Understanding the Water-Energy Nexus: 
A Princeton University Case Study

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LIST OF ABBREVIATIONS

BAU – business as usual
Btu – British thermal unit
CCF – 100 ft²
CHW – chilled water
DT – dekatherm
EUI – energy use index
Ft – feet
FY – fiscal year
Gal – gallon
HP – horsepower
HRSG – heat recovery steam generator
HVAC – heating, ventilation, and air-conditioning
KWh – Kilowatt-hour
Lb. – pounds
LED – light-emitting diode
MWh – megawatt hours
NJAW – New Jersey American Water
PSEG – Public Service Electric and Gas (of New Jersey)
PSOC – Princeton Sewer Operating Committee
PV – photovoltaic
Sfft – ft²
STM – steam
TES – thermal energy storage
ThGal – thousand gallons
ULSD – #2 ultra-low sulfur diesel
WEFN – water-energy-food network
WEN – water-energy nexus
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I. ABSTRACT

The water-energy nexus is composed of areas in which water and energy use intersect. In order to more fully understand the this nexus, first the water, then the energy sectors are looked at as individual entities, followed by a more thorough examination of the overlap. While the objective of this thesis is to understand the water-energy nexus more broadly, much of the data and analytical work is conducted on the Princeton University campus in order to provide a consistent and easily comprehensible medium about which to study the nexus. It was found that while the embedded energy in water supply is overall insignificant in comparison to the total campus energy demand, the embedded water in campus energy is a significant portion of the total campus water. Decreasing the campus chilled water demand can best reduce both embedded and total water. It was shown that a reduction of campus chilled water demand to 60% of current supply, which amounts to an overall campus energy demand reduction to 89%, can reduce the total campus water (which includes campus water demand and embedded water) by 7%. Overall, reductions in campus energy are shown to be the most significant in increasing campus sustainability and conservation. Using this, and knowledge obtained from potential future research, Princeton University can make more informed and effective decisions in regards to reducing campus water and energy usages.
II. INTRODUCTION

After conducting research on community water and energy consumption, it is evident that in order to most effectively understand a system’s water and/or energy usage, the two should more regularly be studied in conjunction. Howells and Rogner (2014) have noted the common technique of separating such sectors in order to more easily understand the individual roles that either water or energy may play in a societal system, but they have also recognized the need for an overlap between the two. They highlight that due to the increase of these “sectorial interdependencies,” it has become more and more important that the shift from independent study to a greater focus on these overlaps occur. This intersection of water and energy is known as the water-energy nexus, and it is increasingly becoming a more popular topic of study. Researching the water-energy nexus recognizes that there is more to providing water or energy to a system than merely the end product supplied. There is water used behind the energy supply, and similarly, there is energy required to provide water. This overlap provides the basis for this project, and a better understanding of the coupled system will ultimately lead to the strongest and most effective look at how to improve both energy and water provision to small-to-midsize communities, such as the Princeton University campus that is the focus of this study.
The water-energy nexus is composed of the locations where water use and energy use overlap, and this paper looks not only to understand this overlap in general, but also to see how the two interact for Princeton specifically. The main objective of this project is to examine the water-energy nexus and its significance in understanding both water and energy usage separately, as well as the two together. To do so, the topic is studied at first more broadly, then analyzed with data from the Princeton University campus as a case study. In addition, this paper looks at various means of reducing the water and energy usages on campus. The topic of the water-energy nexus is a highly studied one; Princeton has offered entire courses on the topic and has conducted significant amounts of research to both water and energy usages, as well as their intersection. It is the hope that this campus-specific case study will provide a clearer picture of what occurs on campus in the present and how to proceed in the future.

In a 2003 article in the Annual Review of Environmental Resources, upon investigation of how water is used in general, it was found that “[a] substantial fraction of total water withdrawals in some industrialized nations is used for the production of energy, either directly in hydroelectric plants or indirectly for power plant cooling.” Additionally, it was found that this value is at 47% in the United States as opposed to 32% in Europe (Gleick 2003). This significant difference in usage percentages highlights the need for the United States as a
whole to investigate further why their average percentage of water use in this particular sector is so much higher than that of Europe. What are they doing differently that is causing this large difference?

Gleick (2003) notes the scarcity of substantial data collection on actual water use, emphasizing the need for increased research and more systematic data collection. Although it has been over ten years since the publication of this article and studies of direct water use have increased, it is still a less established area of interest relative to principle topics of concern in water studies, including implementing new technologies and conservation programs to meet growing demand, assuring the reliability of water supplies, and enhancing water quality. Additionally, estimations of direct water usage can often show inaccuracies due to the inability to properly quantify yearly supply and flow rates; however, with an analysis framework intertwined with the energy usage and output sector, it is possible to obtain more reliable results pertaining to water usages (Gleick 2003). Looking at other future-predicting studies not only offers further insight into the scope and accuracy of this work compilation, but it will also assist in this increased knowledge pool. A more comprehensive understanding of the water-energy nexus is vital in providing fundamental principles, values, and objectives for a future mindset and analyses that apply to a broad range of locations and scenarios.
To develop a more refined and distinct quantitative perspective on the water-energy nexus, Princeton University is then used as a case study. The first step in understanding the water-energy nexus on campus is to look at what Princeton is currently doing in the water and energy sectors separately. Because this paper looks at the campus water-energy nexus in particular, it intends to show how change or improvement in either the water or the energy sector will affect the other. Similar objectives are found in the work of Bartos and Chester (2014), who created a model to simulate and showcase water-energy interactions within the entire state of Arizona as a system. While the location of their background research and study are significantly different both size wise and geographically than that of the Princeton campus, with different major inputs and outputs, there are similar trends in that energy use requires a significant amount of water, and similarly, water supply produces an energy demand.

For example, Arizona is a large energy exporter, which significantly affects the proportions of where energy supply and demand trends lie in a way different than Princeton will face. However, the overall concept of analyzing these sectors first separately, and then together, applies (Bartos and Chester 2014). Thus, analyzing this work conducted by Bartos and Chester is highly applicable to that of the intended discoveries about Princeton and will help to put the Princeton water-energy nexus findings into a broader perspective.
In addition to representing the current water-energy nexus on Princeton’s campus, the basic model created provides insight onto the effectiveness of potential future changes throughout the campus. As Bartos and Chester (2014) note in their proposal looking forward for future application of their model, they aim to “estimate the cobenefits of future water-energy conservation strategies” with the nexus analysis. Similarly, the effectiveness of a nexus-based analysis and means of reformation are discussed in later sections of this paper. While the model presented does not account for how, specifically, reductions are made, it shows the potential for the significance in impact that can occur. In the discussion however, proposals are made for how to meet these reductions.

The Bartos and Chester (2014) model is composed first of an infrastructure model to represent the Arizona state system, then by a cost-optimization model is added to look at the potential cost savings associated with various resource allocation and reduction strategies. Not only are direct water and energy reductions noted with water or energy-reducing technologies, respectively, but indirect energy and water savings are determined as well. The study found that while these indirect savings of either water or energy by reducing energy or water, respectively, are not the most significant means of reducing the particular resource, that these reductions are still significant. It is also possible that the savings outside of Arizona may differ; just as the inputs
vary to a degree based on location and particular scenario, so will the amount of savings possible and actually achieved. Similarly to how Bartos and Chester analyze system alternatives with the hopes of overall cost reduction, this present analysis looks at various potential system changes with the hopes of resource reduction, as well as more generally to provide more insight into logical future options for the Princeton University management teams to select.

It is intended that this work regarding the water-energy nexus can be of help to this research and aid in further analysis of the system. It begins by looking at what Princeton does now, pertaining both generally to water and energy systems, as well as specifically at the nexus. Using the data provided by previously conducted research, the nexus in particular is analyzed and suggestions are made as to where effective improvements could be made. After establishing these points of most intense nexus presence, it looks both to pitch areas for potential improvement as well as to help with current campus research looking at ways of improving its own efficiency.

In addition to using the campus data provided by Princeton University’s Energy Plant Manager Ted Borer and Environmental Compliance Manager Bob Ortego, this research looks to contextualize within the generalized research on the water-energy nexus and how the Princeton analyses pertain to other locations. As such, the direct model results presented are broad; in the discussion a further
analysis of the Princeton campus and then means of achieving these desired reductions are more specifically proposed. It looks at other locations and uses this information to create more of an extrapolation as to how the campus water-energy nexus is affected, rather than using concrete data from other locations to understand how Princeton is affected by its water and energy usages. Information pertaining to future technological implementations is applied and interpreted from research about the various options. The implementation of these systems can only be projected with assumptions made to the best knowledge of those researching the Princeton campus system.

As a means of further use for this Princeton-specific case study research, it is the hope to take this information back again to a more broad-scale view on the water-energy nexus. While the particular model inputs used pertain directly to Princeton’s water-energy system, it is intended that the results and analysis are useful in gaining additional insight on the general. Specific output values will be directly useful only to the Princeton network, but understanding data trends and resulting overall effects should prove helpful in this broader sense of understanding. Similar to how the basis for previously implemented modeling techniques (such as in Bartos and Chester 2014) in improving a general and system-specific knowledge base, the work that this thesis will eventually encompass is ideally also able to provide similar information to others.
III. RESEARCH METHODS

In order to understand campus energy use, both the amount of energy the campus uses and where the University is using most of the energy are examined. This information is then tied back to the amount of water required to supply these large energy demands. Similarly, the overall water usage on campus is examined, in particular where the most water is being used, and is then correlated back to the water use and its required energy inputs.

Members of the Princeton University staff have provided the majority of the datasets required for campus energy and water analysis. Ted Borer, the campus energy plant manager, has been an integral member in providing the data required to conduct this research. His summarizing PowerPoint presentation includes general statistics for overall campus energy usage, as well as how it pertains to water usage in the campus power plant, and the spreadsheets used to create his presentation were key input sources to this research.

A. Princeton University campus background

The Princeton University campus is located in Princeton, New Jersey, and spans over 500 acres in total. For the purposes of this research, only the main campus area is examined, which is limited by boundaries of Nassau and Faculty Roads as the north and south edges, and University Place/Alexander Road (aside from
Forbes College) and Fitzrandolph Road as the west and east boundaries respectively. Limiting the scope of area investigated to this portion of campus excludes components such as the Graduate College, Forrestal campus, and administrative buildings on Nassau St, but this area focus allows for a more useful and manageable analysis. In the spring of 2015, the University had just over 1200 faculty and staff members and just under 8,000 students enrolled. With over 9,000 people regularly active on campus, there is understandably a large demand for both water and energy.

**Figure 1. Map of Princeton University campus scope area.**

**B. Campus Inputs: Water**

The Princeton University campus uses around 282 million gallons of water per year (MGY). 91% of this supply is currently met by New Jersey American Water (NJAW), while the remaining demand is met by Princeton’s own on-campus well (Borer 52). In order to meet regulations and aid in tracking campus water
usage, meters are installed across the campus. Meters are read in units of 100 cubic feet (CCF), but for analysis the obtained datasets and throughout this thesis, calculations are completed all in gallons, specifically in thousands of gallons (ThGal) for consistency (see Appendix for conversion).

The remaining 9% of the campus water comes from the Princeton University well, located on campus just north of Faculty Rd and west of Elm Dr. A 20HP pump at 147 ft. below the ground pumps the well, and the pump has a maximum pumping flow rate of 165 gal/min. In order to determine the embedded energy for the well water, it was assumed that the well was pumping at its maximum flow rate at a full 20HP. However, because the efficiency of the pump is estimated at 72%, the actual value used for calculation is a pump with HP = 27.7 (Grundfos). If the pump were to run continuously at maximum pumping rate, it could in theory supply a maximum of 86,783 ThGal to the campus. This maximum amount of possible well water supply is used as a constraint in the water-energy nexus model as explained in section IV of this paper, but in reality there are currently policy limits as to how much water the campus can pump at a time. According to Energy Plant Manager, Ted Borer, the campus is not allowed to pump more than 30 MGY from the well, with no month’s extraction exceeding 5 MG. While this analysis does not include these
limited imposed by policy, they are constraints that would need to be addressed before the well could be utilized for more water than 30 MGY.

C. **Embedded energy in campus water supply**

Embedded energy within the campus supply is composed of the energy that is associated with the water supply. This value represents the amount of energy required to deliver an amount of water from source to customer. That is, in the case of water delivery, NJAW has a regionally determined Energy Use Index, or EUI averaged over its area of water supply. An annual Energy Use Intensity (EUI) is a value indicative or the overall energy use intensity of the building, with a lower value correlating to a building with lower use intensity, and a similar calculation can be used for water supply. With an EUI = 2.89, the NJAW water is embedded with 2.89 MWh for every MG supplied. By multiplying the campus water supply by the water EUI, the total yearly MWh embedded for delivery is determined, and it is calculated that this amounts to 738.73MWh. This value of 2.89 MWh/MG is verified as a feasible value for the embedded energy of the water supply by calculating the cost of electricity supply for the NJAW Company to determine its relative cost in relation to the cost at which Princeton buys water, and these calculations are shown in the Appendix section in this paper.
Additional energy considered to be embedded in the NJAW water use is that required for wastewater treatment. Because the water sent to the wastewater treatment plant was from the Princeton campus, this energy must be considered part of the embedded amount for this supply to campus. Domestic and sanitary water, which currently make up around 62% of the campus water demand, are sent to the Princeton Sewer Operating Committee (PSOC) for treatment. The value of energy from the PSOC treatment is calculated with an embedded energy value of 2.85 MWh/MG water treated, as estimated from Table 2.3 of the 2014 EPA water-energy nexus report. The table reports the kWh/MG for the energy intensity of wastewater treatment in California with both lower and upper estimates, and these bounds for wastewater treatment and distribution are averaged in order to find a value for the model calculations, as well as converted to MWh/MG. As indicated, this estimated energy intensity for wastewater treatment (2.85 MWh/MG water treated) is very similar to the NJAW value for supplied water (2.89 MWh/MG).

To deliver water by the campus well, it must be pumped up from the source aquifer to ground level before it is distributed. The well pump is located 147 ft. below the ground and has a horsepower rating of 20HP, and a maximum flow rate of the pump is 165 gallons per minute (gpm). At a rate of 165 gpm, the pump would need to pump for a total of 2,679 hr. per year to meet the current
demand. With an efficiency of 72%, pumping the 20HP pump equates to the equivalent of pumping a 27.7HP pump at 100% efficiency. Pumping this horsepower of pump for this amount of time amounts to a total energy amount of 55.43 MWh. Thus, to supply 26.52MG of water with a needed energy amount, the embedded energy in this water supply can be estimated at 2.09 MWh/MG (see Appendix for explicit calculation).

A smaller EUI value for the well water (in this case, approximately 30 percent less than the NJAW supply) means that there is less embedded energy in the supply by gallon, meaning that it is less energy intensive to deliver well water to campus than it is to deliver NJAW water. In order to determine the maximum possible amount of energy required to run the pump as a constraint for the maximum possible volume of water that could be supplied from the pump, calculations were done with the pump running continuously. It is important to note that performing calculations using the maximum pumping rate and horsepower of the pump could be made more accurate by running well pump tests to determine what the actual pump flow rate and power usages are. However, these values still provide a sufficient estimate for this study.
<table>
<thead>
<tr>
<th>Source of embedded energy</th>
<th>Quantity [ThGal]</th>
<th>Percentage of campus water input [%]</th>
<th>EUI [MWh/MG]</th>
<th>Embedded energy [MWh]</th>
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<tr>
<td>NJAW delivery</td>
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<td>2.89</td>
<td>738.73</td>
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<td>Total</td>
<td>282,137</td>
<td></td>
<td></td>
<td>1310.24</td>
</tr>
</tbody>
</table>

*Table 1. Summary of campus water inputs and their embedded energy for FY 2011.*

### D. Campus Inputs: Energy

There are five current energy inputs to Princeton’s campus: Solar photovoltaic (PV) electricity, Public Service Electric and Gas (PSEG) grid electricity, natural gas, #2 ultra-low sulfur diesel (ULSD), and biodiesel.

Solar PV panel energy is captured and supplied to the campus as electricity from a 27-acre solar field located about three miles from Princeton’s main campus. It was estimated upon its installation that the Princeton solar panel field could provide around 8,000 MWh yearly to campus, but this value was since been surpassed (Solar Collector Field (2012)). There is a physical limitation as to how much solar energy can be provided to campus based on the size of the field and the amount of sunlight during the year. A limit of 11,500 MWh yearly was decided upon as a limit for the maximum electricity able to be provided by the solar field after reviewing the standard amount of electricity provided by the field in previous years, but this number could potentially be an
over or underestimate of its actual capacities. With this limit imposed, the solar 
PV panels have the potential to provide nearly 10% of the current campus 
electricity demand.

Additional electricity is bought locally from PSEG electric company at a 
rate of about 71,000 MWh yearly. The process through which and analysis that 
precedes the purchase of electricity is straightforward in concept, but in practice 
requires a great deal of knowledge about electricity use patterns. Princeton will 
buy electricity from PSEG when it is cheap to do so, and when it is not 
advantageous, will use its own (electricity produced by cogeneration system). On 
the other hand, when it is more advantageous for Princeton to sell its own 
electricity back to the grid, it does this instead. The values used in this analysis 
are over the span of an entire year, so the total net PSEG electricity sent to 
campus during that period of time is used, rather than day-by-day usage data. 
While significant seasonal and daily variations do occur (e.g., due to increased 
load for plug in air conditioning on hot days in the summer), the long-term 
average usage rate used in this analysis allows for an adequate representation of 
the campus electricity needs.

Natural gas is the main fuel burned in the power plant, and it is used 
specifically in the campus cogeneration (cogen) system. The cogen system 
produces steam and electricity, both of which are sent directly to campus, as well
as to the chilled water system in order to produce chilled water (steam is used to run the compressor used in the chilled water system). The campus has an agreement with its local natural gas supply that when the gas company is reaching its maximum supplying capacity with other users, the University will stop using natural gas upon the utility's request. It is during this time that the campus switches to #2 ultra-low sulfur diesel fuel oil (ULSD). This type of occurrence is usually on the coldest days of the year when demand external to the Princeton campus is at its highest. Having this agreement with the utility company allows Princeton to get their natural gas supply at a significantly cheaper rate during the rest of the year due to their willingness to cease use upon the supplier’s request.

The diesel fuel oil used for burning is #2 ultra-low sulfur diesel (ULSD), and is required to meet stringent standards in order to be considered clean enough to be burned in the campus cogen system. Diesel is only used on the coldest days of the year when the campus is not burning natural gas due to its agreement with campus gas suppliers. Currently, ULSD is stored in barrels underground on campus near the power plant, awaiting the times when the University needs to use it.

Biodiesel fuel oil is not currently used in the Princeton University power plant, although the plant is equipped to use it as a fuel input. In 2008 the
University conducted testing using biodiesel to determine how it worked with the campus diesel engine. The University has the permitting documents required to use biodiesel as a fuel input from this year of testing; however, if there were to be a return to using biodiesel, there would be some additional paperwork required. Due to the lifespan of biodiesel, it cannot survive for more than around six months without being burned. That being said, the campus would not have to rely upon biodiesel all of the time but could simply burn biodiesel downwards of 10% of the time in order to use it regularly enough for supply to receive continued use. The values pertaining to biodiesel in this paper are from the 2014 EPA water-energy nexus report and pertain to ethanol biodiesel, because this is the most popularly used type of biodiesel in the United States, and if the University were to switch to using biodiesel in place of ULSD, it would likely be ethanol.

E. Embedded water in campus energy inputs

Just as there is energy embedded in providing the campus water supply, there is water embedded in the campus energy supply. A significant portion of the water to be considered as embedded in the energy supply is that of the water delivered to the campus power plant. Currently, the campus power plant uses over one third of the campus water supply, so it is clear that there is a significant portion of the campus water that aids in producing electricity, steam, and chilled water in
order to meet these campus demands. Additionally, each energy input has its own value for embedded water in order to generate and transmit the energy resource to Princeton’s campus where it is used.

Solar PV electricity supply does not, for this assessment, contain any embedded water. If there were to be a thorough life cycle assessment of solar energy it is likely that there would be water required in the making of the solar panels, but this is in the formation process of the physical panel itself and is not part of the energy this study aims to investigate.

The embedded water in grid electricity is due to its formation from natural gas. Similar to how Princeton University generates electricity through the combustion of natural gas, the electricity supplied through PSEG to campus is also formed through natural gas combustion. There are additional ways of forming electricity, and the embedded water value will vary based on these methods. Because the electricity that is supplied to Princeton from PSEG is mostly formed from the burning of natural gas, the value for supplying energy from natural gas is used in the following calculations, which amounts to an embedded water rate of 0.1Tgal/MWh for PSEG electricity supply.

The extraction of natural gas through hydraulic fracking requires the pumping of water into the ground to release the gas. From the EPA 2014 WEN report, the data used shows a yearly nationwide usage of 25 quadrillion Btu of
natural gas yearly, and a rate of 0.2 billion gallons of water required to yield this supply. Converted to the units used in this study, it is estimated that it requires 9.97 gallons of water in order to supply each MWh of energy from natural gas. This value is rounded to 10 gallons per each MWh of energy, or .01 ThGal/MWh for the purpose of this analysis.

#2 ULSD fuel oil is collected through extraction from the ground, and this process often requires water through the method of hydraulic fracturing and extraction. As of 2010, the EPA requires ULSD to contain a maximum of 15-ppm sulfur in the fuel, a mandate that reduces the environmental effects upon use of the fuel (Cummins Power Generation). Using the value of embedded water in diesel from the 2014 EPA report converted to ThGal/MWh, #2 ULSD has an embedded water value of 0.124 ThGal/MWh.

The value used for the amount of embedded water in a potential campus biodiesel supply is determined from values reported in the 2014 EPA water-energy nexus report for bioethanol. Consumption factors are reported for four different main regions of the country and their relative average consumption factors are determined in order to find an average consumption value. Using the fractions of corn ethanol produced from each region, the converted consumption factors of each region, and a conversion from gallons of fuel to MWh, the average consumption, weighted by the relative supply, in gallons of water per MWh
energy delivered is found. The results are summed to find a total average consumption value. Values for each region are presented in Table 2. From this computation, an average value of 1.177 ThGal/MWh water was determined for biodiesel.

Table 3 summarizes the business as usual (BAU) campus energy inputs, the fraction of total input that each energy type is, the embedded water factor, and total current embedded water, for each campus energy source.

<table>
<thead>
<tr>
<th>Region</th>
<th>Fraction of corn ethanol production</th>
<th>Consumption factor [ThGal H₂O/gal ethanol]</th>
<th>Consumption factor [ThGal H₂O/MWh]</th>
<th>Average consumption [ThGalH₂O/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.5</td>
<td>11</td>
<td>288.72</td>
<td>0.1444</td>
</tr>
<tr>
<td>6</td>
<td>0.15</td>
<td>17</td>
<td>446.21</td>
<td>0.0669</td>
</tr>
<tr>
<td>7</td>
<td>0.23</td>
<td>160</td>
<td>4199.59</td>
<td>0.9659</td>
</tr>
<tr>
<td>Other</td>
<td>0.12</td>
<td>45</td>
<td>1181.13</td>
<td>0.1417</td>
</tr>
</tbody>
</table>

Table 2. Average water consumptions for ethanol biodiesel supply. Regions refer to USDA farm production regions, with states listed explicitly in the Appendix section of this paper (Bauer et al. 2014).

<table>
<thead>
<tr>
<th>Source of embedded water</th>
<th>Quantity [MWh]</th>
<th>Fraction of campus energy input</th>
<th>Embedded water [ThGal/MWh]</th>
<th>Total embedded water [ThGal]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV electricity</td>
<td>11,276</td>
<td>0.0213</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PSEG electricity</td>
<td>70,621</td>
<td>0.1335</td>
<td>0.01</td>
<td>706.21</td>
</tr>
<tr>
<td>Natural gas</td>
<td>392,727</td>
<td>0.7422</td>
<td>0.01</td>
<td>3927.27</td>
</tr>
<tr>
<td>#2 ULSD</td>
<td>54,540</td>
<td>0.1031</td>
<td>0.124</td>
<td>6762.96</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>0</td>
<td>0.0000</td>
<td>1.177</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>529,164</td>
<td></td>
<td></td>
<td>11,396</td>
</tr>
</tbody>
</table>

Table 3. Summary of campus energy inputs and embedded water values for FY 2014.
F. Campus demands: Water

Projected campus water demands are broken down into domestic/sanitary uses, Utilities/HVAC (Heating, ventilation, and air-conditioning), and irrigation. Included in the domestic/sanitary sectors are processes such as supplying toilet water, running showers, and supplying water for faucets. The utilities/HVAC sector encompasses all water that is used in the campus power plant to create chilled water, steam, and electricity. The water accounted for the steam and chilled water loops is only that which is lost during the process of campus heating and cooling. The water circulating around campus is part of a closed loop system, meaning that the water is actually recirculated throughout the campus in its delivery and use and is not the water that is being lost. The water lost in this process from providing and capturing heat is from a completely separate water source, and this is where the significant losses occur, which are captured in these values. The irrigation sector encompasses the water used for watering both natural and artificial grass surfaces and foliage across campus, including both general areas and athletic facilities.
1. **Power plant water usage**

The campus power plant uses about 97 million gallons of water per year, which is around 34% of the total campus water demand (Borer 52). As a clearly significant sector in the campus water usage, a better understanding of the means to supplying Princeton’s energy will provide important insight about campus water usage, energy usage, and the nexus in which the power plant lies. The majority of the water used in the power plant is for the main cooling tower for a process in which rejected hot water is placed until it is cool enough to go through the chiller and then either stored in the thermal storage tank (TES) or distributed throughout the campus. Of this 34% of the campus’s water use is for the campus power plant; the main user in the power plant is the cooling tower, which currently uses nearly half (47%) of the water consumed at the power plant (Borer 52).
Power plant water demands are affected additionally by time of year. Figure 4 shows the difference in monthly water demands within the power plant for year 2011. It is evident by this monthly distribution graph that the stark changes in the energy plant water usages is due to a large increase in the main cooling tower water usage. During the winter months the main cooling tower uses an average of 20,000 gal/day, whereas in the summer it can use over 400,000 gal/day. This drastic increase in water usage is due to the increased usage of air conditioning throughout the campus. Chilled water is supplied at a much higher rate in the summer months in order to cool buildings in comparison to in the winter, which leads to a much higher turnover rate of water flowing through and the water evaporated in the cooling tower as a result. With the continuous addition of buildings to campus and these additions now always including air-conditioned spaces, the required amount of chilled water supply also increases. Most of the older buildings on campus are either without chilled
water air-condition or are retrofitted with individual air conditioning units, which then are reported as an increase to the building electricity demand.

![Chart showing monthly water usages](image)

**Figure 4.** 2011 Power plant monthly water usages (Borer). CoGen Nox = cogen pollution control, CoGen Boiler = water to boilers, Chilled water makeup = well water to replace lost CHW through evaporation of loop water, main cooling tower makeup = water replaced from evaporative cooling of cooling tower, TES makeup (city and well) = water replaced from TES tank evaporative losses.

Figures 5 and 6 show the relationship between outdoor air temperature and the resulting net daily energy produced for Princeton’s campus. Energy demands were normalized by campus square footage for the year of analysis in order to allow for a fair comparison with a campus increase in size. Normalizing removes a potential skew in data, because naturally a larger campus would cause an increase in energy demand. Thus, in accounting for square footage, it can be determined if demand rate by square footage has increased or decreased. Additionally, by normalizing by square footage, this trend can be used to project future increases in demand, as well as demands as a function of outdoor
temperature, without data being skewed by an increase in campus building square footage. Figure 5 presents all energy as an absolute value, while in figure 6 the heat removal for chilled water is reported as a negative value.

It is evident that the amount of energy sent to campus for heating and cooling is directly correlated to the outdoor air temperature. The linear relationship of the net heating added to campus, as shown in Figure 6, allows for an accurate prediction of the amount of energy sent to campus; the lower the outdoor air temperature, the more energy addition required, due to a need to heat buildings across campus. However, upon reaching a temperature of around 60 degrees F, the amount of energy required for campus building temperature regulation increases once again due to an increase in campus cooling. The cooling of campus with chilled water is represented as a heat removal from campus, so the value is reported here as negative. It may initially be confusing that the value is reported as negative, because the removal of this heat does still require an addition of energy. This information is useful both now in the understanding of relationships driving campus usages, and it will also prove quite useful for future numerically modeling in order to predict campus usages in the years to come.
Figure 5. Total daily energy exchange on campus, normalized by campus building square footage.

Figure 6. Net daily energy sent to campus as a function of outdoor air temperature. Note that a negative heat supply refers to the removal of heat from buildings through chilled water cooling.
G. Campus Demands: Energy

The Princeton University power plant is located next to MacMillan Hall in the Southern corner of campus. Princeton University is supplied by a number of fuel sources, including both energy brought to and created on campus. Figure 7 provides a visual diagram of the fuel inputs and resulting outputs of the campus power plant. Electricity, natural gas, #2 diesel fuel oil, and biodiesel fuel oil are used in order to create electricity, steam, and chilled water for campus distribution. Electricity is used for processes such as running lights, operating campus door locks, and powering appliances, while steam is used to heat buildings on campus, and the chilled water system is used to cool buildings on campus. Various members of the Princeton faculty and staff, including energy plant manager, Ted Borer, conduct continued assessment of campus energy usages and efficiencies. Figures 8, 9, and 11 highlight the trends of campus chilled water, steam, and electricity use from fiscal years 1990 through 2015, and each energy output type is discussed in the subsequent sections of 2.3. These three figures are all plotted with the same axis scales, so they can be directly compared to gain a sense of the relative amounts of each energy type supplied to campus, as well as the relative square footage of campus being supplied with each energy type.
Figure 7. Simplified visual diagram of campus energy network (Borer 5). HRSG = heat recovery steam generator. Cogen system is composted of gas turbine, HRSG, auxiliary boilers, and backpressure turbines.

1. **Chilled water**

The chilled water (CHW) system requires inputs of electricity and steam created from the cogen facility, which are then used within the system to run the compressors and pumps to create the chilled water sent to campus in order to provide cooling. Over the past 26 years the building area square footage supplied with chilled water has increased by about two million ft$^2$, with half of this increase having occurred since only 2004. The current chilled water demand is about 100,000 MWh of chilled water, around twice that of fiscal year 1990; however, the peak load reached was during fiscal year 2004 when the campus reached a demand of around 130,000 MWh for the year. A decrease in chilled water demand with a continued increase is supplied square footage is a sign of increased efficiency during campus expansion.
Of the 96M gallons per year (GPY) currently delivered to the power plant, about 45.4M GPY of it is for the chilled water system. Of this 45.4M GPY, the water is delivered to two main parts: the chilled water makeup which is a supply of water that must be added each year due to losses within the system, and the main cooling tower, which is water evaporated to cool the warm water returning from campus after extracting heat when cooling buildings. The cooling tower is the clear highest user of water within both the CHW system itself, and within the power plant as a whole. The cooling tower uses such a high amount of water, because the way it works is that the warm water returning from campus in a closed loop enters at the top of the tower, and then water from a separate supply is sprayed on the outer surfaces of the pipes to evaporate off the top of the tower and allow the water to cool. This evaporation is a significant water sink that drives the high required water supply.
2. **Steam**

Steam generated goes to one of two generalized locations: either out to campus for heating, or to the chilled water facility for the formation of chilled water. Currently, 84% of the steam generated by the cogen facility is delivered across campus to provide heating to buildings and the remaining 16% of the steam generated by the cogen facility goes into the chilled water system to make chilled water. In the past 26 years the campus steam supply area has increased significantly, from about 6.25 million square feet to nearly 8.5 million square feet. During this time period steam usage has also increased, although not as drastically as chilled water usage has increased, although similarly to the chilled water peak, the highest steam usage was at the beginning of the 21st century.
during fiscal year 2003. According to Energy Plant Manager Ted Borer, the reduction from this point can be attributed to increased efficiency in the campus chilled water plant and to campus-wide conservation efforts. The drastic increase in steam-supplied square footage accompanying the less significant increase in steam usage shows a normalized increase in efficiency, which ultimately drives down the building EUI.

![Delivered campus steam and supplied square footage from FY '88-'15](image)

**Figure 9.** Campus steam and total supplied square footage from 1988-2015 (Data from Ted Borer, based off of graphs from Borer PowerPoint).

Figure 10 shows the relative amounts of total steam flow from the cogen plant and where it then goes. It can be seen that while majority is delivered to campus, there is a steady, significant portion delivered to the chilled water system for the production of chilled water.
Electricity is used for a variety of processes on campus, such as providing lighting, powering computers and other electronics, powering air conditioners in locations without chilled water supply, and powering the well pump as analyzed in this study. Similarly to chilled water and steam campus square footage, campus electricity square footage has steadily increased from fiscal year 1990 to fiscal year 2015. As with the steady increase in supplied building square footage, the total electricity steadily increased until fiscal year 2011, after which the electricity usage has decreased by about 5,000 MWh each year. Overall, though, since 2006 the electricity consumption has been relatively steady, hovering around 140,000 MWh per year.
Upon direct comparison of Figures 8, 9, and 11, it is evident that energy supply in the form of steam is the largest of the three in terms of shear amount delivered to campus. It should be noted, however, that while the chilled water MWh delivered to campus is significantly less than that of the steam, the campus square footage supplied with chilled water is also significantly less. The square footage supplied with electricity is similar to that of the steam square footage, and this is logical because more or less all of the square footage on campus would require both heating and electricity, while there are many locations on campus where there is no cooling from chilled water supply.
H. Water-Energy nexus (WEN) Sankey diagram

The Sankey diagram was developed to visually track energy flows from their inputs to outputs within a system, and it has since been applied to other flow domains, such as water and material flows through a physical landscape or economic sectors. Figure 12 is a representative figure for the Sankey diagram created for the 2011 United States water-energy nexus. In this case the Sankey diagram is used not only to track energy usages, but water usages as well, particularly how the two intertwine from supply to demand throughout campus. Each input pathway can be tracked across the diagram in a quantified manner to each of the outputs it supplies, and the relative size of the links between the nodes indicates the magnitude of input and output is being represented. Reading from left to right the diagram shows how inputs travel throughout their usage network and become outputs. Water components are mapped in blue, while energy components are mapped in green.
1. **Princeton University WEN Sankey**

In the case of Princeton’s campus, the Sankey diagram showcasing the water and energy inputs to the Princeton University campus and where they travel in order to produce our water and energy outputs is presented in Figure 13. The campus has seven total inputs, including two water input types and five potential energy input types. The Sankey diagram representing the Princeton University campus is not as extensive as the nationwide diagram, because the analysis done on the campus was not an all-encompassing life-cycle assessment of campus water and energy, and instead the inputs to campus are treated as the beginning of where analysis begins.
To account for embedded energy and water in the water and energy supplies, respectively, current literature and company supply information were used as detailed in the previous section to determine these amounts. Additionally, many of the EPA Sankey diagram components are not included, because the encompassed system of analysis was simplified in order to allow for an adequate understanding and application to the campus without such a complexity that the general trends would be lost. The ultimate goal of this diagram and this analysis as a whole is to get a broader understanding of where the largest nexus spots on campus are and how future conservation efforts could provide significant reductions, rather than to scrutinize minute variations resulting from natural and often insignificant variations by year or reporting reliability. The simplifications made are thus in an effort to increase the clarity of the Princeton water-energy system by focusing on only that encompassed within the network on campus. For example, it is not necessary to scrutinize over the specific ways in which electricity from PSEG is formed, and instead an average value suffices in order to provide the essentials means for analysis.
Figure 13. Sankey diagram for Princeton University water-energy nexus. Water values are in thousand gallons [ThGal] and energy units are in megawatt hours [MWh] for ease of viewing relative scales.
IV. WATER-ENERGY NEXUS MODEL

There have been multiple papers on the topic of water-energy nexus modeling, as well as papers on similar types of modeling. For example, the material flow analysis modeling framework is a highly applicable way to effectively model a system such as the water-energy nexus. Ultimately, the Sankey diagram is used as a means of tracking where inputs go and how they turn to outputs, so these various means of tracing such materials and processes effectively captures just how they occur.

Using collected and analyzed data pertaining to the Princeton campus, a simple model is developed here to help predict campus usages for the future. These values are then used to calculate the specific amount of required energy supplied by the three energy types being delivered. By using the past data as the basis for model calibration, once the model meets the old data with an appropriate fit, then values for future years and scenarios can be simulated. Both the business as usual campus case and future technological updates on campus will be tested and results will be compared with a focus on the amount of water and energy reduction possible, as well as how the reduction of one affects the other.

There is an enormous amount of data available on the campus usages for both water and energy, but just as relevant literature has noted, it can be difficult
to formulate this information into a logical and useful compilation due to the methods by which each is tracked. The ways in which information is broken up varies, particularly when comparing water records to energy records. This difference is most significant in the campus power plant, where there is the most significant overlap between campus water and energy.

Water supply to parts of the power plant is reported for specific components of the plant, such as the main cooling tower replenishment and NOx control in the turbine (water is added at an equal mass ratio with fuel to provide NOx control when the engine is run), but for the ease of investigating the nexus, data are analyzed by each of the three main sections of the power plant: the cogen system, the chilled water system, and the thermal energy system. Similarly, the energy plant is best broken up into three more generalized sections: the cogen system, the chilled water system, and the thermal energy storage system. The cogen system is composed of a gas turbine, two heat recovery steam generators, and two auxiliary boilers, and these components are used to generate steam and electricity. The chilled water system is composed of both steam-driven and electric chillers to generate the chilled water for campus cooling. Finally, the thermal energy storage system is composed of a main storage tank that stores thermal energy for future usage in campus energy supply.
The analysis developed in this paper analyzes water and energy use on campus and their intersection, employing optimization methods to minimize the water and energy supplies to campus, including both direct and embedded resources in each resource’s case. The cvx package in Matlab is utilized in order to run convex optimization based on user-manipulated inputs for each of the campus demands in order to calculate the necessary inputs for all demands to be met.

Values for the Princeton specific water-energy nexus scenario were used in the creation of this code and in its running, but it can be applied to other grounds as well. It is a simplified linear representation of these processes, particularly those in the campus power plant, as it assumes that any demand reductions cause proportional reductions in the inputs responsible for each output, whereas in real life the processes are much more complicated in the transfer from oil and gas to electricity, steam, and chilled water. Ratios of inputs to outputs from current data were used to ensure that each component would reduce or increase proportionally.

The code presented here only optimizes to minimize the amount of the water and energy resources inputted to meet the campus demands, regardless of any other factors, such as cost or carbon footprint. It is thus important to recognize that the optimizations presented as best case scenarios with this study
may not actually be the most efficient scenarios when, in reality, many more of these additional constraints or factors would be included in making a more intelligent and informed decision.

This code was written so both types of inputs could be optimized. First, total water supplied to campus is minimized regardless of the energy requirements necessary to accomplish this. Next, the total energy supply to campus is minimized in a similar fashion; the water required to minimize embedded energy is not considered. Once these end-members campus scenarios were run, a scenario that minimizes both uses simultaneously with equal weights was investigated. Finally, the code was used in order to assess how campus inputs would be affected by both reduced demands and by increased efficiency within campus water and energy usage infrastructure.
V. **MODEL RESULTS**

In order to optimize either the total energy and/or total water for which Princeton is responsible, campus demands are inputted and thus serve as the values to be manipulated for further analysis. In this study total water refers to an overall amount of water for which the campus is responsible, which consists of both direct water to campus, as well as any embedded amount of water in the campus energy supply. Embedded water values include the water used to supply all of the energy inputs to campus, as well as the water sent to campus for the running on the power plant. It is important to note, however, that while the power plant water is directly sent to campus, it is still considered an embedded value and not a direct campus demand, so it is not double counted when clarifying between the water demand and the total campus water. The total water demand to campus is only considered to be that sent to campus for domestic/sanitary uses and that used for irrigation. Water needed for the power plant in order to meet the campus energy needs are still counted and added to the water needed, it is just not a user input that can be designated; rather, the energy demand is inputted and the resulting required water to meet said demand is calculated. Thus, when summing for total water, the value is summed to be all that delivered to campus for campus use (domestic/sanitary and irrigation),
water delivered to campus for power plant, and embedded water values in the energy inputs delivered to campus.

Similarly, total energy refers to all of the direct energy that is supplied to meet the campus energy demand, as well as any embedded energy associated with the campus water demand. These embedded energy values include the embedded energy in both the NJAW and Princeton well water supplies, as well as the embedded energy in any water that Princeton sends for wastewater treatment. The energy demand is considered to be the energy supplied to campus, so the net electricity, steam, and chilled water that is distributed to users across the campus area. The campus demand does not include the electricity and steam generated from the cogen system that is sent to the chilled water system for chilled water production, and the electricity supplied to pump the campus well is included in the total campus electricity, so it is subtracted from this value in order to refrain from double counting the value.

Table 4 provides a comparison of the campus inputs and outputs for the current campus scenario with model-optimized scenarios for minimizing first total water, and then total energy, on campus. Column 3 shows the input values for a scenario of minimizing total water regardless of effects on energy inputs. Column 4 shows the inputs required to meet campus demands while minimizing total energy inputs regardless of water inputs changes. In the optimized cases of
minimizing total water and total energy, it was set that both the current campus water and energy demands for each outputs sector needed to be met, but in each scenario, how these demand were met could vary.

In the scenario of minimizing total water, the largest differences from the BAU case are the input values determined for #2 ULSD and natural gas. The value for solar PV electricity is at its maximum value in this scenario, and the PSEG electricity collected is slightly lower than that in the current case. In the minimizing total water scenario, more natural gas is used and the #2 diesel fuel oil is reduced to nearly zero. This change is logical, as the ULSD has a higher embedded water value than the natural gas, and this change ultimately leads to a 6% decrease in the embedded water value and a 2% reduction in total water. This optimized scenario also slightly changed the amounts of water from water input source. The NJAW supply was reduced by 2%, while the Princeton well water supply was increased by 22%. The total energy associated with minimizing total water was 0.28% higher than the current total energy value for campus.

In minimizing total energy, the total energy and embedded energy are actually reported as slightly higher than that of the current campus BAU case, but the values are so similar that it is regarded as obtaining the same result. The model looks to reduce energy by using the maximum amount of embedded energy, and it does so by using the maximum amount of well water to meet
campus supply. The rest of the water demand is then met by NJAW water supply. The modeled output for minimizing energy shows quite a different set of values for energy inputs to campus. Because this scenario looked to minimize total energy, regardless of effects in the embedded water, it did not matter how embedded water was affected. It is evident from the energy inputs of this scenario that while this scenario keeps the total campus energy at about the same, it has a significantly increased total water value due to the increase in embedded water from the changes in energy inputs.

As a means of providing an analysis that is more real-world applicable than the previous two extreme cases, the final scenario run looks to minimize both the total water and total energy equally. This is done by using the calculated current values for total energy and total water and subtracting by the calculated variables for total energy and water, then dividing by the original value to determine the fraction reduction of each. These reductions are then summed, and their sum is then maximized to reach the most optimized scenarios for both total water and energy, with results listed in column five of Table 4. Logically, this scenario chooses to maximize the amount of well water it can obtain, as the well water has a slightly lower embedded energy value than NJAW water supply. Similarly, it maximizes the amount of energy extracted from the sources with low embedded water values. Thus, it maximizes the amount of electricity formed from
solar PV, since its embedded water value is zero, and it does not use ULSD or biodiesel as fuel inputs to the cogen plant, as they both have significantly higher embedded water values than natural gas.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>BAU case</th>
<th>Minimize total water</th>
<th>Minimize total energy</th>
<th>Maximize both reductions equally</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSEG [MWh]</td>
<td>70,621</td>
<td>70,391</td>
<td>74,772</td>
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<tr>
<td>Solar PV [MWh]</td>
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<td>11,500</td>
<td>7,118.7</td>
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<td>Natural Gas [MWh]</td>
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<td>448,810</td>
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<td>#2 ULSD fuel oil [MWh]</td>
<td>54,540</td>
<td>0.0017</td>
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<td>0</td>
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<tr>
<td>Biodiesel [MWh]</td>
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<td>0</td>
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</tr>
<tr>
<td>Princeton well [ThGal]</td>
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<tr>
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<td>1,304.4</td>
<td>1,260.3</td>
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</tr>
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</table>

Table 4. Comparison of current business as usual (BAU) campus inputs and outputs and outputted values for model-optimized campus inputs. In each case all of the current campus demands need to be met. What the optimization does is determine the optimal way in which to meet said demands while minimizing additional embedded values that Princeton in turn becomes responsible for when accounting for total water and energy.
Figures 14 through 17 show the effects of making reductions of either water or energy on the subsequent campus total accountable energy or water. In Figure 14 both the domestic/sanitary and irrigation water demands were reduced, and the amount of water saved is used to calculate the overall reduction in current campus water demand. The reduced water demand is then used as an input to the model, along with still needing to meet the current energy demand. It is evident by Figure 14 that water demand reductions do not have a significant effect on the total energy associated with campus and that the means by which the water is reduced is not relevant in making the reductions. While the embedded energy value in the NJAW water supply is slightly higher than that of the well water, it does not significantly affect how energy is reduced with water reductions. Ultimately, the embedded energy value in the campus water supply is extremely small in comparison to the total campus energy demand, so reducing water in the hopes of reducing energy as well is ultimately an ineffective means of reduction.

Similarly, Figure 15 shows the effects of water reductions on the fraction of total campus energy that is embedded energy from the water supply. Again, the embedded energy value is so small compared to the overall energy demand that reductions in water supply, and this embedded energy, causes such a small
difference in the total energy that it is ultimately insignificant and an ineffective way of reducing energy.

Figure 14. Resulting fractions of current total energy associated with campus needed to meet various reduced campus water demands. Reductions in water result in total campus energy, but the overall reduction is minimal.

Figure 15. Effects of campus water reductions on fraction of total campus energy that is embedded. Reductions in campus water demand result in a reduction in the percentage of total energy that considered embedded, but the effect is minimal. In general, the amount of total energy that is embedded in the water supply is under 1%.
Figures 16 and 17 show the effects of campus energy reductions on total campus water. Energy reductions are achieved through four different scenarios: through an even overall energy reduction (for example, a simultaneous 10% reduction in campus electricity, steam, and chilled water demand), as well as single energy type fractional reductions. Figure 16 presents the effects of these current energy demand reductions on the total campus water demand, and Figure 17 shows the effects of energy demand reductions on the fraction of total water that is an embedded value. It is evident from both of these figures in comparison to figures 14 and 15 that while the means of which to reduce campus water were insignificant on reducing energy demand, campus energy reductions can have significant effects on the total campus water and the fraction of the total water that is embedded in the energy supply.

Although reductions in campus energy demand can significantly reduce total campus water, these two figures show that the type of energy reduced is crucial to how significant the reduction is. For example, in Figure 16, fractional electricity and chilled water reductions are shown up to an overall campus energy reduction of about 88%. However, a campus electricity reduction of this size has hardly any effect on the total campus water, while a chilled water reduction of this size reduces the total campus water by nearly 7%. Similarly, a steam reduction of this campus magnitude reduces the total campus water by about 2%.
When all three of the energy demand types are reduced by a set fractional amount, the total water is reduced by about 3%.

Similar to the trends shown in figure 16, figure 17 shows that the fraction of total campus water that is considered to be embedded is affected by the type of energy reduced. At the current campus energy demand, the embedded water is estimated to constitute nearly 36% of the total campus water. Electricity reductions have hardly any change on the amount of water that is considered embedded. A campus steam reduction to 65%, which amounts to an overall energy reduction to 82%, reduces the total water by 2%, and a reduction of chilled water, achieving an overall campus energy reduction to 91%, reduces the embedded water by 4%, from 35% to 31% of the total campus water.

It is logical that steam and chilled water reductions would have significantly stronger effects on the total campus water, because these two energy types are extremely water dependent. Inputs to the cogen facility, where steam is created, have higher embedded water values in general than those for PSEG or solar PV electricity. Additionally, water is directly inputted both to the cogen system and to the chilled water system for steam and chilled water production, respectively, so reductions in these types of energy have direct effects on the water to be brought to campus as well.
Figure 16. Reductions in total campus water as a result of campus energy demand reductions.

Figure 17. Effective reductions in fraction of total water that is embedded water as a result of reductions in campus energy demand.
VI. DISCUSSION

Looking at water and energy associated with Princeton as a whole is a crucial method by which to conduct analysis in order to better understand a more representative picture of Princeton’s water and energy usages. The two are strongly linked, as shown within the scope of this project network as a whole, on a smaller scale, as shown by individual components of the Princeton, and on a scale even larger than the Princeton campus, shown by the U.S. EPA water-energy nexus report (Bauer et. al 2014). Reductions in campus water demand affect the total energy associated with campus, and similarly, reductions in campus energy demand affect the total water associated with campus.

There are three general ways in which there is embedded energy in the campus water supply. Campus water supply is embedded with energy for three main reasons: energy that NJAW uses to supply water to campus, energy used to pump Princeton University campus well water to meet campus demands, and energy required to treat campus wastewater that is sent to PSOC. With an EUI of 2.89, the total gallons of water supplied yearly currently amounts to around 739 MWh needed to meet the campus NJAW demand. Compared to a campus electricity demand of nearly 122,000 MWh, reducing water usage with the hopes of additionally reducing electricity is not going to make a particularly significant impact.
Just as there is the embedded energy in water, there is embedded water in the energy supply. The water supplied to the power plant currently amounts to 34% of the total water supplied directly to campus. It is most advantageous to minimize the energy supply required to go to campus, as delivered to campus as electricity, steam, and chilled water, which are the direct outputs. It requires much more energy input and water input to produce these energy outputs than the water and energy inputs required to produce water outputs to campus.

Princeton’s sustainability plan includes three main objectives with the overall goal of creating an increasingly environmentally conscious campus, both theoretically and in practice. The three main objectives of the plan are: to reduce campus greenhouse gas emissions, to conserve campus resources, and to increase campus research, education, and civic engagement. To reduce greenhouse gas emissions, the University is looking to reduce campus CO₂ emissions to 1990 levels by 2020, to reduce cars driving to campus by 10% by 2020 in order to reduce associated greenhouse emissions, and to reduce campus fleet emissions. To increase campus resource conservation, the campus is looking to minimize the potable water going to irrigation, to reduce personal water use by 25% in order to get back to 2007 personal water usages, and to increase the fraction of sustainably sourced food supply from 20%. Finally, the hope of increased research, education, and civic engagement is to get the Princeton University
community as a whole to more thoroughly understand both its local and global impacts in regards to environmental sustainability. (A Sustainability Plan for Princeton 2008)

Keeping these two resources in mind, both as direct values needed for campus as well as the underlying embedded values, the following sections consist of proposed methods through which to reduce campus water and energy usage, as well as some discussion pertaining to their projected effectiveness at reducing said resources. The analysis of each potential campus improvement is only based in the effectiveness as reducing water and energy as resources and does not account for other metrics, such as cost or CO₂ footprint, both of which are important to consider and would be beneficial means of providing a fuller analysis. Adding these metrics in future research would likely prove beneficial in even further understanding the nexus and external means of influencing the overlap between water and energy within a system.

A. District hot water system

In addition to the Princeton Sustainability Plan goals that are to be achieved in the relatively near future, the campus energy management team has been conducting additional research pertaining to usage and emission reductions through larger means of reduction as well. One potential means of reduction is through a future campus upgrade to a district hot water system, rather than
continuing to use the current district steam system. This newer and emerging technology has been implemented on a few other campuses nationwide and is of high priority to campus energy analysts.

District steam is more old-fashioned than district hot water, with a much longer and extensive history of use, particularly in the United States. Ultimately, it is less efficient than a district hot water system due to higher water losses within the system, as well as higher thermal losses in the heat transfer across the system due to a larger difference between the temperature of the steam and the desired temperature within a building being supplied. District hot water is a newer system of building heating, particularly in the United States. There are a few already implemented scenarios of district hot water systems implemented on North American college campus, such as at Stanford University and the University of British Columbia.

Some components of a steam system replacement with a district hot water system include the high upfront cost of initial construction and installation of the system. The piping network around campus is different than that of the district steam system, so the pipes that currently deliver steam to campus buildings would need to be replaced. This upfront cost is high, and the process itself is also quite invasive, as it requires digging all throughout campus in order to install the new pipelines. The installation would thus need to be coordinated for a time
when the campus could be mostly inaccessible to patrons while the ground is under construction. This could best occur during the summer, particularly because the campus is not intensely heated like in the winter and the ground is warmer and thus easier to dig, but with Princeton hosting so many activities regardless of whether school is in session, many adjustments to the University scheduling and planning would have to be made.

The appeal of a district hot water system is that it reduces how much cooling towers are used for cooling the returning water supply back down to a chilled enough temperature for return to campus. Instead, a district hot water system takes advantage of the smaller differential between water returning from campus after being used for heating or cooling. This smaller differential decreases the energy required heat or cool water again for supply back to campus, and it also reduces the water lost to evaporative cooling. While it would be an intensive installation, Stanford University’s example gives enough evidence to the potential for significant reductions for a university campus upon this conversion from district steam to district hot water.

1. **Stanford University district hot water system**

Stanford University finished the implementation of its new district hot water system in the summer of 2013. According to Stanford’s sustainability page, changing the university from district steam to hot water has reduced campus
water usage by 15%. Using a district hot water system allowed for the elimination of their previously large reliance on cooling towers, which they, similar to Princeton, previously used for heat discharge. Instead, the system combines campus heating and cooling systems and puts discharged heat from cooling back into the campus heating system; it is through this combined system that the system has been able to meet 93% of the campus heating load through this upgrade. Regardless of the extensive and invasive installation process that the system required (including 22 miles of underground piping across campus) Stanford’s upgrade puts them on the cutting edge of campus water and energy system technologies. The implementation of district hot water is a prime example of the intertwined nature of water and energy usage and how the desired reduction of one intrinsically requires a decrease in the other as well, and with this installation, Stanford is an example for the rest of the country of how such reductions can be made.

One component to consider when comparing the implementation of a district hot water system at Stanford University versus comparing one here is that the climate of Stanford is much milder than that of Princeton. This difference in outdoor temperature would have an effect on the necessary heat supply and removal to buildings on campus. Knowing this information would make it possible to make an estimate of the difference in effect due to the
increased temperature variation of the East Coast in comparison to the West Coast, but the savings on Stanford’s campus could not be assumed to be directly the same as those that Princeton could expect to experience.

B. Increased building efficiency

Updating the efficiency of buildings on campus also has the potential to cause reductions in both campus water and energy demands. In an effort to understand the relative water usage amounts on campus, the water supply amounts of campus laboratories from 2007-2015 are compared. Using reported yearly laboratory water usages and 2014 building square footages, each laboratory is normalized by its respective square footage and yearly water usage trends are analyzed. It is evident after normalizing yearly water usage by building square footage that the Old Frick/Hoyt Laboratory was the highest water consumer. There was a dramatic shift in this usage from 2009-2011 as the new Frick building was completed and campus chemistry was moved into the new building.
Removing the Old Frick/Hoyt Laboratory data allows for a clearer view of the data trends for the remaining campus laboratories. Within the past two to three years, the lab by lab water usages by square footage have been relatively constant, with all of the labs using about 45 gal/ft$^2$ or less. The highest value, which is for the Lewis/Thomas labs, Guyot, and Shultz laboratories, is currently calculated with the square footage of Guyot at 50,000 ft$^2$. This average value results in a total campus yearly laboratory water usage of about 22.3 million
gallons, which translates to about 8% of the campus water usage. Further work regarding campus laboratory water usages should include investigation as to why they vary by lab. Determining whether these differences are due to the experiments being run in the building, differences in building efficiency, or other factors will prove quite useful in understanding how these usages can subsequently be reduced.

It is also evident from looking at building by building usage amounts that there are no significantly large energy using culprit buildings, but that the building energy usage is more due to the face that there are a ton of buildings that individually are not particularly impactful, but that combined with over 200 other campus buildings each requiring supply, they all together require a large amount of energy. Many of the buildings on campus are centuries old, and they are not as efficient as possible in terms of retaining heating (and cooling, where applicable) that it is supplied. By increasing building tightness and overall efficiency, the amount of heat needed to be added (or removed) from a building could be significantly decreased, and as it has been shown on a large campus-wide scale, the most effective means of reducing campus inputs is to reduce energy usages, as an energy reduction will decrease both the campus energy and water demands.
1. **Building by building energy supply comparison**

Using the EUI values previously calculated for campus buildings, the contributions of chilled water, steam, and electricity are examined. In the 2014 Energy Report dataset for buildings across campus, values for total chilled water, steam, and electricity are listed for each building. Each energy usage value is converted to kWh in order to sum and analyze the total energy supplied to each building. Values are reported in ln(kWh/ft²) and are a means of providing normalized values for buildings in order to make a normalized comparison. This comparison of EUI values with the individual components of the building-by-building values allow for a relationship between the overall value and the components to be extracted. Since the chilled water, steam, and electricity supplies have different amounts of embedded water per kWh, the analyses of these energy components separately, and comparison the EUI values, is important in the context of the campus water-energy nexus.

Buildings with a reported total energy delivered value of zero were removed before values were graphed. This was done in order to remove data points that did not have any reported values for the building; it is possible that a building could have a chilled water value of zero if the building is not equipped with chilled water cooling (Instead, if anything they have electricity-dependent AC units), but a reported value of no steam delivery to a building does not make
sense, as the climate of Princeton is not warm enough for which to have buildings that do not receive any heating.

Upon the inclusion of all other points, the sum of total kWh delivered from chilled water and steam followed a linearly increasing trend with the total kWh/ft² delivered to the campus buildings. Both Figures 19 and 20 are plotted after having taken the natural log of the values being examined in order to better show the trends among the data, which can be used in predicting future campus energy usages by type in a future study. Figure 19 shows these relationships with a strong correlation between the total energy delivered and the highly water-related energy delivered (steam and chilled water). The total energy values are inclusive of all three types of energy, so there is a fraction of automatic correlation between the total and either set of points. However, this plot shows that the overall value is more indicative of steam and chilled water energy than electricity.

In Figure 20 the natural log of building chilled water and steam is plotted against the natural log of building electricity to look for a correlation indicating overall building efficiency. While, in this instance, only the data for campus buildings averaged for one year was used in plotting, in future research if daily data could be obtained for buildings, this information could be used to look for a stronger indication of how electricity load can predict heating and cooling loads. One way in particular that would effectively do such would be to plot ln
(CHW/STM) on the y-axis, rather than their sum. This ratio would indicate how electricity load varies with seasonal changes. Additionally, once data points were plotted, a base load electricity supply for buildings could be determined by finding the amount of electricity with which all buildings are supplied.

Finally, figure 21 shows the amount of campus electricity going to chilled water. It highlights that since 2003, the electricity load to the chilled water system has remained relatively constant around 20,000 MWh per year, while the campus electric demand has increased from about 100,000 to 120,000 MWh. While it is much less than the total campus electricity used, that one process itself still uses about one seventh of the campus electricity, which is quite a significant amount for just one process. This trend is indicative of the way in which total electricity demand has evolved over the past decade in that while the campus has expanded, the electricity required at the chilled water plant has not increased.

Similar to how the dataset reported multiple buildings with zero energy delivered, which is clearly incorrect as these buildings are not self-sustaining, there are likely errors in the dataset that affect the exact accuracy of the resulting findings; however, the main objective of this analysis is to understand more how these sectors interact than exact values of intersection. It is this broader question of why that provokes a desire for a better understanding of the water-energy
nexus applied to Princeton’s campus and to make steps going forward in order to make appropriate decisions regarding usages and policies.

![Graph](image)

**Figure 19.** Ln of highly water-dependent energies vs. Ln total energy delivered, both normalized by square footage for 2014. Each data point represents one campus building.
Figure 20. Ln highly water-dependent energies (CHW and STM) vs. Ln electricity supplied per building for 2014, normalized by square footage [Ln(kWh/sqft)]. Each point represents one building.

Figure 21. Princeton University main campus electrical usage (Borer).
C. Campus lighting

Much of the lighting on campus is still supplied by old-fashioned, low efficiency lighting. Replacing such a high number of these lights would initially cost a significant amount of money, but it is posed as a potential means for energy reduction because the energy savings and environmental impact reduction potential far surpasses the initial upfront cost of buying the new lighting. The use of light-emitting diode (LED) lights throughout campus has the potential to significantly reduce the electricity used to light the campus. An additional means of reducing electricity usage as contributed by campus lighting would be to reduce and/or remove the lights throughout campus that are permanently on. In many public spaces across Princeton’s campus there is no option to turn off the lights in the hallways or rooms at all, resulting in a constantly powered system that is often unused. An ability to turn off these lights or a system upgrade of installing automatic sensor lights would additionally aid in producing drastic electricity reductions.

Princeton’s current effort at reducing the electricity demand for lights has been the ongoing initiative of replacing over 100,000 old-fashioned lighting fixtures across campus with high-efficiency LED lights. The most recent installment of this effort has been in Jadwin Gymnasium, where 839 lighting fixtures were replaced with LED lights that each are 100-170 watts less than the
lights replaced (A Sustainability Plan for Princeton). In an effort to understand the magnitude at which a campus wide update like this could affect on the electricity demands, this update is expanded to a campus wide replacement. If 100,000 lights were to be replaced and created a 135W reduction each, there would be 13.5MW less power required each year. If these lights were on for an average of eight hours a day, or for 2,922 hours in the year, this would be an energy need of 39,447 MWh that could be reduced by the efficiency update. The current electricity demand to campus is nearly 122,000 MWh, so this rough estimation indicates that this type of efficiency update could provide a reduction in the demand by about one third of what is currently required.

Granted this is only a rough estimate, as some lights may be on for longer of shorter periods of time and the wattage reductions may be different, this rough estimation gives an order of magnitude idea for what the potential in electricity reduction could be from an increase in lighting efficiency. It should also be noted that the lifespan of higher efficiency lights is longer, so this update would create less waste and need for light servicing across campus. Additionally, as shown previously in the Results section, reducing electricity demands would have an effect on the overall energy demand, but in an attempt of also reducing water consumption is not the most effective means of reduction. That being said, even if electricity reduction does not have as significant of an embedded water value as
steam and chilled water do, the potential for a reduction in electricity demand by one third would still significantly reduce campus demands.

D. **Green roof installation**

Green roofs are often installed for storm water runoff management and building energy reduction through decreased building heat gain and loss, so the installation of green roofs has the potential to affect both the campus water and energy demands. Liu and Minor (2005) implanted two different thickness green roofs and studied how they affected both the storm water runoff and energy demands of the buildings. They found that, in both cases, the runoff was decreased by an average of 57%. In regards to energy losses, the heat flows were found to be 70-90% less in the summer and 10-30% less in the winter.

Specifically, it was found in the winter (a summer value was not reported) that there was around a 2 W/m² reduction in the energy lost from the buildings. With an estimated roof square footage of 4.25M ft² (1/2 of campus square footage, with the assumption made that buildings are on average two floors tall), this wattage reduction could potentially reduce campus heat loss by 15,473 MWh each year. As with any plant life, however, these roofs require water supply in order to be sustained. Depending on the weather in its location of installation, the rainfall may suffice to keep it adequately watered, but if this is not the case there may be an additional increase in required campus irrigation demands.
E. **Wastewater treatment update**

Currently, 62% of the water delivered to campus is then sent to the Princeton Sewer Operating Committee (PSOC) for wastewater treatment. The average EUI of treating wastewater is 2.85 MWh/MG of water treated (Bauer et al. 2014). While the energy efficiency to treat wastewater could be increased by the treatment facility plant, this is not something Princeton University has any control over, so it is not a feasible option for the campus to reduce energy used in wastewater treatment. However, one aspect that Princeton can control is the amount of water being sent from campus to the wastewater treatment facility. Various means of reducing water sent to the treatment plant, such as updated utilities in bathrooms (showers, toilets, sinks) would decrease the volume of water discharged from Princeton to PSOC. Investing time, money, and effort into these technologies across campus could prove useful in terms of reducing water across campus, but a more in-depth analysis of the actual volumetric changes in water entering and leaving campus, as well as how new fixtures would affect energy usages, would prove useful is assessing the overall impact of reducing water output to wastewater treatment facilities.

F. **Biodiesel fuel usage**

Another potential alternative to change the campus energy system in particular would be to change from #2 ULSD completely to biodiesel fuel oil. Princeton is
already mostly equipped with the machinery to burn biodiesel in the power plant, and this was tested for a year in 2008. Some permits would require updates to allow for significant amount of biodiesel use, but it is a relatively inexpensive and troublesome process in order to make its burning possible for campus. Biodiesel is advantageous as compared to #2 ULSD because it is created from crops rather than a nonrenewable fossil fuel like oil. As highlighted by this analysis, the main difference between the two is in the amount of embedded water in the biodiesel compared to #2 ULSD. While the ULSD has an embedded water value of 0.124 ThGal/MWh in its supply, the biodiesel has an embedded water value of 1.117 ThGal/MWh, which means that an equivalent size supply of biodiesel has on average ten times the embedded water than that of #2 ULSD. Because it is made from plant matter, the water required to grow these crops is included in the embedded water total for biodiesel, which is why it is more significant of a value than that of the ULSD. In this particular model, thus, biodiesel is not an optimal fuel due to this significant difference in the embedded water value. However, it is important to note that this conclusion is because this model is optimizing for the total water and energy used regardless of cost and CO₂ impact. Biodiesel, due to its formation from plants, also cannot be stored for more than six months without use, so it would need to be used more regularly than the ULSD currently is. The USLD is currently only used during the coldest days of the year when the gas...
utility meets its demand and Princeton University agrees to switch to diesel in order to maintain a cheap natural gas price for the rest of the year.

While it is outside the scope of this project, it is also important to note that the creation of biofuels ties strongly with the food sector, which can be analyzed along with water and energy usages in what is called the water-energy-food nexus (WEFN). Similar to the WEN, the WEFN looks at the overlaps and interactions between these sectors. The growth of plant matter for usage in energy supply not only depletes vital water resources, but it also takes away from a supply that could be going to food. The potential of reducing food supply and area that could be used to grow other crops raises significant concern about the usage of biofuels. According to the 2014 World Water Development Report, 70% of the world’s water demand is for agriculture, 20% is for the industrial sector, and 10% is for domestic usages (WWAP 2014). It is evident that agriculture is already quite a significant portion of the global water demand, and increasing crop productions would further raise this demand. Aside from concerns of decreased availability of agriculture for food demands, the increased need for water further highlights the embedded water in fuels, particularly biofuels, production, and that in this study analysis biofuels are seen as unappealing.
G. **Zeroscape campus**

Creating a zeroscape campus consists of utilizing a natural environment where the irrigation on campus is eliminated, and neither the real nor artificial fields/greens would be watered as they are currently. At this point there are 10.5 MGY water used to irrigate the Princeton campus, and a zeroscape campus would eliminate this demand (aside from the small fraction for maintaining artificial turf fields). In order to effectively maintain an attractive zeroscape campus, it is likely that Princeton would need to make some initial replacements of the various foliage types around campus in order to remove plants that required a particular amount of additional water. Reducing campus irrigation is part of the current sustainability plan, which is looking specifically to reduce the amount of potable water being used on campus for irrigation purposes.

This method of reduction is ultimately not the most significant potential reduction campus could make, as irrigation constitutes a small portion of total water usage (only about 9% of campus water usage). It is important to note that while, like previously mentioned, a conservation effort such as reducing or eliminating campus irrigation is a positive step toward increasing campus environmental consciousness, its impact is small compared to other potential efforts that the campus could implement.
VII. FUTURE RESEARCH

A. Increased analysis complexity

Probably the easiest way to make this research and data analysis further applicable to making decisions in practice would be to add additional constraints to the objective function being optimized. This study only looked at minimizing the embedded energy in water supply and the embedded water in energy supply, but adding additional means to optimize water and energy inputs would further this research and it’s real-world applicability. The data used for this campus analysis was small in comparison to data used in other water-energy nexus studies. As was previously mentioned, it can be difficult to find adequate data that correspond to similar sectors in general, let alone sections of a sector in question. However, with a sustained effort to gather adequate data about a system in question, once the data is obtained it can be analyzed in a similar manner as in this study. Overall cost and greenhouse gas emissions, for example, would be two metrics that would likely prove useful in adequately optimizing a system in question. Cost is often the ultimate driver in a scenario, as it is advantageous to choose the most cost effective solution, and in addition, as sustainability and environmentally conscious efforts increase, taking note of greenhouse gas emissions provides an additional method by which to track the efficiency of Princeton, or of that of another area to be studied.
B. Applications beyond Princeton University campus

The analysis conducted in this study pertains specifically to the Princeton University campus system, but it is highly applicable to additional systems both smaller and larger than itself. As shown in current literature on the topic, it can be difficult at times to quantitatively analyze the water-energy nexus of a system due to a misalignment or lack of adequate data. Upon the collection of sufficient data about whatever sector is to be studied, similar concepts can be calculated and analyzed for any system in question. These principles can be studied both at a smaller and more detail-intensive scale, as well as at a much larger system scale with additional generalizations made in order to best represent the system in question.

C. Putting the water-energy nexus in perspective

In addition to the water-energy nexus intersection study, the intersection between the water and energy sectors along with the food sector is becoming more commonly studied, and it is known as the water-energy-food nexus. As shown with the agricultural impact of supplying the crops necessary to create biodiesel, the agricultural sector is highly water intensive. As an example of the water intensity of food supply, it takes 1,845 gallons of water to supply one pound of beef for consumption (Mekonnen and Hoekstra 2012). With over 5,000 undergraduate students, most of whom eat from some type of meal plan through
the University, the food sector of Princeton’s consumptive usages is likely a very significant portion of its overall environmental impact. For a sense of scale, the campus consumes 10.5 MGY of water for campus irrigation purposes. This amount of water in terms of embedded gallons in purely beef supply campus would be the equivalent amount of each undergraduate student eating 1.1 lb. of beef per year (see Appendix for calculation). Clearly, while reducing water and energy in any means possible is a positive step in reducing environmental impact, there are sectors of reduction that may produce more significant results in global scale reduction when accounting for embedded resources, rather than merely looking at direct campus resource reductions. That being said, an additional useful future application of this project in regard to Princeton’s consumptive usages would be to add the food sector to the analysis in order to gain a greater sense of perspective on the Universities impact.
VIII. CONCLUSIONS

The water-energy nexus underlies opportunity for significant increases in both water and energy usage reductions, and a better understanding of the topic in general will help lead to these improvements. Much of the information found in this study can prove quite useful in future research as water and energy are increasingly studied together. Efforts to most effectively reduce campus water and energy usage can be achieved through targeting energy reductions, and in particular through reducing campus steam and chilled water demands. Because these two energies are heavily embedded with water, their reduction allows for a decrease in the overall campus energy demand, as well as a reduction in the total water associated with campus.

An increase in the understanding and focus on water and energy analyses as a combined effort means to aid in the continued efforts of efficiency improvement. The Princeton University campus will continue to grow and expand, and the need to preserve resources will follow suit. With a broader perspective of how various conservation efforts can affect water and energy usages, increasingly more knowledge-based decisions can be made in the future to achieve these desired reductions effectively and efficiently, and to provide a fuller perspective for to implement further technology while continuing to keep resource conservation in mind.
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Grundfos. Technical Data: Model 150 GPM, Model 150S.


APPENDIX

Number of gallons \([gal]\) = meter reading \([CCF]\) \(*\) \(\frac{100 \text{ ft}^3}{1 \text{ CCF}} \) \(*\) \(\frac{7.48 \text{ gal}}{100 \text{ ft}^3}\) \(\quad (1)\).

Thousand gallons \([\text{ThGal}]\) = \(\frac{\text{gallons} [gal]}{1000}\) \(\quad (2)\).

<table>
<thead>
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<th>Unit conversions</th>
<th>MWh</th>
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<tr>
<td>dT (dekatherm = 1M Btu)</td>
<td>0.29300</td>
</tr>
<tr>
<td>gal #2 diesel</td>
<td>0.04074</td>
</tr>
<tr>
<td>gal diesel (biodiesel)</td>
<td>0.03810</td>
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<tr>
<td>HP-hr.</td>
<td></td>
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<tr>
<td>Ton-hr.</td>
<td>0.00352</td>
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Table 5. Energy unit equivalents to 1 MWh of energy.

![Graph](image)

Figure 22. Daily heat supplied to campus as a function of outdoor air temperature, normalized by campus square footage, for 2012-2014. Each point represents one day.
Figure 23. Daily heat removal from campus as a function of outdoor air temperature, normalized by square footage, for 2012-2014. Each point represents one day.

Verification of NJAW EUI = 2.89 MWH/MG feasibility

\[
\frac{2.89 \text{ MWh}}{1 \text{ MG}} \times \frac{\$0.10}{\text{KWh}} \times \frac{1000 \text{ KWh}}{1 \text{ MWh}} = \frac{\$0.289}{1000 \text{ gal}}
\]  

Note: A price of $0.10/KWh of electricity is a value given by Ted Borer, as based off of his knowledge of the price to provide electricity to the Princeton campus.

Current water buying rate for Princeton University = $5.62/1000 gal

Electricity used for supplying NJAW with its water supply. From these calculations, amounts to approximately 5% of the price at which it sells its water, which thus shows that an EUI = 2.89 is a reasonable estimate.
Calculation of Princeton well EUI

20 HP motor at an estimated 72% efficiency (from Model 150S efficiency curve of a pump with a capacity at 165 gpm)

\[
\frac{20 \text{ HP}}{0.72} = 27.7 \text{ HP}
\]  

(4).

So it is as though a 27.7 HP pump is pumping to account for the 20 Hp pump being only at 72% efficiency.

\[
26.52 \text{ MGY} \times \frac{1 \text{ min}}{165 \text{ gal}} \times \frac{1 \text{ hr}}{60 \text{ min}} = 2679 \text{ hr pumping time}
\]  

(5).

\[
27.7\text{ HP} \times 2679 \text{ hr} = 74,202.42 \text{ HP hr} \times \frac{0.00007456 \text{ MWh}}{\text{HP hr}} = 55.33 \text{ MWh}
\]  

(6).

\[
\text{EUI} = \frac{55.33 \text{ MWh}}{26.52 \text{ MG}} = 2.09 \text{ MWH/MG}
\]  

(7).

It is reasonable to obtain an EUI value that is about 30% less than that of NJAW.

USDA farm production regions

<table>
<thead>
<tr>
<th>Region</th>
<th>States included</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>IA, IL, IN, MO, OH</td>
</tr>
<tr>
<td>6</td>
<td>MI, MN, WI</td>
</tr>
<tr>
<td>7</td>
<td>KS, NE, ND, SD</td>
</tr>
</tbody>
</table>

Calculation of met equivalent to current campus irrigation

\[
\frac{15,400 \text{ m}^3 \text{ water}}{1 \text{ ton beef}} \times \frac{264.17 \text{ gal}}{1 \text{ m}^3 \text{ water}} \times \frac{1 \text{ ton}}{2204.6 \text{ lb.}} = 1845 \text{ gal water/lb. beef}
\]  

(8).

\[
10,500,000 \text{ gal} \times \frac{1 \text{ lb beef}}{1845 \text{ gal}} \times \frac{1}{5200 \text{ undergraduates}} = \frac{1.1 \text{ lb. beef}}{\text{undergraduate student}}
\]  

(9).