2016 Climate Neutral Campus Energy Alternatives Report

Appendix D: Campus District Heating System Evaluation

Notes Regarding Appendix D:

This appendix contains content from an internal study ("Cornell University Campus Distributed Heating System Long-Term Plan") completed in June 2015 by Facilities Engineering under the guidance of Energy & Sustainability (E&S). This study was aimed at evaluating the long term costs and benefits of options related to the campus district heating system.

The purpose of including the prior work was as follows:

- To assess the costs and benefits of maintaining the existing (steam) district heating system versus other long-term options (partial or full conversion to hot water)
- To provide essential "background" information that could be used by a consulting firm in the future to help with any proposed re-design or expansion needs (without such a report, this information was only available in multiple locations and some prior information was outdated).

The attached document is an update of the 2015 report. Some information from the 2015 report (and included in this appendix) has been superseded or is no longer valid, and the scope of the two studies differed. Specifically, readers should note the following:

- The cost information contained herein has been redacted. To properly inform the CNCEAR, E&S staff conducted a cost-estimating workshop that included creating a conceptual model for a new hot water conversion and included contingency and project costs at levels not included in the 2015 report. To avoid confusion on expected costs, cost information in this report was redacted. The updated cost estimates are much higher and are reflected in the CNCEAR report.

- Due to this (substantial) change in costs, essentially all of the financial evaluations of this report are no longer valid. Notes have been added to this effect throughout the text.

Despite this significant change, Appendix D was included as it does provide further details not included in the CNCEAR which may be of interest to those planning future changes on campus.

TABLE OF CONTENTS:

EXECUTIVE SUMMARY AND RECOMMENDATIONS

Overview

This report includes the following:

- Documentation of the existing Campus Distributed Heating (steam-to-hot-water) system physical and operational parameters
- Documentation of existing and previously-developed capital plans for improvements to the system
- Recommendations for potential improvements to the system, including applicable costs and impacts on operations and reliability
- Analysis of, and recommendations for, future capital planning strategies to achieve University goals including:
  - Minimize future capital expenses and operating expenses (quantified as an overall "Present Value" of expenditures over time)
  - Operate in an environmentally-responsible manner
  - Provide opportunities for the incorporation of renewable, recoverable (waste), or recycled heat into the central heating system

Primary Conclusions

The study and analysis of the existing steam supply and distribution system resulted in the following primary conclusions:

- The existing steam supply and distribution system is effective. The system reliably provides the heat for campus needs and is well-maintained.
- Energy conservation has been extremely effective at avoiding unneeded growth in steam demand and related capital needs.
- Despite astute management, the thermal losses in the distribution system are significant (about 19% of all energy entering the distribution system is lost between the central plant and the served buildings). Losses of this scale are typical for steam distribution systems.
- A conversion of the distribution system to a lower-temperature system (hot water) is necessary to allow centralized integration of renewable or low-carbon energy as required to pursue Climate Action Plan (CAP) initiatives. It will also result in a significant reduction in distribution loss (reducing the ~19% losses to losses in the ~1-4% range).
- Buildings designed for lower temperature hot water supply and return will increase system efficiency and enable to effective utilization of input energy.
- Modern hot water distributions systems are less expensive to design, build, and operate and are safer than steam distribution. However, due to the "sunk cost" of prior steam distribution investment, immediate replacement of the steam system with a hot water system likely cannot be achieved while meeting the rigorous Present Value (single-bottom line) financial objectives based

on the desired University real discount rate (investment return rate) of 5.4%. Well-planned and thoughtful incremental replacement over time it necessary to simultaneously meet both financial and non-financial goals.

Section 5 includes more details on this analysis; Section 6 discusses these conclusions in greater detail.

Summary Recommendations

Recommendations resulting from the analysis described in this report include the following:

- **Maintain the primary steam supply system.** While alternative low-carbon or no-carbon solutions are a longer-term goal, the proper operation and maintenance of the existing steam supply system will ensure reliable and cost-effective campus heating in the interim and will provide a back-up source to any new system until proven out.

- **Maintain or enhance redundancy of heating supply and distribution capacity whenever the system is expanded**. Redundant supply equipment ensures that campus needs can be met despite occasional equipment failures and facilitates timely equipment maintenance; redundant ("looped") distribution systems enhance reliability and supply constancy and permit distribution system repairs and improvements without unacceptable service disruptions.

- **Continue aggressive energy conservation.** Energy conservation at both the building and system level is the most cost-effective tactic for avoiding unnecessary capital expansion of supply and distribution systems and reducing costs for future replacements. Cornell's energy conservation programs have significantly reduced both steam peaks and average loads.

- **Extend the distribution of hot water, starting at the distribution periphery**. At the building level, nearly all steam is converted to hot water for heating and hot water use. A gradual and well-planned expansion of peripheral hot-water loop sub-systems serving multiple buildings, such as currently in place for portions of West and North campus, significantly reduces the maintenance burden of steam traps and similar conversion equipment, improve safety and reliability, and improve system performance by reducing thermal and water losses. Maintenance can then be focused on the most critical "core" of the (remaining) steam distribution system.

- **Establish and enforce formal heating system design standards that prescribe building system temperatures immediately.** Future buildings and current building heating system upgrades should be designed to allow for both a lower supply temperature and a significantly reduced return temperature limit. This would significantly reduce costs of future system infrastructure and enable integration of cost-effective renewable and waste heat recovery as these technologies are developed and implemented.

- **Complete a systematic evaluation of existing buildings to document individual building temperature settings and needs.** Utilize this information to plan and implement adjustments to building control settings and plan future system modifications necessary to allow lower-temperature building services.

- **Before 2035, convert the current "primarily steam" system to a "steam-driven cascading heat system".** In this improved system, the majority (or all) of the campus heat is distributed as hot water. As alternative heat sources (i.e., Earth Source Heat, Heat Pumps, Biomass Boilers, or similar) become available, this system will allow integration of these resources at low cost. The life cycle cost (Present Value) of this solution is slightly lower than the "Business as Usual" based on predicted gas pricing without carbon taxes or other incentives/disincentives, and this solution is necessary to accommodate renewable energy (Earth Source Heating) in the future. This solution offers the lowest environmental impact (lowest “carbon footprint”), enhances reliability, and improves safety of the options studied.

- **Purchase software and build an in-house steam system model to replace the current model prepared by outside consultants.** Software appears to now be available which is affordable ($5,000-7,500) and designed for this task. Creating and utilizing an in-house model supports essential planning, design, and construction impacts support for Energy & Sustainability in their management of the steam system.

Section 6 provides more detailed recommendations, expanding on the recommendations included in this Executive Summary.

SECTION 1: PURPOSE AND SCOPE

Purpose and Scope

The purpose of this project is to provide guidance and recommendations for future capital and O&M actions to ensure a reliable, efficient, and effective thermal distribution system.

The current thermal distribution system is highly reliable. However, the costs for operating and maintaining this system are substantial and increasing over time; continuing planning is important to ensure that improvements keep pace with aging of the system.

Additionally, thermal distribution system heat losses represent a significant opportunity for primary energy supply (and associated greenhouse gas emissions) reductions, a goal of Cornell's Climate Action Plan. The 2014 Cornell Energy Fast Facts estimate that losses in the thermal distribution system (the difference between metered exported steam and cumulative metered steam used in buildings) average ~19%. Other internal estimates, as documented in this report, similarly suggest net losses are in the range of 15-20% overall. Reduction of these losses represents the greatest single opportunity for reducing greenhouse gas emissions campus-wide with the exception of Earth Source Heating or a similar alternative central energy technology that requires no fossil fuel.

Cornell's thermal losses, documented herein, are considerably lower than many other older institutional steam systems. For example, the U.S. Army Corp of Engineers (CRREL Report 95-18, 1995) estimated that over 40% of energy is lost from typical military steam distribution systems due to the inherent challenges of steam distribution and inadequate maintenance. Other sources (IDEA) suggest that losses of 15-20% are common even for well-maintained steam distribution systems like Cornell's. Nonetheless, this ~19% loss represents a substantial amount of wasted heat and energy overall and an opportunity for measureable improvement in overall campus energy performance.

Moreover, source-substitution technologies under consideration as part of the Climate Action Plan all require a lower-temperature heating distribution system to be feasible. In some cases (such as heat pumps), a lower-temperature distribution system is not only preferable, but absolutely necessary. For other potential alternatives, as documented in this report, a lower-temperature distribution system may not be technically essential but is in all cases necessary to make the technology cost-effective and practical.

While energy savings are laudable, significant systematic changes must also be fiscally-responsible and consider the importance of high reliability. A primary goal of this study is to provide information and tools to help determine if thermal losses can be reduced in a manner that is cost-effective and does not adversely impact reliability.

The scope of this work is the entire heat distribution system for Cornell's Ithaca Campus, from central plant boilers (including Heat Recovery Steam Generators, or HRSGs) at the Central Energy Plant (CEP) to the campus buildings that are fed by the CEP. Within that scope, this Plan should encompass the following goals:

- Document the existing conditions and system constraints, to aid in future operations, maintenance, and planning
- Recommend design and policy standards for infrastructure to enable future reliability and cost-effective operations of the heat distribution system
- Recommend future best practices for the current steam system that encompass these primary goals:
    a. Meet campus demands

b. Maintain high reliability
c. Improve safety
d. Keep life-cycle costs as low as practical
e. Accommodate sustainable (lower “carbon footprint”) operation in future years

SECTION 2: STEAM SYSTEM DESCRIPTION

System Introduction

The Cornell Central Energy Plant (CEP), located on Dryden Road, provides co-generated steam for space heating, hot water, and research needs to over 150 buildings on the main campus. Steam is distributed through a buried steam pipe distribution network totaling over 13 miles of pipe. Condensate is returned to the CEP through a similar buried pipe distribution network with a similar length of pipe.

The steam is produced from a combination of two dual-pressure heat recovery steam generators (HRSGs) associated with two 15 MW gas turbines and from additional boilers fueled primarily by natural gas. Most of this equipment also will accept #2 fuel oil as a back-up fuel. Two additional dual-fuel boilers will be installed in 2015 to provide reliability to the steam system (replacing temporary boilers installed during the heating seasons from 2012-2015).

Operating boiler combinations are determined based upon facility load, fuel costs and operational considerations. With the exception of the low-pressure HRSG stage (designed to improve overall efficiency), steam is produced by the HRSGs (high pressure state) and boiler(s) at high pressure and reduced using steam turbines (cogeneration). The byproducts of the steam pressure reduction through the steam turbines (together with the low pressure HRSG stage) are low pressure steam and additional electricity.

Existing Steam Production

As noted above, the Central Energy Plant system consists of multiple boilers and HRGSs producing high-pressure steam. Table 2-1 provides a summary of these units.

Table 2-1: Steam Production Capacity

Boiler/HRGS No.	Steam Pressure Output (psig)	Reliable Capacity (lbs/hour)*	Year in Service
HRGS 1	400/200	148,000	2009
HRSG 2	400/200	148,000	2009
Boiler 5	400	88,000	1965
Boiler 6	400	97,000	1993
Boiler 7	400	97,000	1993
Boiler 3 (2015)	400	75,000	2015 (scheduled)
Boiler 4 (2015)	400	75,000	2015 (scheduled)
TOTAL		**729,000 (gas)** **453,000 (oil)***	

**Note: Tested capacity. Boilers are dual-fuel with the exception of Boiler No. 5, which can only operate on natural gas. HRSGs capacity running on oil are also lower (~ 59,000 lbs/hr each) since HRSG output is bolstered by duct burners, which only accept natural gas.*

The CEP also includes primary equipment which helps support the steady production and distribution of steam. Support equipment includes:

- De-aerator (DA) system (rated for 350,000 pounds/hour) with feed-water equipment
- Condensate system surge tank (replaced in 2014)

- #2 oil storage tank (662,000 gal) and transfer equipment. This system dates to 1959, but reduced in volume and refurbished in 2008.
- A high-pressure direct natural gas piping system connecting to an interstate pipeline (installed in 2008)
- A comprehensive central Plant Control System (most pre-2008 controls were replaced over the period 2012-2015)

In addition to the primary electrical generation in the combustion turbines, the additional generation of power through the steam turbines is also substantial. Steam generated at 400 psig is processed by two steam turbine generators to generate up to 8 MW of electricity, reducing the steam pressure to 75 psi in the winter (when steam demand is highest) and 35 psi steam in the summer for campus uses. However, several units (including the final HRGS sections) generate lower-pressure (200 psig) steam; this steam has insufficient pressure for the steam turbines and is used for distribution purposes only.

Distribution System Description

As noted above, steam is generated by a combination of HRSGs and stand-along boilers at a pressure of either 200 or 400 psi. The 200 psi steam is used primarily for heating purposes and fed directly into the distribution header after pressure reduction. The 400 psi steam is fed to one of two Steam Turbine Generators (STGs) that first use the steam to generate electricity. The byproduct of the steam turbine generator is low pressure steam distributed to campus for heating purposes.

The steam piping system originates from the Central Energy Plant (CEP). Cornell maintain a comprehensive mapping and inventory of steam piping assets throughout the system. Figure 2-1 shows a simplified plan view of the system map. Cornell's digital mapping includes data about all segments of the distribution system, including piping size, age, materials, manhole locations, valve locations, and similar information.

Figure 2-2 shows the portion of the system nearest the heating plant supply, Three (3) steam supply lines exit the CEP; the first two are 18" (nominal diameter) and leave in a northerly direction toward central campus. On the north side of Cascadilla Creek, the easternmost line reduces to 16". The third line is 16" and heads towards the western end of campus. The 18" steam line branches east and west following Campus Road and again east and west at Tower Road. The East Branches feed the State-Owned buildings on the East Campus. The second main follows Hoy Road and feeds the Endowed Buildings on the West side of Campus and eventually to the residences on the North Campus. The two feeds tie together along Tower Road between East Avenue and the Alumni Fields. These connection points allow for diversion of steam in the event of pipe failure, replacement or repair, as well as pressure stability through a wide range of building demands. The distribution system includes other strategically-placed loops that improve reliability and constancy of pressure, as generally shown in Figure 2-1, although there are locations along the perimeter (for example, the feeds to West and North campus) where a single steam line feed is critical for groups of facilities. In addition, essentially all facilities are each fed from a single distribution lateral, so maintaining these lines is critical to reliability.

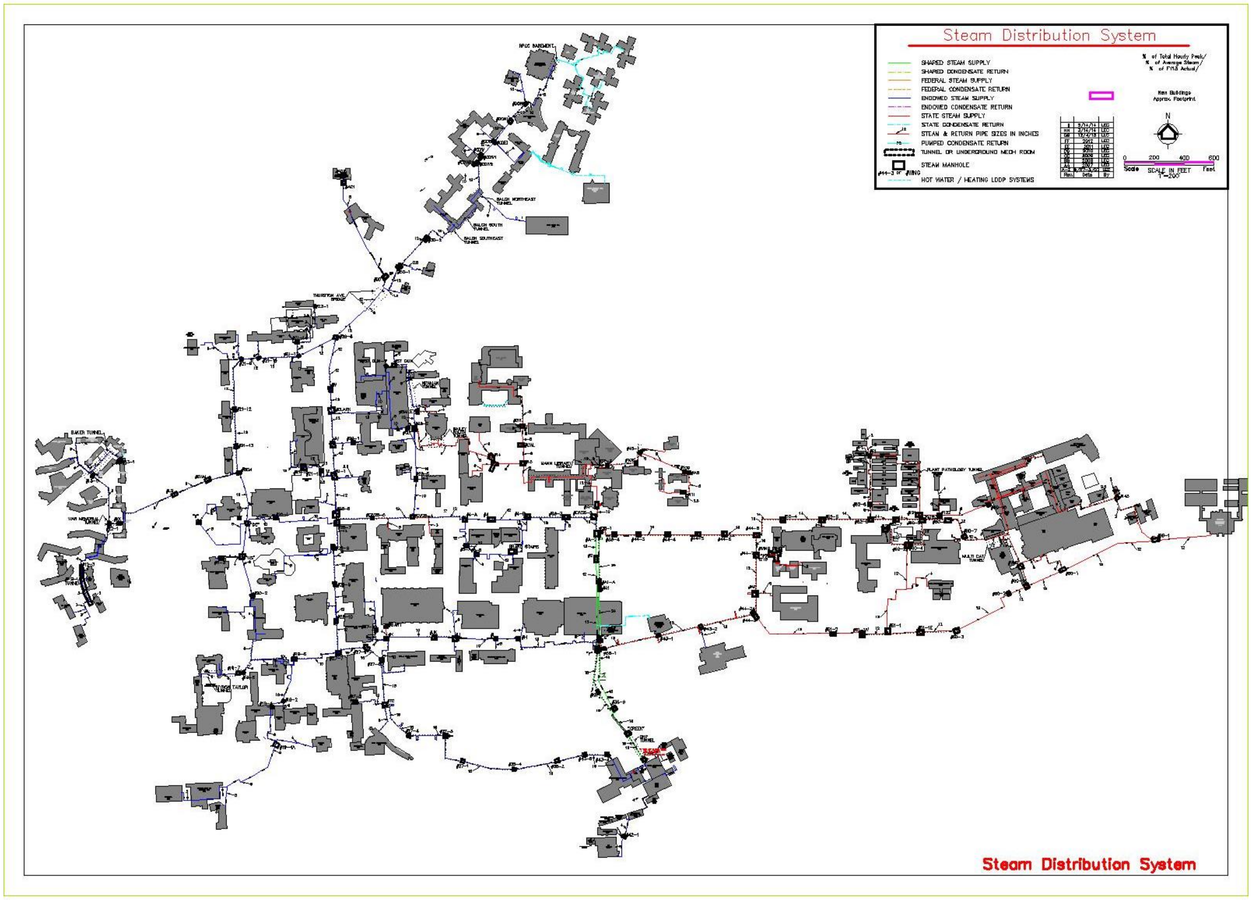


Figure 2-1: Overall Distribution System Map

While all of the largest campus building demands are served by the central system, some outer portions of campus (previously referred to as “Precincts 7, 8 and 8A”) are not served by steam from the Central Heating Plant, and another areas (former “Precinct 9”) has only a small steam service.

During the process of converting steam to building heat (hot water), condensate is produced. To recover as much water and entrained heat as practical (i.e., to optimize system efficiency and reduce water and water treatment costs), condensate is collected at each building and pumped back to the CHP. In addition, condensate resulting from system thermal losses is removed at select manholes along the system. Due to the need to remove some water impurities and because of the inevitable loss of some condensate in the system, some make-up water is needed. Overall, boiler water make-up is approximately 180 million pounds of water per year. This equates to a water make-up rate of about 15%, based on the ~1.2B pounds of steam leaving the CEP annually.

Steam condensate collected within the system and at each building is returned to a storage tank where the water is reconditioned (filtered and chemically-treated). The water is then pumped to a de-aerator, where the oxygen is removed, and finally back to the operating boiler(s), where it is once again converted to steam to complete the cycle.

To meet campus demand, the HRSGs (with optional variable input duct burners) are typically utilized first, then other boilers are brought on line as needed, subject to operating limitations. Combustion Turbine/HRGS combinations are generally utilized only as needed to meet campus steam demand (generally requiring one set in summer and both sets at other times), although some exceptions are made (i.e., some excess electricity may be generated during summer when electric rates are highest, or over period when operating limits or conveniences justify steady operation). When campus demand exceeds the capacity of full-operating HRGSs (with full duct burner operation), other boilers are brought on line to match load. In this way, operation is termed "load-following". However, for reliability reasons one or more boilers may run at low output on oil, especially in winter, so that this dual fuel capability is available on short notice in the event of any gas or combustion turbine interruption.

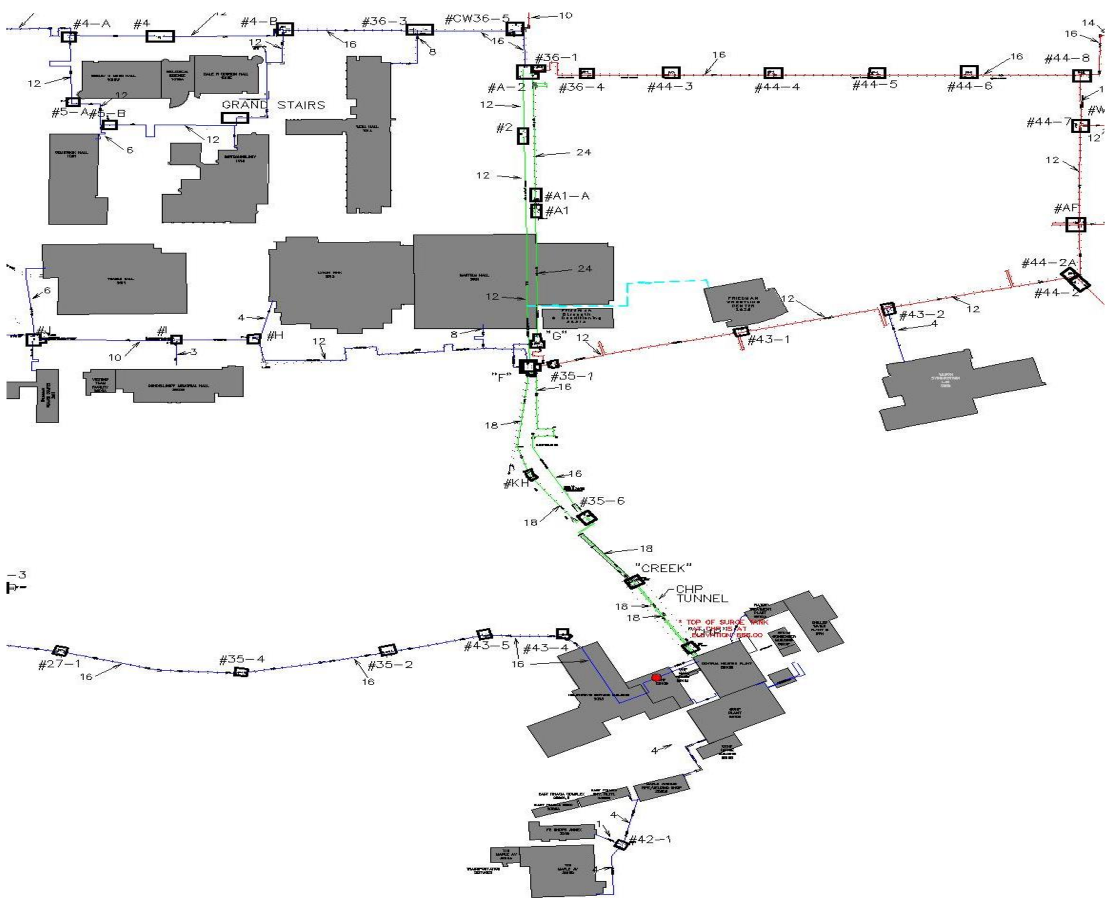


Figure 2-2: Heating Distribution Supply from CEP

Steam Demand

The steam needs of campus vary continuously based primarily on campus activity and weather conditions. A plot of a typical annual steam production is shown as Figure 2-3. While steam use year-round averages about 150 MMBtu/hour with hourly peaks in the range of 400 MMBtu/hour (2014-2015 peaked at 378 MMBtu/hour).

Steam distributed to campus is utilized by roughly 150 individual campus facilities. Nearly all of the steam use is for building heat and/or hot water, and is generally transferred to the buildings through a steam-to-hot water converter at the building location. In a few areas, the steam-to-hot water converter supplies multiple buildings, including small building complexes (such as in North Campus, where a hot water supply sub-system provides heat to a townhouse complex).

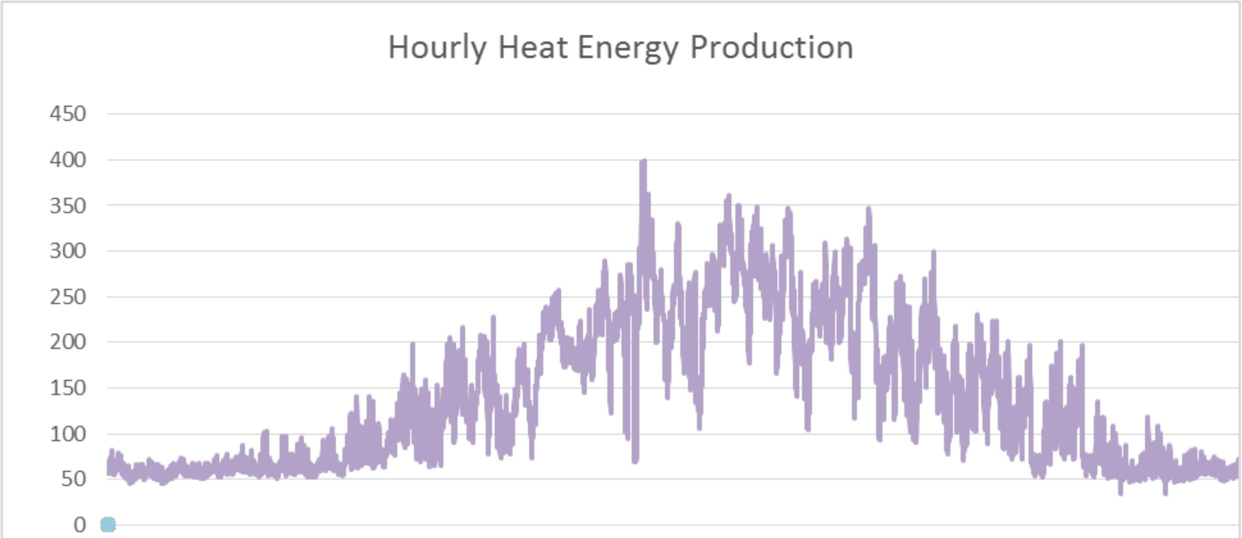


Figure 2-3: Cornell Campus Central Steam System Hourly Production (Typical Year)

Peak steam demand dictates both supply and distribution sizing. To plan for future steam needs, a steam demand study, focused on peak supply needs, was commissioned in 2013 and concluded in 2014. This study provided the estimates of current and future steam demand as indicated in Figure 2- 4.

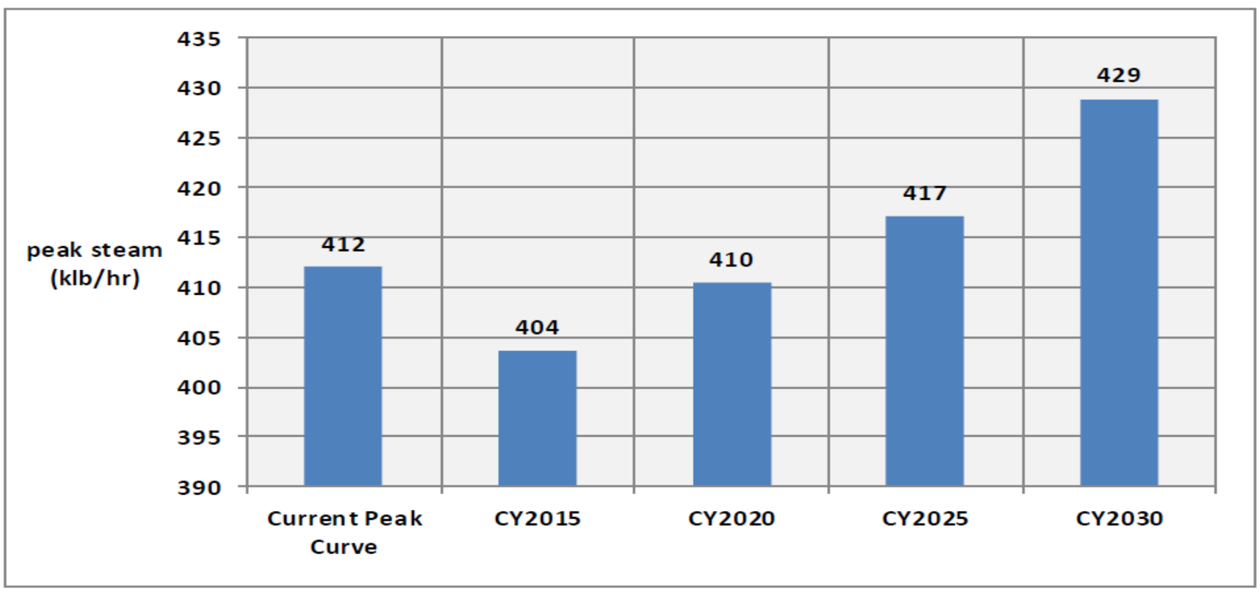


Figure 2-4: Future Peak Demand Forecast

Note that the vertical scale is not zero-based; the overall increases appear significant but are actually relatively modest (about 6% over 15 years). Even those relatively small forecasts increases may be too high; although this study included a consideration of the impacts of energy conservation, it now appears that energy conservation efforts may have been significantly more successful than predicted, based on steam use in the winter of 2014-15.

Energy Conservation: Impacts of Steam Demands

Multiple large scale energy conservation efforts have been implemented at Cornell over the years. Some significant efforts are outlined here. These include both supply-side projects (which reduce the input energy needed to supply campus heat and electricity) and demand-side projects (which reduce demand at buildings and facilities). Full-time staff including two experienced Certified Energy Managers help oversee the University's energy management program for the central plants (supply side) and the buildings (demand side). With decades of staff experience, energy conservation at Cornell is showing extremely positive results rivaling any institution in the nation.

Supply-side projects in the last several decades have included:

- Microprocessor-based control equipment replaced former digital controls, starting in about 1985, providing much higher reliability, accuracy and automation and allowing optimization of boiler dispatch. Digital controls have been periodically enhanced and upgraded ever since this conversion.

- Boiler steam pressure was doubled to 400 psig in 1985 so that cost-effective steam turbine electric generators could be installed. These steam generators now generate 30 million kWh per year in electricity (approximately 12-15% of total campus use) at about twice the thermal efficiency of conventional power plants.

- The Combined Heat and Power Project (2008) added twin 15-MW combustion turbines with heat recovery steam generators to allow for primary (gas-driven) co-generation. Since this addition, the CEP has two stages of electrical generation (utilizing the combustion turbines first, then the steam turbines), allowing Cornell to cost-effectively produce most (85%+) of the electricity required to operate the campus annually.

- Other supply side energy conservation projects include variable speed drive draft fans, pump and fan variable speed drives, lower plant distribution pressures, installation of various technologies for improvements on combustion efficiency, replacement of Boilers #6 and 7 (and current replacement of former boilers 1 and 2 with new boilers 3 and 4), and distribution system leak repair and insulation upgrades.

On the supply side, dramatic and lasting conservation results are achieved by continuously optimizing our building automation and control systems, heat recovery systems, and lighting systems. Conservation-focused preventive maintenance on these systems reduces usage and maintains performance. Conservation studies and capital improvement projects add the latest features that can be cost effectively retrofitted to existing systems. New construction and renovation on campus are guided by mandated features, energy usage intensity goals, and life cycle cost benefit analysis.

The Energy Conservation Initiative (ECI) reduces both total demand and peak demand. The overall steam savings are forecasted at 70,000 klbs/year by FY 2015, ~7% of the typical ~1,000,000 klbs in annual steam sales. The percentage reduction in the peak is assumed to be half of the sales reduction, or ~3.5% of the peak (about 14 MMBTU/hour of ~400 MMBTU/hour).

ECI efforts were projected to negate the impacts associated with current construction projects, reducing the peak to 404 klbs/hr for 2015 and keeping the peak curve for 2020 comparable with the pre-ECI (2012) peak curve. By 2030, barring future similar successes and allowing for modest growth, the 1-hr peak steam demand is projected to be 429 klbs/hr, an increase of approximately 4% over the calculated current peak of 412 klbs/hr.

The success of energy conservation may be understated, based on the performance of the system over the 2014-15 winter. During that winter, which included a record-setting cold February in Ithaca, New York (with a total of 14 days with temperatures reaching below 0^{o}F, two days with temperatures at -18^{o}F or below, and an average temperature over the entire month of 10.3^{o}F) steam demand peaked at only 378 kBtu/hour. Moreover, this peak was for only one hour, on a -22^{o}F morning, which was below the calculated-basis -20^{o}F minimum value. Peaks on other days were more than 10% below the peak predicted based on prior data based on exterior temperature, suggesting consistently lower steam use than predicted.

Overall, recent performance, combined with detailed projections, suggests that reduction in system losses and continued energy conservation could eliminate additional steam project needs in future years for decades, preventing the need for supply system expansion. Nonetheless, maintenance and end-of-life replacement of steam-producing systems will still be needed, and some expansion is possible if growth outpaces projections, decisions are made to curtail aggressive energy conservation in the longer run, or climate change results in colder-then-predicted future winters.

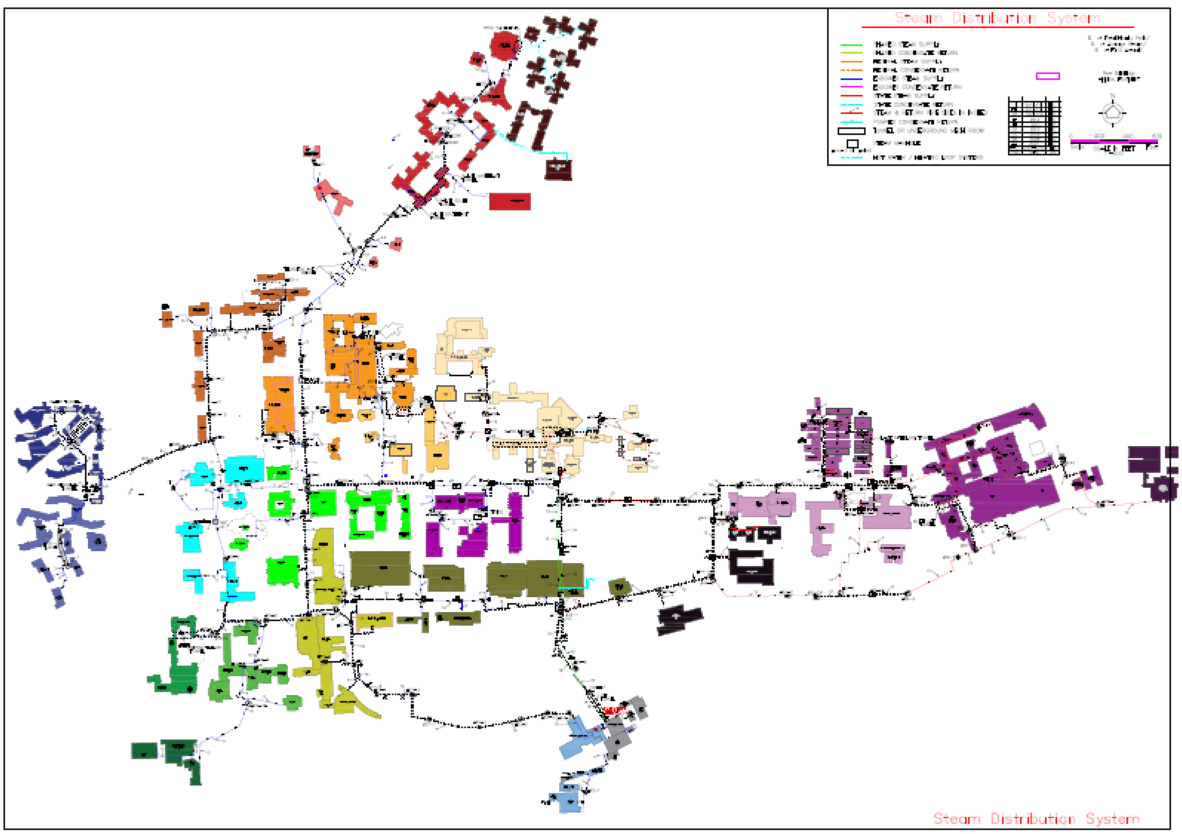


Figure 2-5: Campus System Divided into Sub-Systems

Steam Use by Area of Campus

Cornell also has individual steam monitoring at nearly every building on its system and therefore can determine steam demand on a building-by-building basis, or for specific areas of campus. Figure 2-5 provides a summary of the system usage through different areas of campus. In this figure, distribution "sub-systems" that each consume ~40-50 MMBtus at peak (~10-14% of the total system peak) are shown in varying colors. The "boundaries" of the various campus areas shown are somewhat arbitrary; Figure 2-

5 provides a general sense of how diverse the heat demand is and what portions of the system have the greater demands.

High-Use Buildings and Individual Building Use Data

The present generated steam used by all metered campus buildings is about 1.04 trillion BTU (per FY2013 Cornell University Energy Fast Facts).

Certain facilities have higher steam demand than others. These facilities are shown in Figure 2-6. Table 2-2 provides data on the use in these facilities; as the table indicates, the heating demand of these 10 buildings consume about 30 percent of the overall metered steam energy use.

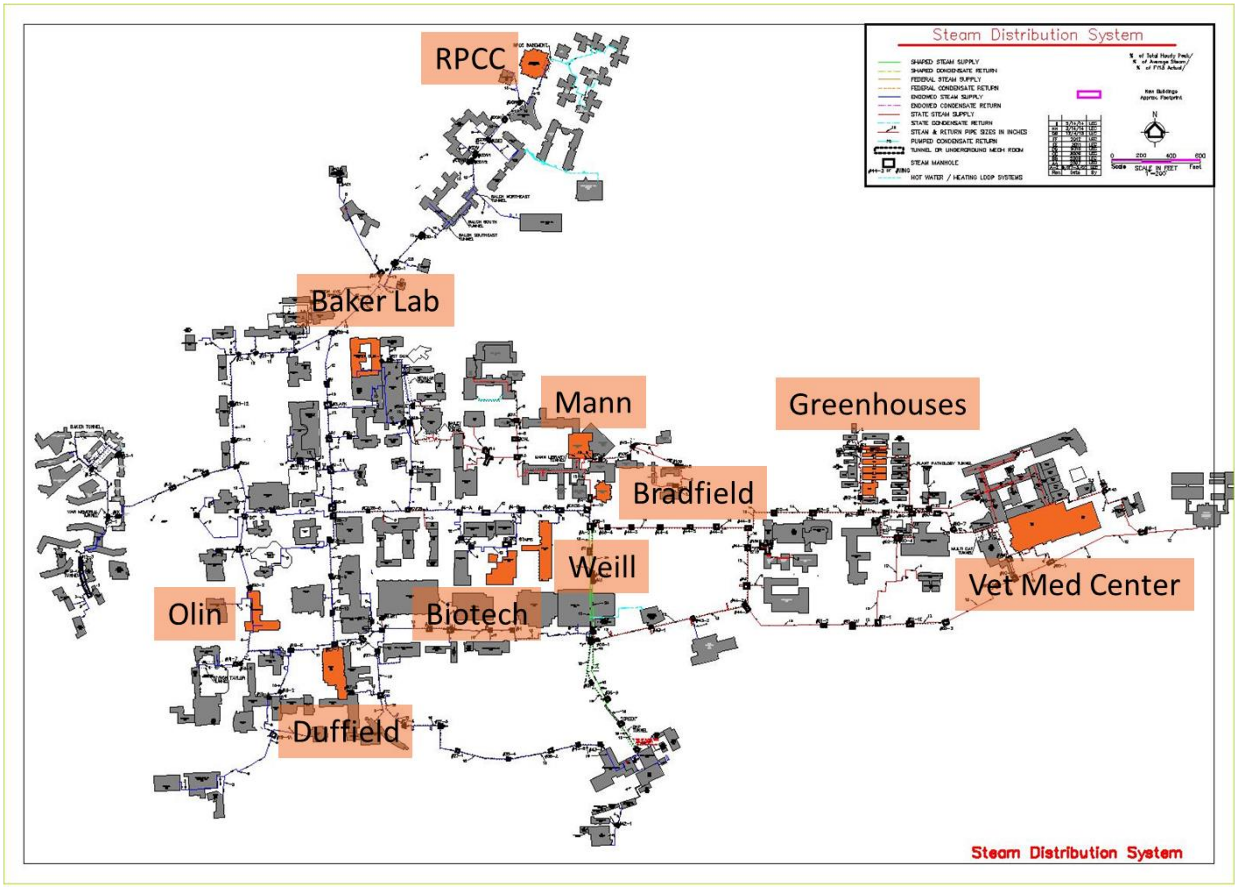


Figure 2-6: "Top 10" Steam Use Buildings

When considering peak loads rather than annual usage, the list is similar. As seen in Table 2-3, RPCC (which also includes the adjacent high-rise residences) now occupies the top line due to a higher peaking factor (higher peak-to-average steam requirement). In this case, 11 buildings are shown as the bottom three have similar peak loads; these 11 buildings in total require about 36% of the peak steam use of the campus.

Table 2-2: Building on Campus with Highest Annual Heat Demand

Facility name	FY13 Steam use (MLB)	% of Campus Total
Veterinary Medical Center	49,788	5.28%
Robert Purcell Community Center (RPCC)	36,057	3.82%
Duffield Hall	29,070	3.08%
Weill Hall	26,237	2.78%
Baker Laboratory	26,143	2.77%
Bradfield Hall	24,671	2.62%
Mann Library	23,887	2.53%
Biotechnology	22,738	2.41%
Tower Road East Greenhouses 1045G	22,427	2.38%
Olin Chemistry Research Wing	21,170	2.24%

Table 2-3: Campus Buildings with Highest Peak Steam Usage

Facility Code & Bldg Name	Annual Steam Use (2013) klbs	Est Peak (-20ºF) (#/hr)	Aver Steam Use (#/hr)	Peak-to-aver ratio	% of total system peak
3212 Robert Purcell CC (RPCC)	36,057	35,000	4,120	8.5	8.6%
1164 Vet Medical Center	49,788	20,000	5,684	3.5	4.9%
2019 Baker Lab	26,237	15,000	2,995	5.0	3.7%
1150C Shurman Hall	21,058	12,000	2,404	5.0	2.9%
2000 Duffield Hall	29,070	12,000	3,318	3.6	2.9%
1014 Weill Hall	26,237	12,000	2,995	4.0	2.9%
1018 BioTechnology	22,738	10,000	2,596	3.9	2.5%
2083 Olin Chem Research	21,170	8,500	2,417	3.5	2.1%
1045G Tower E Greenhouses	22,427	8,000	2,560	3.1	2.0%
1068B Guterman Lab	21,871	8,000	2,497	3.2	2.0%
1028B Bradfield Hall	24,671	8,000	2,816	2.8	2.0%

A complete tabulation of the steam demand for all 150 metered buildings on campus is included as Appendix C.

Steam Quality (Pressure and Temperature) Demands

Steam demands vary by building. Most buildings use steam converted to hot water to provide building heat and (usually) hot water needs. Until about 2013, the typical building heating system was designed (i.e., heat transfer and delivery equipment sized) based on the availability of steam at a minimum of 35 psig (corresponding to a saturated steam temperature of at least 281ºF). No explicit standards exist currently to otherwise restrict either the temperature used for sizing internal heat transfer sources (like coils or radiators) or to ensure that adequate transfer occurs to minimize return temperatures. As will be discussed later, these types of standards may be critical to cost-effective replacement systems in the future. Currently, building supply loop temperatures typically range from about 180ºF to almost 200ºF, while building heating loop return temperatures (which are currently are not typically monitored) are said to range from about 140°F to about 170°F.

In addition to these "standard requirements", a few building have special needs. Table 2-4 below lists a sampling of buildings with known special steam or heating requirements (a recommendation is that a systematic evaluation of all buildings be documented so that building-by-building temperature and special needs are available for future planning and design).

Table 2-4: Sampling of Buildings with Special Steam Requirements

Building Name	**Special Steam Requirement**
Riley-Robb	This building is heated directly by steam, not hot water
Vet Med Facility, Human Ecology, CALS, Vet	This building includes an autoclave that uses steam directly
Stocking Hall Dairy	While heating is with hot water, this building also uses a smaller (unmetered) amount of direct steam to provide "instant" hot water for sanitary cleaning needs.
Vet Class Expansion	This building is being designed to allow heating with a lower temperature (200°F) source.
Guterman Lab	Associated greenhouses have a steam sterilization unit
UHSF	Designed for lower temperature building heat (160°F)

Distribution System Condition, Assessments, and Maintenance

Portions of the distribution systems date to the early 1920's. Over a decade ago, Cornell implemented a plan to replace the majority of the distribution system. Replacement has continued incrementally. Table 2-5 below provides some basic statistics regarding current system age based on information from the steam model.

Table 2-5: Heating Distribution System Length and Age

Distribution Sub-System	**Total Piping Length (linear feet) by age**		
	< 20 years old	**20-40 yrs old**	**> 40 years old**
Total	30,254	15,293	15,868

The figures above do not include system laterals to the buildings.

The condition and suitability of the distribution is continually assessed using both highly formal and less formal processes. Formal inspection programs include annual steam manhole inspections, periodic inspections at building entry points, responses to issues (visible steam reported at vent, manhole, or building), and an annual infrared fly-over. Other inspection programs are conducted periodically in response to any systematic concerns (i.e., questions about condition of steam traps, etc.)

Condition assessments may result in immediate actions (as it typical for even modest steam leaks) or for longer range capital planning (for example, where infrared measurements suggest a section of piping has higher-than-normal heat loss). In addition, as seen in Figures 2-5 and 2-6, heat losses from steam can sometimes be apparent at the surface during certain weather conditions; in this photos surface snow-melt has been accelerated in areas directly above a steam line with a suspected leak or insulation failure.


Figures 2-5 and 2-6: Surface snow melt revealing heat loss along steam line (2014)

Steam System Modeling

Cornell Energy & Sustainability (then Cornell Utilities) commissioned for the development of a steam system model in ~2001 to provide a tool for analyzing the impacts of various steam pipe sizes and new building demands on overall steam pressure and availability. This model was jointly developed by Utilities (providing the bulk of the data from system records) and a consultant (GIE, now CHA) who “owned”, built, and ran the model on a contractual basis on behalf of Cornell.

The modeling software was initially developed to model pipelines with compressible ideal gases, however, the software has been found applicable for modeling steam as well.

Cornell has in the past reviewed the option of purchasing software and having internal energy engineers use that software to help manage the system. Barriers to that approach have included the high cost of the software (due to the limited number of large steam distribution systems currently still in operation, there is a limited market to help offset the high price of software development) and the expertise needed to set-up and run the programs.

A more recent investigation into the availability of software found that most of the commonly-marketed software systems available are marketed as “full-service packages” requiring expensive (~$100K or more) annual feels by consultants to set up and manage. Many such systems are not available for private purchase or are not designed so that an engineer or staff person knowledgeable about their system, but not about the quirks of the software, could reasonable utilize the project. However, an engineering contact of Bill Sitzabee, Cornell Vice President for Project Administration and University Engineer, recommended the following software package, should Cornell wish to own and operate their own steam model:

- For total plant supply and generation equipment:
    - ThermoFlow (Thermoflow, Inc, Southborough MA)

    - GateCycle (General Electric product, part of “GE-Enter” software suite)

- For distribution systems:

    - AFT Arrow (for compressive fluids, like steam) or AFT Fathom (for incompressible fluids, like hot water) (Applied Flow Technology, Colorado Springs)

Based on a review of on-line information, it appears that the AFT Arrow software would be suitable for our steam distribution system. The ATF Website lists the following pricing for this system:

Full Licenses	Stand-alone Licenses	Network Licenses
AFT Arrow	$5,000.00	$7,500.00

The AFT Fathom is prices slightly lower ($4200 and $6300 for stand-alone and network licenses, respectively).

Model Benefits

Benefits of such a modeling system includes the following:

- Provides the ability to rapidly verify the impact of design or operational changes on the overall steam availability in the system. For example, in a “looped” system, the model can estimate the steam pressure still available at a distant building when one “leg” of the loop is taken out of service for maintenance or repair.
- Includes a number of “calibration factors” which allow the user to consider real data (steam pressure and temperature at various locations in the system) to “calibrate” the model and verify its reasonableness.
- Allows (with proper calibration) a reasonable estimate of thermal or steam losses in the system, and model the impacts that would result from changes to those variables. These estimates are important in helping to assess the operating cost impacts of future design standards.

Steam Model Limitations

Despite these advantages, the current steam model has some limitations.

- Due in part to limited data on steam pressure and temperatures at sufficient points in the system, the current model is not well-calibrated. For example, it currently predicts much lower steam losses (from thermal conversion to water or minor steam losses) than measured by other available data sources.
- A significant effort is required (and a lot of data) is required to develop the model or significant portions thereof; typically, some shortcuts are made due to incomplete available information or the budgeted time allotted to the exercise. For example, it is very difficult to accurately predict the current thermal resistance of the insulation on a 100-year-old steam line even as this may be the most critical information needed for accurate thermal loss calculations.
- Cornell does not own the software or the rights to run the model independently, and as such is dependent on our consultant and their availability to conduct “model runs”. While this has not been a significant concern in the past, it does limit our ability to use the model on short

notice to respond to steam emergencies; conduct multiple iterative tests to evaluate multiple design options, conduct "table-top" training exercises, or otherwise manage our own system.

- The current software provides only a specific set of graphical tools (of limited value) and has not been updated to reflect some of the more sophisticated graphical outputs produced by other modeling tools. These graphical tools are often especially useful for communicating to an audience less familiar with the characteristics of buried steam distribution.
- The current Cornell model appears to be outdated and does not appear to include the most accurate available data. Les Cooke, who maintains the steam mapping on behalf of E&S, believes that the current (2015) information in FPNMS is accurate and that the generators of the model may not have used GIS to determine proper lengths; FPNMS documents about 56,000 linear feet of steam distribution piping while the model shows over 61,000 feet.
- The software has a relatively specialized market. The sophistication of the analysis combined with the small market has, at least in the past, resulted in a relatively high cost of purchase and operation.

Thermal Loss Estimates and Potentials for Improvement

One goal of a comprehensive district steam management plan is to reduce system losses. Unlike modern hydronic (water-based) heating systems, steam heating systems typically have relatively high thermal losses, resulting from basic steam distribution principals:

- Steam is distributed at high temperature, creating a continuous loss of energy by thermal conduction in buried piping, and by conduction, convection, and radiation in tunnel-installed piping. Even a well-insulated steam pipe is typically designed with the outer insulation surface temperature of ~100^{o}F, resulting in steady heat loss to the sub-surface or surface environment.
- Steam tunnels are typically ventilated to remove excessive heat and moisture, which can destroy waterproofing and damage concrete reinforcing. Unfortunately, venting may also create the unintended result of increased thermal losses. Insulation breaches or flaws increase the amount of heat loss.
- Steam is distributed at relatively high pressure; any leaks in the system will result in a loss of steam to the environment. While Cornell believes there are minimal losses today due to aggressive maintenance and replacement programs over the past few decades, in many older systems significant energy can be lost in this manner.
- Steam is distributed in a superheated state (as "dry steam") but as heat is transferred, the steam converts to liquid water and is removed through a variety of distribution line and building condensate traps. While these traps are designed to restrict the loss of steam, steam leaks across the seating surfaces of traps (or through traps that are stuck in an open position) are commonplace in most larger distribution systems. Depending on the design, some of this steam heat may be captured in the condensate returned to the plant, but other portions may be vented by various safety systems in the plants or condensate pumping systems.

Steam thermal losses can be estimated and evaluated by various methods. Table 2-6 indicates some of the methods used by Cornell to evaluate or estimate thermal losses.

Table 2-6: Overall Thermal Loss Estimates

Method Used	Loss Estimate	Comments
Metering of Production, Export, and Building Use	20-23% (see Appendix C)	Estimate based on steam meters (in plant) and total of building (condensate) meters. This value would therefore also include any unmetered steam usage, including steam leaks that are unmetered. Estimate already accounts for any energy returned as condensate.
Steam Model Estimates	5% (based on review of past model run output)	Thermal losses only; does not include any direct steam losses or unmetered steam use. Model may not adequately estimate losses in oldest sections or at building entry points; model does not include laterals or other minor piping systems or losses from equipment.
2014 Fast Facts Estimate	19%	Published losses in 2014 Fast Facts
2009 CAP Estimate	8-12% (overall)	From work by consultant AEI during production of CAP; analyzed data provided by Cornell. AEI also estimated that older lines (example: line to Guterman) had higher losses (i.e., ~340 BTU/hr/ft for this line to Guterman). This represents a significantly higher unit heat loss (~20%) than the overall estimate of 8-12%.
Industry Values	8-40% (steam) 1-10% (water)	Sample of wide range of typical values found in the literature USAF; USACOE; IDEA; university studies)
Annual fly-overs	Qualitative only	Uses infrared to reveal subsurface areas of high heat loss. Might be possible for consultant to use color variation to create some estimates
Frequent Visual inspections	Qualitative only	Staff trained to observe for steam leaks and insulation failures and repair same promptly. Could enhance with infrared inspections to check for trap failures?
Steam pressure/temperature measurements	Spot Checks	Used for trending and verifying overall performance; can aid in model calibration; limited sites currently (3 of which 2 are operational 2014).
Metering	Trending	Plant meters used daily to verify performance at plant; building meters are available for trending to check for changes in measured usage (or possible meter problems).

SECTION 3: BASELINE CAPITAL AND OPERATING PLAN

This section documents the baseline capital and operating plan for the Distributed Heat System. This plan is based on maintaining the current steam system and is the basis for comparison of alternatives as detailed in Section 5 – Alternatives Evaluation.

Current Planning Process

Cornell University currently (2015) approves capital planning on a year-to-year basis. Although capital spending projections are provided for future years, these projections are not "approved" spending plans and often are altered considerably based on University resources and priorities. Depending on financial conditions and priorities, work may be advanced (to enhance reliability) or deferred (to save money). Cornell's Utilities professionals have engaged in departmental capital renewal planning for decades to promote the right balance of spending to ensure reliability without excessive costs.

The current best-documented example of longer-range capital renewal/planned maintenance planning is through the Facilities Physical Needs Management System (FPNMS) system. The FPNMS system includes a systematic and complete inventory of every section of steam piping and every manhole within the Cornell System, with data on materials and ages of these systems and a projected date for renewal (replacement) of the system based on age. As such, FPNMS provides the basis for long-term capital planning.

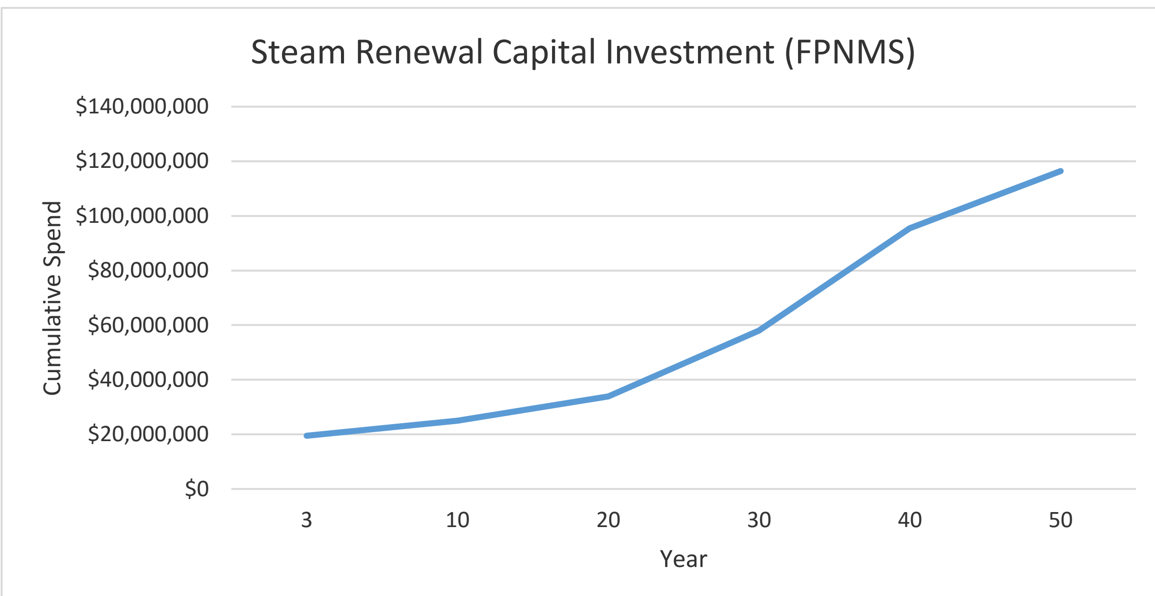


Figure 3-1: Future Capital Spending (in 2015 Dollars) as predicted by FPNMS

As shown in Figure 3-1, the total capital spending (i.e., total value of the steam distribution system) over the planning life of FPNMS (which approximately coincides with the expected services life of the steam system) is about $118M (2015 dollars).

FPNMS is a useful planning tool, but it is not itself sufficient for capital planning. While FPNMS provides a reasonable expectation of future expenditures based on pipe age, the actual future expenditures will likely be less efficiently implemented. Like any utility, replacement tends to occur in a less predictable manner, reflecting an aim towards overall campus construction efficiencies. For example, the construction of a major building or reconstruction of a primary roadway is typically accompanied by significant utility work required to serve new loads, re-route utilities away from conflicting infrastructure needs, or replace older but not end-of-life sections during a period in which the area is already disturbed, to avoid a second disturbance (and need to repave or resurface) at the true utility end-of-life. Similarly, there is significant manhole repair work in recent years that has resulted from road salt intrusion into manholes; many of these systems were not at the "end of life" calculated by FPNMS. Most of these situations result in additional utility spending that may not be captured by FPNMS estimates.

Conversely, some items identified for replacement by FPNMS may be deferred. For instance, a section of piping that is at its theoretical end-of-life, but not showing signs of imminent failure, may be deferred several years for replacement if other replacement work is planned in the area that might be cost-effectively combined with the replacement of the end-of-life system. In these cases, using FPNMS to calculate Present Value of future expenditures may tend to over-predict that cost.

Considering all of these factors, it is acknowledged that an FPNMS Present Value analysis will likely under-predict the true Present Value of all future work, but nonetheless provides the best available basis for making this "Base Case" estimate.

Incorporating and Evaluating Risk

Creation of a viable capital and operation plan to evaluate appropriate future expenditures must include an evaluation of risk. This risk evaluation considers both the risk of action (which may vary by the action chosen) and the risk of no-action. Typically, these factors are combined to form a quantified "risk matrix" that allows a utility planner to weigh various risk probabilities and impacts to determine a quantified risk for each portion of the system.

Risks to consider when evaluating when and whether to replace all or portions of Cornell's existing heat distribution infrastructure include the following:

- Age and condition: while much of the system is in good shape, there remain portions which are very old, some of which includes asbestos-cement piping or asbestos-containing insulation.
- Impact of failure: the number and use of buildings in various portions of the system and the assumed impact of failures of various portions of the system need to be considered. For example, accommodates may generally be feasible to reduce the impact of heating system interruptions to individual classroom or office spaces, while some animal or plant growing or holding areas may only be able to tolerate loss of service for an hour or so before risking irreparable damage to these living teaching and research resources.
- Recovery time: An estimate of the failure recovery time is another consideration. For example, a failure within a looped system area might be minimized in short order with strategic valve isolation, while a pipe or valve failure in an area served radially might entail a much longer outage that could extend across many facilities.

Fully incorporating risk is a complex process. For the purpose of this analysis, the base case assumes that the risk of deferring work beyond a 40-year life is the "tipping point" where the financial risk exceeds the improvement in economic performance reflected by the "Present Value" analysis. Thus, the Base Case neither accelerates nor defers work but merely utilizes the FPNMS timetable (based on 40-year average service life) of steam systems.

Approved and Proposed Capital Plan

Multi-year capital planning has been in place within Cornell Utilities for many years, although the process has changed from time to time over the years. However, at Cornell currently (2014), Capital Plans are only approved on an annual basis and formally proposed over a five-year period (for future consideration of approval).

This Capital and Operating Plan will therefore consider the approved and proposed 1-year and 5-years plans, respectively, while anticipating future costs over a longer period, consistent with internal planning.

Integration with Campus Development

Planning for the campus steam system must be integrated with other existing and evolving campus planning efforts. These efforts include:

- Campus Master Plan: This document provides planning-level guidance on where development is likely to occur on campus, the projected rate of development, and the anticipated integration of central utilities into that plan.
- 5-Year Capital Plan: While capital funds are approved year-to-year, the published Capital Plan documents the next five years of planned and requested future funding for capital projects. Steam infrastructure projects are included in this Plan. In addition, the overall Plan is used by Utilities to predict the timing and scale of future energy growth, to align the utilities capital planning with planned future facility capital developments that require changes to the heating distribution system.

Costs and Present Value

This report includes budget-level capital estimates for projected future steam system maintenance, replacement, and improvement, and improvements. These estimates are based on utility engineers' assumptions regarding pipe size and routing and cost information specific to the campus heat distribution system.

In addition to the up-front capital costs, a Life Cycle Assessment (LCA) is generated to develop the present value of the proposed development plan, resulting in a Present Value (PV) assessment for different alternatives. The PV includes necessary capital, operating costs (O&M) including fuel costs, and similar detailed estimates. The PV is used to compare the total cost of the project over the project life, and is used to determine the most cost-effective solution for the University. Appendix B documents the assumptions used by Cornell for this PV analysis, which follows the general policy of LCAs for all energy-related work on campus.

Management Principles

Creating a Capital Plan for the heat system requires development of a rationale and prioritization decision that includes factors like PV, relative risks, and other similar factors. Cornell's FPNMS system includes data and a logic prioritization that provides a starting point for more comprehensive planning of utilities infrastructure. To more fully realize this plan, the more nuanced integration of FPNMS information with other planning needs and priorities would be required.

In addition to project-level decisions, technology decisions require a similar analysis. For example, the costs of water treatment may vary by system (hot water requires different water quality concerns than steam) and valves may be in manholes or direct-buried, with different impacts on serviceability. Similarly, maintenance actions like valve or pumps maintenance needs to be considered for various valve and types and designs.

Capital Spending over Time

This document estimates needed "base case" (or "business as usual") spending over time and broadly recommends future planning actions. While it is not a comprehensive capital or operating plan, it is intended to provide guidance in future planning actions.

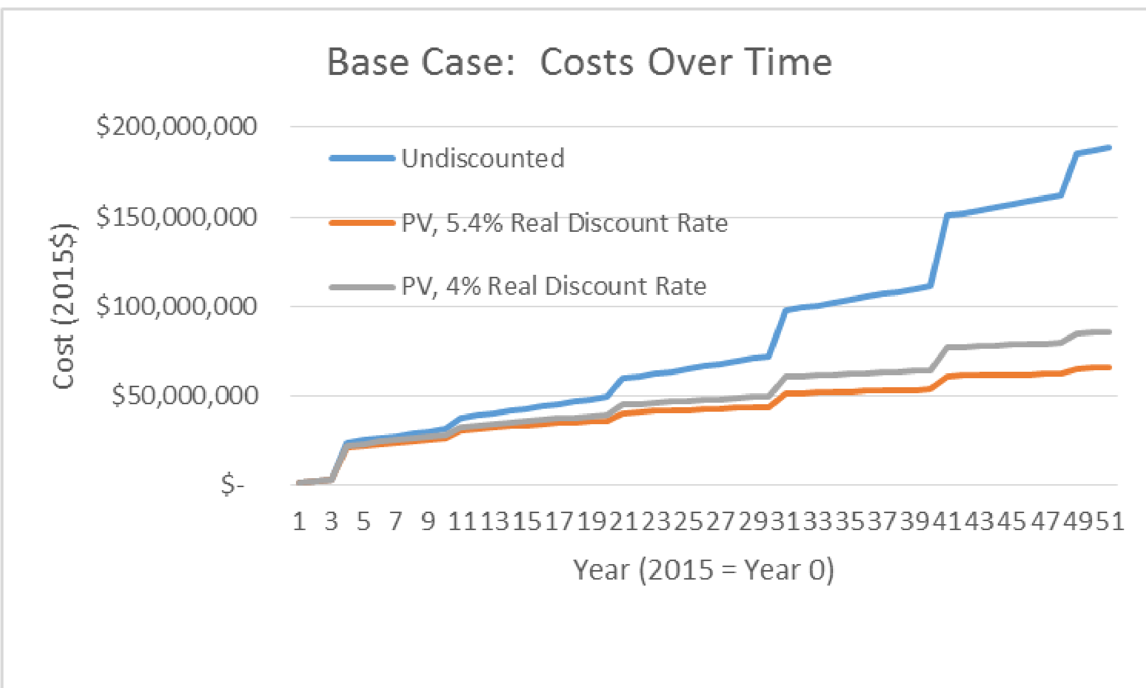
Results of Base Case Financial Analysis

Analysis of the financial results of the maintaining the steam system overtime is described in Section 5 (with reference to the appendices for details on analysis methods, data sources, and assumptions). Figure 3-2 shows the impact of Discount Rate (required return on investment) on the projected spending over time (this figure based on $4/MMBtu gas base price).

As the figure readily shows, the discount rate has a significant and substantial impact on the analysis. For example, the actual expenditures of about $188M create a total PV over time of about $66M with a Real Discount Rate of 5.4%. For a more modest Real Discount Rate of 4% rather than 5.4%, the PV is $86M.

– and a complete replacement of the system within 10 years would be the resulting financial recommendation based on PV, even at the lowest modeled energy value. At higher energy values, even faster replacement warranted.

Figure 3-2: Accumulated Base Case Spending Over Time; Actual and Discounted



SECTION 4: INTEGRATION OF LOW-CARBON AND RENEWABLE ENERGY

One consideration in the 20-year Capital and Operating Plan is the potential future integration of renewable and/or low-carbon heating sources. A concurrent Thermal Resources Report is being developed (2015) to document potential sources of such energy which may be utilized to further Cornell's commitment to its Climate Action Plan, which seeks to move Cornell towards Climate Neutrality, with a goal of 2035 for meeting that target (in 2014, the original 2050 goal was revised to 2035 by then-president David Skorton, responding to a request for "acceleration" originating in the Faculty Senate).

A number of potential sources for low-carbon and renewable energy to help meet this goal have been studied to date, with a focus on supplying the robust heating needs of the Ithaca campus. These sources include the following:

- Earth Source Heating (essentially zero-carbon)
- Ground-Source Heat Pumps (lower carbon)
- BioFuels, using combustion of gasification (essentially zero-carbon if sustainably harvested locally)
- Waste/recovered heat (low carbon/no new carbon)
- Hot water storage (low carbon/no new carbon)

In investigating these potential resources, it became apparent that the temperature of the heat distribution system strongly influences the availability and efficiency of the potential heat resources. Specifically, each of the feasible options studied either require lower temperature heat distribution (i.e., hot water rather than steam) or, at least, are much more feasible and cost-effective when temperatures are lower.

Determining the appropriate temperature for a future system involves a series of optimization exercises; generally speaking, the lower the temperature of recovered waste or renewable heat, the more heat available from such sources or the more cost-effective it is to recover that heat. However, lower grade heat has a diminishing value to the campus district heating system, which was predominately designed with the assumption that steam was available (and would always be so) for heating needs.

Similarly, the specific design temperatures (both supply and return) of a hot water distribution system also impacts the costs dramatically. This relationship is analyzed in Appendices A and B.

While the CAP is a "living document" and is continually being updated to reflect the latest available information on technology, impacts, and costs, the current "Plan A' solution involves the integration of Earth Source Heating (ESH) and bioenergy. For the purpose of this report, this combined energy system can be abbreviated as "B/ESH". The combination of these two disparate technologies may not be intuitively obvious, but is judged to have merit based on a detailed consideration of their differing impacts and limitations. Specifically, as shown in Figures 4-1 and Table 4-1, a solution representing portions of both technology (where ESH is used for the bulk of the thermal load annually, but bioenergy supplements the peaks and reduces the combined capital cost), is preferable to either solution independently (as analyzed in more detail in the Thermal Resources report).

The analysis of the potential for the Hybrid EGS, which is being conducted in more detail in a separate engineering review ("Thermal Resources Report"), preliminarily reveals that the systems may be cost-effective if and only if the distribution temperatures are controlled appropriately.

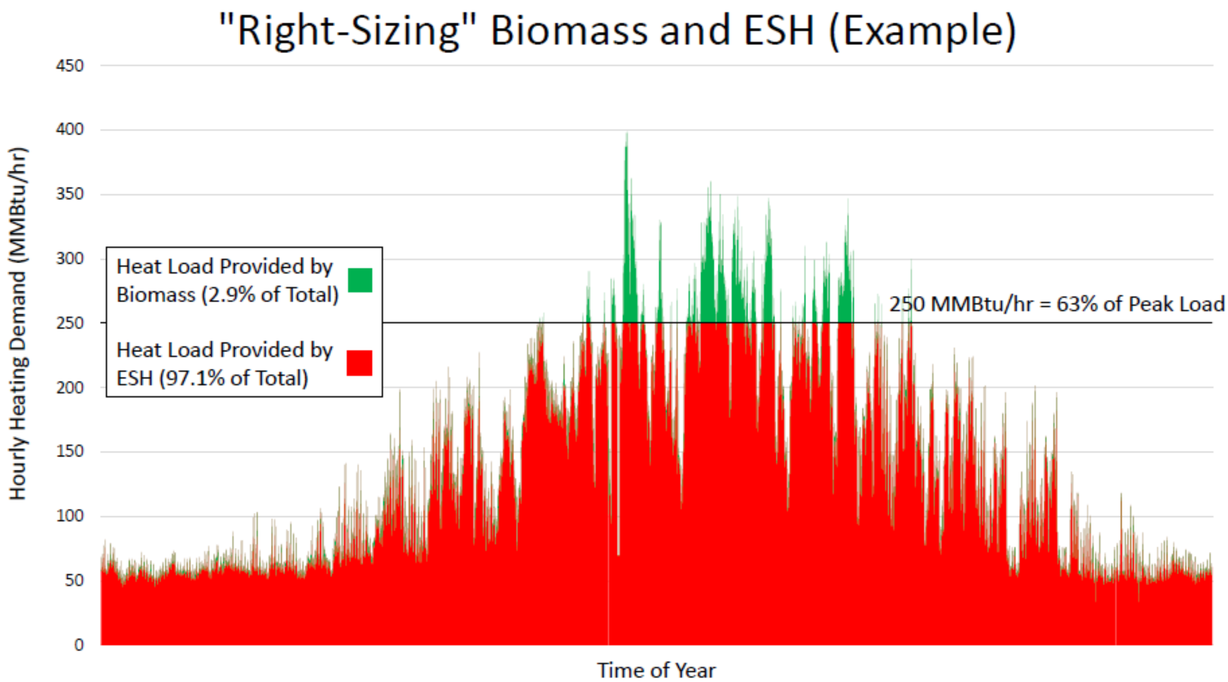


Figure 4-1: Optimization of B/ESH Technologies

Table 4-1: Optimization of B/ESH Resources – Relationship of Peak ESH Capacity

EGS Peak Capacity (MMBTU/Hr)	EGS Annual Load MMBTU	Biomass Annual Load	
		(MMBtu)	% of Total
50	437,863	781,331 note 1	64.1%
100	742,802	476,393 note 1	39.1%
150	951,822	267,372 note 1	21.9%
200	1,095,955	123,239 note 2	10.1%
250	1,178,426	40,768	3.3%
300	1,211,353	7,832	0.6%
350	1,218,362	832	0.1%

Notes:

[1] This amount of wood material cannot be sustainability harvested from Cornell lands; additional suppliers needed

[2] This amount of wood is considered the maximum achievable from sustainable management of Cornell Lands. (source; David Weinstein, Cornell DNR)

Reducing the heat losses of the distribution system has a significant impact on the amount of biomass that would be needed in the future to meet peak loads. Table 4-2 shows this impact, based on the assumption that distribution losses are mostly thermal and could be reduced in half through the upgrade process (actually loss reduction would likely be closer to an 80-90% loss based on data from other institutions that have recently converted their systems).

Table 4-2: Reduction in Biomass Needed to Supply System after Conversion

EGS Peak Capacity (MMBTU/Hr)	Estimated Biomass Annual Load (MMBtu)		
	Current (2013)	After Conversion	Reduction After Conversion
50	781,331	697,583	83,748 (11%)
100	476,393	427,246	49,147 (10%)
150	267,372	231,904	35,468 (13%)
200	123,239	101,480	21,759 (18%)
250	40,768	30,418	10,350 (25%)
300	7,832	5,076	2,756 (35%)
350	832	532	300 (36%)

Compared to traditional (fossil fuel) sources, the use of biomass will have both positive and negative social and environmental impacts, as discussed elsewhere. In general, Cornell lands are resource-limited, so any reduction in the amount of biomass needed will reduce all impacts – both positive and negative – on the local community. A more comprehensive discussion of these analyses and consideration may be found in the Thermal Resources Report.

The cost for an ESH system is directly related to the required temperature of the recovered heat, since subsurface temperature varies with depth. In the Ithaca area, the variation is about 30^{o}C (54^{o}F) per kilometer, so to get higher temperatures, one must drill deeper – and drilling costs with depth are more exponential than linear.

Biomass energy may not be as temperature-limited, but the availability of energy from biomass sources are also strongly temperature-dependent. The steam or water generated by a boiler can only add energy to a distribution system at lower temperature, so the lower the temperature, the more energy that is available from a given resource. Dropping the temperature below the saturation point of the exhaust gases allows one to incorporate the "Higher Heating Value" (HHV) of a fuel, rather than just the "Lower Heating Value"; the "bonus" is about 5%. Coupling that with the lower energy available based just on temperature may penalize a steam system 10% or more from the supply side (not including distribution losses), compared to a typical hot water distribution system. While this may not seem a fatal limitation, it is a severe penalty in a renewable-resources-limited world.

Bioenergy alone is unlikely to be a potential source for the bulk of Cornell's heating needs due to the scale of biomass needed and the local impacts of large-scale biomass use (discussed further in Thermal Resources paper). However, integration of biomass with other technologies is promising. As the Thermal Resources Study report shows, potential sources of renewable or low-carbon thermal energy are also strongly impacted by the thermal distribution temperature. Examples include:

- *Heat Pumps*: Many campuses and institutions are finding ways to incorporate heat pumps to move “waste” heat to heating systems, or to use air-source or ground-source heat pumps as primary heating units. However, typical heat pumps do no supply hot water temperatures above about 175^{o}F. Some specialized heat pump systems are being designed for higher temperature, but such application generally increases electrical needs to drive the heat pumps (compared to a lower temperature output and the same heat load).

- *Waste heat*: Facilities like the Wilson Synchrotron have available “waste heat” that is currently shed using condenser units and Lake Source return water. Waste heat from research and industrial-like processes may be captured by systems that operate at lower temperatures, but Cornell cannot capture this heat through exchange with a steam distribution system.

- *Solar thermal*: Conventional, lower-cost solar thermal systems, like those on the CCHPP office roof or adjacent to the Plantations Welcome Center, typically supply temperatures up to about 200^{o}F. Although there are also industrial power generating systems producing much higher temperatures, “low-tech, low-cost” collectors cannot be integrated into campus distribution where temperatures may exceed 300^{o}F or higher.

Determining the right temperature for the system is an “optimization” evaluation. A conceptual level evaluation was performed related to the “design temperature” at which hot water is supplied to the Cornell distribution system from a renewable resources. Some of the competing priorities include the following:

- A lower temperature hot water system is the safest, least expensive to operate (lowest losses), and best use of renewable resources (lower cost to obtain lower temperature resources).

- A higher temperature hot water system is the cheapest to construct (lowest distribution size), up to about 248^{o}F maximum temperature (higher temperatures limit the piping and insulation selections).

- Cornell’s current campus is designed for heat distributed (as water or steam) at higher temperatures (at least 210^{o}F) to serve current needs and avoid extensive re-engineering within the facilities.   In the future, this temperature could (and should) be reduced assuming new buildings are designed to accept this lower temperatures (more on this subject later). Reducing temperatures not only allow better incorporation of renewable and low-carbon/no-carbon resources, but also result in smaller distribution piping since each gallon of water can deliver more differential energy.

A simple “optimization” of these conflicting priorities is presented in Appendix A, the results of which are graphically represented in Figure 4-2. This analysis concludes that a design temperature in the range of 220^{o}F, with the capacity to increase this to a peak temperature of about 248^{o}F (the limit for typical hot water distribution piping), provide a good balance. This would allow:

- Sufficient temperature to support existing building heating loads (but not internal building steam loads), minimizing in-building changes, and to allow for reasonable distribution piping sizes (discussion to follow), while significantly reducing conductive heating losses (compared to steam).

- Relatively low required operating pressure (hot water will remain in liquid form at 248^{o}F at a pressure of about only 15 psig), avoiding the need for high system pressures (which also create safety concerns).

- Temperatures which are reasonably achievable in this region with the proposed Earth Source Heating program (see separate report on thermal resources) and economically feasible to achieve with other renewable resources (biomass, solar thermal).

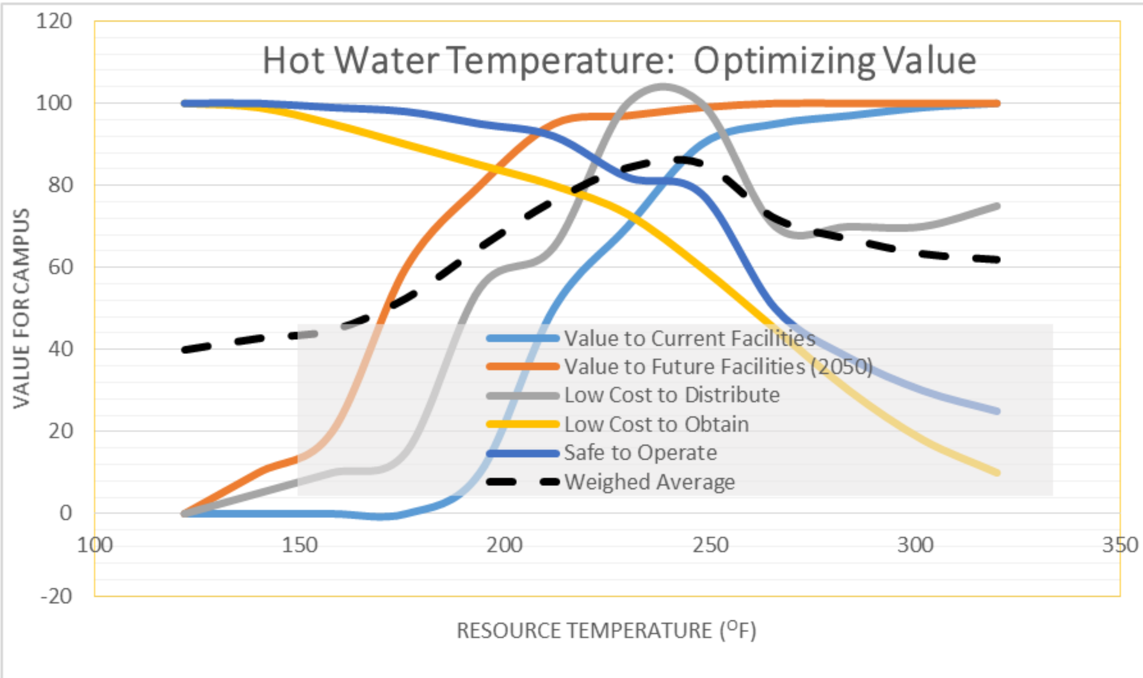


Figure 4-2: Conceptual Graphical Representation of Optimal Temperature Evaluation

SECTION 5: ANALYSIS OF ALTERNATIVE SCENARIOS

Scenarios and Results

In this Section, alternative scenarios are presented and analyzed to help determine future Capital and Operating scenarios that will meet the project of reliability, affordability, and sustainability (see Section 1: Project Goals).

In addition to the Base Case (Section 4), specific alternatives scenarios include the following:

- Improvement in steam pipe insulation (change in design standard)
- Replacing the entire steam heat distribution system with a hot water (HW) distribution system. Some multiple buildings are fed from a single heat exchanger. This alternative includes three sub-scenarios based on different replacement schedules.
- Replacing only a portion of the steam distribution with hot water and retaining a substantial level of thermal distribution in the form of steam.

All of the analyses require a number of assumptions and sub-analyses. These sub-analyses are described as well in the appendices, although some of the most important elements of that assumption are included in this Section for clarity. Table 5-1 summarizes the primary financial results of these analyses, which were conducted using custom Excel spreadsheets built for this purpose:

Table 5-1: Alternative Analyses Financial Results (Net Present Value)

Scenario	**CAPEX and incremental OPEX** (*Net Present Value, $US Millions*)			**Notes**
	Margin Cost Basis		**Billed Rate Basis**	
	Lower Energy Value ($4/MMBtu)	**Higher Energy Value ($8/MMBtu)**	**Energy at $25/MMBtu**	
Steam Base Case	***$ 65.6***	***$ 80.6***	***$ 144***	***Maintain current system indefinitely***
Update 7-2016: Data on cost for conversion redacted; analysis incomplete in light of revised financial information developed by E&S in 2016. See CNCEAR report for revised cost information.				

Appendix B provides details on the assumptions holistically utilized and individually in those analyses.

Table 5-2 provides a summary extends of the conclusions reached as one extends the analysis beyond the single-bottom line of the distribution system in isolation, and considers other positive and negative impacts of future decisions.

Table 5-2: Additional Impacts of Scenarios

Scenario	**Summary other Impacts**
Steam Base Case	**Positive:** Normal Construction Impacts, Lowest Short-Term Capital Outlay; **Negative:** Not compatible with renewable energy integration at district

	scale, lowest environmental performance (high carbon emissions); Retained worker risks
Better Steam Pipe Insulation	Same as above; better financial performance as energy value increases
Replace Distribution System w/HW in year 5	**Positive:** Highest environmental and O&M performance, highest potential for integration of renewables at district scale, reduced long-term work risks. **Negative**: Higher short-term construction impacts, high short-term capital outlay,
Replace Distribution System w/HW in year 10	Same as above but construction impacts and capital deferred 5 years; positive impacts also deferred.
Replace with HW in increments, complete by 2035	Same as above, except all impacts spread out over time (both negative and positive impacts); this option requires good planning over a long period and careful execution to ensure effectiveness.
Hybrid HW/Steam	Similar to above but resulting in slightly lower benefits while requiring operation and maintenance of dual systems requiring different maintenance actions; complete renewable transformation probably not possible.

July 2016 Update: Cost Information Redacted: Analysis not completed based on update of capital estimate by E&S in July 2016. Based on this revised information, there is no cost-effective replacement strategy. Only the "Base Case" financial analysis remains valid.

Full Description of Scenarios

A more complete description of each of the tested scenarios is included herein, along with a discussion of the financial and non-financial costs and benefits determined by the scenario analysis.

<u>The Steam Base Case</u>

The Steam Base Case is discussed in detail in Section 3. It reflects the current Present Value (PV) of that the current steam distribution system of the FPNMS-modeled lifetime, based on documented replacement and maintenance costs, and system performance (i.e., documented energy loses in the distribution system). This PV is the benchmark against which other systems are considered.

As shown in Table 5-1, the Steam Base Case has a relatively low PV ($65.5 to 80.6M based on the marginal energy costs included), even as replacement of the system over the analysis period is higher ($116M) and steam losses are higher (cumulatively $72 to 119M) over the period. This relatively low PV reflects the strong influence of the healthy "discount rate" (required return on investment) included in the analysis and the relatively small amount of capital replacement scheduled in early years.

Table 5-2 shows both the benefits and negative impacts of the "steam base case". Of note, as discussed further in Section 4, the steam base case would not allow the integration of future renewable energy of any type currently being considered; although it could (inefficiently) support biomass-to-steam.

<u>Better Steam Pipe Insulation</u>

This analysis assumes the "Steam Base Case" except that anytime steam piping is replaced, it is replaced with a better-insulated piping systems. Based on the assumptions of cost and thermal improvement, this option provides a PV that is close to the Base Case, but improves over the Base Case as the value of energy increases. This option would marginally increase unit construction costs over the Base Case and marginally improve environmental performance (i.e., lower thermal losses).

Replace Distribution System w/HW in year 5

7/2016: Financial Information Redacted

Replace Distribution System w/HW in year 10

7/2016: Financial Information Redacted

Replace with HW in increments, complete by 2035

7/2016: Financial Information Redacted

Implementing this scenario would require additional planning and likely result in some adjustments to scope and schedule to result in effective sub-systems and an effective final overall system, and some of these adjustments may increase costs marginally. As systems are improved to hot water, those portions of the system will have lower thermal losses and lower maintenance requirements, and incremental renewable energy may be able to be incorporated if properly planned and placed on campus, even before 2035.

Table 5-2 indicated the positive and negative impacts of this scenario in comparison with other scenarios.

Hybrid HW/Steam

7/2016: Financial Information Redacted

The principal advantage of this alternative, compared to other scenarios, is lower early capital outlay; its overall financial performance is relatively poor and additional long-term costs may result from having to operate two different systems with different operating and maintenance needs; it would allow the incorporation of substantial renewable energy but not a total conversion to a studied low-carbon or renewable energy technology on a district scale.

Alternatives not evaluated for financial return

Other planning options were also discussed as potential scenarios for financial evaluation. The following alternatives were not fully evaluated for the reasons described below:

- Modification of pipe sizes. Utilizing smaller or larger pipes would impact both capital and operating costs and could affect the reliability of heating supply. However, since Cornell does not own the steam model, it was not possible to efficiently compare schemes so that impacts could be understood. The optimal sizing of pipe systems should be included in any future new design.
- Expansion of looped systems. Key central facilities are part of a looped campus system that, with appropriate valve operation, can allow problems to be isolated while service is retained to all or most facilities in the area. However, some areas of campus (such as West Campus residential areas) are served with "radial" lines that are not looped. Within the limited funding limitations of this study we were not able to provide a cost evaluation of the impacts of providing a greater degree of looped and redundant systems as we had no in-house modeling tool available and no data to suggest that Cornell has experienced and significant financial losses in the past due to lost

service. However, redundancy remains a key goal and should be considered as part of any system replacement or expansion.

- Alternative operating pressures. An in-house modeling (or funding to pay a consultant to complete modeling) would also be needed to determine if current operational pressures are optimal. Currently, the knowledge and experience of staff are used to determine appropriate operating pressures for each season; some conservatism is typically used to ensure all facilities receive the heat energy they need to operate fully in all seasons.

SECTION 6: CONCLUSIONS AND RECOMMMENDATIONS

This report documents the following:

- The existing Campus Distributed Heating (steam-to-hot-water) system physical and operational parameters
- The existing and previously-developed capital plans for improvements to the system
- Analysis of alternative future capital activities to achieve University goals including:
  - Minimize future capital expenses and operating expenses (quantified as an overall "Present Value" of expenditures over time)
  - Operate in an environmentally-responsible manner
  - Provide opportunities for the incorporation of renewable, recoverable (waste), or recycled heat into the central heating system

The results of the alternatives analysis are reported in Section 5, which included both a Base Case scenario (continued operation and maintenance of the existing steam heat distribution system) and six alternative scenarios. Based on the evaluation of those scenarios as summarized in Section 5, two scenarios are selected and recommended as best meeting the goals noted above, as summarized in Table 6-1 below**:**

Table 6-1: Base Case and Recommended Alternative(s)

Scenario	**Total Investment*** (*Net Present Value*)	**Notes**
Steam Base Case	*$65.6 M to $144 M*	*(Base case – does not meet stated University goals)*
7/2016: Financial Redacted		

***Note:** The range of Total Investment figures above represent different energy evaluations; see Section 5 for details. All results assume a required Real Discount Rate of 5.4%.

Conclusions

The following is a summary of the conclusions resulting from this report:

- Cornell operates a reliable and effective steam distribution system.
- However, due to the nature of steam, this system has the following disadvantages:
  - It prevents the incorporation of efficient forms of waste heat energy, renewable energy, and low-carbon energy (for instance, from renewable or waste sources boosted by heat pump technology or direct waste heat from cooling systems).
  - It is more dangerous than modern hot-water distribution and has a greater potential for catastrophic failure

- Distribution using steam is inherently inefficient by nature of the losses associated with the phase change to hot water (steam needs to be converted to hot water to serve building needs)

- Transforming the campus heat distribution system from steam to hot water is necessary for the University to meet its Climate Action Plan goals
- Transforming the campus heat distribution, if carefully planned, can create a favorable financial result (best Present Value) over the long run. Implementing this plan will require significant capital in early years (more than the "base case), but will provide the lowest "burden" to future generation of Cornellians due to its lower operating (energy) and maintenance (people) costs, improved safety and reliability, and improved ability to alternative energy forms, especially low-carbon energy, "waste" energy, and renewable energy.
- At the periphery of the system, essentially all of the steam is converted to hot water for use in buildings and facilities. A gradual and well-planned expansion of peripheral hot-water loop sub-systems serving multiple buildings, such as currently in place in various locations on campus (West and North campus, primarily) could reduce the maintenance burden of steam traps and similar conversion equipment and reduce overall system losses.

Recommendations

The following recommendations are made as a direct results of the analysis completed in this report:

Recommendation 1: Maintain existing core steam supply infrastructure.

Although the original steam piping system was installed in 1889 using engineering guidelines of the times, most of the system has been replaced a minimum of two times, excluding repairs. Upgrades and improvements continue to this day (2014). Newer steam infrastructure consists of Grade Beam and Precast Masonry Conduit; more than half of the current system is of this modern design. This current system has a high value and, based on alternative analysis, the incremental efficiency improvements represented by other significant alternatives will not provide sufficient improvement in the near term to warrant wholesale replacement at this time.

While alternative low-carbon or no-carbon solutions are a longer-term goal, the proper operation and maintenance of the existing steam supply system will ensure reliable and cost-effective campus heating in the interim and will provide a back-up source to any new system until proven out.

Recommendation 2: Provide and/or improve redundancy in the steam distribution system.

As noted in Section 1, several areas of the campus have constrained and/or single-source steam service. Even in areas where redundant steam feeds exist, not all of the piping routes are consistently large enough to carry the full load, and some areas of campus have multiple feeds into one location but then offer limited redundancy to each building. As the campus focus on research continues to grow, redundancy of services becomes a critical issue for the continuity of living research.

The University should continue its efforts to proactively increase pipe sizes as replacement is required and to make yearly allocations to increase redundancies and looping of services in area of the campus with a research focus. Redundant ("looped") distribution systems enhance reliability and supply constancy and enhance the ability to make distribution system repairs and improvements over time without unacceptable service disruptions. Similarly, Redundant supply equipment ensures that campus needs can be met despite occasional equipment failures and facilitates timely equipment maintenance.

Recommendation 3: Continue demand-side energy conservation measures to minimize increases in energy capacity needs on campus.

Over the last 10 years, the campus space consuming energy has continued to increase. However, due to conservation efforts, the energy usage has been steady or slowly decreasing due to a significant positive impact of conservation efforts. Newer buildings on campus tend to have higher comfort requirements and/or more intensive research needs, which inherently consume large amounts of energy on a per square foot basis. The energy conservation efforts of the University should continue and should be incorporated into each new building design for the campus as it moves forward. To encourage consideration of the true cost of energy supply, the billed rate for heat and electricity should be used as the basis for LCA assessments of building options that affect energy use. Energy conservation at both the building and system level is the most cost-effective tactic for avoiding unnecessary capital expansion of supply and distribution systems and reducing costs for future replacements.

Recommendation 4: At the steam system perimeter, expand use of cascading systems serving multiple buildings.

At the periphery of the system, essentially all of the steam is converted to hot water for use in buildings and facilities. A gradual and well-planned expansion of peripheral hot-water loop sub-systems serving multiple buildings, such as currently in place in various locations on campus (West and North campus, primarily) could reduce the maintenance burden of steam traps and similar conversion equipment and reduce overall system losses. As the hot water distribution is expanded, maintenance can be focused on the most critical "core" of the (remaining) steam distribution system. This approach is recommended for the following reasons:

- Based on the analysis documented in this report, this approach provides the best life-cycle value for Cornell
- It improves environmental performance with moderate impact to campus. Improved environmental performance is due to the following factors:
    - The reduction in periphery steam lines reduces steam and thermal losses, thereby reducing the amount of input fuel needed at the Central Energy Plant to provide campus heating needs.
    - The building sub-district systems are at a lower temperature, thus they can readily accept renewable or waste energy sources, which typically are available at a lower temperature.
- It improves future reliability
- It reduces annual capital outlays compared to other reconstruction options.

Recommendation 5: Establish and enforce formal heating system design standards that prescribe building system temperatures immediately.

As discussed in Section 4, relatively small reductions in building heating system temperature designs reflect a growing international trend that can result in a significant reduction in distribution piping size, especially if considering lower-temperature sources of heat in the future. Future buildings and current building heating system upgrades should be designed to allow for both a lower supply temperature and a significantly reduced return temperature limit. This would significantly reduce costs of future system infrastructure and enable integration of cost-effective renewable and waste heat recovery as these technologies are developed and implemented. Reasonable temperature reductions are well within the design ability of current design professionals. Section 4 provides some examples of savings possible.

Recommendation 6: Complete a systematic evaluation of existing buildings (can be completed with in-house personnel) to document individual building temperature settings and needs. Utilize this information to plan and implement adjustments to building control settings and plan future system modifications necessary to allow lower-temperature building services.

Recommendation 7: Before 2035, convert the current "primarily steam" system to a "steam-driven cascading heat system".

In this improved system, the majority (or all) of the campus heat is distributed as hot water. As alternative heat sources (i.e., Earth Source Heat, Heat Pumps, Biomass Boilers, or similar) become available, this system will allow integration of these resources at low cost. Even if none of these replacement systems are built, the hot water distribution can still be fed with hot water generated from steam, reducing peak and annual heating needs and potentially delaying or eliminating the need for additional steam boilers to accommodate growth. Of the conversion options, this solution offers the lowest environmental impact (lowest "carbon footprint"), enhances reliability, and improves safety of the options studied. To implement this solution requires advance planning to incrementally reduce the extent of the steam distribution system in favor or more extensive hot water distribution, minimizing direct steam distribution.

Recommendation 8: Purchase software and build an in-house steam system model to replace the current model prepared by outside consultants.

Software appears to now be available which is affordable ($5,000-7,500) and designed for this task. Creating and utilizing an in-house model supports essential planning, design, and construction impacts support for Energy & Sustainability in their management of the steam system. In addition to long-range planning and operations support, a working model can facilitate emergency response planning for any unexpected system disruptions.

APPENDIX A

Design Basis Steam and Hot Water Size and Temperatures: Case Selection

Summary

The technical and cost analyses included in this planning document require assumptions regarding the temperature and pressure to be used in the system and the type of infrastructure that would be applied. This section considers both the qualitative and quantitative advantages and disadvantages of systems of different sizes, pressures, and piping materials in order to determine reasonable selections for analyses.

Based on the discussion in this section, the following assumptions were made for all future systems utilizing hot water:

- The water supply temperature and return temperatures were assumed to be as follows:
    - Distribution Supply: 225°F typical, 248°F max, 200°F min
    - Distribution Return: 175°F min
    - Heat Exchanger Approach Temperatures: 5°F min
    - Building Supply Temp: 190°F max
    - Building Return Temp: 170°F max, 120°F min

- New buried water distribution and return piping will be pre-insulated to the standards of *EN-253: District heating pipes – Pre-insulated bonded pipe systems for directly buried hot water networks - Pipe assembly of steel service pipe, polyurethane thermal insulation and outer casing of polyethylene*

Cornell's North Campus system was installed using pipe which conforms to European Standard EN 253. This pipe will operate routinely at temperatures up to 120°C (248°F) and occasionally to 140°C (284°F). While we do not expect to operate above about 250F, the fact that the standard spec allows occasional higher temperatures without damage provides some margin of design and operating safety. Special insulation (urethane) formulations allow higher temperatures, although thermal expansion and other factors need be considered and the cost of accounting for higher expansion, higher thermal losses, and other similar issues generally create practical limits which restrict design to these temperatures. Therefore, we are assuming "standard" EN-253 piping systems rather than more expensive "custom" fabrications.

Similarly, in considering the "base case" (continuing to utilize the steam system), the following assumptions are made:

- The water supply temperature and return temperatures were assumed to be as follows:
    - Distribution Pressures: 35 psig minimum at "end of line" buildings
    - Maintain current design standards, including Insulation at current levels (note: additional insulation is also considered as an "alternative" case)

General Assumptions for all Construction Cost Analyses

These figures are in 2015 US dollars used for comparison analysis, but do not represent final cost estimates. Final cost estimates for any specific section of pipe will be dependent on final layout (especially number and type of fittings requires, surface conditions and replacement requirements, depth to rock, and similar factors. The cost of manhole replacement in particular is highly dependent on the arrangement of valves and traps in the manhole, number of interconnections, local conditions, and similar factors.

Background

Thermal energy distribution is typically either steam or hot water (hydronic). Hot water systems can be either "low temperature", "medium temperature", or "high temperature". Some typical definitions for these temperature classifications are as follows:

Lower Temperature Hot-Water Heating System (LTW): LTW systems operate up to a temperature of 250^{o}F (121^{o}C). The maximum allowable working pressure for a LTW system is usual 30 psi (2 bar). LTW systems may be used both interior to buildings and within distributions systems

Medium Temperature Hot-Water Heating Systems (MTW): MTW systems operate at temperatures above 250^{o}F (121^{o}C), up to 350^{o}F (177^{o}C). The maximum allowable working pressure for a LTW system is usually 150 psi (10.5 bar). MTW systems are typically used in large hot-water distributions systems and process applications.

High Temperature Hot-Water Heating Systems (HTW): HTW systems operate at temperatures above 350^{o}F (177^{o}C); the maximum operating pressure for an HTW system is usually less than 300 psi (20.7 bar). HTW systems may be used for large distributions or process applications.

At Cornell as for most modern facilities, heat is primary distributed within buildings as hot water with a temperature of about 200^{o}F or less. As this hot water is used in coils and radiators, the temperature is reduced; depending on the system and design the return temperature may be anywhere from about 100^{o}F (if the systems are somewhat undersized, radiant floor or other lower-temperature heating is used, or a "cascading" system is used which may include sidewalk ice melting of other secondary use) to about 180^{o}F (if the overall system is oversized, high-temperature systems are needed, or the heat transfer coils are oversized, so that only partial heat transfer occurs). Therefore, any of the above systems can theoretically support the existing building needs. However, there are advantages and disadvantages of each system, as outlined in the table below:

Table A-1: Qualitative Differences Between Distribution Systems:

	Steam	**LTW**	**MTW**	**HTW**
Piping Size Needed	Small*	Medium-Large	Medium	Small
Heat Loss to Ground	Large	Small	Medium	Large
Cycle Water Loss	Medium	Very Small	Small	Small
Ability to Incorporate Renewable Energy	Low	High	Medium/Low	Low
Safety Risk	Medium/High	Small	Medium	High
Overall Capital Cost	High	Medium	Medium	Small-Medium
Routine Repair Costs	High	Low	Low	Medium

**Steam delivery piping size may be comparable to LTW or MTW, but the return (condensate) pipe is smaller, so the overall piping size needed is typically smaller.*

Discussions of these qualitative differences follows:

Piping Size:

Steam has historically used for heat distribution due to its distinctive benefits. Steam moves through piping systems as a result of pressure gradients; as it is converted to water at building (steam converted to water and released in steam traps) the local pressure is reduced and more steam pushes out, so that no pumping is needed. Steam also embodies the energy of phase change; the conversion of steam to water at the saturation point (212°F at atmospheric pressure; ~300°F at delivery pressures) releases the heat of enthalpy, which pound-for-pound is several times the energy of just the temperature difference. However, steam is also much less dense than water, so piping size may be larger or smaller to distribute that steam, depending on the endpoint needs and the characteristics of the water systems being compared.

For water systems, the pipe size depends on the maximum design velocity (or pumping capacity) at peak conditions, the distribution temperature, and the building temperature needs (exit temperature from the building system). From that information on can size the piping needed for a building or set of buildings, as demonstrated by Table A-2 below. In this example, the distribution pipe of a system supplying 80,000 MMBTU/hour at peak (about 20% of our current peak), if limited to 212°F at peak, would have to be at least 10.5 inches in diameter. However, allowing the temperature at peak to range to 250°F will decrease the necessary pipe diameter to 7.4 inch (8 inch nominal), assuming the building loop returns water at 170°F or lower under peak conditions. Thus, higher temperatures systems generally require smaller piping.

Table A-2: Sizing Example, Hot Water Piping for 80,000 MMTBU/hour peak load

Thermal demand (BTUs/hour)	Max velocity ft/sec	Pressure (psig)	Dist Max Temp °F	Bldg Exit Temp °F	ΔT (2x5°F approach) °F	Pipe Dia (in)
80,000,000	4	0	212	170	37	10.50
80,000,000	4	15	250	170	75	7.38
80,000,000	4	30	274	170	99	6.42
80,000,000	4	60	292	170	117	5.91

Heat Loss to Ground:

The thermal losses of a steam system are higher than LTW systems due to the higher temperature of the steam and the inability to reduce this temperature substantially over periods of low energy demand (i.e., summer) without losing the pressure needed to move it along. For hot water distribution, the heat loss to the ground is related to the temperature of the system; a well-managed LTW system typically has thermal losses of less than 5%, three times smaller than typical steam or HTW.

Cycle Water Loss

Early steam systems did not incorporate condensate return, so all of the water used to make steam would be wasted in each cycle. Modern steam systems, like the one at Cornell, are designed to maximize the return of condensate. Nonetheless, there are losses of water both in reconditioning water to reuse in boilers and in minor steam losses in the system that, in total, account for about 15% of the water used in each cycle (as documented in Section 2).

Hot water distribution systems are substantially closed-loop and water loss in these systems would be essentially zero during normal operations. Some water may be lost due to leaks or draining associated with maintenance, repair, or expansion activities.

Ability to Incorporate Renewable Energy

The ability to incorporate renewable energy at the distribution level is mostly limited by the temperature of the system; the higher the temperature, the lower the potential. Modern distribution systems that aim to maximize source energy efficiency and incorporate renewable resources operate at lower temperatures. With a steam or HTW system, only energy that is hotter than the distribution temperature can add energy to that system. All supply systems (boilers, geothermal systems, solar heating systems) must be able to produce temperatures higher than distribution temperature in order to be used. Lower temperature distribution design may therefore substantially improve the cost-effectiveness of renewable energy options.

Safety Risk

Steam under pressure can be a significant risk to workers and staff. Steam leaks may not be visible and can lead to severe burns (or even death); as a compressible gas, steam may continue to flow for extensive times at a leak site. There have also been cases of asphyxiation from steam (death as a result of steam displacing oxygen while simultaneously causing burns to the respiratory system) within manholes or other confined spaces (like tunnels).

Hot water can also cause serious burns, but is a much lower risk due to its lower temperature, the inherent visibility of a water leak, and liquid water's incompressible nature; a pressurized water vessel will lose pressure rapidly in a leak situation. However, systems with water above 212°F can "flash" to steam in a leaking situation to atmosphere, and that risk increases with temperature. HTW in particular may be "steam-like" in its behavior, in that it is under pressure and may flash more violently to steam. Generally, the risks to operators and bystanders increases with for higher temperature hot water systems.

Overall Capital Cost

Accurate cost estimates require detailed assumptions as to design and site conditions and materials spec. A quantitative assessment of costs options is included elsewhere in this report. The discussion here is limited to a more quantitative assessment to support the conclusions shown in Table A-1.

The capital costs to construct a steam distribution system is generally higher than the cost for constructing a hot water distribution system. Although the average piping size may be smaller than hot water distribution (as a result of both higher temperature delivery and the relatively small size of condensate return), the system typically requires additional infrastructure to minimize heat losses and support operations. Figure A-1 and A-2 show a simple cross section of the two systems reflecting the current design standard for steam and hot water as applicable to the Cornell campus, with some approximate per-length cost information (presented in more detail in Appendix B).

The simpler installation methods for modern hot water distribution result in generally lower costs. Hot water systems can normally be installed in simpler buried trenches rather than precast tunnel structures, and therefore generally require slightly smaller excavation. Additionally, hot water isolation valves would typically be buried type (like water valves) and so the system does not typically require manholes. Steam manholes are expensive to construct and maintain, due in part of the need to access steam traps and due to the hot and wet conditions which promote corrosion, thus requiring stainless-steel metals (including rebar metal) and similar conservative design practices.

Figure A-2 shows the current design standard for LTW hot water distribution (the only type on campus). For hot water systems that are not LTW, the costs are likely comparable. Higher temperature water systems generally will require smaller piping, but hotter temperatures require alternative piping selection (standard pre-insulated piping is rated to 248^{o}F only to protect the insulation against thermal degradation and expansion due to temperature would exceed the criteria of standard specs) and thicker insulation (to minimize thermal losses). MTW and HTW systems would also likely require additional design consideration due to the inherent dangers of higher pressure/temperature fluids, at least at the building interfaces.

A more complete analysis of cost is beyond the scope of this Appendix; hot water systems need pumps and plate-and-frame heat exchanges and the overall cost differences are subject to the exact design standards chosen including service temperatures, building temperatures, materials, and approach temperatures. However, this qualitative assessment supports the selection of the appropriate hot water class for comparison, and suggests the potential for systems other than steam to be cost-effective.

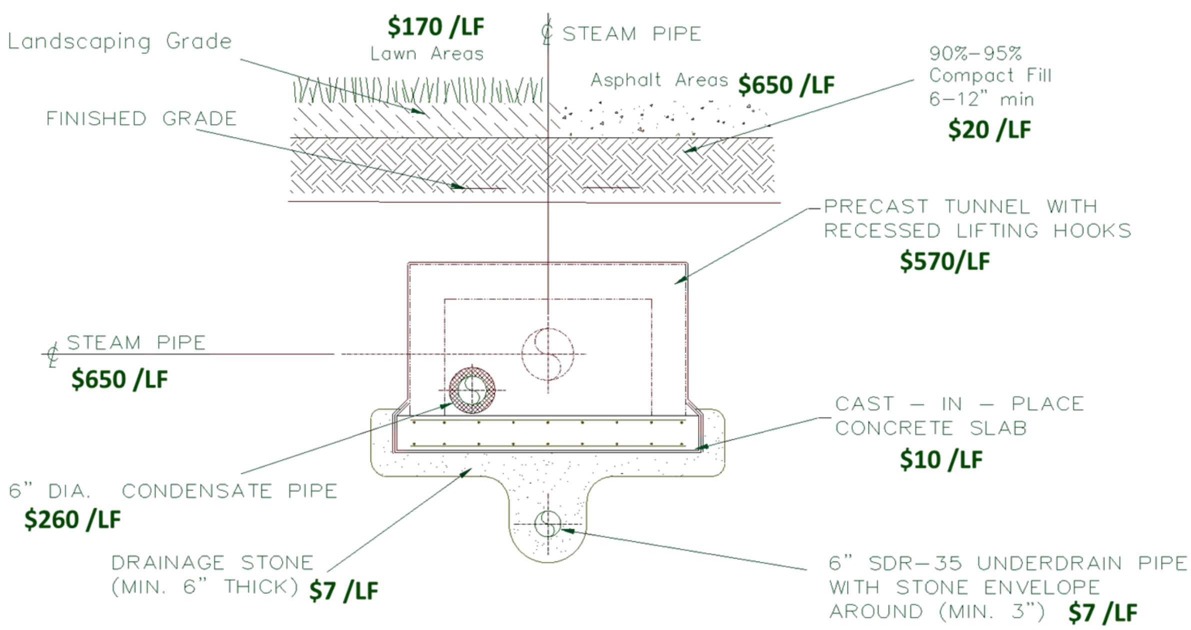
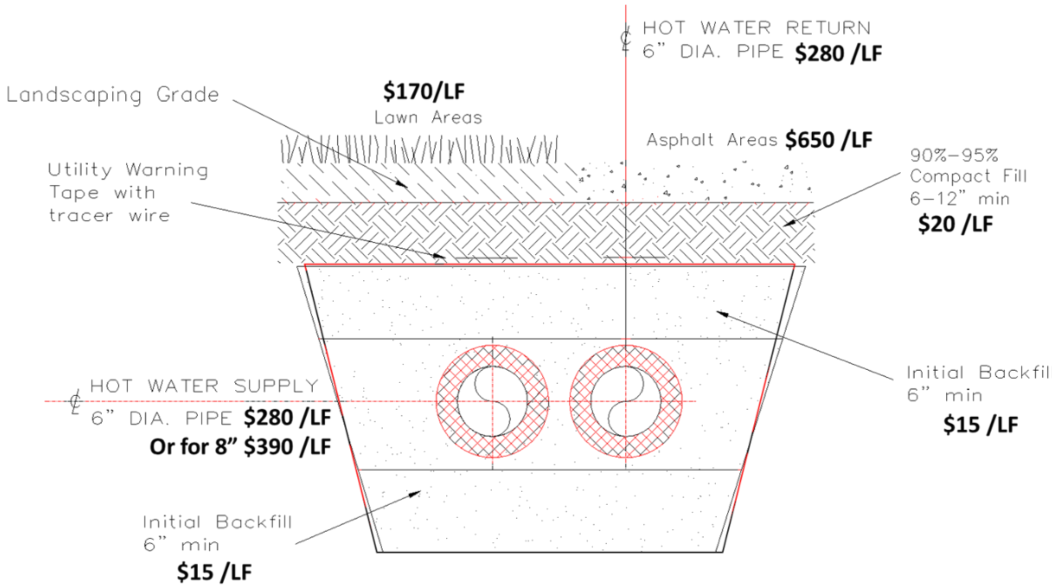


Figure A-1: Typical Steam Distribution Line (Cross-Section)



<u>Figure A-2: Typical Hot Water Distribution Line (Cross-Section)</u>

Analysis and Case Selection

The mostly-qualitative considerations included in this Appendix were used to determine the "base case" and "alternative hot water case" for quantitative analysis.

For the "Base Case", the continued construction and operation of a steam system built to current design standards is assumed. From this "Base Case", other options may be qualitatively and quantitatively compared (i.e., steam with better insulation, LTW, or similar options).

For the "Hot Water Distribution" case(s), the use of LTW is assumed. LTW is chosen rather than MTW or HTW for the following reasons:

- LTW systems support high enough temperatures (up to 250°F) to fully support building demand needs (up to about 200°F) with enough temperature difference to allow reasonable pipe sizing. Advantages of higher temperatures are generally incremental with diminishing returns.
- LTW systems are the safest option.
- The cost difference between LTW and MTW or HTW is not expected to be substantial (depending on assumptions and materials used, costs could be lower or higher)
- Higher temperatures exceed the design capacity of standard pre-insulated hot water distribution piping, a piping system that is gaining widespread acceptance and has been considered to have a long service life.
- Higher temperature supply temperatures would limit the options for renewable energy; a relatively minor increase in temperature above the minimum needed for cost-effective distribution could completely eliminate some renewable opportunities and add cost and reduce the effective energy supply of all renewable options. Even with conventional (fossil-fuel-based) heat generation, lower temperatures distribution systems allow more of the generated energy to be used for heat (or, conversely, more to be used for electrical generation while still generating sufficient pressure/temperature for heat).

- Higher temperature supply water creates a higher potential for "steam flash" hazards
- Building temperatures used in the example analysis is similar to typical temperatures in use today and likely to result in little or no change in interior building hot water system (although any systems requiring steam interior to the buildings will need replacement).

In considering an LTW system, designing a system to the full LTW range (to 250°F under peak conditions) is recommended. Lower delivery temperatures could substantially increase pipe sizing, depending on building temperatures and similar factors. Other campuses (such as U of R) have successfully designed similar systems to "ramp up" to higher temperatures only when needed based on demand.

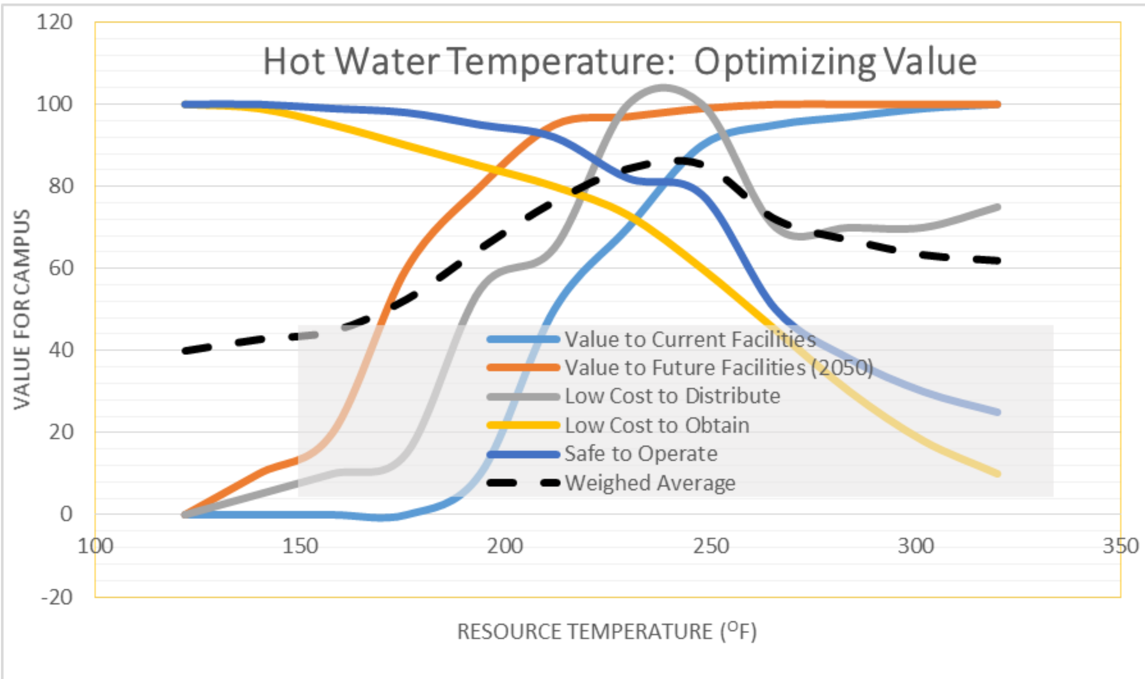


Figure A-3: Optimized Temperature Range for Hot Water Distribution at Cornell

A graphical representation of this analysis is depicted in Figure A-3. As this figure demonstrates, a temperature up to about 240-250°F represents the "sweet spot" where the higher value for distributed water is found. For the purpose of our work moving forward, we will consider this temperature range to be our "design basis" for a future water system.

It is also recommended that standard pre-fabricated piping systems meeting the design standards of *EN-253: District heating pipes – Pre-insulated bonded pipe systems for directly buried hot water networks - Pipe assembly of steel service pipe, polyurethane thermal insulation and outer casing of polyethylene.* This standard was developed in the European Union, which has the most successful history with these types of hot water system and is gaining acceptance across the U.S. (including installations at U of R, Stanford, and Cornell). However, the detailed analysis of alternative scenarios could also recommend specific areas of re-use of existing distribution systems or other similar alternatives on a case-by-case basis.

APPENDIX B: COST ANALYSIS ASSUMPTIONS

Summary

This appendix provides background and back-up to the cost and system loss information included in the body of the Thermal Systems Planning report. Cost details are provided here for reference from that text. In deriving estimates used in this section, the proposed steam and hot water systems utilize the same basic system assumptions (temperatures, pressures, line sizes, etc.) as presented in Appendix A.

The following cost summaries were developed from the information that follows in this Appendix.

Table B-1: Cornell Budget Costs for New or Replacement Heating Distribution Work

Supply Line (diameter)	Cost Per Trench Foot of Distribution System		
	Steam Distribution (incl tunnels, condensate return, & manholes)	HW Distribution (direct-buried supply & return)	HW Distribution (includes building heat exchangers, system HXs, and pumps)
3" - 4"	$ 1,200	***7/2016: DATA REDACTED: An internal E&S estimate that included contingency and soft costs was performed. The result of that analysis was that a total project cost for the complete replacement of the steam system with a steam-driven hot water systems (designed to accept renewable heat as such became available) would be about $235M, which is more than any reasonable BAU case.***	
6"	$ 1,500		
8"	$ 2,100		
10"	$ 2,200		
12"	$ 2,300		
14"	$ 2,500		
16"	$ 2,800		
18"	$ 3,000		
24"	$ 3,200		

Purpose and Limitations Regarding these Estimates

Costs for both steam and hot water piping systems are very dependent on installation methods and standards and contractor costs. As will be evident in the cost information presented, the actual materials cost for piping, even including fittings, is a small portion (less than 15%) of the total installed cost of hot water systems and a relatively small portion (~30-35%) of the total installed cost of a steam system. The rest of the costs are for labor, valves, manholes (for steam), backfill, resurfacing, equipment, tools, trenching safety equipment, traffic control, and other similar elements of the project, as well as for overhead and profit. Therefore, actual project-specific unit costs may vary significantly depending on distance between buildings and connections (which affects the number of valves and fittings and the labor required to make connections, etc.), depth of construction, surface conditions and restoration needs, and other factors.

However, many of these costs will be similar for either system (steam or hot water), and thus using broad cost averages remains a reasonable way to compare the costs for alternative systems. For example, either system built into a major roadway, like East Avenue, will encounter similar issues related to depth of bury (to provide protection and avoid other utility crossings), traffic control, and resurfacing standards.

Similarly, design decisions will significantly affect pricing. For example, both Stanford and University of Rochester have used custom Alfa-Laval heat exchanger/pump/control set-ups for their work, but Stanford's specifications and controls preferences result in higher costs. U of R reported their average per-skid cost to be about $35K, while Stanford's skids average over $60K. While functionality is similar, specific design standards may significantly alter costs. As another example, Cornell typically includes three valves (one for each leg) at every building service tee; Stanford includes less frequent line valves, with a minimum of one per three buildings, which provides a lesser degree of isolation but reduces costs.

Therefore, these costs should be understood to be useful for relative comparison analysis only. For any capital work that may result from this study and similar planning considerations, project-specific cost estimates using actual site conditions will be needed. Some factors not included in this analysis are as follows:

- Steam system replacement costs do not include replacement in building systems (steam-to-hot-water convertors or in-building condensate removal, tanks, or pumping systems). While periodic replacement of such systems is needed, it is not always timed with distribution work.

- The current steam manhole repair work (as documented in FPNMS, with a total deferred maintenance cost of about $31M) was not separately included in the "base case" for steam line capital work, since the steam line FPNMS costs includes an allowance for new manholes.

- Total O&M costs are not calculated, only cost differentials to allow comparisons (i.e., reduced energy losses for hot water versus steam and reduced maintenance for traps and pumps within the distribution system).

- Extraordinary potential building conversion costs. We are assuming that the system delivers hot water at sufficient temperature (i.e., providing 180-190F in the building) so as to avoid large-scale conversion requirements in most buildings. To partially compensate for this lack, we increased our estimates for the total building "tie-in" costs.

Distribution System Costs

The following sections detail the assumptions and costs attributed to new or replacement steam or hot water systems on campus. For the purpose of this study, two parallel methods were used to estimate replacement piping costs.

First, available project cost information from recent past projects was also reviewed and compared. This included both Cornell information on steam distribution replacement and information on hot water infrastructure costs from Cornell and other comparable institutions.

Next, these estimates were compared to a conventional "Engineer's Opinion of Probable Cost" estimate using the Means® Facilities Construction Cost Data (2014), supplemented by recent price information for the pre-insulated EN253 pipe (since this information is not in Means®).

Figures B-1 and B-2 show the basic layouts of the steam and hot water distribution systems, respectively, that formed the basis for these estimates. The costs shown for the components of these projects are those developed through the Means® analysis for a specific distribution pipe size (12").

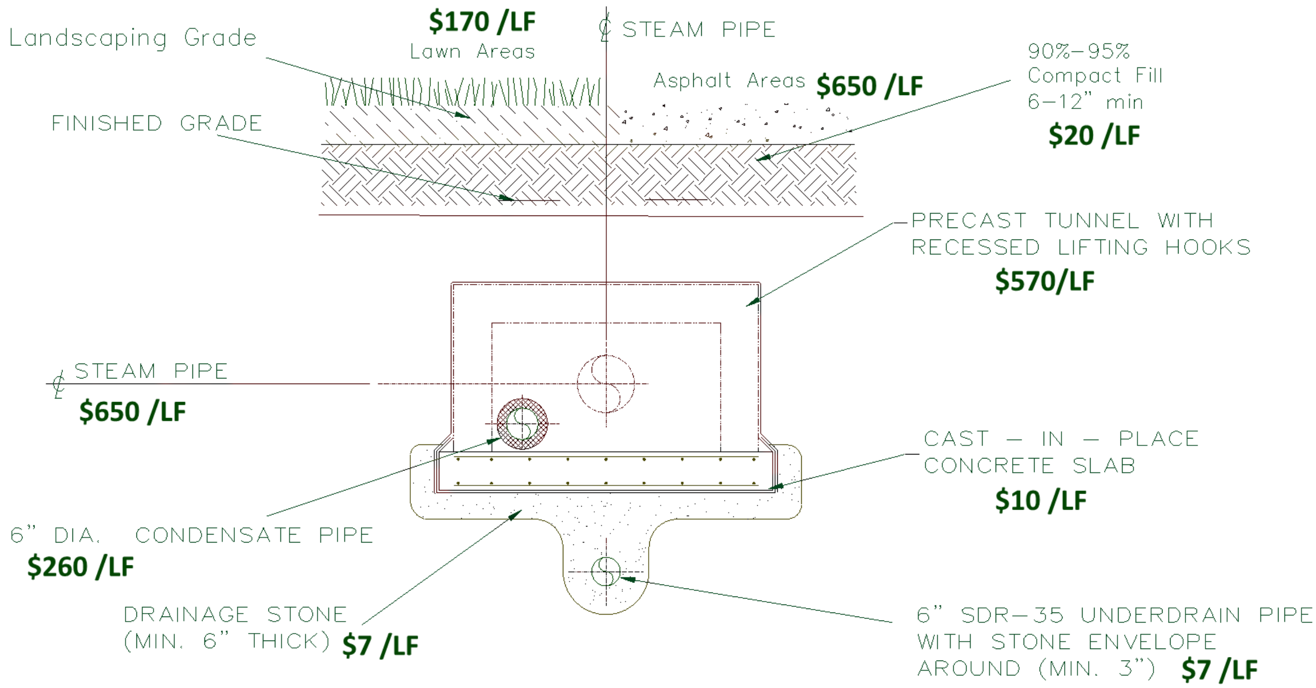


Figure B-1: Steam tunnel trench isometric

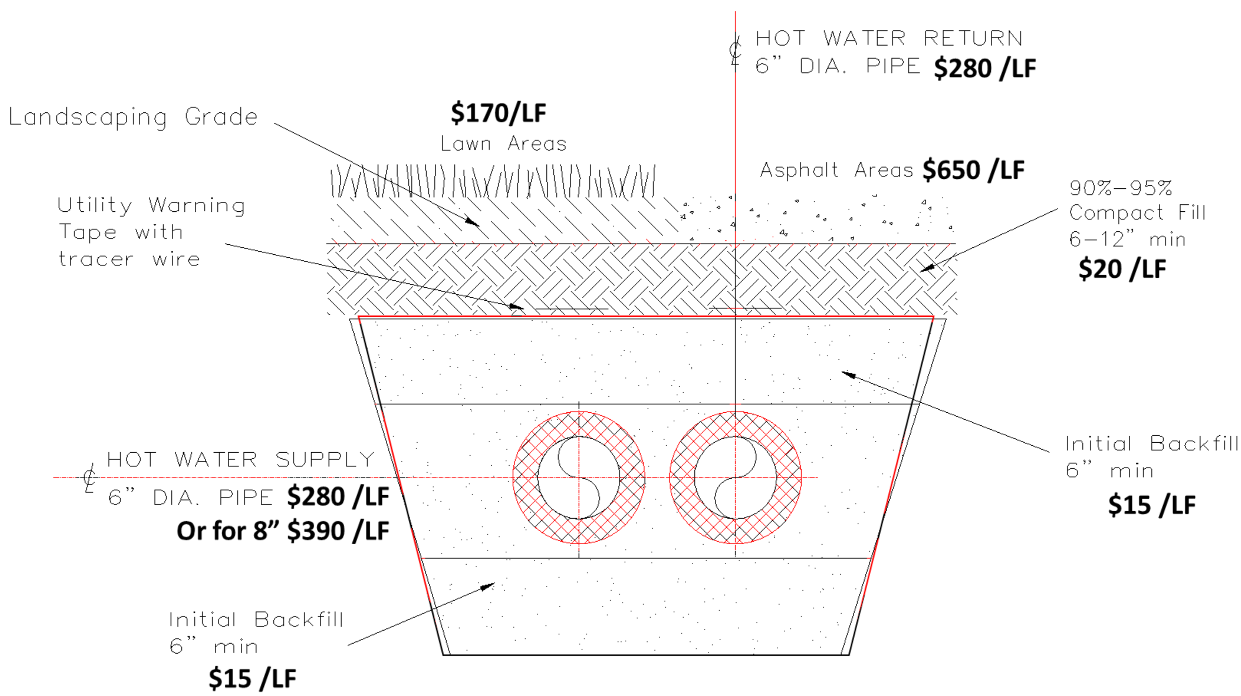


Figure B-2: Hot water trench isometric

Cost Information Based on Sample Past Projects:

Steam

Cornell has a long-standing steam maintenance and repair program and good cost information and history to support estimates for this work. Separate from the work of this report, the estimates developed have been incorporated into the Facilities Physical Needs Management System (FPNMS) system. These costs represent budget total project costs for steam work. This data is summarized in table B-1:

Table B-2: Cornell Budget Costs for New or Replacement Steam Work

Steam Line (diameter)	Cost per Trench Foot (incl tunnel, cond return, & MHs)
3” - 4”	$ 1,200
6”	$ 1.500
8”	$ 2,100
10”	$ 2,200
12”	$ 2,300
14”	$ 2,500
16”	$ 2,800
18”	$ 3,000
24”	$ 3,200

The total system replacement cost for all of the steam distribution (including distribution manholes) is about $116M.

In addition to these figures, Cornell has a separate FPNMS budget for steam manholes. This data is summarized as follows:

- Number of steam manholes: 146
- Replacement/major rehab cost per manhole:$140-280K (there is also a single $1M manhole)
- Total Installed Value: $32.5M

However, based on conversations with Les Cook and Frank Perry, who collaborated on the data in FPNMS, the steam manhole FPNMS costs are largely duplicated in the steam manhole FPNMS costs; while managed separately due to historical maintenance requirements, steam line replacement includes the costs of manhole replacements completed with new runs of steam pipe. While steam manhole work frequency may exceed steam line frequency, this analysis did not include additional expenses for separate steam hole maintenance work.

Hot Water

Cornell has less direct experience with buried hot water piping of the style proposed for future work. Therefore, Cornell’s site experience is amended by getting additional cost information from two other Universities (Stanford and University of Rochester) with recent experience in this type of construction.

Cornell completed a hot water distribution project for North Campus in 2014. The total Construction Cost (total PAR amount) was $904,000 plus the purchase price for the piping. The project consisted of the following quantities of piping:

- 320 linear feet of 8” pipe (not including fittings)
- 880 linear feet of 6” pipe (not including fittings)
- 80 linear feet of 4” pipe (not including fittings)
- 1160 linear feet of 3” pipe (not including fittings)

Thus, a total of 2,440 linear feet of piping (not including fittings) were part of the project.

The materials invoice for this work (including all pipe, fittings, tools, leak detection, training, etc., but excepting valves, which were not pre-ordered) was $95K – averaging less than $40/linear feet. The material costs for the larger pipe was not appreciably different (including all fittings, the 8” piping costs $37.50 per linear foot, although tools/equipment, leak detection systems, shipping, and training accounted for ~25% of the total material order).

Overall, including all distribution work and work within buildings to integrate these systems, the costs averaged about $80 per (two-pipe) trench-foot for materials and about $741 per (two-pipe) trench-foot for the rest of total project costs, or an overall average of $821 per (two-pipe) trench-foot of new systems.

The University of Rochester completed a project in 2015 and graciously shared their financial data on that project. The project included extensions of their system to nine (9) dormitory buildings, including the following quantities of piping:

- 1400 linear feet of 4” pipe (not including fittings)
- 200 linear feet of 3” pipe (not including fittings)
- 960 linear feet of 2” pipe (not including fittings)

Thus, a total of 2,560 linear feet of piping (not including fittings) were part of the project.

The total materials invoice for this work (including all pipe, fittings, tools, leak detection, training, etc., but not including valves, which were ordered separately) was ~$84K – averaging less than $33/linear feet, or ~$66 per two-pipe trench-foot. The material costs for the larger pipe was not appreciably different (including all fittings, the 4” piping costs $23.32 per linear foot, although tools/equipment, leak detection systems, shipping, and training accounted for 38% of the total material order).

U of R also shared their overall construction costs. Overall, the total cost for all installation work involved (inside and outside the buildings) was about $586,000 – or the equivalent of about $460 per trench-foot based on the total length of piping installed. Adding the material costs, the total cost for the project averaged $520 per (two-pipe) trench-foot of new systems. Additionally, U of R spent about $616K for the demolition of steam systems and installation of new heat exchangers in 9 buildings (about $67K per buildings). That breakdown was about $328K for the Alfa Laval per-piped, assembled units and $278 for the total install. All work was done utilizing union labor.

Stanford University also graciously shared cost data related to their recent campus-wide hot water conversion project. That project included nearly 25 miles of pipe (about 12.5 trench-feet based on a two-pipe system) of piping ranging from 4” diameter to 24” diameter, with “most piping in the 8-12 inch diameter range and most service laterals in the 4-6 inch diameter range”. They reported the following project cost information for this system:

- The overall average project cost was about $800 per (two pipe) trench foot

- The typical range for different sub-project areas (with different surfaces, levels of congestion, etc.) was $400 to $1000 per trench foot.
    - They also reported the total project cost of the "underground portion" was $60-70M. (This equates to an average of about $1000/trench foot for the ~66,000 trench feet of work, higher than their above estimate).

- The most expensive area, representing about 450 feet in a highly congested "urban" setting, was about $2,400 per trench foot. This high-unit-price work represents only about 0.68% of the total pipe length.

- Most piping was relatively shallow (2' minimum burial depth); in the areas of "worst congestion", some piping had to be installed at depths up to 14' to avoid other systems; in some areas piping was installed at more shallow grade with reinforced concrete covering to protect it.

- All workers were unionized and paid union wages.

Stanford also provided a lot of information on building tie-in and improvement costs. Some of the data noted during this talk follows:

- The total underground work and building conversions (i.e., total project less the central plant work) was roughly $209M. Thus, in addition to the roughly ~$60M spent per the above for the distribution piping replacement, Stanford spent a much larger amount (~$150M) overall for "building conversions".

- "Building conversions" included installing custom Alfa Laval heat exchange/control/pump skid packages (material cost about $125K per building; total install about $160K per building) and other mechanical room and building work to allow the building to operate at the relatively low temperatures that their heat-pump-driven system would provide (174.5°F at heat pump location; design for buildings was about 160°F supply, aiming for 110°F return – although current return temps are in the 120-130°F range).

- Building conversion work extended throughout the buildings. A rough average was about $500K total per mechanical room (ranging from $250K to $750K), although some heat exchangers were used to serve multiple buildings. Stanford spent an additional $1.5M for work in the building (ranging from $550K to $3.2M). Some building were previously all steam and the work includes a wide range or work from replacement of 3-way valves with 2-way to re-piping pre-heat to the return side to lower return temps to wholesale energy conservation efforts including building shell insulation improvements.

Costs for these sample projects are summarized in Table B-3.

The large difference in "hookup" costs appear related to Stanford's conversion from a steam system to a lower temperature system driven by heat pumps (their new design criteria is 160°F supply and 110°F return), whereas U of R and Cornell supply temperatures are higher and return temps were not required to be as low, greatly reducing the need for extensive building conversion work.

Table B-3: Representative Cost Data, Recent University Projects

Project	Aver UG Piping Cost (per 2-pipe trench-ft)	Hookup Cost (per bldg.)	Notes
Cornell North Campus (3”-8”)	$821	$50K	$821/TF UG installation cost included hookup (less materials)
U of Rochester Dorms (2”-4”)	$520	$67K	Hookup includes steam demo in buildings. Some field steam capped and abandoned in place.
Stanford Campus-Wide (4”-24”, 10” aver)	$800 - $1000	$500K	$500K is average of mech room costs; some connections serve multiple bldgs. Total building work averaged $1.5M to facilitate lower temp heat-pump design.

From the data on past projects we constructed Table B-4, which provides our study-basis unit cost averages for hot water system distribution as a replacement for steam (not including retrofits in buildings).

Using the results of the Cornell, Rochester, and Stanford building hook-ups as a guide, and recognizing the differences between the work scopes, for the purpose of this study we also estimated the cost of distribution work including the conversion from pipe-in-tube heat exchangers to shell-and-tube heat exchangers. Currently, there are about 150 metered steam connection points within the Cornell distributed steam system. While some economy may be realized through use of multi-building heat exchangers (see body of document), for the purpose of this analysis Cornell’s renewal is assumed to involve 150 new connections at a budget cost of $200K per building, for a total cost of about $30M.

Table B-4: Budget Costs, New or Replacement Hot Water Distribution Work

HW Line (diameter)	Cost per Trench Foot (direct-buried supply & return)
3” - 4”	$ 600
6”	$ 700
8”	$ 900
10”	$ 1,000
12”	$ 1,200
14”	$ 1,400
16”	$ 1,600
18”	$ 1,800
24”	$ 2,000

Replacing steam at end-of-life also involves some work interior to buildings (and steam convertors and/or traps and/or condensate pumps may be replaced at end-of-life regardless of distribution age). Replacing steam with hot water will also require some additional work in certain buildings beyond the $200K/building estimate. Because not all costs are known and some will balance, this analysis does not include additional interior costs for the purpose of comparison.

Our spreadsheet analysis reveals that the total value of the distribution work (not including building hookups) is about $60M. Therefore, to incorporate our estimate of building hookup expenses associated with replacement of sections of the steam line in a systematic way, we added a 50% cost figure to the unit prices uniformly. Thus, we have the following cost table (Table B-5) for the purpose of comparison:

Table B-5: Budget Costs, Hot Water Distribution, including Building Hookups

HW Line (diameter)	Cost per Trench Foot (direct-buried supply & return)
3” - 4”	$ 900
6”	$ 1050
8”	$ 1350
10”	$ 1,500
12”	$ 1,800
14”	$ 2,100
16”	$ 2,400
18”	$ 2,700
24”	$ 3,000

Finally, the hot water distribution system will require one or more centralized steam-to-hot water convertors (to utilize heat produced in the Central Utility Plant) and several large pump stations. There are several locations which such a system might be constructed that would not require the construction of new building spaces, but the cost of these system will still be significant. The construction of system could be incremental (i.e., several locations where steam converts to hot water, with pumping located to serve these sub-sections) or centralized (a single large steam-to-hot-water convertor system with centrally-located pumping), depending on the final approach chosen.

For the purpose of this study, we have assumed that the total cost for this system will be about $6M. Allocating this cost over the entire system, this will add about 6.7% to the overall per-unit distributed cost. Table B-6 provides this “complete” cost table.

Table B-6: Budget Costs, Hot Water Distribution, including Building Hookups & Pump Stations

HW Line (diameter)	Cost per Trench Foot (direct-buried supply & return)
3" - 4"	$ 960
6"	$ 1,120
8"	$ 1,350
10"	$ 1,600
12"	$ 1,900
14"	$ 2,200
16"	$ 2,600
18"	$ 2,900
24"	$ 3,200

Checking of Estimates using Means® Data

FPNMS estimates represent our best source of cost data for the campus, utilizing decades of campus experience. Nonetheless, we also performed a "standard" component-by-component cost estimate for these systems using the Means® Facilities Construction Cost Data (2014) construction cost guides. An analysis using a conventional cost estimate using was used, supplemented by recent price information for the pre-insulated EN253 pipe. Adequate information exists in Means® for reasonable steam pipe estimating; although a Cornell Standard steam tunnel is not included in the guide, an alternative concrete structure of similar costs was used). The results of that exercise are compared in Table B-7, below.

Table B-7: Cornell Budget Costs for New or Replacement Steam Work

Steam Line (diameter)	FPNMS Cost per Trench Foot (incl tunnel, cond return, & MHs)	MEANS® Cost per Trench Ft (same assumptions)
3" - 4"	$ 1,200	$ 1,800
6"	$ 1.500	$ 2.000
8"	$ 2,100	$ 2,200
10"	$ 2,200	$ 2,200
12"	$ 2,300	$ 2,300
14"	$ 2,500	$ 2,400
16"	$ 2,800	$ 2,600
18"	$ 3,000	$ 2,800
24"	$ 3,200	$ 3,000

In summary, a take-off using Means® results in similar pricing but with a tighter price range. One reason for this may be that we assumed the same surface conditions, whereas in actual practice most larger lines are located under roadways or at greater depth (to avoid crossings) whereas many small lines may be under landscaped areas. In any case, since the bulk of Cornell's lines are in the intermediate sizes, the Means® check confirmed that these cost estimates were, overall, reasonable.

The end of this section contains some additional details regarding the Means® cost estimate.

Natural Gas Pricing

Cornell's investment in a direct connection to an interstate gas pipeline as part of the CCHPP project has allowed Cornell to obtain preferred natural gas pricing, rather than be subjected to typical utility commercial pricing structures.

National pricing is often linked to prices at a physical location. A common benchmark location is the "Henry Hub". The Henry Hub is a distribution hub on the natural gas pipeline system in Erath, Louisiana, owned by Sabine Pipe Line LLC, a subsidiary of Chevron. Like many energy commodities, pricing can be volatile; Henry Hub pricing, is currently (2015) at prices below recent historical averages, as shown in the Figure B-3.

Cornell's location near to the recent development of the Marcellus Shale in nearby Pennsylvania provides us with natural gas pricing which is currently (in early 2015) substantially below Henry Hub pricing. Because of limitations in the number, capacity, and range of distribution pipelines, Ithaca is located along a location considered to have "stranded assets" which results in some developers having to sell below their price of development.

However, projecting future costs is notoriously difficult. For the purpose of this study, we assume that natural gas pricing remains at relatively low prices (assuming $4 per MMBtu) in the short term, followed by a gradual and steady increase over time at the rate of inflation plus 1%. Since energy costs in this range are not a primary factor in the overall financial analysis, this simplification is considered adequate for the purpose of this work. However, as Figure B-3 demonstrates, a much higher level of price volatility is normal and likely; substantially higher costs would warrant action sooner.

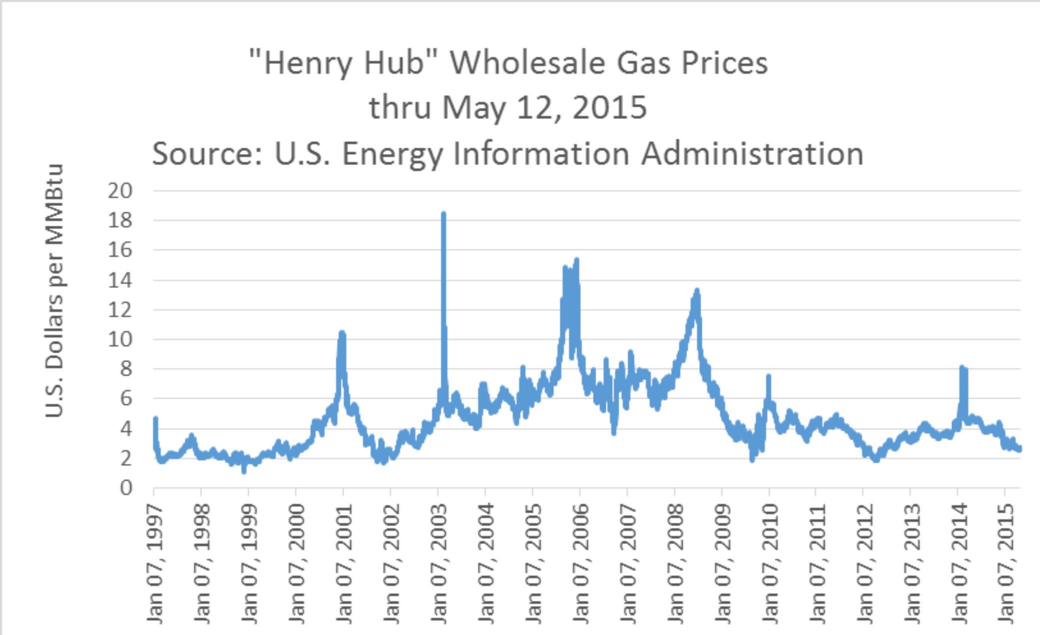


Figure B-3: Historic National Wholesale Gas Prices

Marginal versus Billed Rate Analysis

A comparison of options can also be completed on the basis of "billed rates" for heat or on just the marginal rate for the energy (gas) supply. A "billed rate" analysis is sometimes recommended to incorporate the "true" total cost of designing, building, operating, and managing the steam supply and distribution structure over the long run. It can be argued that this type of analysis is appropriate to typical long-term decisions about how to manage utility infrastructure, although in our specific analysis it may involve some level of "double-counting" since certain capital and operating costs are already incorporated into the existing marginal-rate-based options analysis. However, without some costs beyond the marginal cost of gas, some financial benefits of a lower-energy system are not incorporated (for example, a system with lower losses allows deferment of additional supply systems and may allow for a more optimal overall CHP system operation).

Cornell's steam billed rate (~$25/MMBtu) is high enough to significantly change financial decisions, as the evaluation results (Section 5) confirm. Comparisons using marginal rates are included in the presentation of options to help "bracket" the true total value that can be assigned to different alternatives, but it is generally understood that this rate is higher than appropriate to incorporate the true value of financial impacts.

Carbon Tax

This analysis predominately considers "single bottom line" market pricing, without respect for environmental or social impacts. One way to integrate fundamental environmental impact of actions involving the use of fossil fuels is to conceptually impose a "carbon tax" on various options, which then allows decisions based on utilize typical financial performance calculations while "valuing" environmental concerns at an appropriate level.

While the U.S. does not currently have a carbon tax, some institutions have included a virtual carbon tax into financial decision-making, and select nations have imposed formal carbon taxes as a way of transforming their energy economies. The World Bank provides a summary of some of the carbon taxes of various nations:

http://www.worldbank.org/content/dam/Worldbank/document/Climate/background-note_carbon-tax.pdf

This information shows a wide range of carbon taxes in force, from a low of $2/metric ton of carbon equivalent (Japan) to a high of $168/metric ton (Sweden). For the purpose of this analysis, a carbon tax would have the effect of increasing the valuation of the energy savings for each scenario. Because the combustion of natural gas releases approximately 53 kg of CO_2 (equivalent) per MMBtu of energy value, one can calculate the cost impact of various tax levels within the range reported by the World Bank, as demonstrated in Table B-8.

As Table B-8 suggests, based on current pricing (early summer 2015) of less than $4/MM Btu for natural gas delivered to Cornell, a carbon tax of $2/MT would have little impact on project economics, while a tax of $100 or higher may fundamentally alter financial decisions. For example, Table B-9 represents the results of a life-cycle PPA analysis using a (market or internal) gas price of $8/MMBtu

Table B-8: Effect of Carbon Tax on Natural Gas Valuation

Carbon Tax, $/MT CO_2 (equiv)	Increase in Valuation of Natural Gas ($/MMBtu)
$ 2.00	$ 0.11
$ 10.00	$ 0.53
$ 40.00	$ 2.12
$ 60.00	$ 3.18
$ 100.00	$ 5.30
$ 140.00	$ 7.42
$ 168.00	$ 8.90

Table B-9: Effect of Carbon Tax on Present Value Analysis

Effective Carbon Tax ($/MT)	PV for Base Case ($4 Market Gas)	PV for HW Transformation (2025)
$0	**$65.6M**	***7/2016: Cost Data Redacted***
$40	**$73.5M**	
$100	$85.4M	

This relationship can also be shown in graphical form. As Figure B-4 demonstrates, a change-over to hot water becomes more cost-effective as carbon emissions are valued higher. The break-even point for this example is about $63/MT-CO2 equiv. Essentially, externalizing the costs/value of CO2 has the same effect as increasing the price of nature gas in terms of Present Value computations. Thus, a "carbon tax" or similar external mechanism to place a value on the environmental benefit of lower CO2 emissions helps improve the comparative financial performance of a more complete switch to hot water distribution.

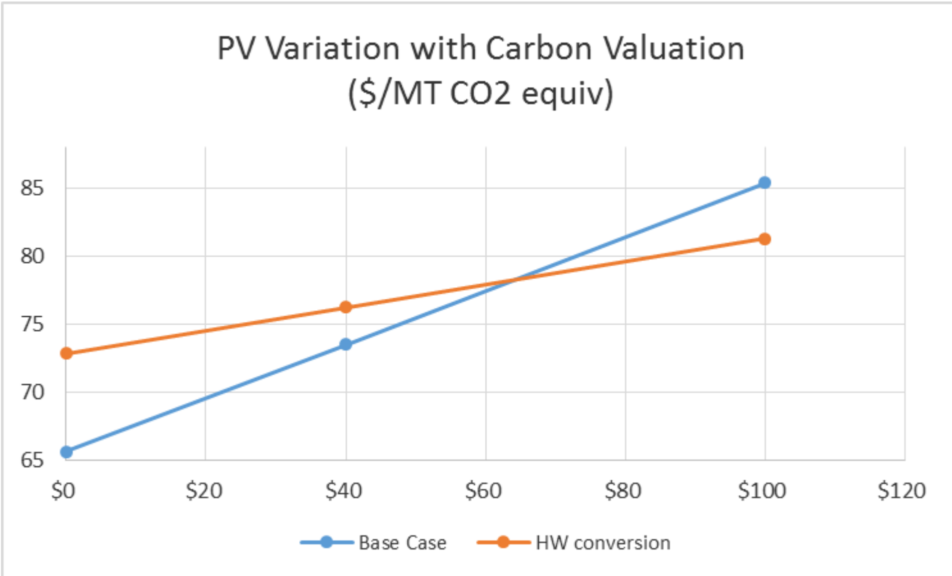


Figure B-4: Present Value Variation with Carbon Valuation

(PV in Millions of 2015$$; Carbon Valuation in 2015$/MT CO2 equivalent)

7/2016: Update: Figure B-4 is no longer valid, but is retained to demonstrate general impact of Carbon Valuation on Present Value comparison.

Details of Means Cost Estimate

The following is an item-by-item estimate was created for capital costs related to the Steam Distribution System.

Excavation, Bedding, and Backfill
To estimate the costs of various capital options, a baseline design was proposed and an estimate developed for that base design. This section summarizes those assumptions and cost basis elements.

The anticipated trench width would need to accommodate excavation and material storage adjacent to and below the pipe, and trench side slopes per current safety regulations. Contractors may utilize procedures which allow for work to be completed from outside of the pit, but for locations where in-pit work is necessary the contractors will be required to provide appropriate slope protection (additional cut or trench boxes).

Pipe-bedding and pipe-zone materials consist of all of the fill surrounding the pipe in the trench zone from 6 inches below the pipe to 12 inches above (or as designated in final/official design standards). This material must be compacted so that pipe walls are well supported. Pipe zone material is typically specified to be sand or a mixture of small aggregate and sand particles.

Trench and structure backfill must be compacted to a minimum of 90 percent maximum compaction. Where the pipeline is constructed under roadways, the backfill will need to be compacted to a minimum of 95 percent maximum density.

The total trench size (and therefore cost) is estimated for a 12" pipe size; the cost would not be expected to vary significantly for typically steam piping between about 8" diameter and 16" diameter.

Steam System Design

The actual operating pressures and associated temperatures within the systems at each specific building/site at any given time depend upon the pipe's location along the distribution system, the weather conditions, the time of year as well as the time of day. Plant steam is typically used as the primary source of heat for campus buildings/systems that are within the service area of the central distribution system. For the purpose of this evaluation, we used the Cornell Design Standard steam pipe. A 12" pipe size was used for this "typical" section; variations in installed pipe costs from Means® was used to adjust for varying pipe sizes.

Actual pipe sizes within the distribution system vary depending on the load they serve. For the purpose of our evaluation, which involves only one section of the steam distribution system, pipe sizes ranging from 8" to 16" were evaluated, reflecting the sizes of distribution piping currently in this part of campus.

Valves

Where a main line connects to another main, or a main branch (a branch that serves multiple facilities) connects to a main, valves are installed to maximize reliability and operational flexibility. An isolation valve should be at each branch steam distribution and pumped condensate return line near the point where the pipe connects to a main line. The Cornell campus standard includes a three-valve arrangement at each branch connection in order to maximize reliability and operational flexibility; this arrangement was assumed to continue for the purpose of this evaluation. A "stop valve" should also be installed in each steam/condensate line just inside each building at its service entrance. This valve is considered a part of the steam/condensate distribution system just as if it was located within the tunnel system and selected accordingly.

Pressure Reducing Valves

Where steam enters a building, the distribution pressure is typically reduced at the building interface for safety and cost reasons (high pressure interior steam is more hazardous and requires more costly control components). Pressure reducing valves are installed inside buildings for this reason. In a typical arrangement, high-pressure steam enters the basement mechanical room where it is regulated by two sets of pressure-reducing valves. Medium-pressure steam (30-40 psig max) and low-pressure steam (~12 psig max) feeds vary in the building.

Expansion Compensation

Expansion compensation is accomplished through use of expansion loops and the installation of mechanical expansion joints throughout the system. The installation of mechanical joints requires a vault in the tunnel system to accommodate their size and movement; some loops or offsets also are accommodated in vaults. For mechanical expansion joints a sliding expansion joint with a packing manifold is typically employed. For hot water systems, the predominant method of designing for expansion is to use pipe bends, expansion loops, and/or special backfill material.

Direct Buried Piping

There are a few limited instances on campus where steam lines are directly buried into the ground. However, this design is not approved for future distribution lines and is not in accordance with campus standards. For the purpose of this evaluation, all future capital projects are assumed to require piping in tunnels, as per the Campus Standards. Some condensate piping, however, may existing outside of tunnels. For the purpose of this planning document all future piping or piping replacement is assumed to be within tunnels (i.e., meet current Cornell Design Standards).

Steam Tunnels

Much of the existing steam and condensate distribution piping on campus is installed within utility tunnels. The current standard is for tunnels to be provided in conjunction with all new steam lines. Each utility tunnel is made of cast in place reinforced concrete slabs with precast removable rectangular covers.

Hot water systems are typically constructed with buried valves, since there are no steam traps or other areas where the benefits of manholes outweigh the overall costs.

Manholes/Vaults

For steam systems, all valves, expansion joints, traps and drains are located within vaults/manholes and a man-entrance is provided at each. Each vault is sized and configured to provide adequate access for operation of each valve. This may require that more than one entrance be provided for a given manhole. Each manhole/vault is constructed water-tight to ensure that tunnels passing under roadways are not vulnerable to damage by road salt. However, because maintaining completely sealed manhole covers has been found to be impractical, the manhole concrete is designed with additional concrete covering over rebar, and with stainless steel rebar (an atypical spec), to reduce corrosion from leakage of road salt into the (hot and moist) vaults, and thereby improve manhole life. A tile/gravel drain system is provided to minimize hydraulic pressure and protect against ground water infiltration.

Drip trap assemblies are located in manholes and are provided for condensate removal from distribution piping at intervals typically not more than 500 feet apart. Condensate discharge lines are extended and connected to condensate return units within adjacent buildings or to condensate pump stations within the system.

Condensate Return System

Steam systems require condensate return systems, which include condensate traps, receivers (tanks), pumps, and controls. For the purpose of this analysis, the condensate systems within buildings are not included in the distribution costs. The costs condensate systems within manholes (which are predominantly gravity-based) are assumed to be captured within FPNMS within the costs for manholes, which in turn is captured within the overall system pricing.

Hot water systems return water through a parallel return water pipe.

Heat Exchangers

Shell and tube heat exchangers are located at each building site mechanical room. Depending on the building heating system arrangement, there may be a single heat exchangers or multiple heat exchangers for different temperature services (building heat, reheat, domestic hot water, etc.). Currently, maximum temperature and return temperatures in buildings are not highly standardized and vary significantly; the highest typical hot water temperature setting is about 190^{o}F, although most buildings could meet their heating needs with 180^{o}F supply temperatures.

Cost Breakdown for LHW Distribution System

An estimate was created for capital costs related to the Low-Temperature Hot Water (LHW) Distribution System. This estimate includes the component-by-component costs that follow:

Excavation, Bedding, and Backfill
The total width of working space needed depends on several factors including depth of pipe cover, size of the pipe, encountered soils, contractor means and methods, and size and type of excavation and pipe handling equipment used by the contractor. The anticipated trench width would need to accommodate excavation and material storage adjacent to and below the pipe, and trench side slopes per current safety regulations. The bottom of the excavation pit must provide ample working room of clearance all around the pipe and related structures during installation. For the purpose of this evaluation, we have assumed trench width to be minimum 3 to 4 feet plus outside diameter of the pipe.

Pipe-bedding and pipe-zone materials consist of all of the materials surrounding the pipe in the trench zone from 6 inches below the pipe to 12 inches above (or as designated in final design standards). This material must be compacted such that pipe walls are well supported. Pipe zone material is typically specified to be sand or a mixture of small aggregate and sand particles.

Trench and structure backfill must be compacted to a minimum of 90 percent maximum compaction. Where the pipeline is constructed under roadways, the backfill compacted to a minimum of 95 percent maximum density.

Pipe diameter
The design must optimize the total life-cycle cost for the system, which is a function of both the energy and capital construction costs for the various pipe diameters throughout the system. The pipe diameter that meets the hydraulic constraints and also yields the lowest life-cycle costs will be optimal. For planning and conceptual design purposes, as discussed in Appendix A, we are assuming a pre-insulated system meeting Spec EN 253 will be utilized.

Pipes are sized based on demand and temperature drops across the building heat exchangers. Depending on final design, piping sizes for the loads in the sub-distribution section being considered will vary from about 6” to about 16”.

Supply and Return Temperature
Cornell does not have any supply and return temperature design standards in place for current and future buildings. After consulting with other institutions that do have standards, we have selected for the purpose of this evaluation a maximum building supply temperature required is 180F and a maximum overall return temperature (building average) of 140F, or a 40F delta.

The importance of maintaining building temperatures is detailed in Section A.

As noted previously, many buildings have multiple steam-to-hot-water convertors based on different temperatures, and future buildings can be designed with “cascading” systems with different temperature requirements – i.e., that can take 150^{o}F or 160^{o}F return temperature and use it for reheat or preheat or certain fan-coil units or radiant heating. The result is that the overall return temp can be much lower - as low as 120^{o}F or so on peak days, which reduced distribution pipe sizes and improved overall energy efficiency. It is assumed that some level of effort may be needed in select buildings (systems or controls) to improve the temperature differential and thus

Isolation Valves
Mainline isolation valves will need to be provided to limit the length of pipeline that must be repaired, cleaned or maintained for access and system shutdown, and in the event of an emergency. Isolation valves are recommended at the pump station(s), at line branches and will be incorporated at other sites as necessary to allow appropriate isolation for maintenance and control. Butterfly valves are suitable for use as isolation valves and were used in our calculations.

Expansion Compensation
Expansion compensation in this system is typically accomplished by means of expansion loops and pipe bends; no added expansion joints so as to eliminate the extra need to build vaults for maintenance around each section.

Pipeline Access
Valve boxes will be installed for pipeline access to accommodate initial construction and inspection as well as future maintenance requirements.

Corrosion protection
The pre-engineered systems are total sealed as installed and include leak detection. Corrosion protection of the pipe interior will require appropriate water treatment, similar to that required for the steam system. However, because the system has extremely low water-makeup (in contrast to the steam system) and the water never enters boilers or similar equipment, water treatment needs are not excessive after water chemistry is initially

Pumps
Circulation pumps are needed to move the hot water through the distribution piping and can be located in a common location with the steam-to-hot-water conversion. Each pump discharge line will need to be equipped with a valve for pump control, a check valve to prevent backflow in the event of a power failure or other pump shutdown, a butterfly valve for closing the discharge line when a component upstream of the butterfly valve must be removed for servicing, two air relief valves (to eliminate air pockets in the discharge line), a pressure sensor (for low and high discharge pressure shutdown), and a pressure gauge.

For a high degree of reliability, three pumps each accommodating 50% of the maximum flow can be provided (allowing for any one pump to be taken out of service at any time). Further design work would be used to verify the number and specifications of pumping units to be installed. The more pumps, the greater the flexibility in delivering various flow rates, but at a higher capital cost.

Pumps can be modular (included in the pre-constructed heat exchanger/pumping/controls skid for each building) or can be more centralized. For the purpose of this report, we assumed that distribution point includes a smaller modular pumping system with three (3) pumps each rated to 50% of the maximum design duty; this allows any one pump to be removed from service whenever necessary for maintenance. Pumps would be equipped with variable speed drive units for optimal performance. Generally, pumps should operate in the 75-85 percent efficiency range.

Heat Exchangers
Depending on the way in which the system is transitioned to hot water, one or two levels of heat exchange may be required. For systems still relying on steam as supply, steam to hot water conversion tube and shell heat exchangers sized for the entire sub-distribution loop will be required

and stationed in a building with space to house the units and other required equipment. The lower level of the chilled water plant that is currently out of service may be an appropriate location to house a system to serve east campus (there is also available space in the VRT). Additionally, existing steam to hot water tube and shell heat exchangers used to heat individual buildings will need to be replaced with hot water to hot water plate and frame heat exchangers. Overall, since condensate pumping systems will no longer be needed in the individual buildings, space needs will be reduced. However, work phasing will be important since temporarily locating both types of systems in each building may not be feasible in some buildings with limited mechanical space.

Further design will be needed to optimize the number and size of heat exchangers that will be installed at the main site location to service all of Vet Campus out toward Guterman and the greenhouses. Having two plate and frame heat exchangers at lower flow rate capacity instead of just one larger will allow for greater flexibility in ease of operation and maintenance since these units will be servicing that entire campus wing. Rather than have one large heat exchanger it is generally desirable to have two smaller equal size units which is critical in the case of a malfunction in one of the units allowing for at least one unit to continue producing output heat to the campus buildings.

Using these assumptions, Means® estimating software was used to estimate the cost for distributed hot water infrastructure. Figures B-5 and B-6 show ”screenshots” of sample cost estimates for steam distribution and water distribution, respectively.

Figure B-5: "Screenshot" of Sample Mean(s) steam cost breakdown/estimate

Qty	CSI Number	Item	Unit	Total	Total Incl. O&P			
Pipes								
3500	33631 310 5620	BS pipe stnd 1" CS insul 1200F 6" diam	L.F.	$ 743,400.00	$ 910,000.00			
3500	extrapolation	BS pipe stnd 1" inslul 1200F 12" diam	L.F.		$ 2,275,000.00			
3500	33411 350 1010	drainage pipe 6"	L.F.	$ 15,400.00	$ 21,525.00			
Elbow joints								
12	33631 310 4820	elbow CS insul 1200F 6-5/8" diam	Ea.	$ 22,694.16	$ 25,800.00			
8	33631 310 4830	elbow CS insul 1200F 8-5/8" diam	Ea.	$ 16,129.44	$ 18,200.00			
14	33631 310 2880	elbow CS insul 1200F 12-3/4" diam	Ea.	$ 33,914.16	$ 37,800.00			
Valves								
24	33121 610 3616	valve butterfly w/ lever 8" diam	Ea.	$ 29,904.00	$ 34,800.00			
2	33121 610 3716	check valves 8"	Ea.	$ 5,042.00	$ 5,700.00			
Excavation and groundwork								
6222.222222	31231 613 1354	excavation 1/2 CY	B.C.Y.	$ 43,991.11	$ 57,866.67	$8.27	excavation on a LF basis	
10	31231 920 0650	dewatering	Day	$ 1,650.00	$ 2,490.00	$0.36	dewatering on a LF basis	
1037.037037	31232 316 0100	Fill stone	L.C.Y.	$ 38,722.96	$ 45,629.63	$6.52	fill on a LF basis	
259.2592593	03311 335 0100	cast in place concrete	C.Y.	$ 24,759.26	$ 27,222.22	$7.78	concrete on a LF basis	
875	33051 613 0460	precast concrete vault 4'x4'x4', 6" thick	Ea.	$ 1,630,125.00	$ 1,990,625.00	$568.75	vault on a LF basis	
14000	32921 914 1700	lawn	S.F.	$ 459,900.00	$ 595,000.00	$761.67	OR	
14000	32011 720 0350	road	S.F.	$ 1,547,000.00	$ 2,296,000.00	$1,247.67	total groundwork on a LF basis	
Manholes								
11		total manhole costs ($150,000 each)			$ 1,650,000.00			
		pull the costs from FPNMS						
		cost for repair/replacement ranges from		total costs	**$ 7,697,658.52**			
		$8,000 to $280,000						
				total costs on LF basis	**$ 2,199.33**		FPNMS cost estimate	$ 2,300.00
				total piping costs on a LF basis not including manhole costs	**$ 1,712.76**			

Figure B-6: “Screenshot” of Sample Means® hot water costs breakdown/estimate

Qty	CSI Number	Item	Unit	Total	Total Incl. O&P		
Pipes							
7000.00	33611 320 0760	BS pipe stnd 1/2" PU insul 250F 8" diam	L.F.	$ 2,281,370.00	$ 2,730,000.00		
Elbows							
26.00	33611 320 2130	elbow 90 or 45 8" diam	Ea.	$ 61,838.40	$ 72,800.00		
Heat Exchanger							
2.00	23571 610 0300	HX 40F-180F 10PSI shell and Cu tube 600 GPM 3/4"	Ea.	$ 114,750.00	$ 128,000.00		
5.00	23571 913 3100	HX Plate 400GPM	Ea.	$ 186,250.00	$ 209,000.00		
Valves							
24.00	33121 610 3180	valve butterfly 8" diam w/ box	Ea.	$ 32,904.00	$ 37,800.00		
2.00	33121 610 3716	valve check 8" diam	Ea.	$ 5,042.00	$ 5,700.00		
	33121 315 8830	vavle box	Ea.	$ -	$ -		
Pumps							
4.00	22112 313 2020	pump pressure 400 GPM 7-1/2 HP 4"	Ea.	$ 163,000.00	$ 182,400.00		
Excavation and Backfill costs							
3111.11	31231 613 0090	excavation 1/2 CY	B.C.Y.	$ 16,831.11	$ 23,955.56		
3111.11	31232 316 0200	Fill sand	L.C.Y.	$ 82,102.22	$ 101,111.11		
3111.11	31232 316 0500	Fill compaction	E.C.Y.	$ 3.66	$ 5.80		
14000	32921 914 1700	lawn and mulch	S.F.	$ 459,900.00	$ 595,000.00	$ 205.73	**OR**
14000	32011 720 0350	paved asphalt road	S.F.	$ 1,547,000.00	$ 2,296,000.00	$ 691.73	**total ground work**
				total costs	**$6,385,422.47**		
				total costs on LF basis	**$ 1,824.41**		
				total piping costs on a LF basis not including pumps heat exchangers	**$ 1,006.53**		

APPENDIX C

Building Energy Use Data

Facility Code	Facility name	GSF	FY13 ACTUALS (MLB)	Steam Peak lb_hr_at_0F	Avg Steam lbs_hr
1164	VET MEDICAL CENTER	321,395	49,788	17,035	5,325
3212	ROBERT PURCELL COMMUNITY CTR	95,079	36,057	33,500	3,692
2000	DUFFIELD HALL	149,762	29,070	8,300	3,096
1014	WEILL HALL	272,242	26,237	11,400	3,202
2019	BAKER LABORATORY	233,676	26,143	9,748	2,785
1028B	BRADFIELD HALL	159,619	24,671	4,500	2,159
1027	MANN LIBRARY	136,870	23,887	4,500	3,207
1018	BIOTECHNOLOGY	173,983	22,738	8,000	2,371
1045G	TOWER RD EAST GREEN HDS 1045G	1,190	22,427	7,651	2,392
2083	OLIN CHEMISTRY RESEARCH WING	105,612	21,170	8,100	2,190
1150C	SCHURMAN HALL	56,497	20,102	10,300	2,404
1068B	GUTERMAN BIOCLIMATIC LAB	117,890	19,363	7,700	2,497
2087	URIS HALL	187,041	17,830	5,300	1,945
2082	CLARK HALL	250,151	16,214	4,200	1,526
1140	VET RESEARCH TOWER	125,507	15,879	5,104	1,595
2033	STATLER HALL & AUDITORIUM	197,233	15,811	6,900	1,660
1022	PLANT SCIENCE BUILDING	171,008	14,413	2,700	1,392
2076	PHYSICAL SCIENCES BUILDING	204,029	14,030	5,400	1,569
1064	MORRISON HALL	140,763	13,251	5,900	1,434
1019E	DALE R CORSON BIO SCIENCE WING				

		50,462	12,207	4,070	1,272
2020	WILLARD STRAIGHT HALL	114,690	12,115	3,204	1,002
1165	EAST CAMPUS RESEARCH FACILITY	82,686	12,053	4,600	1,362
2086	JOHNSON MUSEUM OF ART	63,768	11,155	3,687	1,153
2021	MYRON TAYLOR HALL	133,670	11,009	3,257	1,018
3009	BALCH HALL	166,814	10,645	2,900	1,090
1166	NYS Veterinary Diagnostic Lab	131,271	10,233	3,904	1,221
1076	BOYCE THOMPSON INSTITUTE	120,828	10,121	3,500	987
3032	CARL BECKER HOUSE	169,290	9,994	3,629	1,134
2016	SCHWARTZ CTR-PERFORMING ARTS	107,672	9,911	3,031	947
2024	OLIN HALL	129,664	9,438	2,732	854
1062	RILEY-ROBB HALL	112,049	9,419	3,600	982
2043	GRUMMAN HALL	16,289	9,086	3,103	970
1009	IVES HALL	110,605	8,860	3,553	1,111
1001	BARTON HALL	155,177	8,775	1,338	418
3018	CLARA DICKSON HALL	168,791	8,354	3,161	988
2037K	KIMBALL HALL	30,143	8,318	2,651	829
2047	OLIN LIBRARY	240,026	8,135	3,343	1,045
1081	COMSTOCK HALL-ACADEMIC II	110,380	7,554	2,200	938
3202A	BAUER HALL	30,504	7,447	2,212	691
2051	FRANK H T RHODES HALL	214,505	7,429	2,582	807
1153J	CLINICAL PROGRAMS - AMBULATORY	5,529	7,077	2,381	744
2070	BARD HALL	49,366	7,019	2,846	813
1061E	BLAUVELT LABORATORY	1,616	6,983	2,358	737

2008	LINCOLN HALL	91,253	6,904	2,470	772
2084	SPACE SCIENCES BUILDING - CRSR	56,969	6,669	2,150	672
1080S	KENNEDY HALL	108,971	6,600	2,031	635
1015A	M VAN RENSSELAER HALL	180,625	6,578	2,478	775
1011	HUMAN ECOLOGY BUILDING	125,609	6,511	4,300	702
3026	MARY DONLON HALL	133,594	6,403	2,207	690
2046	HOLLISTER HALL	115,288	6,301	2,414	755
2725	FED NUT LAB	47,095	6,239	1,913	598
2039H	PHILLIPS HALL	99,774	6,090	1,799	562
3003	RISLEY, PRUDENCE RESD. COLLEGE	96,336	6,009	1,801	563
1028E	EMERSON HALL	56,976	5,923	2,900	686
2631	BARTELS HALL	151,900	5,771	1,695	530
3033	HANS BETHE HOUSE	142,901	5,757	5,200	626
3034	WILLIAM T. KEETON HOUSE	136,522	5,629	2,026	633
2007	OLIVE TJADEN HALL	50,567	5,517	2,400	589
2611	TEAGLE HALL	78,520	5,067	1,591	497
3004N	BAKER NORTH	18,918	4,812	1,914	598
2602A	VISITING TEAM FACILITY	8,349	4,778	1,590	497
3201	GEORGE JAMESON HALL	65,999	4,739	1,408	440
3031	ALICE H. COOK HOUSE	78,438	4,602	1,410	441
3001	CASCADILLA HALL	98,624	4,593	1,411	441
2085	WILSON SYNCHROTRON LAB & RING	125,434	4,274	2,500	501
1045A	KENNETH POST LAB	9,552	4,253	1,405	439
3035	FLORA ROSE HOUSE				

		83,141	4,198	1,636	511
2014	ROCKEFELLER HALL	124,529	3,990	2,273	710
2049	SNEE HALL GEOLOGICAL SCIENCE	74,599	3,953	1,600	500
2004	SIBLEY HALL	87,612	3,947	1,181	369
2032	SAVAGE HALL	33,695	3,929	2,000	624
2023	HUMPHREYS SERVICE BLDG	74,922	3,759	1,116	349
2010	URIS LIBRARY	99,024	3,666	1,600	351
1163	VET EDUCATION CENTER	34,875	3,649	1,200	449
2613	LYNAH RINK	68,693	3,590	1,708	534
2026	DAY HALL	87,977	3,557	1,186	371
2081	MALOTT HALL	84,615	3,544	1,440	457
3028	HUGHES HALL	62,324	3,472	1,245	389
2704	GANNETT HEALTH SERVICES	38,478	3,468	1,127	352
2029	NEWMAN, FLOYD D. LABORATORY	52,201	3,312	1,147	359
2047A	KROCH,CARL A LIBRARY	99,541	3,210	630	570
3002	SAGE HALL	150,716	3,178	2,100	285
1042W	WING HALL WING	33,148	2,928	1,200	281
3011	LYON HALL	21,168	2,893	1,129	353
3204	ROBERT J & HELEN APPEL COMMONS	62,197	2,868	1,031	322
2002	WHITE HALL	42,755	2,838	831	260
1162A	POULTRY LARGE	19,387	2,754	1,041	325
3007	ANNA COMSTOCK HOUSE	20,291	2,652	894	279
1063	FOOD SCIENCE LAB	39,053	2,646	951	297
1042A	WING HALL	27,963	2,583	1,000	396

1041	STOCKING HALL	93,508	2,554	1,140	356
2638	FRIEDMAN WRESTLING CENTER	16,351	2,422	968	303
2013	GOLDWIN SMITH HALL	127,046	2,399	883	276
1148	ANIMAL HEALTH DIAGNOSTIC CENTER	20,889	2,303	789	246
1007E	DOLGEN HALL	13,281	2,256	900	253
2038	ANABEL TAYLOR HALL	53,194	2,211	741	232
1015W	M VAN RENSSELAER WEST	40,719	2,157	842	263
2616	HELEN NEWMAN HALL	65,849	2,103	612	191
2042	CARPENTER HALL	50,577	2,033	582	262
3090	SHELDON COURT	48,881	1,997	645	202
2001	MORRILL HALL	40,611	1,986	660	283
2017	RAND HALL	30,732	1,916	486	152
2003	MCGRAW HALL	59,343	1,856	760	182
2011	STIMSON HALL	61,439	1,806	594	186
1150G	WASTE MANAGEMENT FACILITY	4,200	1,795	524	164
3010B	MAPLE AVE 120	40,771	1,732	534	167
1024	BAILEY HALL	47,431	1,574	900	134
1016	COMPUTING & COMMUNICATIONS CTR	60,100	1,467	532	166
1025	CALDWELL HALL	31,316	1,459	490	153
1084B	LRG ANIMAL RES. TEACHING UNIT	8,256	1,377	440	138
4777	MARYANN WD 120, PHI KAPPA PSI	24,103	1,365	496	155
1043	LIVESTOCK PAVILION	14,360	1,342	646	202
4747	FOREST PARK LANE 1, SIGMA PHI	19,876	1,315	457	143
3005	FOUNDERS HALL				

		19,984	1,314	404	126
3006H	BOLDT HALL	16,448	1,307	463	145
4741	FOREST PARK LA 2,PSI UPSILON	23,120	1,295	547	171
2061	WARD CENTER FOR NUCLEAR STDIES	26,030	1,252	489	153
3012	MCFADDIN HALL	23,081	1,241	399	125
2005	SAGE CHAPEL	22,201	1,238	374	117
4776	MARYANN WD 104,DELTA TAU DELTA	18,277	1,235	363	114
2009	BARNES HALL	21,618	1,115	431	135
3036	NOYES COMMUNITY AND REC CENTER	28,760	1,091	370	116
1023H	TOWER RD WEST PURPLE GH 1023H	10,150	1,076	367	115
1003	IVES HALL FACULTY WING	55,260	1,013	357	97
3802	PAUL MILSTEIN HALL	52,675	915	840	77
2610	GRUMMAN SQUASH COURTS	17,104	890	350	109
2015	FOUNDRY	11,127	788	252	79
1029	FERNOW HALL	29,501	763	402	126
2006	A D WHITE HOUSE	23,232	755	218	68
2631A	FRIEDMAN STRENGTH & CONDTN CTR	11,265	691	342	107
1026	WARREN HALL	128,355	684	1,032	323
2040	BIG RED BARN	4,773	681	156	49
1040	RICE HALL	31,415	668	790	247
2088	THE CORNELL STORE	37,165	645	340	55
3016	PDC SHOPS ANNEX	8,760	630	263	82
3004S	BAKER SOUTH	18,945	613	120	78
4767	THURSTON AVE 626	8,770	383	122	38

2080C	MAPLE AVE PIPE/WELDING SHOP	4,688	366	117	37
3126	NOYES LODGE - BEEBE LAKE	9,111	337	170	55
1070	BRUCKNER LAB	18,053	260	150	31
1047	CALS SURGE FACILITY	9,283	213	63	20
2080B	E ITHACA ENVIRONMENTAL HEALTH	4,895	141	55	17
3004T	BAKER TOWER	31,355	114	35	12
1162B	LARGE ANIMAL ISOLATION	3,925	89	40	8
1023A	TOWER RD WEST PURPLE CNS 1023A	3,773	5	427	134