange heat pump system will not be compatible with these buildings.

4.8 Sewage Heat Recovery

Similar to low temperature geo-exchange systems, it is possible to use sewage systems as a heat sink or low grade heat source. The closest waste water treatment plant to Smith College is the Northampton Treatment Plant. To estimate the potential energy recovery from sewage at the Northampton Treatment Plant, the flow monthly flow rates through the wastewater plant for the

[7] Lund, J.W., Freeston, D.H., and Boyd, T.L., 2010. Direct Utilization of Geothermal Energy 2010

years of 2001 to 2010 were reviewed. This was used in conjunction with a typical sewage temperature profile for temperate regions such as Northampton to calculate the energy that could be recovered on a monthly basis.

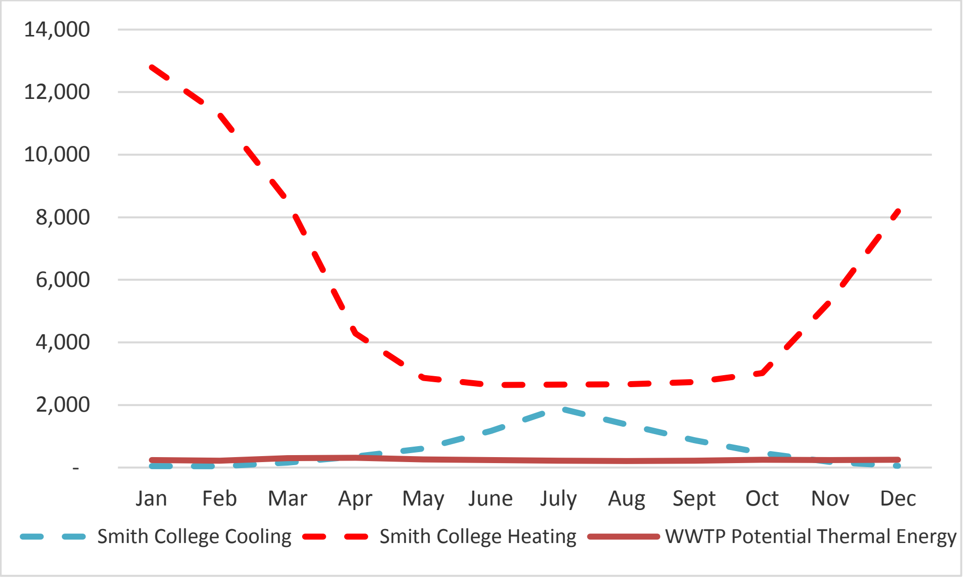

Figure 18: Northampton Treatment Plant Estimated Low Grade Thermal Energy (MWh)

Annually this system would be able to provide almost 3,000 MWh of energy but as can be seen in Figure 18 it only provides approximately 4% of Smith College's annual thermal load. In order to transfer the thermal energy between Smith College and the wastewater plant there would be at minimum 2.1 km of piping as well as a large amount of road disruption (see Figure 19). Given that the Northampton Treatment Plant would only contribute a small portion of the college's annual thermal energy demand, it would be difficult to justify the high capital cost of installing such a system.

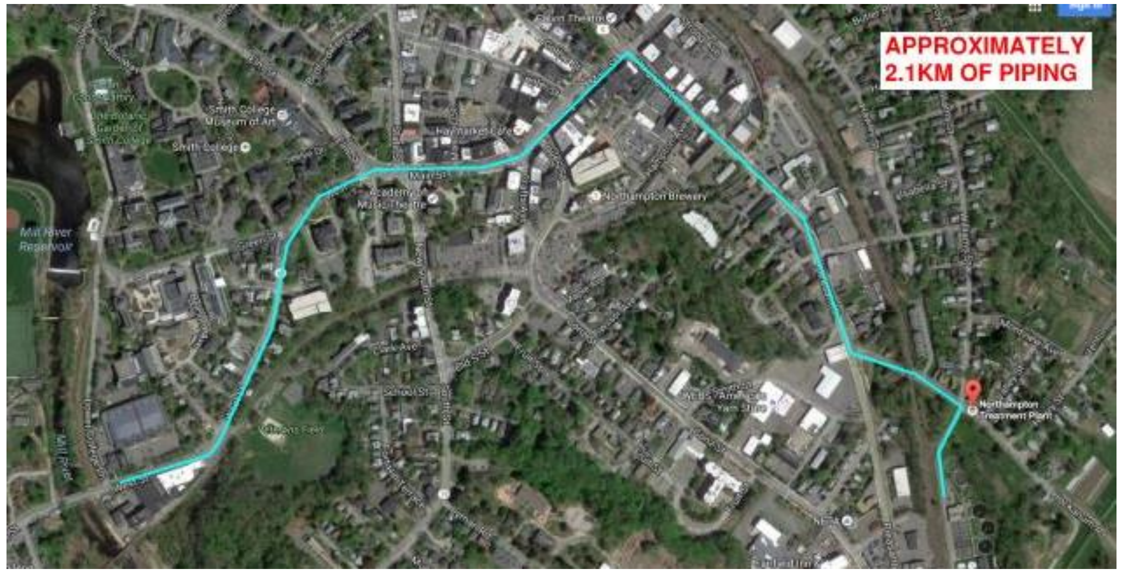

Figure 19: Proposed Pipework Route from Smith College to the Northampton Treatment Plant

5. TECHNOLOGY REVIEW

5.1 Introduction

For each low carbon energy source or fuel available to Smith College, there are a number of different technologies that could be used to meet the College's various energy demands (i.e. heating, cooling or electrical demand). This section will review five applicable technologies that could be implemented with the energy sources available to Smith College, their benefits and limitations, and review their application at Smith College.

5.2 Cogeneration and Tri-generation

Cogeneration systems combust a fuel to power a turbine generating electricity and then, with the by-product waste heat, generating hot water used for heating. In essence this means facilities receive twice the benefits from a cogeneration facility: they receive both electricity and thermal energy (that they would have otherwise required fossil fuels). If a cogeneration system operates year-round to generate electricity, the waste heat that cannot be utilized for heating during the summer months must be rejected or used for other purposes such as tri-generation.

Tri-generation systems start with the same steps as cogeneration (burning fuel and converting the energy to electricity and hot water), but adds on an additional cooling generating step. Instead of rejecting waste heat, it is redirected to power an absorption chiller to produce chilled water that can be used for cooling. This is the distinct advantage of tri-generation: it uses waste energy to meet all of a building`s thermal needs year round.

Given the energy demand mix and it annual demand profile of Smith College, both cogeneration and/or tri-generation technologies based on low-carbon biofuels are applicable components for the college decarbonisation strategy.

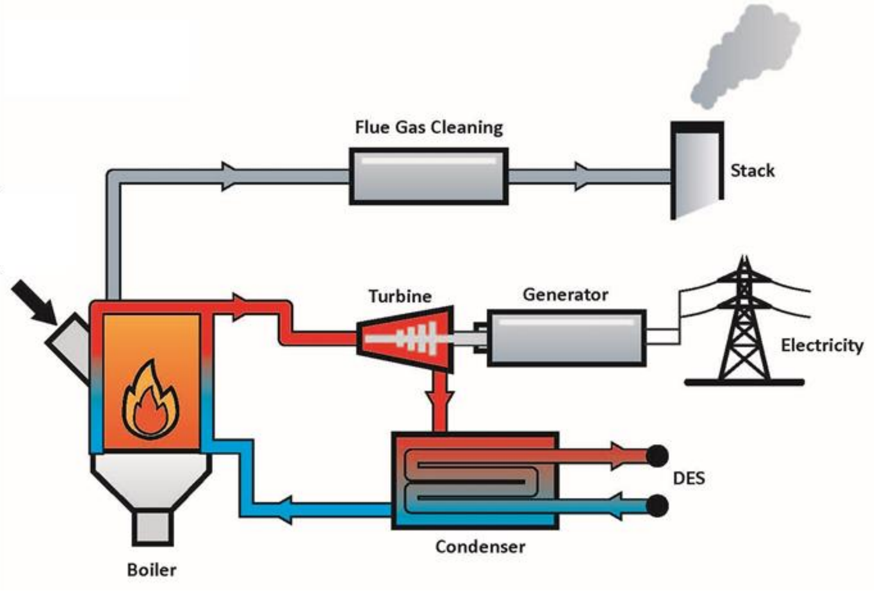

Figure 20: Cogeneration Diagram

5.3 Solar Photovoltaic (PV)

Photovoltaic systems (PV) convert solar radiation energy directly into electricity. The electricity can either be fed back into the grid or used in a nearby building. Photovoltaic panels, commonly known as solar panels, are modular which allows the systems to be easily sized for a specific application. This also allows the systems to be installed in either large 'solar farms' or spread across different buildings in small systems, without dramatically affecting the overall system performance.

Figure 21: Example of a Rooftop Solar PV System

PV systems, however, do not generate electricity at a constant rate. As their electricity generation is based on available solar radiation, they generate more electricity during the summer months. In addition to this their efficiency at converting the available solar radiation into useful electricity is relatively low, with the average photovoltaic cell efficiency ranging from 10% to 25%. As such, a large PV surface area is required to generate substantial amounts of electricity.

At Smith College, initial estimates found that in order to meet 33% of the campus's current annual electricity consumption PV systems would need to be installed on all available buildings on campus. This is a total roof area of approximately 10 acres.

5.4 Hydrogen

Hydrogen (H_2) is technically not an energy source. It is an energy 'carrier' like electricity and can be used as a means for storing energy. Although hydrogen is one of the most abundant elements on our planet, it is not naturally available in abundance in its isolated form as H_2. In its natural form, it is in atmosphere in concentrations too low for practical use. The majority of hydrogen on our planet is usually bonded with either carbon or oxygen atoms. When bonded in almost limitless combinations with carbon, it represents the basic structure for all forms of organic molecules in our biosphere. When bonded with oxygen it is most often locked as a molecule of water.

To obtain pure hydrogen, to be used as an energy source it needs to be first extracted either from a suitable hydrocarbon source or water. Over 90% of commercially available H_2 is produced by extracting it from fossil fuels (natural gas). This source and process is not carbon neutral as it generates carbon dioxide released from fossil fuels as a by-product. Another method of pure H_2 production is by electrolysis which uses electricity to break up water molecule into its component H_2 and O_2.

To produce pure hydrogen in a sustainable carbon neutral manner using electrolysis, the electricity required to power the process must be generated using carbon neutral, renewable technologies. Given that electricity already represents the most valuable and most versatile form of energy with unlimited end uses within our society, and given that there are losses associated with every energy conversion process, it is only the surplus of the free electricity generated by renewable technologies that would represent suitable low-carbon energy source for pure hydrogen production. Examples of such technologies include intermittent electrical generation technologies such as solar photovoltaics or wind power.

Given hydrogen's very low volumetric energy density at standard pressure and temperature, storing adequate quantity of hydrogen in reasonable volumes for practical uses requires additional processing. To increase its energy content in available storage volume, commercial electrolysers produce hydrogen at a moderate pressure of 100 psi. For even more efficient storage additional compression is required and storage in specially made hydrogen storage tanks or cylinders at relatively high pressures ranging from 2,000 to 10,000 psi. On average, about 15% of the hydrogen's energy content is used up by the energy required for hydrogen pressurization. For this reason, many commercial installations do not compress hydrogen for storage.

Once produced, the pure hydrogen can be used as a fuel for combustion (in this instance referred to as catalytic reaction) in a catalytic burner, generating heat and water as a by-product, or for electricity and heat generation in a fuel cell, generating electricity, with water and waste heat as by-products. Neither of these two processes generate CO_2, since pure hydrogen does not contain any carbon.

Hydrogen Fuel Cells

Over the last 20+ years, the primary focus of hydrogen related industries has been on developing technologies for transportation applications, mainly fuel cells for automotive industry. There have been relatively few hydrogen technology developments and commercially available products for stationary fuel cell applications in the building industry. The stationary fuel cells can be used for CHP applications. They can achieve up to 47% electrical power generating efficiency and total efficiency of around 80% provided all waste thermal energy is utilized as part of the CHP system. A fuel cell in this application operating with locally generated and stored hydrogen would be an ideal backup power and heat generation technology during the time periods when the renewable source isn't available to produce surplus electricity and hydrogen.

Hydrogen Combustion

Pure hydrogen can also be combusted in a catalytic burner to produce steam or hot water to be then used to drive a turbine to generate electricity. The waste heat can be utilized in the same way as in more conventional CHP applications. It is also possible to add pure hydrogen in relatively small proportion to other gaseous fuels, such as natural gas and use it as an enriched fuel blend in more conventional combustion appliances.

It might be possible to consider using up to 10% pure hydrogen/natural gas blend as the fuel for the Smith College existing turbine while using the existing burners. Aside from having to include a new complete set of technologies and components for hydrogen generation by electrolysis, compression, storage and associated hydrogen distribution piping, as well as safety components in case of potential leak (hydrogen is highly explosive), this would not provide a permanent carbon neutral solution because 90% of the fuel blend for the existing turbine would always require natural gas with its associated high carbon emissions.

Although it is possible to invest in off-site technologies for renewable power generation (i.e. solar PV or wind power) to have sufficient surplus to be then used for hydrogen production, the scope of this report focuses mainly on identifying opportunities for on-campus renewable electricity generation.

As discussed in the section on PV technology above, even if PV systems would be installed on all available roof area of all buildings on campus (approximately 10 acres) it would generate only 33% of the campus's current annual electricity demand. It is unlikely that even a PV system of this size would be able produce sufficient surplus of renewable electricity to make application of hydrogen technology economically viable at this time.

5.5 Onsite Biogas

Using anaerobic digestion process biogas production requires raw fat and protein rich organic waste, such as food and animal waste as the primary feedstock. The predominant gas produced during this process is methane and it can be used as a fuel source in a similar manner to natural gas.

There is not enough quantity and continuous generation of suitable organic waste feedstock available at Smith College to consider on-site biogas generation.

Figure 22: Example Anaerobic Digestion and Biogas Plants in Sweden

5.6 Heat Pumps/Heat Recovery Chillers

Given the low grade nature of some of the most abundant and readily available energy sources such as geo-exchange, heat pump technology is required to provide heating and cooling. Heat pumps can operate in two individual modes. When the system is in cooling mode heat is absorbed from the conditioned environment and rejected to the sink using a similar refrigeration cycle as those used by refrigerators. When the system is in heating mode the cycle operates in reverse and heat is absorbed from the energy source and transmitted to the conditioned environment.

Due to the low grade nature of the energy sources used by heat pumps the technology is best suited to low temperature district energy systems as it is un-able to produce high temperatures. This restriction also means that heat pumps are not capable of generating electricity and in fact draw electricity during operation.

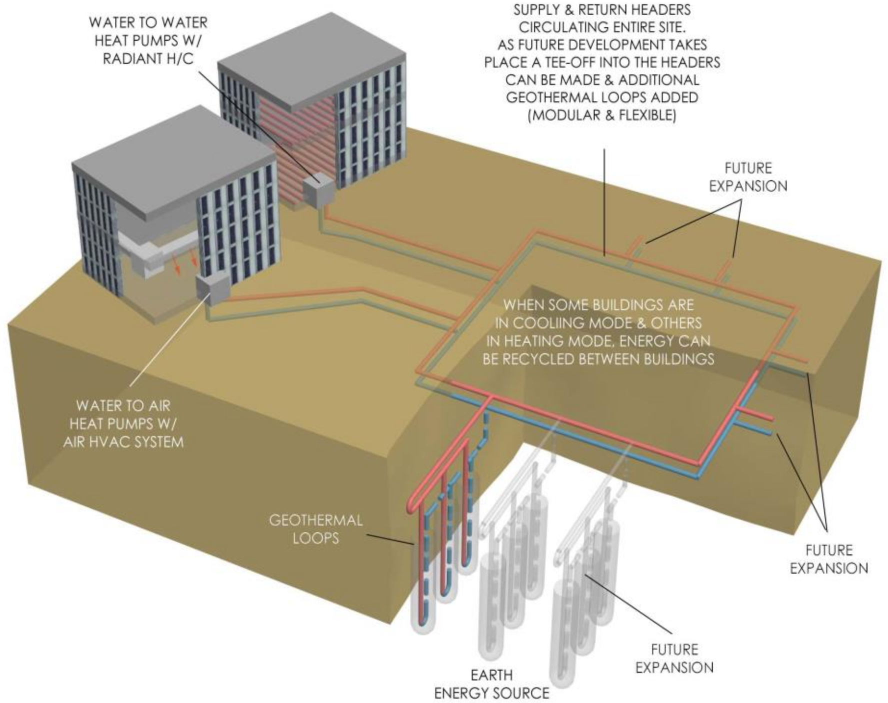

Figure 23: Simple Refrigeration Cycle in Heating Mode

5.7 Organic Rankine Cycle (ORC)

A system using an Organic Rankine cycle to produce power is similar to a standard steam turbine except that instead of the steam driving the turbine, the ORC transfers the driving thermal energy into a closed loop filled with an organic working fluid (heavier mass fluid as opposed to water) to drive the turbine as it expands. The organic working fluid boils at lower temperatures than water and therefore allow the ORC turbine operation at lower input temperatures. This system, like a traditional cogeneration/ tri-generation system, can produce both electricity and thermal energy with the difference being that the output temperature is always lower than the primary temperature driving the ORC process and can only be used with hydronic heating systems.

Figure 24: Example of ORC System

The lower temperature that is characteristic of the ORC system removes maintenance issues relating to steam and due to the higher density of the fluid it is possible to have smaller systems provide the same amount of power. The GHG reduction potential of this technology is dependent on the type of fuel used in the boiler generating the primary thermal energy and in the case of Smith College using B100 biofuel, which is considered a carbon neutral energy source, would allow the ORC to achieve carbon neutrality.

6. IMPLEMENTATION OF CAMPUS ENERGY DECARBONIZATION

6.1 Introduction

As outlined and discussed in Section 6 above, and in addition to incorporating the narrowed down applicable low-carbon technologies discussed in the Section 7 and 8 above, we have developed four fundamental options, plus one hybrid option to cover the entire range of possible energy decarbonization options for Smith College campus. These five options are described and discussed in more detail below.

6.2 Option 1. - Centralized High Exergy

Given the realistic potential of securing a viable long-term supply of biodiesel, this option would essentially involve fuel switch from current natural gas with high GHG emissions to locally sourced biodiesel that is manufactured from waste cooking oil and therefore considered as zero carbon fuel. The existing dual fuel boilers burners in the central steam heating and CHP plants would be converted to operate with renewable biodiesel. A new CHP unit, capable of operating with renewable biodiesel, would need to be installed. The existing steam and chilled water distribution network would remain operational in its current configuration and with its current seasonal operation schedule. This option does not require any building energy efficiency upgrades or upgrades to existing HVAC systems in any of the existing buildings on campus served by the central steam and chilled water systems. It will also be compatible with future addition and expansions to the campus solar PV systems.

This single fuel switch for the steam boilers could be implemented in relatively short time frame and with relatively small capital deployment. At the same time it would achieve the most significant GHG emissions reduction in the initial shortest time frame possible.

The limitation of having the CHP turbine off during the summer season would remain due to the lack of consistently high campus cooling demand and the respective relatively high output capacities of the existing CHP turbine and the absorption chiller combination. In order to protect the turbine, its peak output can be only reduced by 15-20%. The corresponding reduced steam generation output is still in excess of what is required to power the absorption chillers controlled to meet the campus heating demand. Given the absorption chillers can generate chilled water only down to 44F consideration of introducing chilled water storage to the system turned out to be not practical.

In summary, Option 1 would include the following components:

- Large scale fuel switch from natural gas to biodiesel
- Conversion of the existing boiler to biodiesel and installation of a new renewable biodiesel compatible CHP unit
- Existing central steam boiler plant remains in operation
- Existing centralized Steam and CHW distribution network remains in operation

Key Benefits:

- Largest achievable GHG emissions reduction in the shortest time step
- Continues to use the existing steam and chilled water plant
- Continues to use the existing campus steam and chilled water distribution network
- Continues to use the existing building HVAC systems
- Lowest initial capital cost requirement from all options

Key Limitations:

- Biodiesel supply availability and cost will need to be confirmed and long term contract secured
- On-site biodiesel storage will be required
- Compatible with only other high-exergy supplementary energy sources and technologies
- Options for new renewable biodiesel compatible CHP units will need to be investigated

6.3 Option 2. - Decentralized High Exergy

This option would involve implementing a large-scale installation of new individual building level biodiesel fuelled boiler plants over a long time period while gradually reducing the dependence on and ultimately terminating the use of and reliance on the existing central steam heating plant, the steam distribution networks and the CHP plant. This option is only mentioned to cover of all possible options. In terms of achievable GHG emissions reduction it is much less effective than Option 1 above, since the transition to decentralized heating plants would take a long time to implement. In addition, the CHP plant would ultimately be taken out of service as well, as a consequence of terminating the use of steam heating plant and the steam distribution network. In terms of practical implementation and excessive cost implications it has no merits, and is therefore not recommended for further consideration.

In summary, Option 2 would include the following components:

- Large scale fuel switch from natural gas to biodiesel over a long period of time
- Installation of new individual building level biodiesel boiler heating plants
- Gradual and eventual decommissioning of the existing central steam boiler and CHP plants
- Gradual and eventual decommissioning of the existing centralized steam distribution network
- Existing central cooling plant and chilled water distribution network remains in operation

Key Benefits:

- Continues to use the existing building HVAC systems
- Continue to use the existing central cooling plant and campus chilled water distribution

Key Limitations:

- Excessive capital and operating cost outlay over long time period
- Insufficient GHG emissions reduction
- Gradual and eventual Increase in electricity demand due to the CHP plant taken out of operation
- The installed aggregate boiler capacity would be significantly higher than the capacity of the central heating plant
- No opportunity for thermal energy recovery or thermal energy demand reduction due to demand diversity
- Compatible with only other high-exergy supplementary energy sources and technologies

6.4 Option 3. - Centralized Low Exergy

This option would involve a large-scale upgrade of the exiting cooling plant to include central heat recovery chillers/ heat pumps with concurrent addition of a large vertical closed loop geo-exchange field serving as a low-grade thermal energy source/sink for the system, as well as an addition of a new low temperature heating water distribution networks. And lastly, it will include eventual upgrades to the individual building level heating systems to be compatible with the low temperature heating water. The existing chilled water distribution network will remain in operation. This option would take a relatively long time to implement, mainly due to the construction of a new low-temperature heating water distribution network and individual building level heating systems upgrades.
As the new low-temperature heating network would be implemented and individual building switched over to it over a long time period, the use and dependence on the central steam plant and steam distribution network would be gradually reduced and ultimately terminated. However, once completed it would provide the most energy efficient fully electric low-carbon energy system, best resilient against external factors mainly waste product biofuels availability and cost.

In summary, Option 3 would include the following components:

- Upgrade of the existing central cooling plant to include heat recovery chillers/ heat pumps
- Installation of a new large vertical closed loop geo-exchange field serving as a low-grade thermal energy source/sink for the system
- Gradual installation of a new low temperature heating water distribution network
- Concurrent upgrades to individual building level heating systems to operate with low temperature heating water
- Gradual and eventual decommissioning of the existing central steam boiler and CHP plants
- Gradual and eventual decommissioning of the existing centralized steam distribution network

Key Benefits:

- Most resilient option against external factors mainly waste product biofuels availability and cost
- Highly energy efficient central plant with heat-recovery capabilities comprised of heat recovery chillers/ heat pumps
- Fully compatible with and able to utilize any low-exergy thermal energy sources or sinks available on campus (Geo-Exchange, Air-Source, Heat Recovery)
- Fully compatible with any supplementary high-exergy energy sources and technologies
- The existing chilled water distribution network would remain operational and fully utilized

Key Limitations:

- Requires a long time to implement and transition from the existing high exergy to the new low exergy systems
- Requires concurrent upgrades to individual building level heating systems to operate with low temperature heating water
- The existing central steam heating plant and steam distribution network would be gradually decommissioned
- An All-electric system would increase the electricity demand on the existing grid in addition to de-commissioning of the existing natural gas-fired CHP plant

6.5 Option 4. - Decentralized Low Exergy

Similar to the decentralized high exergy option described above, this option would involve implementing a large-scale installation of new individual building level heating and cooling plants based on heat pump technology using low-grade thermal energy source and sinks such as geo-exchange or ambient outdoor air. This transition would be implemented over a long time period while gradually reducing the dependence on, and ultimately terminating the use of and reliance on the existing central steam heating plant, the steam distribution networks and the CHP plant, as well as on the existing central cooling plant and chilled water distribution network.

Although this option would be appropriate for new highly energy efficient buildings, and would certainly provide more effective and resilient low-carbon solution when compared to the decentralized high exergy option, in the context of Smith College with the existing centralized heating and cooling plants and distribution networks already in place, it is difficult to justify. It would be possible to have all new or substantially renovated existing buildings served by their own independent highly efficient low-carbon systems, but this would diminish the overall cost and carbon reduction effectiveness of any of the centralized decarbonization options.

In summary, Option 4 would include the following components:

- Installation of new individual building level heating and cooling plants based on heat pump technology and using low-grade thermal energy source and sinks such as geo-exchange or ambient outdoor air
- Concurrent upgrades to individual building level heating systems to operate with low temperature heating water
- Gradual and eventual decommissioning of the existing central steam boiler and CHP plants as well as cooling plant
- Gradual and eventual decommissioning of the existing centralized steam and chilled water distribution networks

Key Benefits:

- Resilient option against external factors mainly waste product biofuels availability and cost
- Can be implemented incrementally, building by building
- Highly energy efficient building-level plants with heat-recovery capabilities comprised of heat recovery chillers/ heat pumps
- Fully compatible with and able to utilize any low-exergy thermal energy sources or sinks available on a building level
- Fully compatible with any supplementary high-exergy energy sources and technologies available on a building level

Key Limitations:

- High capital and operating cost outlay over long time period
- The existing central heating and cooling and CHP plants as well as steam and chilled water distribution networks would become redundant
- Would require energy efficiency upgrades to each building as well as their HVAC system conversion to a low-temperature heating system compatible with heat pump technologies
- An All-electric system that would increase the electricity demand on the existing grid
- The existing steam and chilled water distribution networks would become redundant unless they would be converted to and utilized as a common “Ambient Temperature” source and sink network

6.6 Option 5. - Centralized Hybrid High & Low Exergy

Since Smith College does have a well-functioning and maintained existing centralized heating and cooling plants and distribution networks already in place, developing a more comprehensive centralized decarbonization strategy will provide the optimal option. Option 1 provides the most significant GHG emission reduction in a relatively short term and capital cost effective step while carrying with it a relatively high risk related to long term availability and cost of biodiesel. Option 3, on the other hand, provides an ultimate, most resilient low carbon solution with minimum risk to external uncertainty related to low carbon fuel availability and cost. However, it does require a relatively long period for implementing the transition from the existing to the new centralized energy systems configuration.

Therefore, Option 5; a centralized hybrid high and low exergy strategy essentially represents an intermediate, medium term progression step between the initial Option 1 to be implemented in a short term, and the ultimate Option 3 that will take a long term to implement.

6.7 Summary

Based on the above described, analysed and discussed campus energy decarbonization options, we recommend the following implementation strategy broken down into short, medium and long-term steps:

1. Short Term

   Implement Option 1 consisting of a fuel switch for the existing steam boilers from natural gas to renewable biodiesel and maintaining the central steam heating, CHP and central cooing plants in operation. Discussions with Solar Turbines Inc. indicate that they currently do not recommend converting the existing CHP unit to B100 biodiesel, as they cannot guarantee that the fuel will not damage the CHP unit turbine hardware. B100 biodiesel is also not as commonly used as a diesel replacement as B20, and Solar Turbines Inc. raised concerns about a lack of industry wide specifications for B100 (particularly compared to B20). While it is possible for the existing CHP units to use B20 biodiesel, as previously discussed the GHG emissions from B20 biodiesel are comparable to natural gas and therefore do not help the College achieve carbon neutral performance.

   As an initial step we recommend the College convert the existing steam boilers to B100 biodiesel to achieve the most significant GHG emissions reduction possible in the short term, and then further investigate the possibility of converting the existing CHP unit to B100 biodiesel with Solar Turbines Inc. and Northeastern Biodiesel. Although the existing CHP unit is well maintained, it will reach the end of its life in the next 15 to 20 years. One of the risks of converting an existing turbine to a new fuel source is the long term impact this could have unit's performance and maintenance requirements. As the CHP unit reaches the end of its service life, these risks are diminished and it may become more cost effective to convert the unit to B100 biodiesel. Delaying the conversion of the CHP units will also give the College more time to investigate other potential renewable fuels that might be simpler to use with the CHP unit.

2. Medium Term

   Implement Option 5 consisting of initial part of a large-scale upgrade of the exiting cooling plant that will include:

   - Central heat recovery chillers/ heat pumps,
   - A large vertical closed loop geo-exchange field serving as a low-grade thermal energy source/sink for the system,
   - A new low temperature heating water distribution networks, and
   - New absorption chillers.

   During the medium term, the existing central stem boiler plant and CHP plant and the steam distribution network continue to remain in operation while more and more buildings and their heating systems get upgraded and switched over to the new low temperature heating system.

3. Long Term

   Complete transition to Option 3 which will include completion of the new low-temperature heating water distribution network and upgrade of the remaining existing buildings and their heating systems to enable final switch over from the remaining steam service to the new low-temperature heating water network. By this time the existing steam central heating plant and steam distribution network will have approached the end of their service life and will be decommissioned. The new biodiesel plant installed during the medium term will continue to operate in this mode, except on a larger scale.

   At some point in time during the medium term, the existing CHP turbine will start exceeding the demand on steam heating. At this point it will likely start approaching the end of its service life and should be replaced with a lesser capacity biodiesel boiler system, ORC unit/steam turbine and absorption chillers. The biodiesel boilers would be sized to operate with B100 biodiesel. The boilers, ORC unit/steam turbine and absorption chillers will be sized to meet the actual sustained cooling energy demand of the campus. During the heating season the new biodiesel boilers will generate steam to power the ORC unit/steam turbine with the by-product heat being uses to meet the campus's space heating and DHW demand. In the cooling season the new boilers will still be used to drive the ORC unit/steam turbine, but the by-product hot water will be used to drive the new HW absorption chillers.

7. RECOMMENDED STRATEGY

7.1 Introduction

Based on our analysis, we recommend Smith College implement the following campus energy decarbonization strategy deployed in three broadly defined (Short, Medium and Long term) steps in order to become carbon neutral by 2030. The three distinct steps outlined below constitute a continuous progression from the existing campus energy systems configuration towards, and ultimately achieving, a highly energy efficient and reliable low carbon campus energy solution.

7.2 Short Term Strategy

As a first step towards carbon neutrality, we recommend the College implement a fuel switch for its existing boiler plant from its largest source of GHG emissions (natural gas) to a carbon neutral source. Switching from natural gas to biodiesel would allow the College to significantly reduce its annual GHG emissions while requiring the least number of changes to the existing boiler plant. Figure 26 shows the College's heating demand profile, as well as the different system that would be used to meet it. If Northeastern Biodiesel are able to supply enough biodiesel to meet the College's current boiler fuel consumption, the College would be able to reduce its annual GHG emissions by 44% in this initial first step. Figure 25 outlines the energy and emissions flows at Smith College of the short term strategy is implemented.

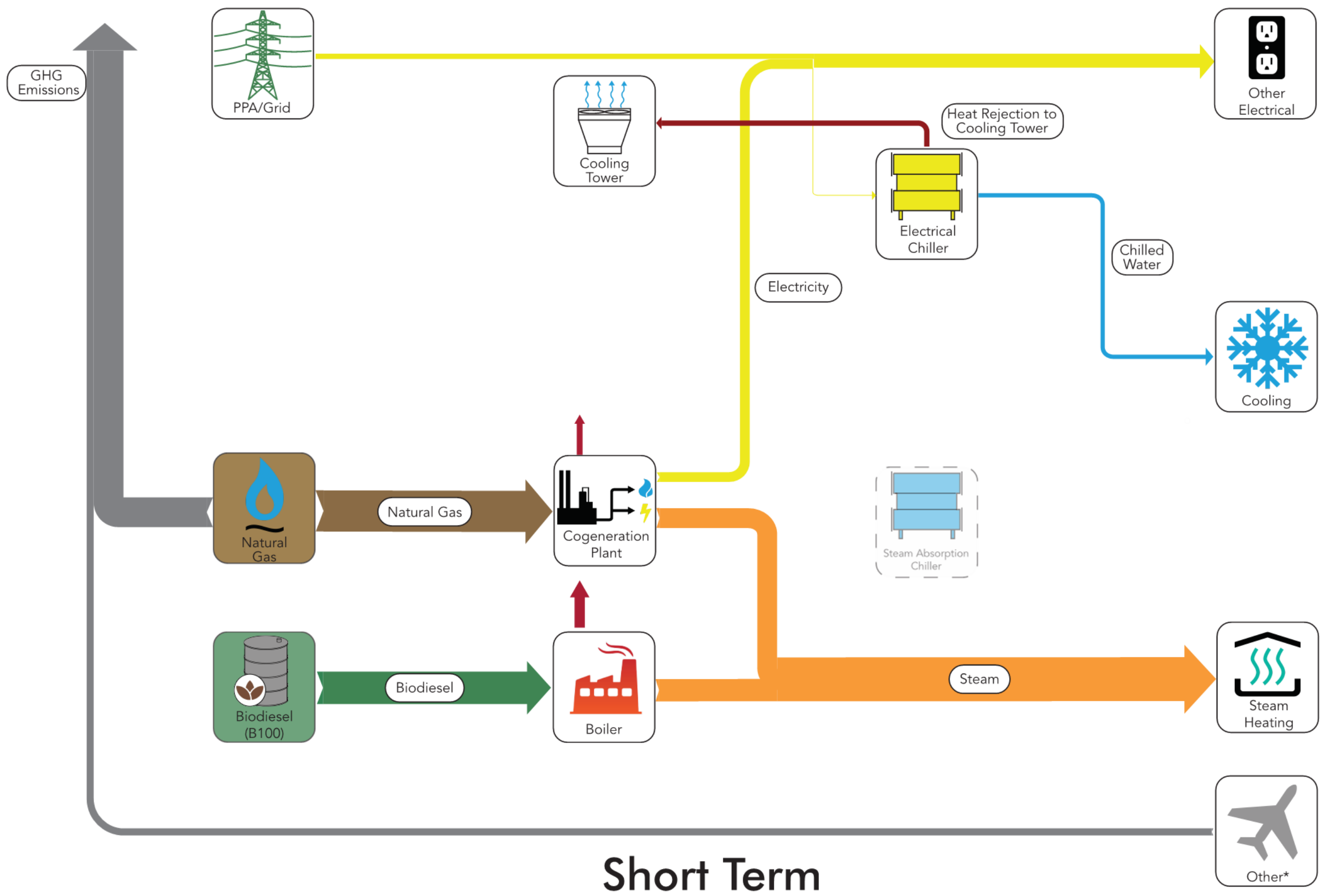

Figure 25: Energy and Emissions Flow (Recommended Approach, Short Term)

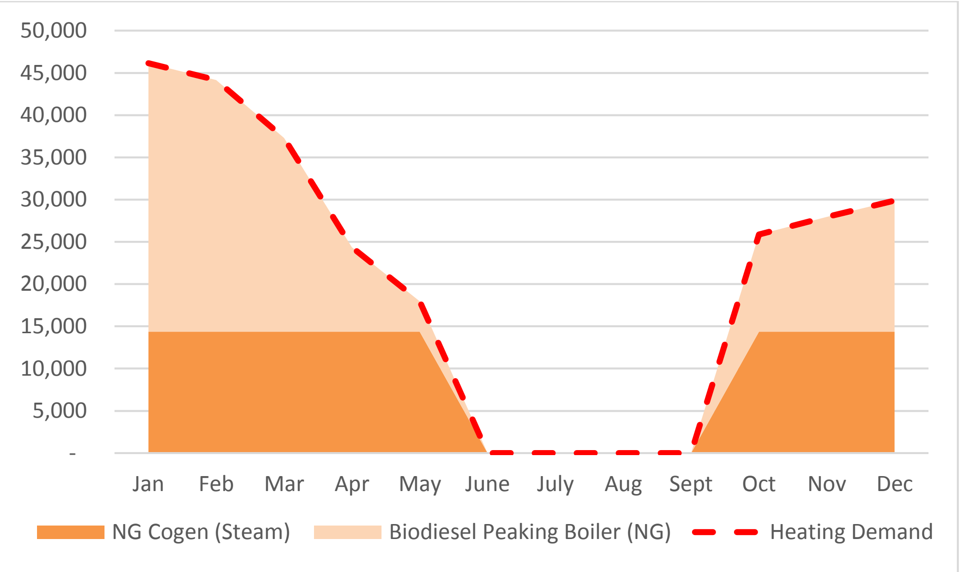

Figure 26: Heating Demand by System (Short Term, MMBTU)

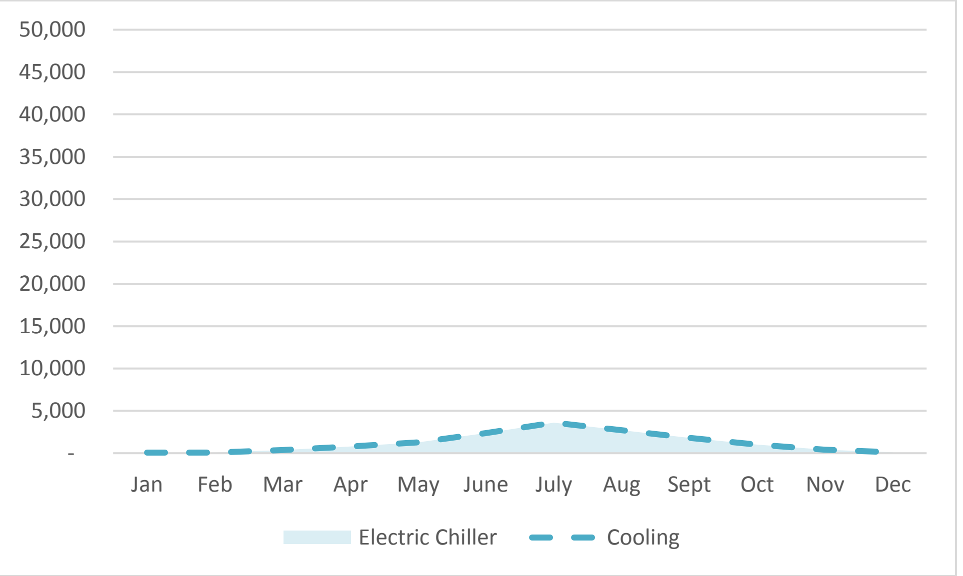

Figure 27: Cooling Demand by System (MMBTU)

7.2.1 Short Term Infrastructure Development

B100 Biodiesel Storage and Handling System

The different chemical properties of biodiesel, compared to petroleum diesel, mean that its handling and storage may require different infrastructure to conventional systems. As previously noted, the low freezing point of B100 biodiesel means measure such as heat tracing fuel lines, insulating dispensers and below grade storage may need to be considered. The existing diesel fuel handling system at Smith College will also need to be reviewed for its compatibility with B100 biodiesel. If the existing system is not compatible, then the cost of installing a new fuel handling system will need to be added to the project cost.

In addition to this the ongoing monitoring requirements of biodiesel (such as the addition of clod flow additives and monitoring for microbial degradation) should be factored into the new system's ongoing maintenance plan. The biodiesel changeover is part of the 'short term' plan and once complete will account for a significant portion of the GHG reductions required by the project. The key limitation to simply doing only this short term strategy is that the campus will be exposed to a high risk of becoming entirely dependent on its source of biodiesel. Biodiesel is significantly harder to acquire than traditional fuels and due to limited suppliers it has the potential to increase considerably in price.

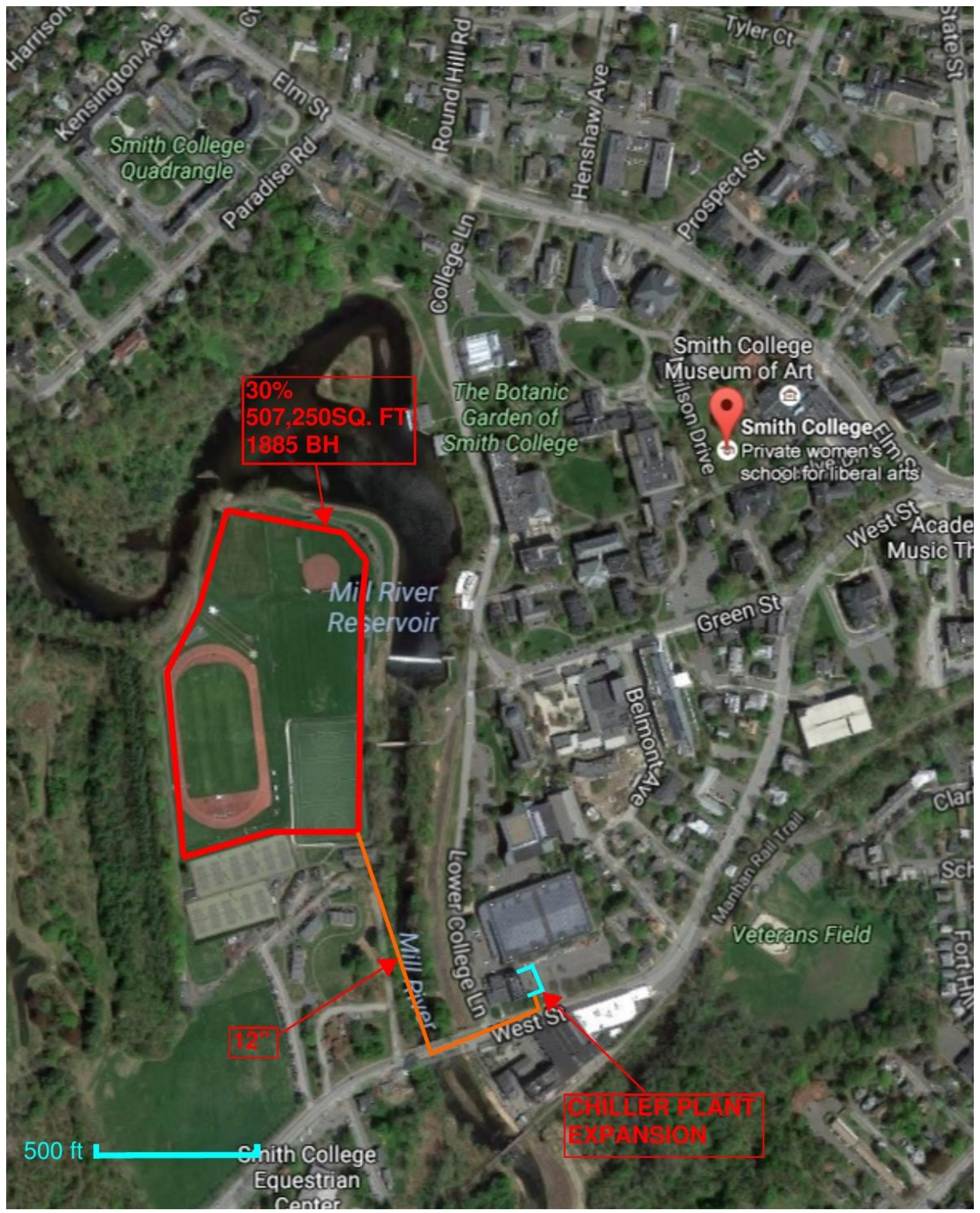

Figure 28: Geo-exchange Field Area and Piping

7.3 Medium Term Strategy

In the medium term we recommend the College begin to implement more significant changes to its mechanical plant that would allow it to continue being carbon neutral, but improve the overall efficiency of its heating and cooling systems and reduce its reliance on a biodiesel. The installation of a low temperature heating system, including 3 initial heat recovery chillers/ heat pumps and a 1,800 borehole (at 400ft depth) GHX field on the Athletics Field (Figure 27), would allow Smith College to diversify its energy sources while taking advantage of the simultaneous heating and cooling that occurs on the campus. We recommend the College commence the medium term strategy immediately after the initial short term strategy is completed.

Figure 29 shows the College's annual heating demand and the different systems that would be used to meet it, if the HR chillers, GHX field and 50% of the low temperature heating water network were implemented in the medium term. The annual cooling demand profile, as well as the proportion met by different systems, would not change from the short term option (Figure 27). Figure 31 outlines the energy and emissions flows at Smith College if the medium term strategy was implemented.

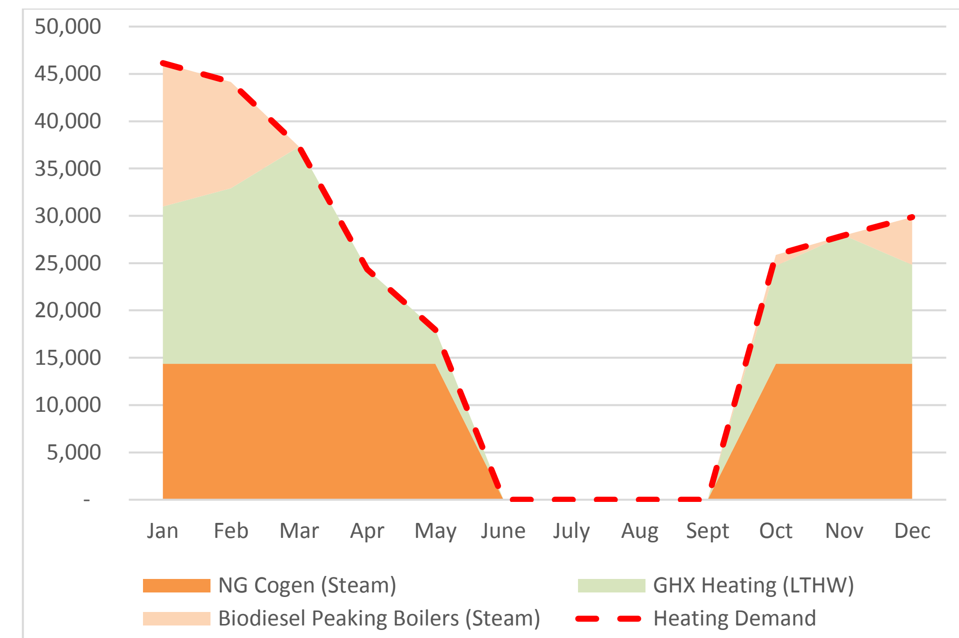

Figure 29: Heating Demand by System (Medium Term, MMBTU)

Another step the College could take in its decarbonization plan, would be to expand its CHW network to include the residential buildings to the north of the campus. Expanding the CHW network will increase the existing CHW plant efficiency and usability, as well as facilitate the installation of new absorption chillers in the long term strategy. Figure 27 below shows the College's annual cooling demand and the different systems that would be used to meet it.

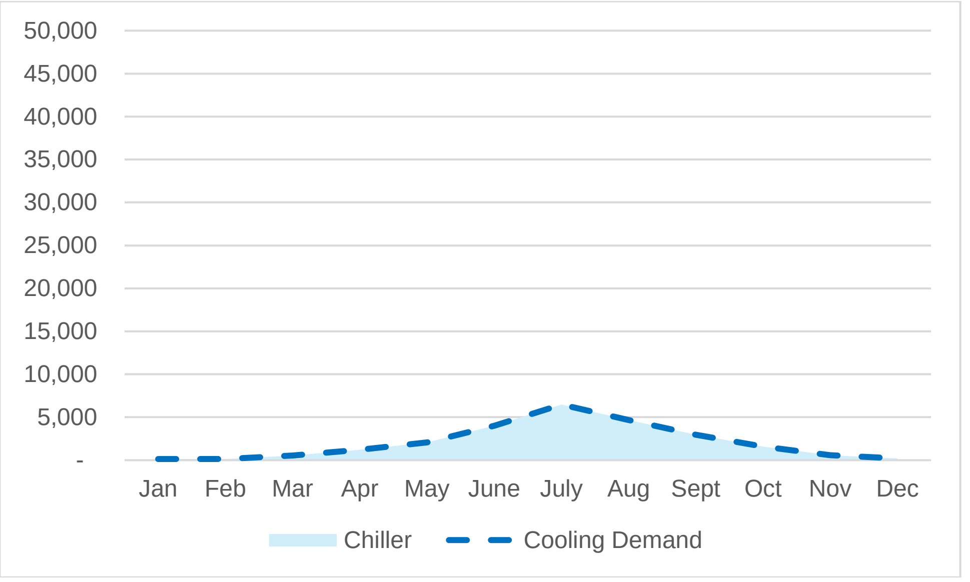

Figure 30: Cooling Demand by System (Medium Term, MMBTU)

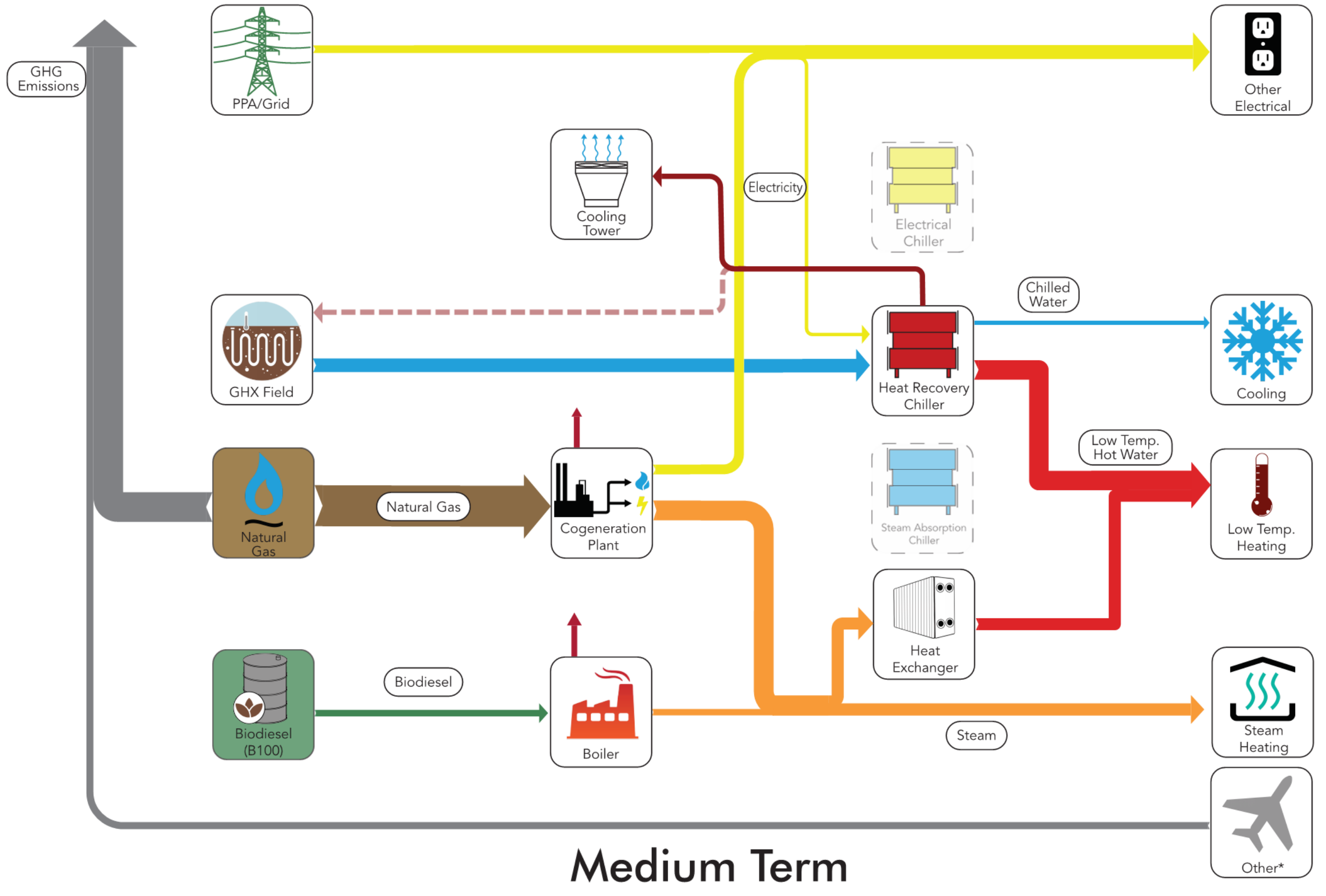

Figure 31: Energy and Emissions Flow (Recommended Approach, Medium Term)

7.3.1 Recommended Infrastructure Development

Geo-exchange

In order for the geo-exchange field to support the recommended 30% of the peak heating design capacity an area of approximately 510,000 ft2 (12 acres) would be required. This is equivalent to the majority of the campus's Athletics Field. The geo-exchange system would consist of approximately 1890 boreholes (at 400ft deep) spaced in a 16ft grid. The boreholes will feed into an approximately 2,000 ft. long 12" main traveling down the West side of Mill River and under the West Street Bridge to the central plant. While the geo-exchange system wouldn't support 100% of the College's peak heating demand, it would be able to meet the majority of the College's annual heating demand. The installation of the geo-exchange field would be part of the 'medium term' step and precludes the operation of the campus's new LHWT network. The LTHW network would be required as the geo-exchange system is un-able to supply the temperatures required by the current steam systems. The new field will provide the majority of the systems resiliency, as the geo-exchange field can provide the majority of the campus' heating and cooling demand independently of fuel prices therefore reducing dependency on biodiesel.

Central Cooling Plant Upgrade and Expanded Use of Chilled Water System

In order to do satisfy the College's thermal energy demands the chilled water system will need to be expanded and the current chiller plant building will expand accordingly. The extension would be a one story building with approximate dimensions of 95ft x 52ft and would contain the required heat pumps, heat recovery chillers, pumps, geo-exchange equipment as well as the required piping and auxiliary equipment. The cooling plant and chilled water network upgrade are part of the 'short term' steps since the current CHP plant provides enough waste heat to power the absorption chillers. Once the geo-exchange system is built in the 'medium term' the building will also use the cooling properties of the field during the summer to provide cooling in the place of the absorption chillers.

In order to connect the desired buildings to the upgraded chilled water network approximately 12,000 ft. of piping would need to be added in order to increase the reach of the current chilled water network which can be built in phases if required. Most notably a main would need to be run to the North residences and the current main near the chiller plant would need to be upgraded to account for the increased flow rates. Alternatively the North/Northeast sections of the campus alone could be added to the chilled water network. Since the residences in the Northwest only account for about 6.5% of the campuses cooling demand it could remain off the central chilled water network saving the costs of approximately 2900ft of piping.

Low Temperature Hot Water Distribution

In order to provide low temperature heating water to retrofitted buildings a new low temperature heating water piping network will be required. To achieve this a new line may be run in parallel to the current steam network which will require approximately 15,500ft of new piping. This piece of infrastructure can be built in stage with new buildings being added to the network as retrofits are completed during the medium and long term. When selecting the order of buildings to connect to the low temperature heating water network, buildings that are significant contributors the campus's annual energy demand (such as Ford Hall or McConnell Hall) should be prioritised. The change to low temperature distribution works in concert with the geo-exchange field allowing the system to be less dependent on the biodiesel powered CHP plant.

One potential way to distribute low temperature hot water throughout the campus, without installing a new LTHW network, would be to use the existing CHW distribution network; the network would distribute chilled water during the summer and heating water during the winter. While this is technically possible it is not recommended because of the different building typologies on campus. During the shoulder season it is likely that some buildings will require heating, while others will require cooling. If the campus only has one distribution network, it would only be able to meet either the heating demand or cooling at any given time.

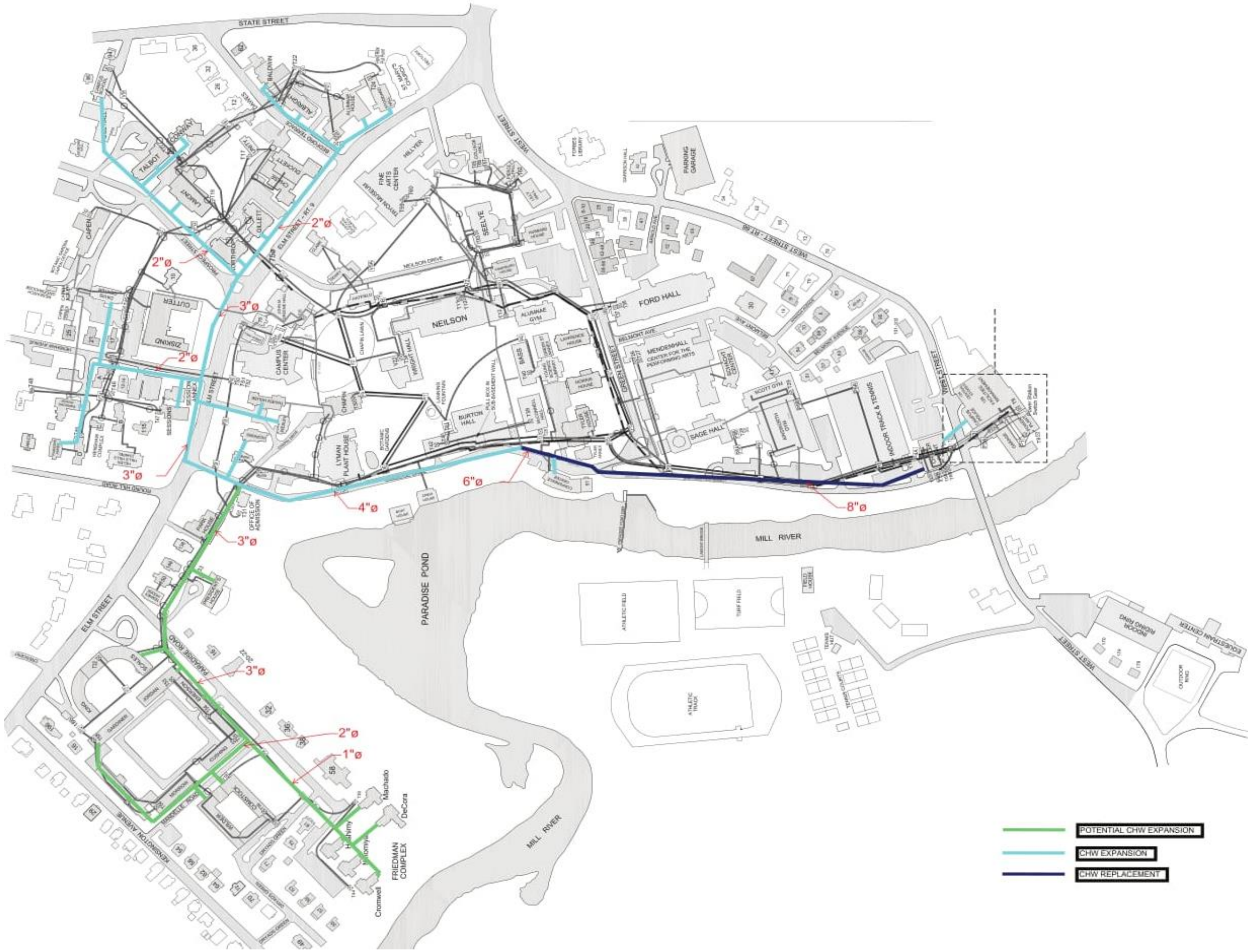

Figure 32: Proposed Chilled Water Expansion Routing

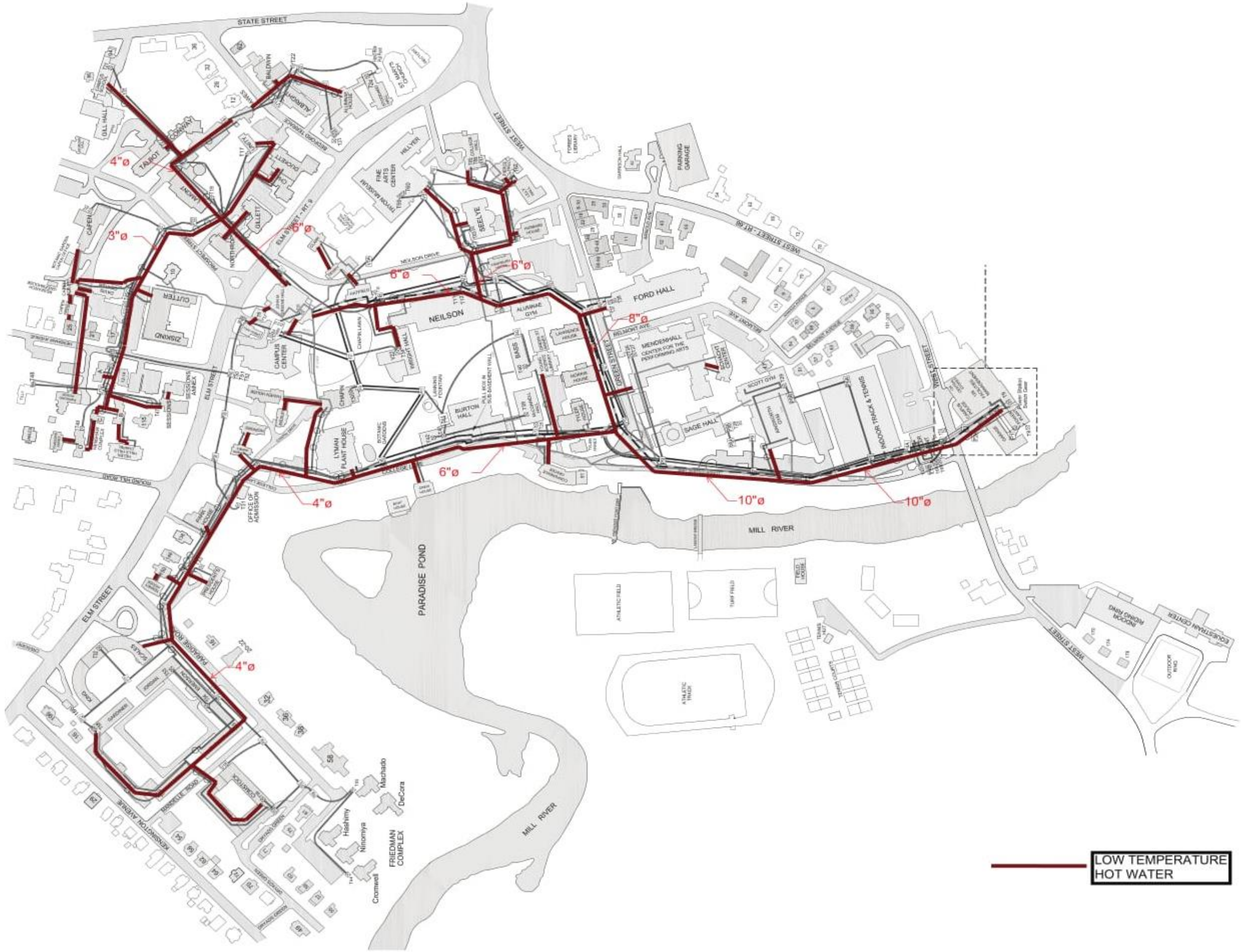

Figure 33: Proposed Low Temperature Heating Water Routing

7.4 Long Term Strategy

Finally, in order to achieve carbon neutral performance by 2030, the College will need to complete the installation of the low temperature heating network throughout the campus and the final portion of the GHX field. Given the age of the existing steam network, it is likely that a small percentage (conservatively estimated to be 10%) of the heating energy generated by the central plant is lost in the distribution network. That would indicate that the actual end-use heating demand of the campus is lower. Once the campus's buildings are switched from steam to LTHW the heating distribution network inefficiency would be reduced (as shown in Figure 35), further reducing the College's annual heating demand and fuel consumption. Figure 35 outlines the College's reduced heating demand profile and the different systems that would be used to meet it, once the low temperature heating water distribution network is complete. Another key part of the long term strategy is the installation of a new biodiesel (b100) compatible boiler, ORC unit/steam turbine and absorption chillers. The annual cooling demand profile, as well as the proportion met by different systems. Figure 34 outlines the final energy and emissions flows at Smith College if the long term strategy is implemented.

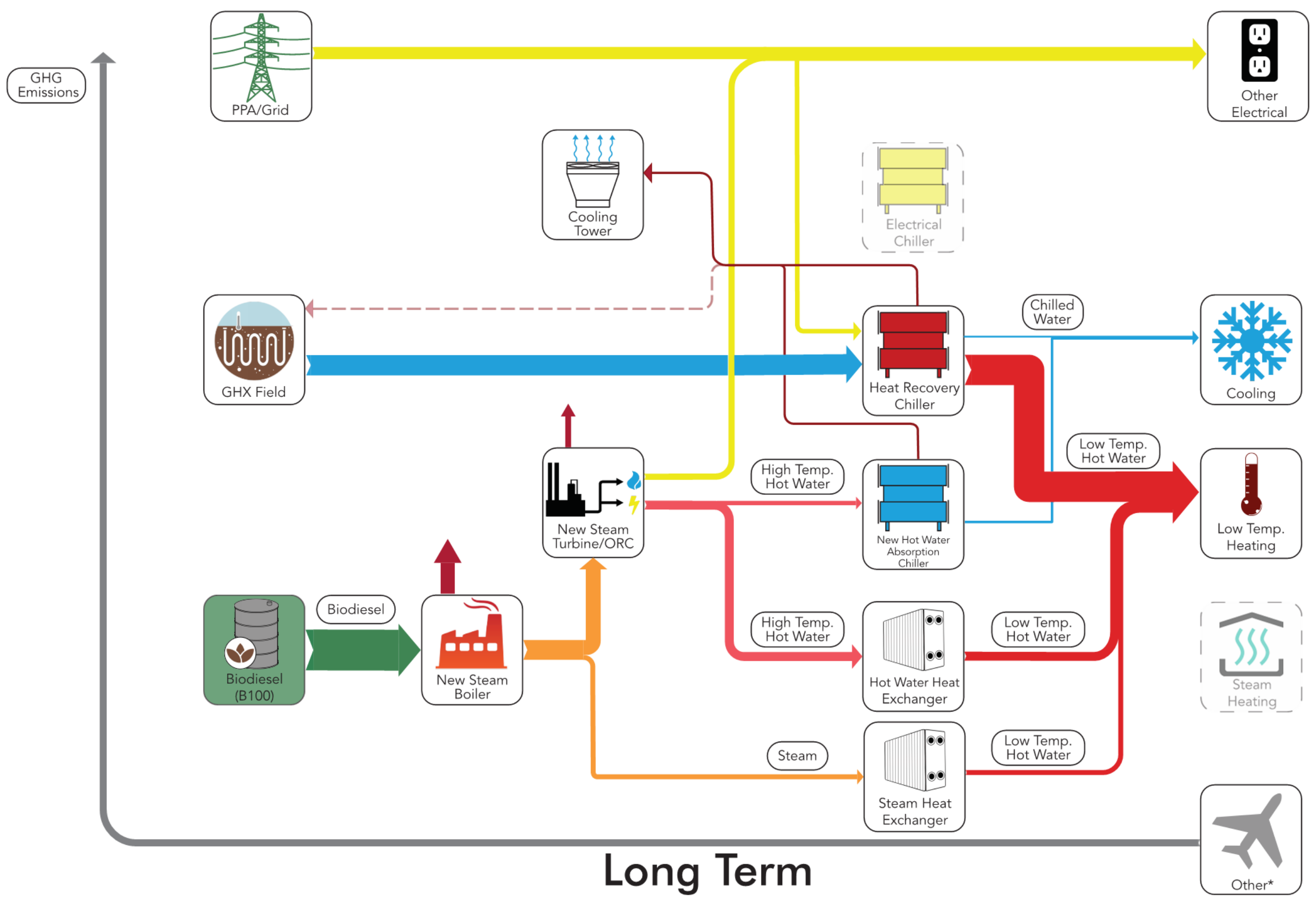

Figure 34: Energy and Emissions Flow (Recommended Approach, Long Term)

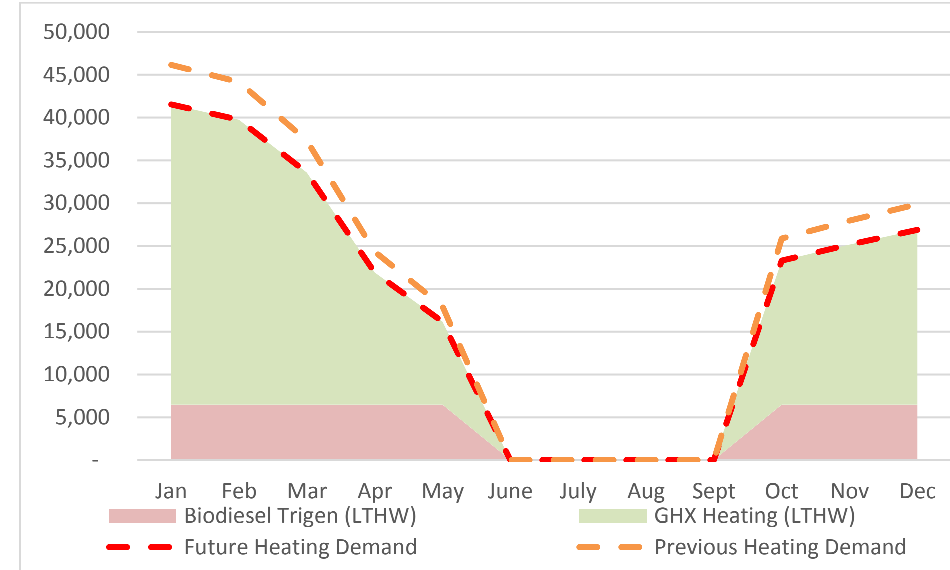

Figure 35: Heating Demand by System (Long Term, MMBTU)

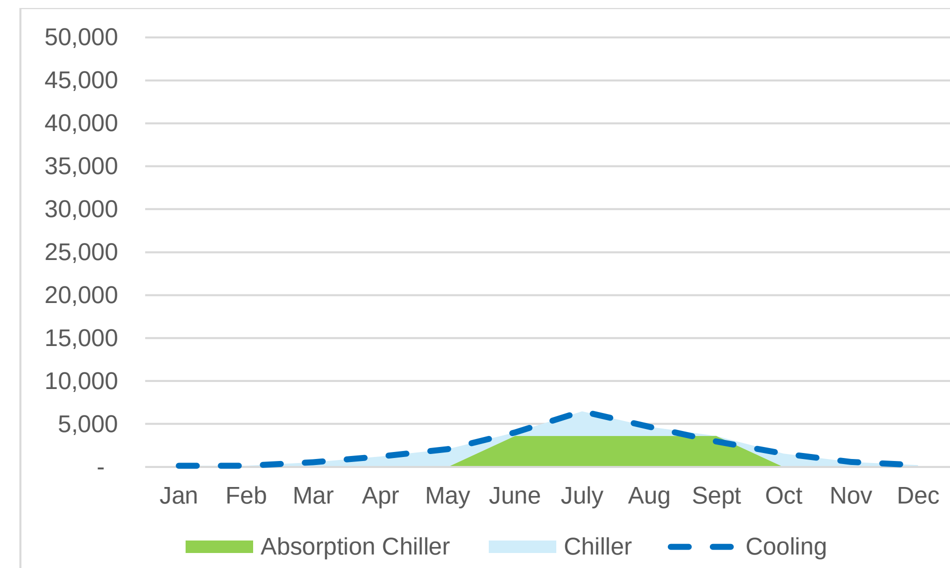

Figure 36: Cooling Demand by System (Long Term, MMBTU)

Figure 37 shows the change in the campus's electrical demand over time, as the different decarbonization steps are implemented. In the short term, the campus's electrical demand will remain relatively stable and essentially identical to the existing demand. In the medium term, as the electric based HR chillers/heat pumps coupled with the geo-exchange field begin to provide low temperature heating, the campus's annual electricity consumption will increase by approximately 3,700 MWhs per annum to reflect the increased electricity consumption of the heating system (using the HR chillers). Finally in the long term, once the low temperature heating water network is complete, there would be another increase in electrical consumption (approximately 3,000 MWhs per annum) as the biodiesel boilers are decommissioned and the HR chiller capacity increases further to take over the remaining heating demand.

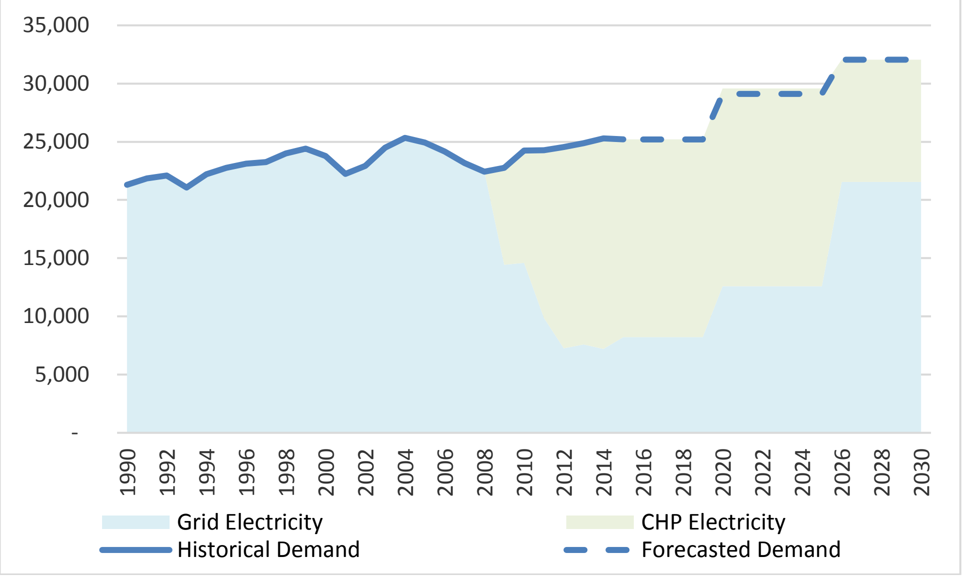

Figure 37: Recommended Approach Electrical Consumption (MWh)

Figure 38 illustrates the changing breakdown of the College's GHG emissions through the different stages of the carbon neutral strategy implementation. A significant reduction in GHG emissions occurs with the implementation of the initial short term strategy and is the result of the fuel switch from natural gas to biodiesel as the primary energy source for the boiler plant. Another reduction in annual GHG emissions occurs in the long term strategy, as the natural gas cogeneration system is decommissioned and replaced with an ORC unit/steam turbine.

During the medium term and long term strategies, as the HR chillers/heat pumps and geo-exchange field are added and used to meet a greater portion of the campus's corresponding annual heating demand, the electricity consumption and annual GHG emissions of the campus will increase. This increase in emissions can either be offset by the installation of renewable electricity generating technology, such as PV systems, or a PPA to ensure that all electricity consumed on campus comes from a renewable source. As in the review of the 2015 GHG emissions, addressing the 10% of emissions related to 'other' end uses not related to the campus's central heating, cooling and CHP plants is outside the scope of this analysis.

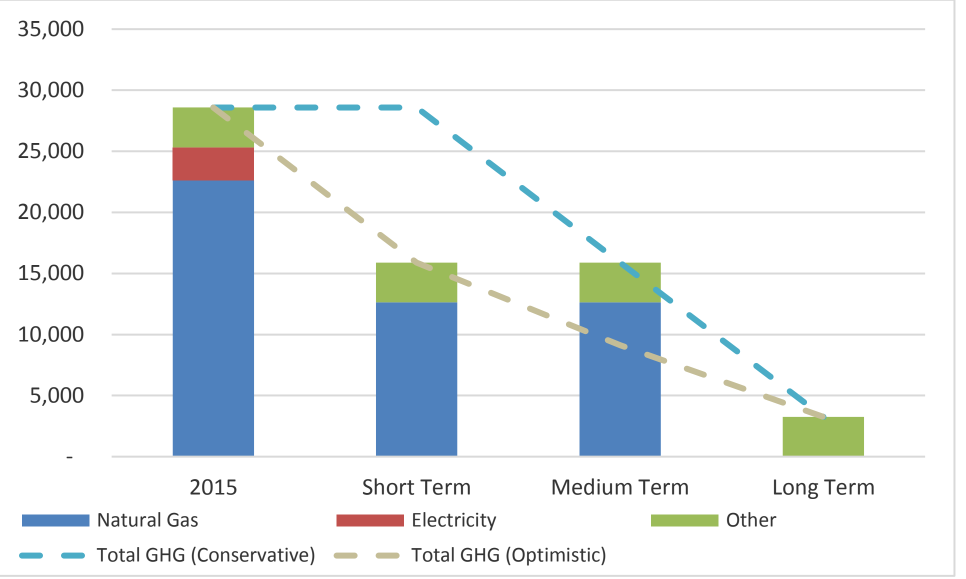

Figure 38: GHG Emissions Comparison

Estimating exact timeframes for implementing each of the zero carbon strategies outlined is difficult due to the high number of unknowns that will need to be addressed during detailed design. Figure 38 therefore also illustrates alternate time lines for the college's GHG emissions reductions, based on more optimistic or conservative timeframes for the different strategies. In the optimistic timeframe both the existing boiler plant conversion to B100 biodiesel and an initial portion of the LTHW network/CHW network expansion are completed by 2020 (the short term). This would significantly reduce the college's annual GHG emissions, as well as give it 10 years to complete the LTHW network/CHW network expansion and associated building retrofits. The college would also have 10 years to complete the research, design, construction and commissioning of a new biodiesel fuelled steam boiler plant, the associated new steam turbine/ORC unit and hot water absorption chiller plant.

In the conservative timeframe the conversion of the existing steam boiler plant to biodiesel and development of the LTHW network/CHW network expansion does not begin until 2020. Until the conversion of the existing steam boiler plant is complete, the college would not see any appreciable reduction in annual GHG emissions. Delaying the installation of the LTHW network and CHW network expansion would also reduce the time available to Smith College to implement this work; work that represents a significant portion of the project's total capital cost. It would also reduce the time the college would have to research design, install and commission the new biodiesel fuelled steam boiler plant, the associated new steam turbine/ORC unit and hot water absorption chiller plant. Ultimately the difference between the optimistic and conservative scenarios is the pace at which Smith College would need to install the zero carbon strategies outlined in this report.

8. FUTURE WORK

8.1 Building Retrofits

We recommend two primary enabling strategies for this. In order to maximize investments in low exergy infrastructure. The first one is a targeted approach to energy demand reduction in high intensity users and the second is a campus wide approach to electrical energy use reductions.

8.1.1 Targeted Building Energy Use Reductions

Smith College staff estimate that 15-25% of overall campus energy use could be attributed to the energy use in Sabin Reed/Burton Hall, McConnell Hall, and Ford Hall. These are science buildings, with wet labs, that are energy intensive by nature, but given the magnitude of their energy use they be a source of significant energy savings for the campus overall. Based on preliminary metering work done by Smith College Staff energy use intensity in these buildings could be over 300 Btu's/Sqft/yr. For reference, an average teaching and administration building on a university campus in the United States according to the Environmental Protection Agencies, Energy Star Portfolio Manager Data base is 134 Btu's/Sqft./yr.

According to National Renewable Energy Laboratory's "Laboratories for the 21st Century – A Best Practices Guide" : energy efficiency retro-fits to wet labs that have focussed on replacing mechanical and ventilation equipment, adding HVAC and fume hood controls, and can yield an average energy savings of 18-25%. Sabin Reed/Burton Hall, and McConnell Hall are older buildings that have out-dated mechanical systems and no centralized controls, or building automation and could benefit from these strategies. In order to achieve deeper savings a more comprehensive approach to retro-fitting these buildings such as looking at alternative spaces would be required. Currently both buildings are limited by low interior ceiling heights that limit mechanical strategies.

Ford Hall, being a newer building we recommend an approach that looks at optimizing existing systems and experimenting with different industrial sanitation protocols that could lower the use fume hoods.

8.1.2 Overall Building Energy Use Reductions

In addition to targeted reductions in high energy use buildings we further recommend a comprehensive lighting upgrade on campus. The majority of buildings on campus are not using LED lighting technology. In commercial building applications comprehensive LED Lighting upgrades can yield lower energy use in buildings by an average of 5-10% depending on the lighting system that is being replaces. The lighting system upgrades typically have a positive net present values and relatively short pay back periods of 5 years or less. We recommend that Smith College investigate further the potential of comprehensive lighting retro-fit in all campus buildings using LED technology. The further benefit of lighting retrofits is that they reduce peak demand and for electricity which means that energy generation infrastructure may be able to be down-sized.

In order to achieve the scale required of retro-fitting over 100 buildings within a 15 year period an energy performance contract model may be a useful tool for financing and resourcing a project of this scale

8.2 New Building Design Standards

Smith College is not projected to grow during the time horizon of this plan. This means that any new buildings will be replacing older building on campus which represents an opportunity for significant savings if the new replacement buildings are suitably energy efficient.

8.2.1 Passive House Levels of Performance:

We recommend for Smith College that any new construction use the Passive House system to define its energy performance metrics. Passive House is an internationally recognized building performance standard that has demonstrated that it regularly achieves 70-90% energy and carbon savings over existing buildings, while providing excellent indoor environmental air quality and thermal comfort. Passive House has been proven out in over 50,000 projects worldwide, in a range of building types that include, higher education, research, administration and residential buildings all of which are present on the Smith College campus. We recommend this approach over other building performance standards such as LEED because of the track record Passive House has in delivering real world energy savings. By comparison many LEED projects that use relative base lines to measure performance have had issues with delivering sustained energy reductions over time.

The fundamental characteristics of Passive House buildings are that they primarily derive their energy savings from building envelope design and are not reliant on mechanical optimization. The reliance on passive solutions contributes to substantial reductions in both heating and cooling loads. Because of this Passive House buildings also limit peak heating and cooling demands and therefore help to optimize the centralized thermal energy solutions proposed in this plan because of their relatively stable energy demands.

9. RECOMMENDED NEXT STEPS

The purpose of this study was to investigate the possible high-level strategies for Smith College to become carbon neutral by 2030 and recommend an approach that is cost effective, technically sound and offers the College a high level of resiliency from external risks. Based on our analysis and the Short, Medium and Long term strategies of our recommended approach, we suggest the College undertake the following next steps to begin its transition to carbon neutral performance:

1. Implement the Short Term strategy that involves switching the existing steam boilers from natural gas to B100 biodiesel, and further investigate the options for using B100 biodiesel with the existing CHP turbine unit with Solar Turbines and Northeastern Biodiesel.
2. Begin concept design of the new low temperature heating system, including the design of the vertical geo-exchange field, the low temperature heating system plant and piping distribution network.
3. Begin concept design for expanding the existing chilled water network, including connecting and upgrading buildings not currently connected to the chilled water network.
4. Review of existing building stock and begin concept design for upgrading existing buildings and their heating systems to be compatible with low temperature hot water heating.

While the implementation of the recommended Short Term, Medium Term and Long Term steps will allow Smith College to achieve carbon neutral performance, it is important to remember that, at this initial stage of the project, there are still a number of details that require further investigation. Details such as the final source of renewable fuel (whether this is B100 from Northeastern Biodiesel or another renewable fuel from a different supplier), for example, or which buildings will be connected to the low temperature heating water network still need to be decided.

These details, however, will not ultimately change the overarching strategy outlined in this report, or prevent the College from achieving its goal of carbon neutral performance. The fundamental principles that the Short Term, Medium Term and Long Term strategies are based on (switching to a low carbon fuel in the short term, then progressively installing and switching the campus to a low temperature heating water system) have the flexibility to be adapted to suit any challenges as they arise.

10. CONCLUSION

Smith College has set an ambitious goal in attempting to become carbon neutral by 2030. In order to achieve this ambitious goal the College will need to make a number of critical decisions in the next few years, all of which will have long term implications on its energy infrastructure. The approach developed and recommended as part of this study will allow the College to make significant reductions to its GHG emission in the short term, thereby buying it more time to properly investigate and implement more substantial decisions regarding its key existing energy infrastructure components and the existing building stock. By following the recommended approach Smith College will not only be able to meet its carbon neutral target, but also modernize its building energy infrastructure to be compatible with any renewable energy technologies that are currently available as well with those that might become available in the future.

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