
Solar Arrays at WPI

- A Feasibility Study of Photovoltaics on Campus -

A WPI Interactive Qualifying Project

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This report represents the work of three WPI undergraduate students submitted to the faculty as evidence of completion of a degree requirement. WPI routinely publishes these reports on its website without editorial or peer review.

Abstract

Renewable energy innovation continues to accelerate as our nation recognizes the negative impact of fossil fuel consumption on the environment and the contribution of fossil fuel dependence to geopolitical strife and economic volatility. In this project, we assessed the feasibility of photovoltaic (PV) arrays for electricity generation and battery storage for peak-shaving at WPI. We modeled the financial viability of PV arrays at WPI and quantified their potential to mitigate carbon emissions. We found that PV array installation was a sound financial investment and that utility-scale battery storage was likely to achieve financial viability within five years. We recommended that WPI formally investigate both of these options.

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Executive Summary

Problem: Unsustainable Energy at WPI

The majority of WPI's energy is derived from unsustainable sources including natural gas, oil, and coal, the breakdown of which can be seen in Figure 1. WPI uses close to 30 gigawatt hours of electricity per year, and the cost of WPI's electricity is rising annually. More than half of the campus emissions are indirect emissions from the electricity that WPI purchases from the grid. Two major objectives of the WPI sustainability initiative are reducing WPI's electricity consumption by 25% by the end of fiscal year 2018 and developing a plan for reducing greenhouse gas emissions.

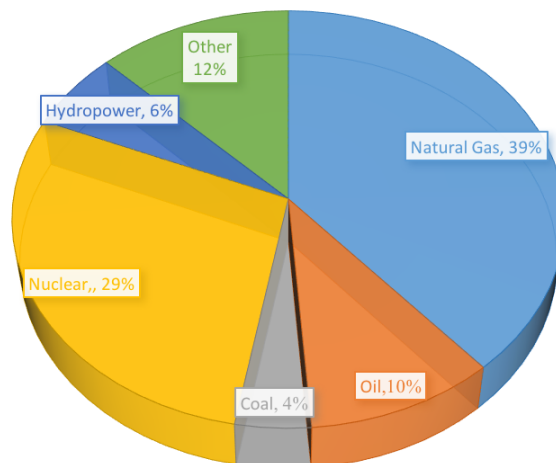


Figure 1: Distribution of WPI's energy sources.

Solution: Solar Panels at WPI

- By generating electricity on-site, solar panels on campus would decrease the total amount of electricity purchased from the grid, thereby reducing the negative environmental effects of the grid-derived, scope 2 emissions.
- The electricity produced by solar panels is free once the equipment and installation break-even point has been met. Solar panel systems pay for themselves and then contribute to reducing the total campus electricity bill, potentially yielding significant savings over time.

Project Goal

The goal of this project was to model viable solar panel configurations at the WPI campus and to propose installation scenarios. The intent behind this goal was to show that PV arrays have the potential to lower the university's carbon footprint, reduce fossil fuel consumption, and save money on electricity bills.

In order to achieve this goal, we utilized the following research objectives:

1. Assess WPI's sustainability goals and explore potential solutions.
2. Investigate WPI's electricity usage patterns.
3. Calculate the physical potential for solar panels on campus.

4. Calculate the financial and environmental benefits of solar configurations on campus.

Key Findings

WPI has an environmental and fiscal interest in renewable energy technology

Although WPI's energy usage is decreasing, its electricity rates are increasing, as can be seen in Figure 2. Concurrently, solar panel technology costs have decreased dramatically, meaning on-site renewable energy technology has become financially viable in addition to being beneficial to the environment.

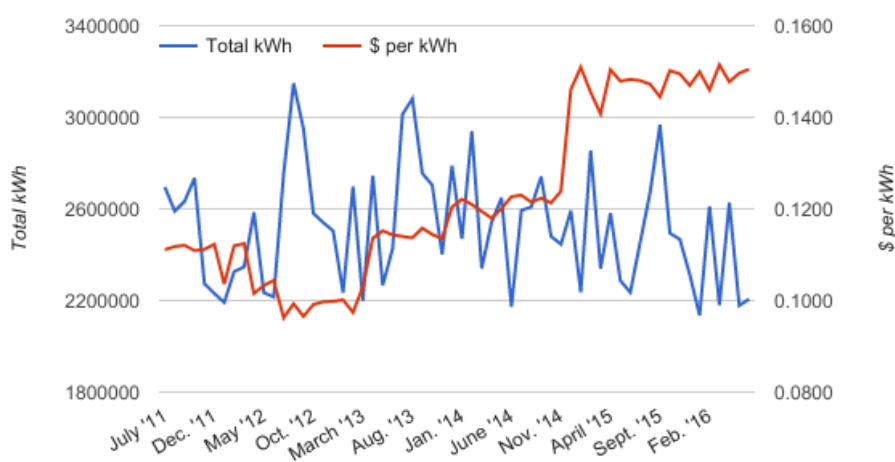


Figure 2: WPI's electricity rates and consumption over 5 years.

The WPI campus has numerous viable array sites

Using HelioScope, a professional-grade PV system design software package, we modeled arrays at twelve different locations on campus and recorded their power rating and annual energy outputs. We found that solar canopies offer the most available space for PV arrays, with the largest being an array over Boynton Lot. As for building mounted arrays, the Sports and Recreation Center can both support a large array and its recent construction implies that its roof is both structurally stable and will not require renovations in the near future.

PV arrays are financially beneficial to WPI

We used the National Renewable Energy Laboratory's (NREL) System Advisor Model (SAM) to predict the fiscal impact of PV arrays on WPI's electricity bills. We simulated four different financial models, an outright purchase, a seven-year capital lease, a 25-year loan, and a power purchase agreement. For each model, we calculated the net present value, payback period, and cumulative after-tax cash flow. We discovered that the net present value of an array correlated positively with its size. Purchasing the array appears to give the largest return on investment, due to the value

of the Solar Massachusetts Renewable Target (SMART) program's feed-in tariff. We calculated this incentive to be approximately \$0.1051/kWh of energy produced for a parking canopy array the size of Boynton Lot, which applies for twenty years.

PV arrays have tangible and measurable environmental benefits that promote WPI's sustainability goals

Given that approximately half a kilogram of carbon dioxide is emitted to the atmosphere for each kWh of electricity generated by non-renewable methods, WPI indirectly caused about 14.7 million kilograms of CO₂ to be released in fiscal year 2016. According to our SAM simulations, if WPI implemented all of our modeled solar arrays, the campus would generate nearly 2 GWh of electricity in the first year. This corresponds to a reduction approaching 1 million kg of CO₂ emissions in that year.

We calculated that over the 25-year life cycle of the arrays that we recommend, they would offset a total of over 22 million kg of CO₂ emissions. The total offset is approximately equivalent to the emissions from burning 1,721,366 gallons of gasoline.

Recommendations

We recommend that WPI formally investigate installing PV arrays on campus

Our investigation has shown that PV arrays on campus would be financially profitable and environmentally beneficial. We recommend that WPI's administration and facilities department further investigate this matter by contacting local solar companies and obtaining cost estimates for arrays. We found that the following locations are currently suitable for array installation: Boynton Lot, East Hall Garage, Gateway Garage, Sports and Recreation Center, Gordon Library, and East Hall. We also recommend that arrays be placed on the following buildings when their rooftops are renovated: Campus Center, Morgan Hall, Daniels Hall, Institute Hall, and Salisbury Labs. Finally, we recommend further investigation into other buildings on campus, such as Atwater-Kent, which may be able to support PV arrays.

When obtaining estimates from solar companies, WPI should consider purchasing the array or obtaining a power purchase agreement. While our models found that purchasing was the most profitable option, the range of potential PPA prices and uncertainties in our estimates could alter that conclusion. If the profits under a PPA approach that of purchasing the array, it may be the better option due to the lack of a capital expenditure by WPI. Similarly, if the university wishes to offset the initial costs of the array, we recommend investigating a capital lease. Our models showed that the capital lease option was more profitable than a twenty-five year loan and would distribute the array's cost over seven years.

We recommend that WPI investigate battery storage in the future

Our research indicated that WPI stands to significantly reduce its electricity bill through peak shaving, a technique that is used to reduce electricity consumption during periods of highest demand. Utility-scale batteries can store energy for discharge during these periods, reducing the draw from the power grid. However, we also discovered that energy storage technologies are still in early stages of market development and are expected to be both cheaper and more technologically advanced in the near future. We recommend that WPI formally investigate installing battery storage to supplement the PV arrays in approximately five years.

As part of this future investigation, we recommend that WPI subscribe to the National Grid Energy Profiler service. This program is relatively inexpensive and would provide historical and current electricity load data for WPI's campus. The data would be invaluable for determining the savings batteries would incur on peak demand charges.

Authorship

Aviv Brest

Aviv was primarily responsible for the HelioScope and SAM simulations. He found reliable sources for many of the simulation inputs to increase their accuracy. He authored the corresponding methodology and findings sections, including the sensitivity analysis. He wrote the recommendations and conclusions section and many of the appendices. Organizationally, Aviv assisted Zach in delegating tasks. He also made contact with several outside organizations to gather information essential to the project. He performed the final editing pass of the report.

Zach Halzel

Zach was responsible for writing the abstract and introduction, and compiling the executive summary. He also wrote large portions of the background and parts of the methodology and findings. He was responsible for much of the style and formatting of the report. He researched case studies at other universities. Zach served as the de facto project manager and maintained the task schedule. Zach worked diligently to define the scope and objectives of our project.

Corey Dobak

Corey was responsible for the analysis of WPI's electricity bills, including demand charges and future trends and created corresponding graphs and figures. Corey developed methods of meaningfully representing that data. Corey wrote parts of the background, methodology, and findings sections. Corey wrote most of the appendix on financial incentives. He also contributed to the formatting of the report, and was largely responsible for compiling and formatting the references. Corey worked with Zach to conceptualize the scope of the project and develop its goals and objectives.

Table of Contents

Abstract	i
Acknowledgements	ii
Executive Summary	iii
Authorship	vii
List of Figures	x
List of Tables	xi
1 Introduction	1
1.1 Global Energy Sustainability	1
1.2 Sustainability at WPI	1
1.3 Project Goal and Objectives	2
2 Background	3
2.1 Energy Sustainability in the 21st Century	3
2.2 The Sustainable Solution	5
2.3 Technology Improvements and Falling Costs	6
2.4 Economics: Policies and Incentives	8
2.5 Sustainable Solutions at Other Universities	9
2.6 WPI's Energy Situation and Goals	10
2.7 A New Approach to Sustainability	10
3 Methodology	12
3.1 Objective: Assess WPI's sustainability goals and explore potential solutions	12
3.2 Objective: Investigate WPI's electricity usage patterns	13
3.3 Objective: Calculate the campus's physical potential for solar arrays	15
3.4 Objective: Calculate the financial implications of solar configurations on campus	17
4 Findings and Analysis	21
4.1 WPI has an environmental and fiscal interest in renewable energy technology	21
4.2 There are numerous locations on campus that could support PV arrays	24
4.3 PV arrays are financially beneficial to WPI	25
4.4 PV arrays have tangible and measurable environmental benefits that supplement WPI's sustainability goals	33

5	Conclusions and Recommendations	36
5.1	Conclusions	36
5.2	Recommendations	37
5.3	Technology and Society	39
5.4	Suggestions for Future Research	40
5.5	Project Conclusion	40
	References	41
	Appendix A: Rooftop and Array Information	45
	Appendix B: SAM Parameters and Simulation Results	51
	Appendix C: Financial Incentives	53

List of Figures

1	Distribution of WPI's energy sources	iii
2	WPI's electricity rates and consumption over 5 years	iv
3	Predicted short-term average residential electricity price	4
4	Analyst estimates and projections of average system price	7
5	Map of the WPI campus	10
6	Cincinnati Zoo solar parking canopy	11
7	Campus demand charges as percentage of total electricity bills	23
8	WPI's electricity rates and consumption over 5 years	24
9	Net present value of arrays	26
10	Cumulative cash flow of Boynton Lot array	27
11	Year 1 savings breakdown for Boynton Lot array	28
12	Cumulative cash flow of Institute Hall array	29
13	Boynton Lot cost and financial parameters sensitivity analysis	30
14	Boynton Lot loan sensitivity analysis	30
15	Boynton Lot PPA sensitivity analysis	31
16	Payback period of arrays	32
17	Payback period sensitivity analysis for Boynton Lot	33
18	Campus emissions	35
19	HelioScope report page 1	47
20	HelioScope report page 2	48
21	Visual representation of proposed arrays (part 1)	49
22	Visual representation of proposed arrays (part 2)	50

List of Tables

1	Annual array energy	25
2	Energy distributed by National Grid by source	34
3	Rooftop material and age	46
4	Cumulative cash flow of arrays	52

Introduction

1.1 Global Energy Sustainability

The majority of the world's nations remain reliant upon fossil fuels as their main source of energy (Shafiee & Topal, 2009). Fossil fuel consumption contributes to pollution, and the burning of fossil fuels is implicated in climate change. The struggle to obtain limited, geographically based resources has also led to geopolitical conflict, such as the Iraqi invasion of Kuwait. By continuing along the path of fossil fuel dependence, we, as a species, may be causing potentially irreversible damage to the environment.

Furthermore, fossil fuels are a finite resource, and one day they will run out (Shafiee & Topal, 2009). Rather than keeping our proverbial heads in the sand, we should preempt these impending disasters by developing robust and environmentally friendly energy alternatives. Humanity is at an energy crossroads. The global energy crisis is not going to fix itself. We must decide on the future of energy that we want to exist, and we must work to make this desirable future a reality.

1.2 Sustainability at WPI

The WPI community has the opportunity to take part in shaping this desirable future of sustainable energy. As an institute of higher learning in the fields of science and technology, we can set an example of embracing forward-thinking technical solutions to solve social problems. We can proactively adopt renewable energy technologies, reduce our carbon footprint, and demonstrate our commitment to creating a sustainable campus and a sustainable world.

Currently, there are no solar PV arrays at the institution, though there are several thermal solar panels on the roof of the Sports and Recreation Center which heat the swimming pools (John Orr, personal communication, September 21, 2016).

Previous student projects at WPI have investigated the feasibility of on-site solar panel installations, but as of this writing, no plans have been implemented. Previous project groups have not looked specifically at using solar panel technology for peak-shaving and demand-side management, which is one new component of our project.

Due primarily to the rapidly falling prices of PV equipment, the national political and economic status of renewable energy, and the continued inflow of evidence backing up climate change, we feel that an investigation into the feasibility of incorporating solar power generation on the WPI campus is worth reviewing.

With the popularity of utility-scale battery arrays rising and their costs falling, we are also intrigued by the potential to utilize batteries for demand-side management of peak loads (peak-shaving). The intent of peak-shaving is to save money on utility bills and reduce the need for the grid to tap into the even more environmentally deleterious peaking plants during times of high demand.

1.3 Project Goal and Objectives

The goal of this project was to model viable solar panel configurations at the WPI campus and to propose installation scenarios with the intent of lowering the campus carbon footprint, reducing fossil fuel reliance, and saving money on campus electricity bills through solar electricity generation and peak-shaving. Specifically, we aimed to:

- Investigate the campus electricity consumption patterns in order to determine total usage, future trends, as well as what impact demand-side management via batteries might have on peak-demand charges.
- Calculate the campus's physical potential to support solar panel arrays for on-site solar electricity generation.
- Calculate the financial implications of solar installation on campus.
- Develop configuration recommendations that will optimize financial benefits to the campus.

We intend for our project to raise awareness of the potential environmental and financial benefits of installing solar panels at WPI. We ultimately hope that WPI will implement these technologies as a meaningful addition to the campus sustainability initiatives of increasing campus energy sustainability, reducing greenhouse gas emissions, and reducing grid-derived electricity consumption.

The next chapter sets up the global and local context of energy use and potential for sustainable solutions. Subsequently we describe our methods for determining the feasibility of implementing solar panel technology at the WPI campus. This leads into our findings and analyses regarding the financial and environmental effects of solar panel installation. We conclude with recommendations based on our findings as well as suggestions for areas of future research.

Background

In this chapter we examine the present global energy context and future trends in sustainable energy before investigating the implications of integrating renewable energy technology on the WPI campus.

2.1 Energy Sustainability in the 21st Century

In the year 2016, it has become evident that humanity's ever-increasing power consumption calls for a thorough investigation into the implementation of innovative new energy production and storage technologies. Our reliance on fossil fuels as a primary source of energy (Hosenuzzaman et al., 2015) is problematic on multiple fronts. Some of the issues underlying our fossil fuel consumption include the negative environmental impact of carbon emissions and pollution as well as the inherent volatility that arises from dependence on commodities such as coal and oil. Fossil fuels are a key global economic indicator and geopolitical events can cause large fluctuations in their value (Larsson & Nossman, 2011).

Environmental, Societal, and Economic Impacts of Fossil Fuels

This growing demand for fossil fuels has propagated such environmentally destructive practices as fracking (Jackson et al., 2014), drilling for oil, and coal mining (David, Mihai, & Maiduc, 2014). Fossil fuel combustion has been implicated in increasing carbon emissions and atmospheric greenhouse gases as well as climate change and global warming. The pollutant effects of fossil fuel combustion are also worth noting. Afflictions ranging from heart attacks to asthma are often caused or exacerbated by exposure to atmospheric pollutants (Hosenuzzaman et al., 2015). The World Bank estimated that in 2013, there were 5.5 million premature deaths around the world due to air pollution, resulting in approximately \$5.11 trillion in welfare losses (*The Cost of Air Pollution*, 2016). These public health and environmental issues will continue to grow if left unchecked, leading to potentially disastrous long-term effects (Solomon, Plattner, Knutti, & Friedlingstein, 2009).

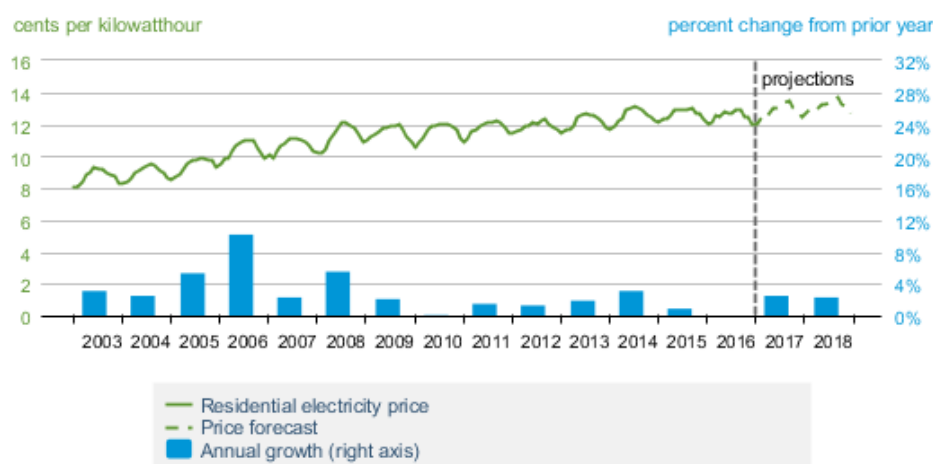
From an economic perspective, coal, oil, and related fossil fuels are a finite resource. As a result, their relative abundance is one factor that influences their global market value. There have been multiple instances over the past century of wild fluctuations in oil and gas prices due to political and economic instability. Examples include the Iraqi invasion of Kuwait in 1990 and the recent global recession in 2008. As humanity continues to utilize more and more power, it is becoming increasingly desirable to mitigate this volatility (Shafiee & Topal, 2010).

Rising Electricity Costs and the Impact of Decentralized Generation

The cost of electricity fluctuates from year to year, however the long-term trend shows a rise in prices. According to the Energy Information Administration, the next fluctuation peak will hit \$13.65 per kWh for the average U.S. resident (*Short-Term Energy Outlook*, 2017), as can be seen in

Figure 3. This upward trend in electricity prices suggests a rise in the future value of renewable energy sources.

As opposed to the traditional model of large, centralized power plants, renewables offer modular power generation distributed throughout communities. However the electrical grid infrastructure was built with the assumption that electricity would flow in one direction, from power plants to consumers. The introduction of small, decentralized power generators, often in the form of wind, solar photovoltaic, or combined heat and power, challenge the delicate equilibrium of the electrical infrastructure (Hadjsaïd & Sabonnadière, 2013). Grid instability could result in the utilities charging higher demand and capacity fees (*Understanding Electric Demand*, n.d.), which would incentivize the consumer to try to mitigate peak-demands. Renewable energy technologies such as battery storage represent one possible solution to manage demand on the client-side (Mahmud, Morsalin, Kafle, & Town, 2016).



Source: Short-Term Energy Outlook, January 2017

Figure 3: Predicted short-term average residential electricity price.

Peaking Power Plants

During periods of high demand, the utility is often forced to tap into reserve power by running peaker plants, which tend to use environmentally destructive fuels, such as natural gas and jet fuel (Masters, 2013). Because it is expensive and challenging for the utility to manage large peaks, utilities tend to charge an extra capacity fee for commercial buildings. This fee is set based on the highest peak electricity usage over a given time period, often quarterly or yearly, and the customer is charged a flat monthly rate in addition to their bill. Large peaks can make up a large portion of the electric bill, so demand-side management can be an effective cost reduction strategy.

Strategies to mitigate peaks are therefore both environmentally and financially advantageous. Note that peak demand charges and capacity charges are interchangeable terms, and are simply titled differently for the electricity producer and distributor.

2.2 The Sustainable Solution

While the fact that the majority of the world's energy is currently derived from fossil fuels presents major challenges for the future of the planet, we stand at a pivotal moment in the history of energy. The increasing viability of sustainable energy technologies is paving the way towards a future far less plagued by many of the environmental and economic pitfalls to which we are currently subjected. These sustainable energy technologies herald a new era in which the production of energy is both environmentally friendly and cost-effective, mitigating and perhaps eliminating both the economic volatility of reliance on fossil fuels and the destructive environmental impact of their procurement and consumption.

Harnessing the Sun's Energy

The sun has been referred to as “the great fusion reactor in the sky” by prominent industry members, such as Elon Musk (Urban, 2015). It's always on, totally free, and it produces far more energy each day than humanity uses in an entire year (Hosenuzzaman et al., 2015).

Unlike terrestrial reactors which utilize nuclear fission, fusion energy from the sun is generated 93 million miles away, so we don't have to worry about nuclear waste products, accidental nuclear disasters, or nuclear weapons getting into the wrong hands. The energy from our extraterrestrial fusion reactor arrives at planet Earth in the form of photons, elementary particles of electromagnetic radiation. Taking advantage of a phenomenon known as the photovoltaic effect, solar panels are able to transduce this energy from the sun into electricity (Lotsch, 2005).

Electricity from Solar Panels

Energy yields from solar panels depend primarily on the combination of solar cell efficiency and insolation. Solar cell efficiency is a ratio of the energy that hits a solar panel to the amount of electricity generated. Solar cell technology on the market is hovering at about 20% efficiency (Green, Emery, Hishikawa, Warta, & Dunlop, 2015), although solar cells with efficiency ratings closing in on 40% are in the developmental phase (Da Silva, 2016).

Insolation refers to the amount of sunlight hitting a certain area over time. This measure varies based on a number of factors, including regional location, weather conditions, time of day, and season. Factors such as the amount of shade and pollution at a given location can also affect insolation. The annual energy yield of a solar cell is therefore the product of its efficiency and the yearly insolation at its precise location.

There are some key benefits to solar panels, chief among these benefits is that solar panels have no moving parts and they require no fuel to generate electricity. Furthermore, the generation of electricity from solar panels produces no carbon emissions or pollution. Replacement of fossil fuel combustion with PV technology saves half a kilogram of CO₂ emissions for every kWh of energy produced (Hosenuzzaman et al., 2015).

Solar power does have a few drawbacks. The first issue is that of solar panel efficiency. Even the best solar panels are less than 50% efficient, and most commercial solar panels hover around

20% efficiency. The inefficiency of solar panels means that the energy yield per surface area is reduced. This obstacle is remedied by simply installing more solar panels until the energy demand is satisfied. Furthermore, Swanson's law predicts that solar panels will continue to increase in efficiency and decrease in price over the coming years, so that fewer solar cells will be required to produce more energy at a lower cost (Swanson, 2006).

The major drawback to solar power is the intermittency and variability of insolation. Since solar panels don't generate electricity in the absence of photon exposure, the energy yield of solar panels is significantly reduced during both the nighttime and inclement weather. Furthermore, insolation varies significantly by location, tending to decrease as distance from the equator increases. For a long time this was a major objection to the adoption of solar power, but with advances in energy storage technology, it is now quite feasible to store energy from solar panels using batteries that are designed for home and commercial use (Sørensen, 2015).

Peak Shaving

Batteries can also be used in creative ways to offset the cost of peak energy usage from the grid. Power stored in batteries can be discharged rapidly by energy management software at the time of a peak load event. This alternative to pulling energy from the utility can be an effective strategy to avoid the costs associated with peak loads and surges (Hanna, Kleissl, Nottrott, & Ferry, 2014).

Peak demands tend to occur during the times of day with the greatest sunlight, and especially during the summer months (Byrne, Letendre, Govindarajalu, Wang, & Nigro, 1996). Air conditioning contributes to the high electricity usage, as well as the fact that this is the time of day when people tend to be working and using the most appliances.

Because peak demand often coincides with peak insolation, the energy generated via PV arrays can advantageously offset the total peaks during these times, therefore reducing the amount of electricity that must be delivered from the utility. In order to take full advantage of this peak-shaving effect, the PV array must be configured in such a way as to send all of its electricity to the building's load, rather than directly to the grid (Boxwell, 2016).

Ultimately, solar power, batteries, and energy management software can be combined into a microgrid combining sustainable energy production and storage with efficient energy distribution.

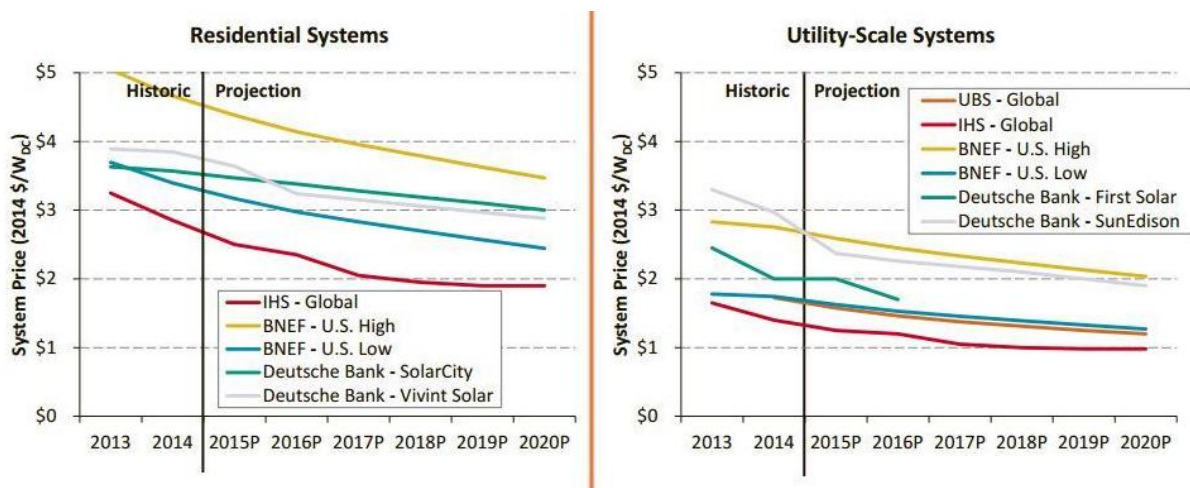
2.3 Technology Improvements and Falling Costs

Solar panels have been falling in price for years, and the initial investment is becoming less of a barrier to entry with each passing year. Through the analysis of various organizations such as Bloomberg New Energy Finance and UBS financial services, we have reason to expect the cost of PV systems to decrease by between 3 to 12 percent per year at least through the year 2020, which is shown in Figure 4.

Trends in PV Array Technology

The trending reduction in price for solar panels is coinciding with technological improvements that are increasing the value of PV systems for residential and commercial use. According to the Department of Energy's SunShot Vision Study from 2012, solar technologies are poised to generate 14% of US electricity demand by 2030, and 27% by 2050.

In 2016, the state of photovoltaic penetration was revisited, and the Department of Energy found that over the past 5 years the levelized cost of energy for solar panels has dropped by 65% (*On the Path to SunShot: Executive Summary*, 2016). They outlined some further changes that could result in an even higher volume of PV integration, including better demand-side management and improvements in PV technology. These changes will both increase the value of a PV system while mitigating grid destabilization.



- Analysts expect the system prices of both utility-scale and distributed systems to continue to fall in the near future
 - Residential systems are expected to reach \$1.5/W - \$3.0/W and utility-scale systems are expected to reach \$1.00/W - \$1.75/W by 2020
 - Analysts project that from 2014-2020, system prices will fall 16%-33% for residential systems and 26%-36% for utility-scale systems, or between 3%-12% per year.

Figure 4: Analyst estimates and projections of average system price.

Adapted from *SunShot Vision Study: February 2012* (2012)

Battery Trends

According to a 2015 levelized cost of storage analysis conducted by Lazard, the cost of Lithium-Ion battery banks are expected to drop by 50% by 2020 (Beetz, 2015), which would correlate to a direct reduction in battery array investment costs. This cost reduction would decrease the pay-back period proportionally, and reduce the risks involved in the types of large-scale investments necessary to outfit a campus with a full-scale battery array.

Spurred on by the growing electric car market, many companies are now selling batteries for energy storage solutions and the prices for these batteries has been declining sharply over the past 10 years (Nykvist & Nilsson, 2015). This trend in battery prices bodes well for the prospect of utilizing batteries for peak-shaving. As batteries continue to become cheaper, their value for the

purposes of peak-shaving and demand-side management will continue to rise.

Doug Telepman, the Director of Commercial Solar Development at Direct Energy Solar, informed us that battery prices will lead to the viability of battery arrays for demand-side management within the next five years, but at the time of this writing the technology is not yet cost-effective on a large scale (Doug Telepman, personal communication, January 19, 2017).

2.4 Economics: Policies and Incentives

Solar and renewable power technologies are still in the early stages of their development, and their proliferation remains dependent on government support. National governments have developed various strategies to promote the use of solar energy, often in the form of financial incentives (Wüstenhagen, Wolsink, & Bürer, 2007). These strategies are quite numerous and vary according to the type of energy used, how much of it is replacing traditional energy (oil, coal, natural gas, and nuclear) usage, and the type of establishment generating the energy. Certain types of organizations are eligible for different incentives, and they can be put into categories such as commercial, industrial, local government, nonprofit, residential, state government, federal government, and schools, just to name a few. The Department of Energy (DOE) has set a goal for 10-15% of energy used in America to be solar derived by the year 2030 (Solangi, Islam, Saidur, Rahim, & Fayaz, 2011).

A recent study by the University of Michigan shows that at least 70 percent of Americans agree that climate change is real and supported by science, demonstrating that from a social point of view the transition to renewable energy is becoming more widely desirable (*Acceptance of Global Warming Among Americans Reaches Highest Level Since 2008*, 2015). While it would be ideal if everyone would invest in renewable energy solely for the environmental benefits, money tends to be a primary motivator for individuals, and the bottom line remains the first priority for most businesses and organizations. Renewable energy is practically free to produce, so the obstacle most people and organizations face when considering the option of implementing renewable energy generation is the upfront cost of the equipment and installation, as well as the bureaucratic hurdles that must be overcome with regards to incentives and tax credits (Irfan, 2015).

A key deciding factor in solar panel purchase is the time it takes for cost savings from utility bill reduction to overtake the initial infrastructure investment. This amount of time will vary drastically depending on many factors. These factors may include: efficiency of the energy system(s), applied incentives and rebates, location, uncontrollable circumstance (weather or malfunction of systems), and change in standard energy costs over time.

One of the benefits for generating renewable energy is the ability to take advantage of government incentives. Many of these incentives are tax credits, so nonprofit institutions such as WPI are not able to take full advantage of them. To mitigate the lack of incentives, educational institutions often implement renewable energy generation with a third-party ownership model. Under this model, the owner, a for-profit company, receives the benefits of the financial incentives and sells the electricity generated to the energy consumer. This allows the for-profit company to pass a portion of the incentive savings onto the consumer.

2.5 Sustainable Solutions at Other Universities

There are a number of microgrid and photovoltaic systems present at nearby universities that could serve as a model for future sustainability developments at WPI. At the University of Connecticut, a microgrid uses fuel cells and a 6.6 kW PV array to provide heat and power during grid outages. It also serves an educational purpose for students studying microgrid design. At Clark University, a 2.0 MW cogeneration system powered by natural gas provides as much as 90% of the campus's electrical loads. At the University of Hartford, all campus buildings were connected to diesel generators to provide heating and electricity during power outages (Buonomano, Conklin, & McQuaid, 2016). As shown in a study by Princeton University, their campus generates the vast majority of its own power onsite, and has one of the largest solar panel arrays of any university (*Solar Energy*, n.d.). On the West Coast, Santa Clara University is developing a renewable energy smart-grid which utilizes software to intelligently distribute energy based on weather reports. This smart-grid is expected to cut energy usage by 50% and reduce costs by 20% (*Renewable Energy*, 2016).

A nearby institution, Worcester State University, has a 105 kW roof-top solar array on its campus library (*Sustainability*, n.d.). This array installation, which was facilitated by the Massachusetts Clean Energy Center, generates over 140,000 kWh of electricity per year. On their sustainability website, they placed a solar dashboard that displays the real-time status of PV electricity generation.

Hampshire college, a private university in Western Massachusetts, has a bold initiative to generate 100% of its electricity on-site via 15,000 solar panels across 19 acres of their 840 acre campus (*Hampshire Is Going 100% Solar for Electricity*, 2016). Under their power purchase agreement, a partnership with SolarCity for both PV arrays and battery arrays, SolarCity will own and operate the system and sell the electricity generated at a fixed price. Their system will generate enough electricity to power over 500 homes, and is expected to offset the carbon emission equivalent of taking 650 cars off the road.



Figure 5: Map of the WPI campus.

2.6 WPI's Energy Situation and Goals

WPI has a 95-acre campus on a hill in Worcester, Massachusetts. In 2015, WPI enrolled 6,573 students. WPI has over 70,000 square meters of roof space, a number of parking lots, and two parking garages which may be suitable for solar PV array installations. Car-port shading structures can be built above the parking lots and, in addition to supporting solar arrays, would provide shade and shelter from inclement weather. An example of such a solar canopy can be seen in Figure 6.

WPI has published a sustainability plan, in which it describes three principles to which it strives: ecological stewardship, economic security, and social justice. The plan outlines numerous goals for academics, campus operations, research, and community engagement. Of particular interest to this report is the goal to reduce utility consumption by 25% over five years. Solar power provides clean electricity with no emissions or pollutants and thus meets the ecological stewardship principle of the sustainability plan. Solar power could be used in conjunction with efficiency and reduction initiatives to reach the 25% goal.

2.7 A New Approach to Sustainability

In the past, several project groups at WPI investigated bringing solar PV to the campus, but to date, these projects' recommendations have not been implemented. While other projects have looked at some aspects of integrating renewable energy onto the WPI campus, our motivation for revisiting and expanding upon these studies is the recent surge in renewable technologies combined with their ever-increasing affordability.



Figure 6: Cincinnati Zoo solar parking canopy
by User:Quadell, licensed under CC 3.0.

In examining the current state of renewable energy technologies and WPI's specific needs and characteristics, we have identified three unique opportunities for further investigation:

1. Examining financing structures such as power purchase agreements (PPAs) in order to take full advantage of the renewable energy tax credits at a non-profit institution and reduce the upfront cost of installation.
2. Roof-top solar alternatives such as solar canopies over campus parking lots to increase the potential solar energy on campus by expanding beyond available roof-space to other potential surfaces.
3. Investigating the potential of solar panels and/or battery arrays for the specific purpose of demand-side management via peak-shaving.

We believe that integrating these solar panel and battery technologies has the potential to work synergistically with the current sustainability initiatives to bring the WPI campus closer to its long-term goals and objectives. The following chapter describes the methods we used to determine the viability of installing these renewable technologies.

Methodology

The goal of this project was to assess WPI's potential to effectively utilize solar panel and battery technology with the intent of lowering the campus carbon footprint, reducing fossil fuel reliance, and saving money on campus electricity bills through both solar generation and peak-shaving. To achieve this goal, we developed the following research objectives:

1. Assess WPI's sustainability goals and explore potential solutions.
 - (a) Develop an understanding of WPI's interest in sustainable energy technologies by communicating with campus faculty and stakeholders.
 - (b) Assess viable implementation scenarios through consultation with local industry professionals.
2. Investigate WPI's electricity usage patterns.
 - (a) Establish historical electricity trends in order to predict future trends of peak usage, general consumption, and costs.
 - (b) Investigate how much money WPI could potentially save if peak demand charges were reduced or eliminated.
 - (c) Calculate carbon emissions from electricity usage.
3. Calculate the campus's physical potential for solar panels.
 - (a) Determine buildings and locations that can support PV installation.
 - (b) Model the PV arrays at these sites and calculate their potential electricity generation.
4. Calculate the financial implications of potential solar configurations on campus.
 - (a) Determine the most fiscally advantageous financing model.
 - (b) Develop an ordered list of PV configurations based on financial viability.

In this chapter, the methods we employed to explore these research questions are outlined and described.

3.1 Objective: Assess WPI's sustainability goals and explore potential solutions

We set out to learn the specific opportunities and challenges that WPI faces with regards to solar panel and battery implementation, and what projects would be worth further investigation. In order to develop clear objectives for this report, we found it helpful to consult with local industry professionals in relevant fields. The perspective of stakeholders and professionals served to clarify our thinking and orient our project towards feasible outcomes.

Component A: Develop an understanding of WPI's interest in sustainable energy technologies by communicating with campus faculty and stakeholders

The key campus stakeholders with whom we met were Professor John Orr, Liz Tomaszewski, and Bill Grudzinski. By meeting with John Orr, WPI's Director of Sustainability, we hoped to learn about current and previously implemented sustainability efforts, as well as details on how the campus uses and networks their electricity.

We met with Liz Tomaszewski, the Associate Director of Sustainability to request information about campus facilities including electricity consumption and building information, all of which turned out to be vital to our methods and analyses.

We met with Bill Grudzinski, Chief Engineer of Facilities, to learn about the structure of the campus electrical network. We especially wanted to obtain information on how easily renewable energy technologies could be incorporated into existing infrastructure.

Component B: Assess viable implementation scenarios through consultation with local industry professionals

We conducted a telephone conversation with Doug Telepman, the Director of Commercial Development at Direct Energy Solar. The objective of this conversation was to learn about typical implementation strategies and financial models for PV arrays and battery storage at educational institutions.

Multiple conversations with Martin Laskowski, a Field Energy Consultant with SolarCity, informed many of our project considerations. We reached out to Martin to gain insight into the current renewable technologies available on the market, as well as for ideas on how to investigate the campus's potential for utilizing these technologies.

3.2 Objective: Investigate WPI's electricity usage patterns

To begin our investigation into the potential of solar power on campus, we first sought a comprehensive understanding of WPI's past electricity consumption. We needed to know how much electricity the campus uses and how much money is spent in order to think critically about the potential impact of implementing solar power on campus.

Component A: Establish historical electricity trends in order to predict future trends of peak usage, general consumption, and costs

We sought data on electricity consumption and costs on campus. Liz Tomaszewski gave us access to the facilities master electricity spreadsheet, which contained monthly electricity consumption and spending from 2007 through 2016. Organizing this data into spreadsheets and graphs allowed us to calculate the current electricity rates and extrapolate future trends.

We analyzed the monthly financial and electricity usage data, consisting of the electricity bills from National Grid and Direct Energy, as well as the master electricity spreadsheet. Of particu-

lar interest were the accounts for buildings with demand charges, such as the powerhouse and Gateway, because of solar and battery technology's potential to reduce these charges.

These methods were adapted from the report "Establishing a net-zero energy campus" by Kwan and Hoffman, from the Sustainable Communities Design Handbook, published in 2010. By creating spreadsheets with electrical and financial data in regards to the entire campus and the peak demand buildings, we were able to sum total costs, find specific campus consumption information, and create graphical representations of this information. This gave us a firm understanding of the consumption on campus so we could better determine how our proposed efforts would affect WPI.

There were some limitations in the data we obtained. Prior to 2012, there are many missing entries, so the data we compiled before this time period was not very useful for our analysis. Furthermore, monthly electricity usage does not paint the full picture of campus electricity consumption. For a more detailed analysis, and to more fully understand the peak demand usage, we would require data on the electricity loads in 15 minute intervals, the time-block used by the utility companies to calculate peak demands. Daily usage curves would add a more thorough understanding of the relationship between peak sunlight hours and solar electricity generation, as well as enable accurate peak shaving analyses.

Component B: Investigate how much money WPI could potentially save if peak demand charges were reduced or eliminated

We decided to calculate the percentage of the campus utility bills that is paid towards peak demand charges. This helped us estimate the effect of demand-side management via solar panels and/or batteries on utility bill peak-demand charges. If the cost-savings of utilizing battery arrays for demand-side management is of a large enough magnitude to offset battery purchase costs, this would benefit the school financially and have a positive impact on the environment. Furthermore, any electricity generated by solar panels during periods of peak demand would also help to reduce campus peak usage, thereby simultaneously reducing the peak demand charges and the charge for total consumption.

Our group visited the WPI Facilities office and spoke to Liz Tomaszewski to gain access to the school's electricity bills, which are separated by building account (many of the buildings on the main campus are tied to a single account via the power plant). We were given access to the monthly electricity bills for each building and analyzed the buildings with highest demand charges over the period of December 2015 through November 2016. This is the year when peak demand fees began to be included as a separate line item on the bills. We analyzed these bills and separated the peak-demand costs from the total bill to reveal the percentage of the total electricity bill that was spent on peak demand fees.

We put this information into a spreadsheet to gain an understanding of the monthly demand of each of the high-demand buildings. From this data we determined the amount of money that was spent on demand fees from December 2015 through November 2016 as well as the demand fees as a percentage of the total bill.

For our demand-charge analysis we looked at the ten campus utility bills of the G-2 and G-3

buildings. We created graphs for each of the buildings demonstrating the percentage of the electricity bill that is associated with demand/capacity charges as well as a graph demonstrating this percentage on a campus-wide scale. These methods for analyzing peak demands on campus were derived from the National Renewable Energy Laboratory (NREL) report *Deployment of Behind-The-Meter Energy Storage for Demand Charge Reduction* (Neubauer & Simpson, 2015).

Our data set was limited to a single year of peak usage because peak demand fees for Direct Energy only appear on the bills after November 2015. While we were able to develop some findings from this data, a longer time-period would give more insight on changes over time. Additionally, we were unable to obtain a load profile of the campus electricity usage over 15 minute intervals. Peak demand is charged based on the highest 15 minute peak during a given month, so a load profile from the utility company or the networked meters would facilitate a more thorough peak-shaving analysis.

Component C: Calculate carbon emissions from electricity usage

The carbon footprint of the campus serves as a baseline with which to compare the environmental effects of solar panel configurations. One of the primary motivating factors for our project was the positive environmental impact of replacing fossil-fuel derived electricity with solar power, therefore we calculated the carbon footprint of the campus as a consequence of the annual electricity consumption.

We used the calculation from Hosenuzzaman et al. (2015) that PV technology intervention saves half a kilogram of CO₂ emissions for every kWh of energy produced, and worked backwards to determine the difference between the carbon footprint of the campus with and without solar panels. This method is simply an approximation, a full carbon footprint analysis would need to be performed to present a more accurate finding, which would go beyond the scope of our project.

3.3 Objective: Calculate the campus's physical potential for solar arrays

Approximating the available surface area (including roof-space, parking lots, and parking garages) that could feasibly support PV installation gave us a starting point to determine the amount of potential energy the campus could generate from on-site solar panels.

Component A: Determine buildings and locations that can support PV installation

Gaining a more precise estimate of the viability of PV arrays on each building was made possible through the documents we obtained from campus facilities. Liz Tomaszewski supplied us with a spreadsheet containing approximate surface areas for each campus building's roof, and Bill Grudzinski gave us a spreadsheet containing each roofs' material structure, when it had been constructed, and when future renovations were planned. The latter spreadsheet can be seen in [Appendix A](#).

We used a web-based software called HelioScope to model PV array configurations on the campus. HelioScope allows the graphical simulation of PV arrays using satellite imaging. It visually

plots arrays in addition to associated wiring and inverters, and generates comprehensive reports which detail the array's power output, yearly energy yield, and physical characteristics.

Through HelioScope, which makes use of several publicly available GIS databases, we compiled a list of potential on-campus sites that are viable for PV array installation. We quickly ruled out many locations where roofs had too many obstructions, odd shapes, or minimal South-facing area and were therefore unsuitable for array installation. Several parking lots were also discarded, as they appeared too heavily shaded to optimally generate solar power. We proceeded to compare the list of viable installation sites with the roof information we received from facilities to further refine it by removing roofs which were old or scheduled for renovation. We considered the following potential array locations. Roof mounted arrays on the Campus Center, Daniels Hall, East Hall, Fuller Labs, Institute Hall, Gordon Library, Morgan Hall, Salisbury Labs, and the Sports and Recreation Center. In addition, we modeled parking lot canopies on the Boynton Lot, the Gateway Garage, and the East Hall Garage.

Our parameters for choosing PV array sites were adapted from the feasibility study chapter of the book *Large-Scale Solar Power System Design* (Gevorkian, 2011). We judged potential solar locations on roofs based on the following criteria: roof age; roof type (flat, pitched, or mixed); and expected roof renovation timeline. As a guideline, we chose roofs that were either ten years old or newer, or were soon scheduled for renovations. We wished to avoid placing arrays where renovations were scheduled to take place early in the installations life, as their presence would incur additional installation costs and they would be inoperable during the process. However, if renovations were taking place soon, we were able to recommend that PV arrays be installed in conjunction with the construction. In contrast to rooftops, parking lot canopies require a new structure to be built and thus are not constrained by current infrastructure age.

Due to limitations in information, particularly about sloped roofs, we avoided certain locations that may be viable for solar arrays, such as Atwater Kent. In addition, our information on rooftop ages and renovation schedules was compiled in 2010. Thus, renovations completed since that date were not listed and we may have ignored viable rooftops.

Component B: Model the PV arrays at these sites and calculate their potential electricity generation

In order to calculate the financial outcomes of different arrays, it was necessary to determine their physical parameters, power output, yearly energy yield, and DC to AC ratio. Once we had narrowed down the potential array locations, we began modeling the arrays using HelioScope. HelioScope has a built-in library of PV panel and inverter models, with detailed specifications on rated power output and size. To compute array size and output, we used Hanwha Q-Cell Q.Plus L-G4 340W solar modules, SolarEdge SE33.3KUS inverters, and SolarEdge P700 power optimizers. Doug Telepman of Direct Energy Solar suggested that we use the aforementioned equipment based on current market supply (Doug Telepman, personal communication, January 19, 2017).

HelioScope takes many inputs beyond module and inverter models. We kept the default of fixed-tilt racking, where the modules have a constant tilt throughout the year, as our research sug-

gested tracking arrays tends to reduce their value. The increase in insolation is often outweighed by the increased cost and size of the array (Salasovich & Mosey, 2011).

To accurately predict the effect of roof obstructions, HelioScope allows “keepout” zones to be specified such that the array avoids those areas. The height of each keepout zone could be input so that HelioScope could model shading. For more details on our HelioScope models, see [Appendix A](#), which describes and justifies the parameters we chose for the arrays.

We discovered HelioScope independently and began using it to model solar arrays. In our conversation with Doug Telepman (Doug Telepman, personal communication, January 19, 2017), he confirmed that it was reputable software and that Direct Energy Solar uses HelioScope to model PV arrays for their professional installations.

As a result of modeling the PV arrays in HelioScope, we obtained the yearly energy output of the proposed arrays. We then calculated the ratio of the sum of the outputs to the total annual energy usage of WPI to determine what proportion of the university’s electrical demand could be offset by solar power. Furthermore, we used the sum of yearly energy outputs to estimate the total CO₂ emissions offset by the arrays. Hosenuzzaman et al. (2015) calculated that PV technology saves half a kilogram of CO₂ emissions for every kWh of energy produced. The emissions offset allowed us to make a strong environmental argument for investing in PV arrays.

$$CO_2AnnualOffset[kg] = \sum AnnualSolarEnergyProduction[kWh] * 0.5[kg/kWh]$$

There were several sources of uncertainty in modeling PV arrays. Rooftop obstructions were difficult to model using HelioScope. Since the GIS maps were two-dimensional, we could not accurately estimate the height of obstructions. Therefore, the shadows caused by those obstructions may be of a different size than what was output by the software, affecting viable array areas. As a consequence, the array power outputs we calculated have some level of uncertainty.

In addition to shading, we specified a PV module and inverter combination suggested to us based on current market supply and technologies. However, the specific models that may be used upon installation will most likely be different. They depend on the individual site locations, size of the arrays, and the market situation at the time of implementation. This assumption further raises the uncertainty in array output.

Finally, our calculation for annual CO₂ offset makes use of a general equation, and does not take into account the specific sources of energy that WPI makes use of. A more thorough analysis would need to be conducted in order to better approximate this value.

3.4 Objective: Calculate the financial implications of solar configurations on campus

Our final objective was to simulate financial outcomes of the proposed arrays and determine if they were viable monetary investments. These simulations formed the basis of our recommendations.

Component A: Determine the most fiscally advantageous financing option for installing PV arrays on the WPI campus

Our recommendations ought to present the best financial option for WPI, which as an educational institution holds a responsibility to its stakeholders of investing its capital wisely. With this in mind, we calculated the payback periods, net present value (a metric which accounts for the present value of money when compared to its predicted future value if invested with compounded interest), and total savings for PV array installations on campus buildings and parking lots. We wished to compare the fiscal differences between a PPA, outright purchase, loan, and capital lease.

We used a software package developed by the National Renewable Energy Laboratory called SAM (System Advisor Model). SAM is a free software package provided by NREL with funding from the Department of Energy. The software is available for download at <http://sam.nrel.gov/download>. This program enables the analysis of performance and financial outputs of various renewable energy configurations. The full SAM project files can be found in the supplemental materials attached to this report.

For each of the twelve arrays we modeled in HelioScope, we examined four financial options: an outright purchase, a twenty-five year loan, a seven-year capital lease, and a power purchase agreement. A capital lease is similar to a short-term loan. WPI would pay off the array for a specified number of years, after which it would assume ownership. Under a PPA, a solar company would install, own, and operate the array at no cost to WPI. The university would then agree to purchase electricity generated by the array at a fixed price. We input the array power output, DC to AC ratio, tilt, azimuth, and shading losses from the results of our HelioScope simulations. The DC to AC ratio is the ratio of the array's rated power output to the inverter's rated input. For some of our arrays, this value was less than 1.0 given the module and inverter models we used. As a ratio of less than 1.0 wastes the inverter's potential, we reset the value to SAM's default of 1.10 in those cases. We found the default system costs to be too low given our research, thus, we modified those parameters to match an NREL PV pricing report released in 2016 (Fu et al., 2016).

For financial parameters, we set the debt percent to zero for the outright purchase model. For the loan model, we assumed 100% of the systems costs would be borrowed for a twenty-five year loan, with an annual interest rate of 5%. For the capital lease option, we set similar parameters, but set the loan term to seven years, a number suggested to us by Doug Telepman (personal communication, January 19, 2017). For the PPA, we set the price of electricity at \$0.10/kWh with an annual escalation of 1%. This was not only the default value, but Doug Telepman also said it would be a good approximation.

We used a website called DSIRE (Database of State Incentives for Renewables & Efficiency) to find applicable incentives for the project. A detailed explanation of these incentives can be found in [Appendix C](#). As a nonprofit institution which does not pay income or property taxes, WPI does not benefit from most of the tax incentives that apply to PV projects. However, it can make use of the upcoming Solar Massachusetts Renewable Target (SMART) program. Under SMART, which is a feed-in tariff program, WPI would receive a flat, production-based incentive in \$/kWh. The

program is scheduled to launch in January of 2018, but many of the details have been finalized. A presentation given in late January 2017 allowed us to accurately calculate the feed-in tariff rate Baker, Polito, Beaton, and Judson (2017). To make this calculation, it was necessary to estimate the average electricity rates WPI paid over a three year period. Since we only had detailed bill information for the year-long period starting in November 2015 and ending in October 2016, we used that period to approximate the three year average.

The final inputs in the simulation were the electricity rates and electric loads. WPI's electricity rates are very complex to calculate, as it receives two bills per month for each of its accounts, one from Direct Energy and another from National Grid. SAM allows the user to input different rates based on the month and time of day. For our analysis, we chose the year-long period beginning with the Nov-Dec 2015 bill and ending with the Oct-Nov 2016 bill. We chose this period because, at its start, Direct Energy began to differentiate between usage and peak demand charges.

For the electric load inputs, we were forced to use the default load profiles for a commercial building. SAM allows for sub-hourly load inputs but the most granular data sets we obtained were monthly values. Conveniently, SAM allows the user to normalize the load profile to monthly bills. However, a more detailed analysis of a PV array's effect on demand charges would require more precise data.

Many of the solar PV feasibility studies we encountered in our research, particularly those from NREL (Salasovich & Mosey, 2011), used PVWatts, a subset of SAM, for financial modeling. We refrained from analyzing battery storage systems using SAM for two reasons. First, Doug Telepman opined that such systems were still in their infancy and would be much more viable in several years (personal communication, January 19, 2017). Second, the lack of detailed electrical load data makes analyzing the potential peak-shaving of battery systems highly inaccurate.

The techniques used in SAM's simulation are based on those detailed in a report (Short, Packey, & Holt, 1995) published by NREL in 1995. Short et al. (1995) recommend using net present value to evaluate and compare mutually exclusive options, such as different financial models. It also stated that it is an acceptable metric for ranking projects based on a limited budget.

We ran the simulation using SAM and compared the net present value, payback, and after-tax cash flow results from different financial models to determine the one which saved the most money. Furthermore, we conducted sensitivity analyses on a number of variables, including the upfront equipment and installation costs, discount rate, inflation rate, PPA price, and loan terms. We performed sensitivity analyses using SAM's parametric mode, which allows the user to run many simulations with different parameter configurations. For our analysis, we varied one parameter per simulation while holding the rest constant at their default values.

While SAM provides a vast array of parameters for input, we used the simplified PVWatts model because we didn't have precise module and inverter models. We used default values for many input fields, which would have to be adjusted if future projects intended to generate more detailed analyses to help WPI plan the implementation of PV arrays. Furthermore, we were unable to obtain detailed electrical load data. This data exists in the form of the National Grid Energy Profiler, a yearly subscription WPI could purchase. The energy profiler would also allow the modeling of battery storage systems, which could further reduce costs. Furthermore, a previous project

(Buonomano et al., 2016) built a database of electrical loads using networked electricity meters on the buildings sub-metered under the powerhouse. Unfortunately, this data was erased before we became aware of it. Future investigations into this matter ought to consider creating a new database for the load data from the networked sub-meters.

Component B: Develop an ordered list of PV configurations based on economic feasibility

Any suggestion made must be financially viable, so we calculated the net present value of our installation scenarios. Short et al. (1995) state that this metric is an acceptable method of ranking projects when presented with a limited budget. The net present value output in SAM represents the combined value of the energy generated by the system, production and tax based incentives, the operating expenses, and debt payments. It also considers the discount rate, which is a measure of the time value of money.

From our financial analyses, we were able to rank the potential PV configurations based on net present value to determine the order in which we would recommend each array installation. We tabulated and graphed the net present value for each proposed system, then we ordered them by descending numerical value. We added certain stipulations based on the age of the roof and any upcoming renovations.

WPI's administration may want to also consider the levelized cost of energy (LCOE) in addition to or in place of the net present value. For a PV array, the LCOE represents the cost per kWh of electricity generated by the array by comparing the total energy generated to the total life-cycle costs. Short et al. (1995) state that this is one of the recommended methods of ranking projects when presented with a limited budget.

Findings and Analysis

In this chapter, we discuss our findings related to the feasibility of solar photovoltaic technology at WPI. We found that WPI has both an environmental and financial interest in renewable energy investments. We modeled arrays in multiple locations on campus, showing that the university has the physical potential to host renewable energy sources. We also analyzed the financial aspects of the proposed arrays, and found that an outright purchase provided the most economic value. Finally, we examined the environmental impact of the proposed arrays and how they can aid WPI in reaching its sustainability goals.

4.1 WPI has an environmental and fiscal interest in renewable energy technology

Professor John Orr, director of WPI's sustainability department, told us that several projects on campus have investigated renewable energy solutions in an attempt to reduce the school's environmental impact, but were ultimately unsuccessful in having their recommendations implemented (personal communication, September 21, 2016). We were informed of multiple examples of local colleges that have installed and utilize solar arrays. He posed the question "why is it that other schools are able to implement these technologies, while WPI has not been successful?"

In 2010, the project entitled *Photovoltaization of WPI* recommended an investment plan to both benefit the WPI community through the use of clean energy and to create monetary savings. The students involved in the project analyzed many of the buildings on campus. They applied multiple economic models to determine both the time it would take to recoup solar investments and the total savings over the lifetime of the arrays. They ranked the buildings by order of payback period and determined that putting an array on the admissions office would be most beneficial by that metric, taking between six and nine year to pay back the installation cost of \$120,250 (Beliveau, Lian, Pyatnychko, & Tariq, 2010).

In 2011, the group which authored *The Truth About Photovoltaics* conducted a similar study of buildings on the campus. They recommended that WPI purchase and install a PV array on the roof of the library. The array would generate 23 kW of power and offset an estimated 1.3 million pounds of CO₂ emissions over its 25 year life cycle. Based on their recommendation of a payment plan, the system would generate more than \$100,000 in profit before needing replacement (Blair, Davis, Russell, & Sudol, 2011).

While WPI has not yet installed PV arrays, the university has demonstrated its commitment to sustainability and the integration of renewable technologies through the WPI Sustainability Plan and the annual WPI Sustainability Reports. Some of the sustainability initiatives that are already completed or in progress include:

- The Sports and Recreation center has solar thermal panels on the roof that heat the pool water. This technology saves more than \$50,000 in operation costs and reduces carbon emissions by 4,400 pounds per year compared to traditional pool heating.

- Monitoring energy usage through real-time networked meters.
- WPI has entered into a contract with a company called NEXAMP. In this contract the university agreed to purchase a set amount of electricity that is generated by off-site solar arrays owned by NEXAMP (J. Orr, Personal communication, September 21, 2016). WPI agreed on a rate for this electricity that will not change with the fluctuation of grid supplied electricity costs. This deal is expected to save WPI about \$100,000 per year.
- The Gateway building has a cogeneration system that offsets 30% of its electrical costs (Buonomano et al., 2016).

Our conversation with Bill Grudzinski confirmed that campus stakeholders and personnel are not only committed to energy sustainability, but to fiscal responsibility as well. He suggested that WPI's electricity costs are likely to rise substantially in the coming years and showcased a keen interest in the potential for mitigating WPI's peak demand fees (personal communication, November 16, 2016).

Electricity bills are made up of various sub-components, including the cost of the electricity, the cost of distribution, and demand/capacity charges. Demand fees are a consequence of the high cost to the utility of managing large electricity usage peaks. WPI has separate accounts for the different buildings on campus so that they are billed based on individual consumption. Only the buildings with the highest consumption have demand charge components in their bills, these are categorized as G-2 and G-3 accounts. Both categories have different rates, but in all cases the cost per kW of demand charges is more expensive than the baseline cost per kWh of electricity consumption. The G-2 and G-3 buildings are as follows:

- The Sports and Recreation Center
- The Powerhouse (which supplies electricity to 29 other buildings on campus)
- East Hall
- Ellsworth Apartments
- Fuller Apartments
- Institute Hall
- Founders Hall
- Faraday Hall
- Stoddard Hall
- Gateway 1

Bill Grudzinski suggested that the campus demand charges were a substantial fee, and it would be advantageous to mitigate them (personal communication, November 16, 2016). Our analysis of peak demands from the electricity bills confirmed this suggestion, and we have calculated that peak demand charges accounted for about 13% of the total electricity bill charges for demand charge buildings in fiscal year 2016. Since the powerhouse is a demand charge building, the vast majority of electricity usage on campus is subject to those charges. The monthly proportion of demand charges to the total electricity bills can be seen in Figure 7.

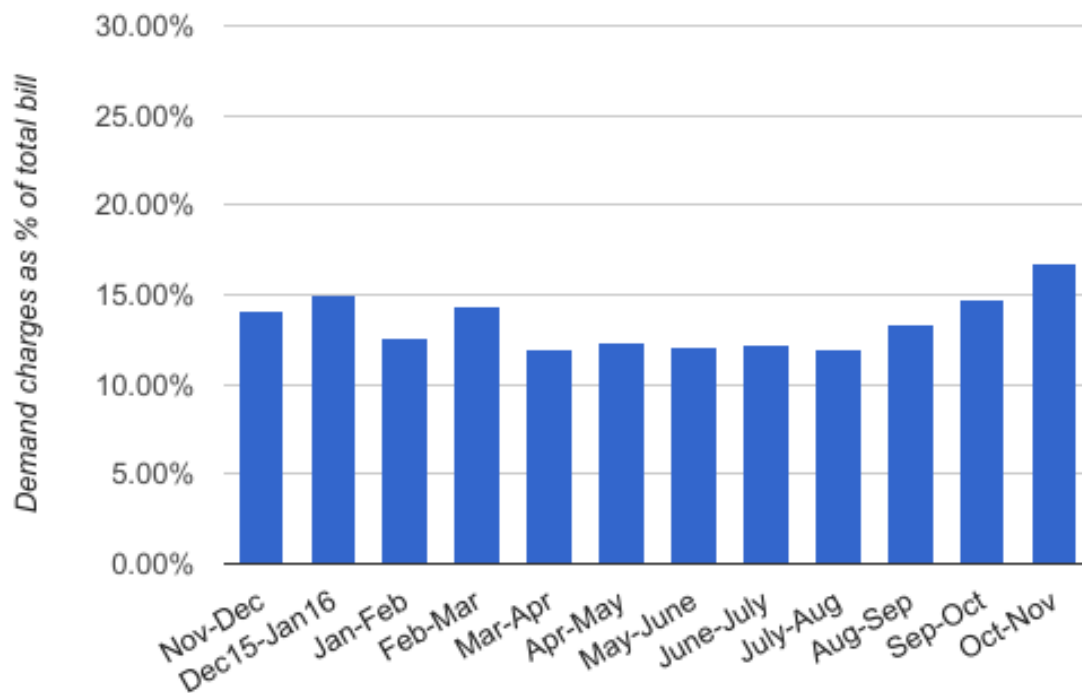


Figure 7: Campus demand charges as percentage of total electricity bills.

WPI used to participate in a demand-management system where high powered appliances would be turned off during peak-demands, but this solution was inelegant and problematic. It was largely automated and lacked the flexibility to deal with sudden, large spikes in electricity usage (Bill Grudzinski, personal communication, November 16, 2016). Peak-shaving via solar power and/or batteries would not interfere with appliance usage during peak-demand times. Because solar panels generate the most electricity during times of greatest electricity usage, such as peak air-conditioning times, they are a perfect tool for assisting in demand-side management of capacity charges.

We analyzed electricity bill data and confirmed that WPI has a strong financial incentive to invest in electricity sources independent from the power grid. WPI purchases its electricity from Direct Energy, and it is delivered to campus by National Grid, a utility company which operates throughout New-England. Based on data gathered from facilities and the WPI Sustainability Report, WPI's annual electricity consumption is in the range of 25-30 gigawatt hours per year. While we calculated that the campus's electrical usage is slightly decreasing over time, we found that the electricity rates are trending upwards, as can be seen in Figure 8. Since solar panel technology costs have decreased dramatically, on-site renewable energy technology has become both financially viable in addition to being beneficial to the environment.

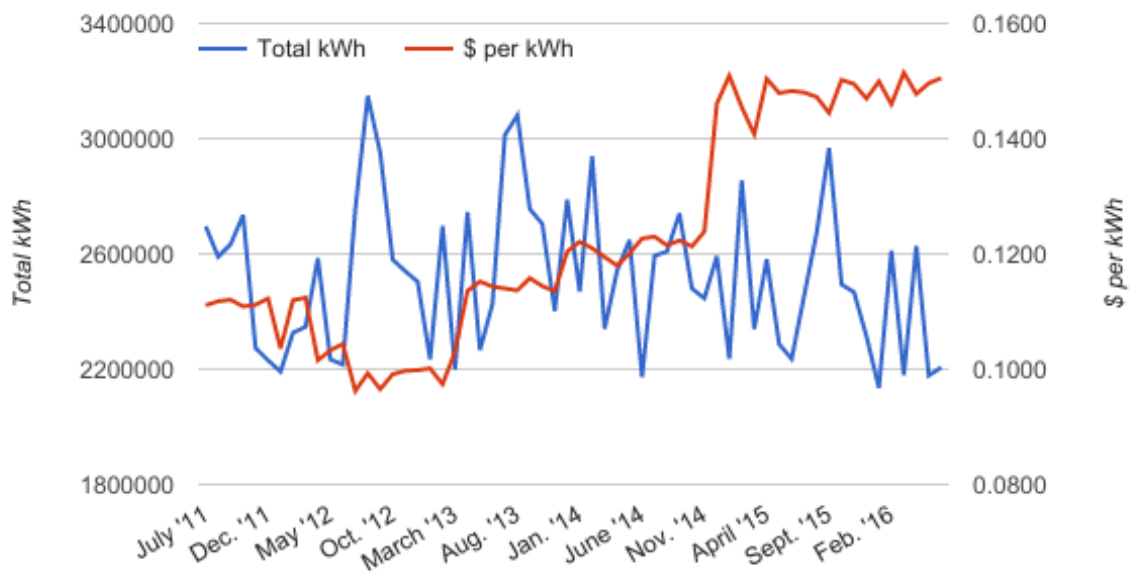


Figure 8: WPI's electricity rates and consumption over 5 years.

4.2 There are numerous locations on campus that could support PV arrays

Our research on WPI revealed that it has the physical potential to support PV arrays. According to data provided by the facilities department, WPI has approximately 70,377 square meters of roof space. However, only a portion of this roof space is viable for rooftop solar installation because of roof obstructions, roofing material, and roof angle/tilt. To mitigate the small proportion of usable roof space, we investigated solar canopies placed over parking lots and garages. We learned from Doug Telepman (personal communication, January 19, 2017) that solar canopies are a viable option due to extra incentives from the state. Solar canopies also provide shelter, shade, and they serve as a highly visible demonstration of the campus's commitment to renewable energy.

Using HelioScope, we modeled arrays at twelve different locations on campus and estimated their power rating and annual energy outputs. The results of the modeling can be seen in Table 1. They show that solar canopies offer the most available space for PV arrays, with the largest being an array over Boynton lot. As for building mounted arrays, the Sports and Recreation Center can both support a large array and its recent construction implies that its roof is both structurally stable and will not require renovations in the near future. The smallest array we modeled was on Institute Hall, which, at a power rating of 14.3 kWdc, resembles a large residential array more so than a commercial one. The units of kWdc represent the direct current electricity produced by the array under standard test conditions.

There were a number of assumptions we made when modeling PV arrays. The first was that all the roofs could support the added weight of an array without added structural support. Further investigation into this matter will require a structural analysis of rooftops. Secondly, a number of arrays we modeled were on roofs that are scheduled for renovations in the near future. Only East Hall and its garage, the Sports and Recreation Center, and the Gateway Garage have been

Table 1: Annual array energy

Array Location	Annual Energy (kWh)	DC Nameplate Rating (kWdc)
Boynton Lot	524,351	429.1
Gateway Garage	439,313	345.8
East Hall Garage	275,410	214.9
Sports & Rec Center	211,091	205.0
Salisbury Labs	106,792	97.9
Gordon Library	93,787	87.0
Daniels Hall	79,536	75.1
East Hall	72,697	66.3
Morgan Hall	61,641	55.8
Campus Center	51,860	47.6
Fuller Labs	37,752	40.5
Institute Hall	15,708	14.3
Total	1,969,938	1679.3

The annual energy and DC power rating of the proposed arrays sorted in descending order

constructed recently enough to support a solar array without renovations within the first ten years of its life-cycle. However, if renovations are completed at the other potential locations, the new roof could be designed so that it could support an array.

The third limitation of our PV array models was shading. It was very difficult to accurately predict the amount of shade caused by roof obstructions and surrounding buildings. The Boynton Lot array is particularly affected, as it sits to the East of a large hill which may create significant shading. Gateway 1 is another potential location which was not fully explored due to numerous rooftop obstructions. Future analysis of array locations should include a full solar survey to alleviate this issue. Like shading, it was difficult to estimate the tilt of arrays on sloped and irregularly shaped rooftops. Thus buildings such as Atwater-Kent, Founder's Hall, and Higgins Labs were not modeled in this report, but could potentially support PV arrays.

4.3 PV arrays are financially beneficial to WPI

We used the NREL's System Advisor Model (SAM) to predict the fiscal impact of PV arrays. For each financial model, we calculated the net present value, payback period, and cumulative after-tax cash flow. We discovered that the net present value of an array correlates with its size, as can be seen in Figure 9. This correlation means that the value of the electricity savings and incentives outweigh the system costs. Thus larger systems are more valuable.

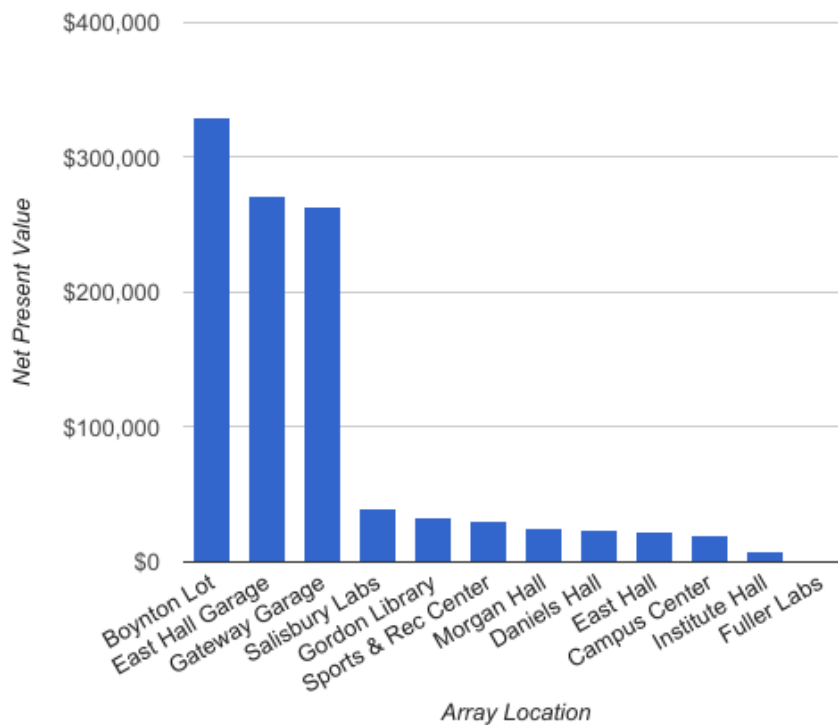


Figure 9: Net present value of arrays. A bar graph showing the net present value of the proposed arrays for the purchase financial model, sorted in descending order. Note that the Fuller Labs array has a negative NPV.

There are several exceptions to the correlation, such as East Hall Garage, which has a higher net present value due to its large feed-in tariff rate and the Sports and Recreation Center, which has a lower net present value due to large shading losses. Only the proposed Fuller Labs array has a negative net present value, -\$34, for the upfront purchase model. While the array will still be profitable, the negative net present value indicates that it is a slightly sub-par investment for the assumed discount rate. One caveat of our results is that the parking lot canopies have additional infrastructure costs that we did not factor into our simulations due to the lack of reliable information on the increased prices. Thus, their value would be lower than the results of our simulations indicate. However, our sensitivity analysis covered a large range of array costs, and showed that they are still good investments, largely due to their lower shading losses and higher feed-in tariff rates.

When examining different financial models, we compared their cumulative after-tax cash flow, which measures the net value of electricity savings, incentives, and costs. However, it does not incorporate the discount rate, therefore ignoring the time value of money. The cumulative cash flows for the Boynton Lot array can be seen in Figure 10. As is evident from graph, purchasing the array gives the largest return on investment, followed by the capital lease, the 25 year loan, and finally the PPA.

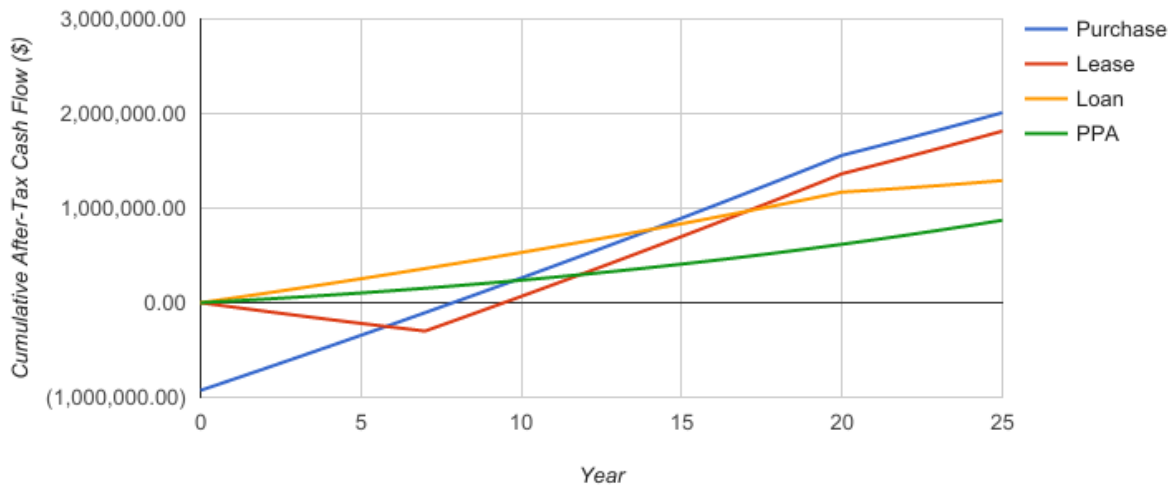


Figure 10: Cumulative cash flow of Boynton Lot array. This line graph compares the cumulative after-tax cash flow of the proposed Boynton Lot array for different financial models.

The large difference between the PPA and the other financial models is due to the value of the SMART program's feed-in tariff. We calculated this incentive to be approximately \$0.1051/kWh of energy produced for a parking canopy array the size of Boynton Lot, which applies for twenty years. For the Boynton Lot array, the feed-in tariff would account for nearly 45% of the total income and savings in its first year of operation, as can be seen in Figure 11. By year twenty, this proportion would decrease to approximately 33%, due to both a decrease in energy production from equipment degradation and an increase in electricity bill savings from inflation.

For the three most profitable financial models, WPI would receive the SMART feed-in tariff. Under a PPA however, the solar company owning the array would receive that income. Consider the nominal levelized cost of energy (LCOE) of the outright purchase model, which we calculated to be \$0.1045/kWh for the Boynton Lot array. It is approximately equal to our assumed value of \$0.10/kWh for energy purchased under a PPA, but incorporates the discount rate, which lowers the value of the investment over time. While we cannot determine the precise PPA rate without a quote from a solar company, the value of the Boynton Lot array is significantly higher for the outright purchase model.

The difference between the purchase, capital lease, and loan are a result of the interest costs of the borrowed money. In exchange for minimal upfront costs, the interest lowers the monetary value of the array. For the Boynton lot array, the cash flow from an upfront purchase passes that of the lease in year six, and the cash flow from a loan in year fifteen. It is important to note that although an upfront purchase model yields the most profit, it does not have the highest net present value. Since net present value incorporates the discount rate, it accounts for the fact that offsetting the costs allows for the entity, WPI in this case, to invest that capital elsewhere. For comparison, the net present values we found for the Boynton Lot array were \$329,436 for the upfront purchase, \$426,302 for the capital lease, \$562,587 for the loan, and \$308,114 for the PPA.

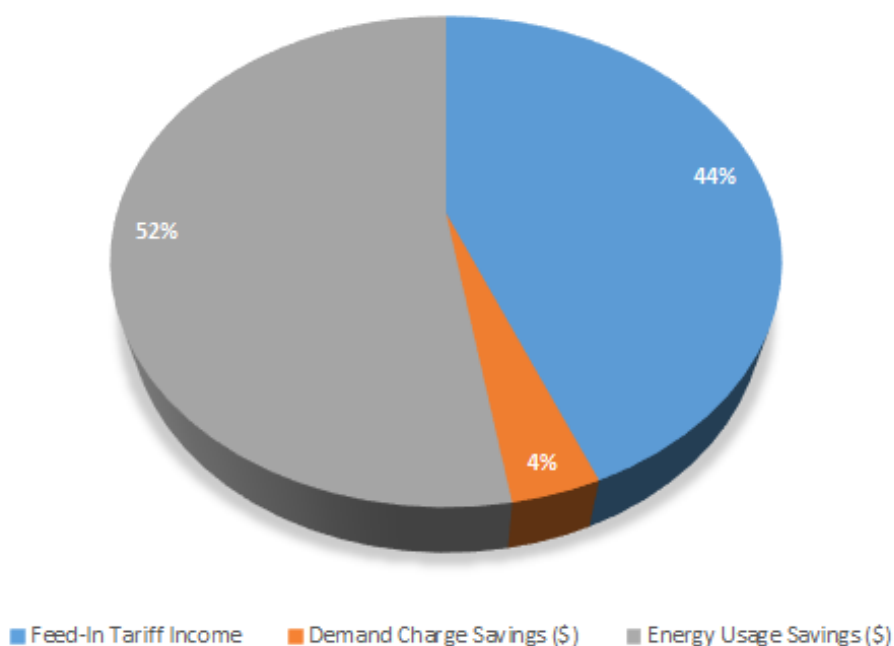


Figure 11: Year 1 savings breakdown for Boynton Lot array. This chart shows the proportions of electricity usage savings, demand charge savings, and incentive income to the total value of the proposed Boynton Lot array in its first year of operation.

The pattern of relative value for different financial options holds true for nearly every array we modeled. The cumulative after-tax cash flow for the smallest array we modeled, on the roof of Institute Hall, can be seen in Figure 12 and shows the same results as the Boynton Lot array. For the Institute Hall array, the shading losses lowered the cash flow from the three WPI-owned models. However, it would likely also raise the PPA rate to meet the solar company's return target, which would lower the cash flow from that financial model as well.

One of the largest sources of uncertainty in our analysis was the cost of purchasing and installing the PV array. We used values from an NREL report Fu et al. (2016) for module and inverter costs, balancing of system equipment, installation labor, permitting, and grid interconnection. Although SAM allows users to specify these costs directly, the values were given in \$/Wdc, scaling costs based on the system size. While this is a good approximation for larger arrays, its accuracy decreases for smaller installations, where flat costs are a larger proportion of the total. We calculated the total costs of the arrays at a rate of \$2.16/Wdc. They range from \$927,371 for the Boynton Lot array to \$30,905 for the Institute Hall array.

We tried to compare different module types in the simplified PVWatts version of SAM, but found that while it accounted for the change in module efficiency, it did not change the pricing of the arrays. When further analysis is conducted on PV installations at WPI, a range of different module types must be examined. Aspects of this future analysis to consider are the price difference between module types and the value from the differing amounts of energy they produce, in terms of both offset electricity costs and feed-in tariffs.

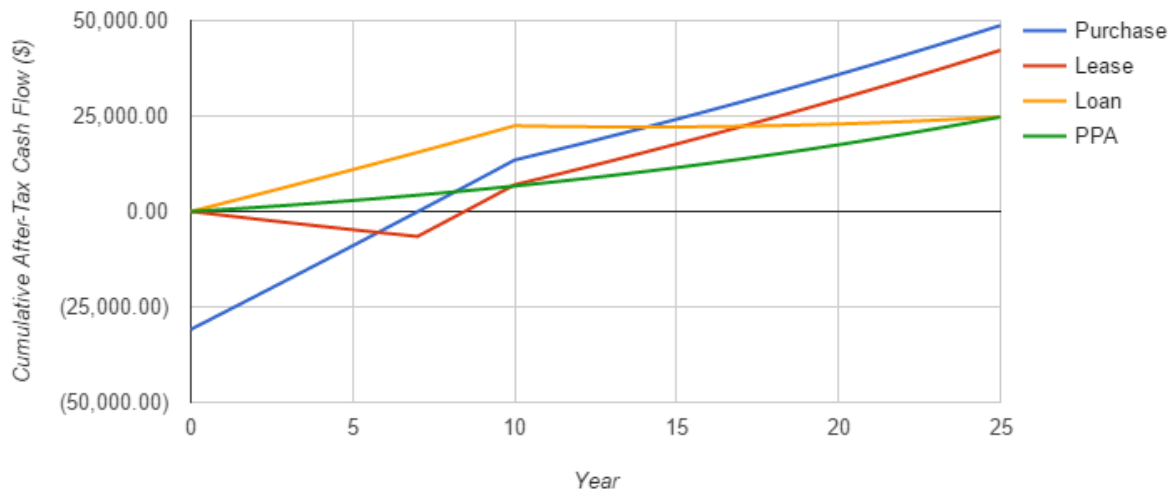


Figure 12: Cumulative cash flow of Institute Hall array. This graph compares the cumulative after-tax cash flow of the proposed Institute Hall array for different financial models.

To mitigate uncertainties in our calculations, we utilized SAM to perform sensitivity analyses on a number of variables. We performed the analyses by varying one variable at a time while holding the rest at their default values. The results of the analysis, which can be seen in Figure 13, show that there is a large amount of sensitivity to the array cost, real discount rate, and to a lesser extent, the inflation rate. The NPV is not as sensitive to other variables, such as the value of the SMART feed-in tariff and losses due to snow accumulation. The sensitivity to array cost is a factor in our recommendations, as we know that parking lot canopies are more expensive than roof-mounted arrays, but were unable to find reliable data as to the extent of this increase.

We performed an additional sensitivity analysis to changes in the parameters of borrowed capital in the loan model. SAM's default values assumed that 100% of the array's upfront cost was borrowed at a yearly interest rate of 5%. We assumed a term length of twenty-five years for the loan. As with the previous sensitivity analysis, we varied one parameter per simulation while keeping the others at their default value. The results, which can be seen in Figure 14, show the changes in net present value for the twenty-five year loan. They indicate that the value of the array is somewhat sensitive to the proportion of upfront costs borrowed, but is very sensitive to the interest rate.

To determine if the PPA was indeed the least valuable option, we conducted a sensitivity analysis on the parameters of the agreement. As can be seen in Figure 15, the net present value is highly sensitive to the PPA agreement price and is somewhat sensitive to escalation in the aforementioned price. It is possible that a PPA could compete with the other financial models at a low enough agreement price. We calculated that in order for the net present value of a PPA to exceed that of the outright purchase model, the PPA price would have to be less than the nominal LCOE. For the Boynton Lot array, the PPA price would need to be \$0.104455/kWh at a 0% escalation rate. Information from our conversation with Doug Telepman suggests that this falls within the price range of a PPA, so it is a model that should be considered in future investigations (personal communication, January 19, 2017).

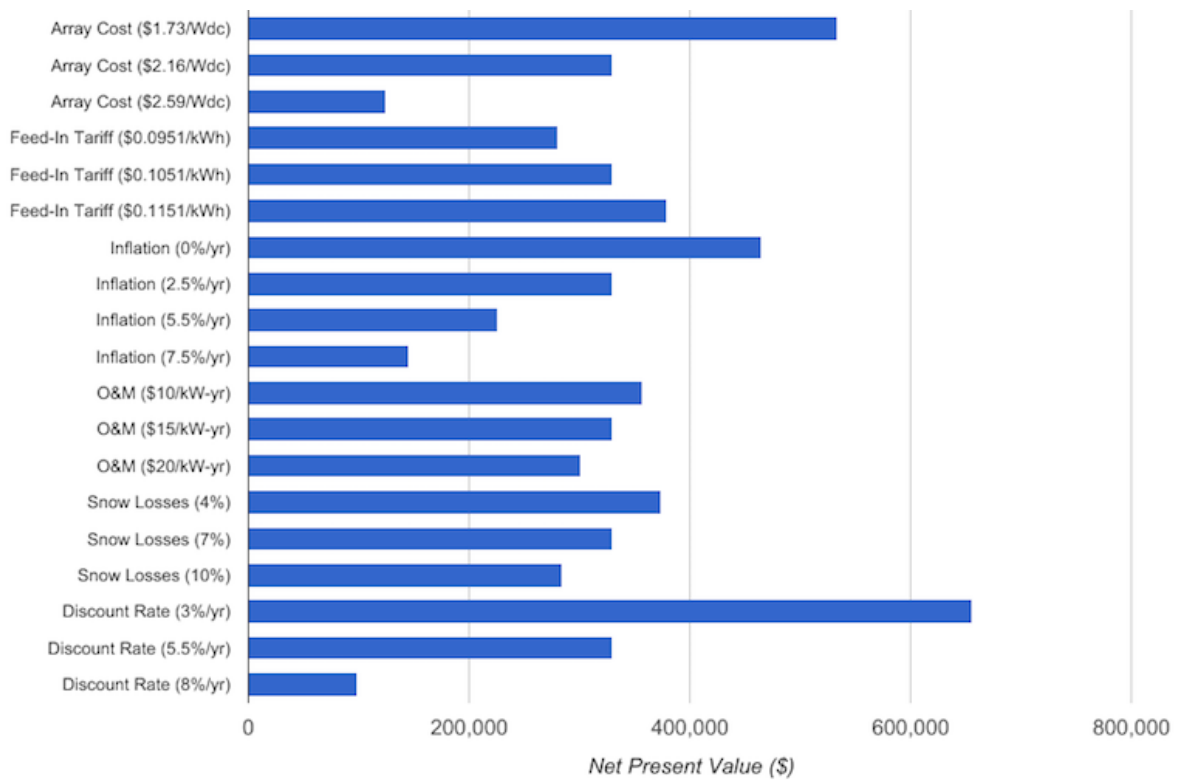


Figure 13: Boynton Lot cost and financial parameters sensitivity analysis. Sensitivity of the NPV to changes in upfront costs, O&M costs, incentive rates, inflation, real discount rate, and snow losses.

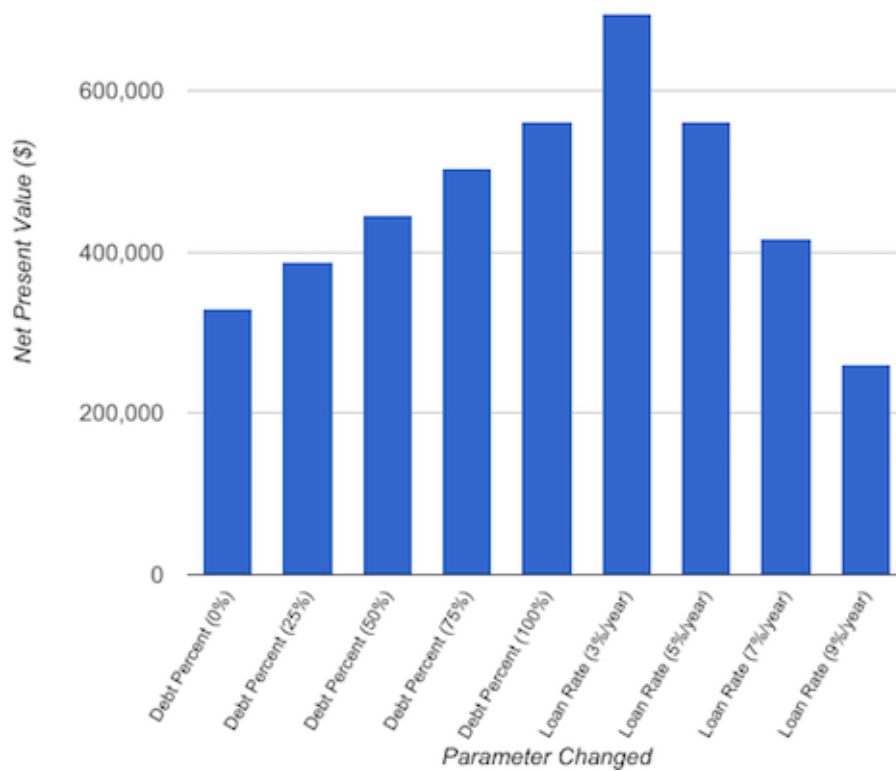


Figure 14: Boynton Lot loan sensitivity analysis. The sensitivity of the net present value of the Boynton Lot array to changes in the borrowing parameters for the loan model.

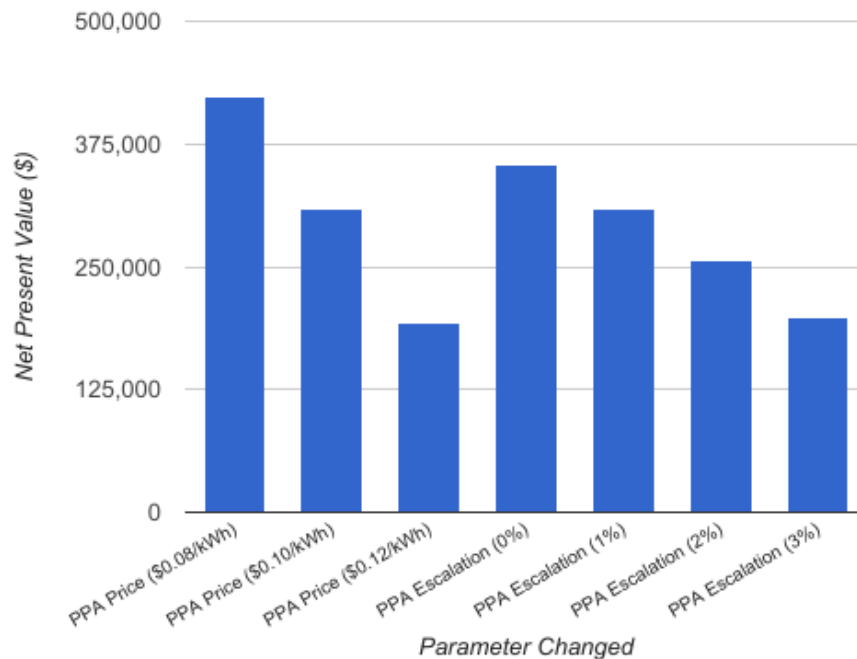


Figure 15: Boynton Lot PPA sensitivity analysis. This chart shows the sensitivity of the net present value to the price and escalation of a PPA for the proposed Boynton Lot array.

As a result of the previous analyses, we concluded that an outright purchase of the array was the most beneficial financial model. However, there is some merit to arguing that delaying the upfront costs through a loan or lease is more beneficial for WPI. A large upfront cost could siphon capital from other programs and departments, or potentially raise tuition. Furthermore, the best option is highly sensitive to the discount rate, which we were not in a position to calculate for WPI as an entity. We assumed a real discount rate of 5.5%, SAM's default value. When further investigation is conducted into PV arrays at WPI, a more thorough financial analysis ought to reveal any discrepancies with our conclusions.

While net present value is the best metric for comparing mutually exclusive options (Short et al., 1995), it is also useful to examine the payback period of the proposed arrays. This value refers to the time it would take for the electricity savings and incentives to recoup the upfront and recurring costs. By its nature, payback period is only applicable in the outright purchase model, or if a loan of less than 100% of the upfront costs is taken. As can be seen in Figure 16, the payback periods of the proposed arrays range from 6.7 to 10.5 years. This is an acceptable time frame for profitable PV installations, and supports our conclusion that an outright purchase is the most beneficial financial model.

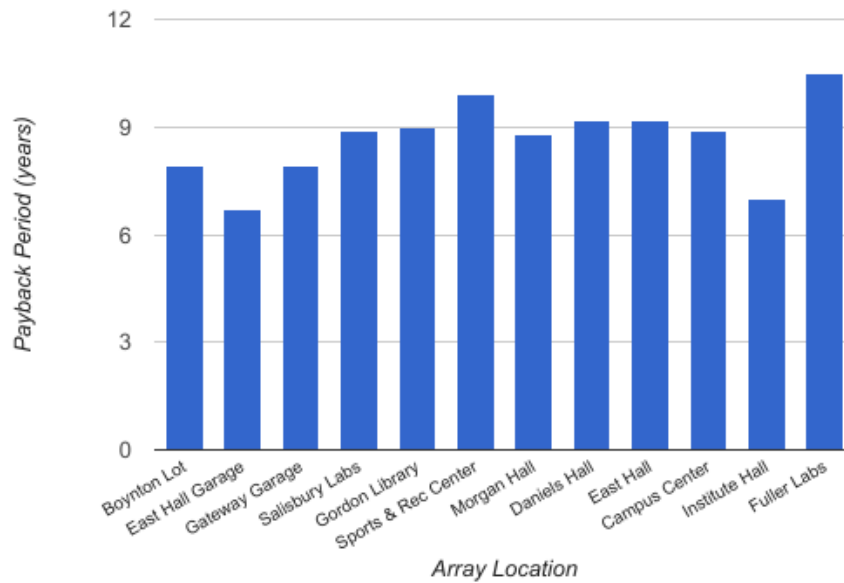


Figure 16: Payback period of arrays. This chart shows the payback period of the proposed arrays for the upfront purchase model and is sorted by descending net present value.

We performed an additional sensitivity analysis on the effects of different parameters on the payback period. Once again, the analysis was performed by varying one parameter at a time while the others were held at their default values. Figure 17 shows the sensitivity of the payback period of the proposed Boynton Lot array. As can be seen from the figure, the payback period is only sensitive to array cost among the variable we examined. This lack of sensitivity further supports the outright purchase model, since errors in our assumption have little effect on the time it would take to recoup WPI's investment in PV technologies.

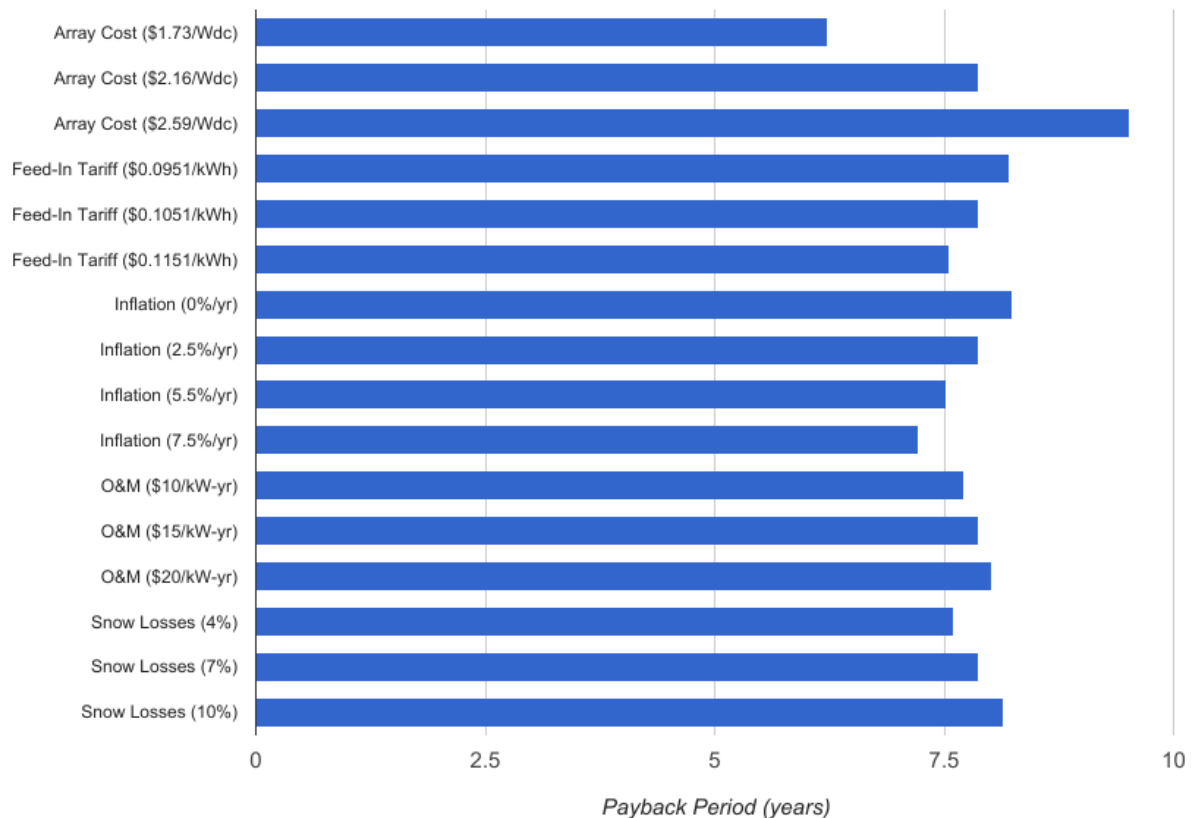


Figure 17: Payback period sensitivity analysis for Boynton Lot. This chart shows the sensitivity of the payback period of the proposed Boynton Lot array to changes in multiple parameters of the simulation. Note that simple payback period is not dependent on the discount rate, thus that variable was not included in this analysis.

4.4 PV arrays have tangible and measurable environmental benefits that supplement WPI's sustainability goals

WPI's energy distributor, National Grid, purchases energy primarily from natural gas, nuclear, and oil power plants (Buonomano et al., 2016). Table 2, which was provided by the WPI's sustainability department, shows the sources from which National Grid derives its electricity. WPI also uses natural gas for thermal energy to pressurize steam tunnels which heat the campus (Trahan, 2015).

Given that the total electricity consumption for WPI during fiscal year 2016 was 29,306,150 kWh, we used the formula given by Hosenuzzaman et al. (2015) to approximate the amount of carbon emissions that could be offset if all of the electricity on campus were produced via PV arrays. According to the report, replacement of fossil fuel combustion with PV technology saves half a kilogram of CO₂ emissions for every kWh of energy produced.

$$\frac{29,306,150.00 \text{ kWh}}{2} = 14,653,075 \text{ kg CO}_2 \text{ per year}$$

Based on the formula that half a kilogram of carbon dioxide is emitted to the atmosphere for each kWh of electricity generated by non-renewable methods, WPI indirectly caused about 14.7 million kilograms of CO₂ to be released in fiscal year 2016.

Table 2: Energy distributed by National Grid by source

National Grid Energy by Type	% of Total Energy
Natural Gas	38.60
Nuclear	28.54
Oil	10.17
Hydroelectric/Hydropower	6.09
Coal	4.05
Biomass	2.06
Trash-to-Energy	2.02
Wind	1.99
Wood	1.61
Diesel	1.48
Solar Photovoltaic	1.11
Municipal Solid Waste	1.07
Landfill Gas	0.56
Efficient Resource (Maine)	0.41
Fuel Cell	0.18
Digester Gas	0.03
Jet	0.01

Results of Environmental Analysis

According to our SAM simulations, if WPI implemented all of our modeled solar arrays, the campus would generate 1,969,398 kWh of electricity in the first year. This corresponds to a reduction of 984,699 kg of CO₂ emissions in the first year of operation. The total CO₂ offset is given by the following function, assuming a 0.5% per year degradation of the equipment, where C₁ is the CO₂ offset in the first year of operation.

$$\text{Total CO}_2 \text{ offset} = \int_1^{25} C_1 * 0.995^{t-1} dt = \frac{C_1 * (0.995^{24} - 1)}{\ln(0.995)}$$

From this function we calculated that over the 25 year life cycle of the arrays, they would offset a total of 22,266,582 kg of CO₂ emissions, an average yearly offset of 890,663 kg of CO₂. The total offset over the arrays life is equivalent to the emissions from burning 1,721,366 gallons of gasoline. It can also be expressed as the amount of carbon that would be removed by 132

acres of pine forest in 25 years. These calculations were adapted from SolarLiberty's educational webpage (*How schools and universities use solar power to generate clean power, 2017*).

The 2015 Sustainability Report released by WPI states that the campus has reduced its greenhouse gas emissions by 7% since 2014, totalling 1,402 metric tons of CO₂. The report goes on to state that the WPI office of Sustainability is currently in the process of developing a GreenHouse Gas Reduction Plan. Our findings directly support this initiative.

Figure 18 indicates that approximately 50% of the campus greenhouse gas emissions are Scope 2, which refers to indirect emissions from grid-generated electricity. The electricity generated by our proposed solar arrays would go completely towards mitigating these Scope 2 emissions.

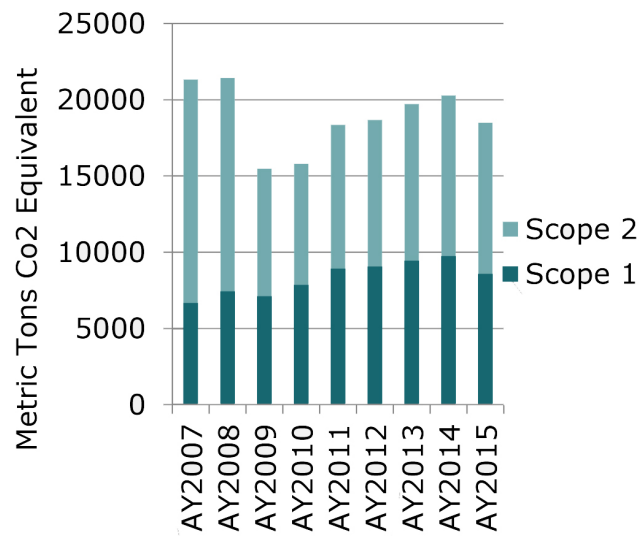


Figure 18: Campus emissions.

Obtained from WPI 2015 Sustainability Report

Conclusions and Recommendations

Worcester Polytechnic Institute has both the desire and capability to invest in solar photovoltaic technology. PV arrays on campus would both benefit WPI financially and assist in achieving the university's sustainability goals. With the continuous downwards trend in the costs of PV technology, we found that arrays were not only viable, but potentially highly profitable. The revenue generated from solar arrays could be reinvested in additional green energy projects.

5.1 Conclusions

WPI has an environmental and fiscal interest in renewable energy technology

By interviewing the directors of WPI's sustainability department and investigating its annual sustainability reports, we learned that the university has a desire to reduce its electricity usage by reducing waste, increasing efficiency, and implementing new technologies. These goals were shaped by WPI's strong focus on the societal impacts of engineering and science. We discovered that there had been previous projects which had attempted to implement PV arrays on campus, but had been unsuccessful in demonstrating significant financial profitability. However, several other institutions in the region have recently installed PV arrays, suggesting that WPI is in the position to make a profitable investment in addition to reducing its electricity use.

We learned from Bill Grudzinski, Chief Engineer at WPI facilities, that electricity costs for the university are expected to rise significantly in the near future. He showed great interest in reducing the peak demand charges WPI pays to its electricity supplier and distributor. We obtained bills and financial spreadsheet detailing WPI's electricity costs and analyzed them to determine that **approximately 13% of the total electricity charges for fiscal year 2016 were peak demand charges.**

There are numerous locations on campus that could support PV arrays

We used roof information obtained from facilities and GIS maps to compile a list of buildings that could potentially support PV arrays. Then we used a software named HelioScope to visually model arrays at twelve different locations on campus, including three parking canopy structures. We specified PV module and inverter models suggested to us by Doug Telepman, the Director of Commercial Development at Direct Energy Solar and found that our modeled arrays measured between 14.3 and 429.1 kWdc in capacity. **Combined, the twelve arrays we modeled could produce almost 2000 MWh annually. This figure represents nearly 7% of WPI's electrical use in FY 2016.**

We were unable to accurately model arrays in several locations, such as Atwater Kent, due to our lack of information on the angle of sloped roofs. Additionally, we avoided modeling arrays on buildings with highly irregular roof profiles and large amounts of obstructions. However, further investigations may show that the aforementioned buildings are viable arrays locations.

PV arrays are financially beneficial to WPI

Once we modeled WPI's physical potential for PV arrays, we used the System Advisor Model (SAM) software developed by the National Renewable Energy Laboratory (NREL) to estimate the financial outcomes of our proposed arrays. We investigated four different financial models, an upfront purchase, a capital lease, a loan, and a power purchase agreement (PPA). We found that not only would WPI recoup its investment under each model, but that it would generate significant profit beyond that point.

Under our assumed costs and conditions, the upfront purchase model provided the greatest profit. **We calculated that the largest array, a parking canopy over the Boynton Lot, would generate over two million dollars in profit over its twenty-five year lifespan with an upfront purchase.** There are advantages and disadvantages to each model. While the upfront purchase model provided the greatest profits, it also necessitates a large initial capital expenditure. The capital lease and loan options defer this initial cost at the expense of decreasing the total profit due to interest payments. The PPA assumes the least risk, as there is no expense to WPI. However under our assumed conditions, this model provides the least savings, primarily due to the value of Massachusetts production-based incentives.

There were a number of uncertainties in our data that we could not correct without extensive aid from a solar company. We estimated factors such as array cost, which depends on local site conditions. Additionally, our assumed costs were based on a 200 kW array, which lies close to the center of our range. The costs for arrays is inversely proportional with size, due to the economies of scale. Finally, we were unable to find reliable sources detailing the increase in costs for parking canopy structure, so our models for the Boynton Lot, Gateway Garage, and East Hall Garage arrays are overly optimistic.

PV arrays have tangible and measurable benefits that supplement WPI's sustainability goals

We calculated the total and average annual CO₂ offset the modeled arrays would be responsible for based on a ratio of 0.5 kg CO₂ emitted per kWh energy produced (Hosenuzzaman et al., 2015). Accounting for degradation of the PV modules, **we found that the modeled arrays would offset over 22 million kg of CO₂ emissions over their twenty-five year life, an average of nearly 1 million kg per year.** The reduction in emissions directly supports WPI's sustainability goals.

The caveat to our calculations is that the stated ratio of CO₂ offset to energy produced is a general estimate. To more accurately calculate the emissions offset, a weighted average of emissions per energy source would need to be calculated for WPI.

5.2 Recommendations

Our investigation showed that PV arrays on campus would be financially profitable and environmentally beneficial. We recommend that WPI's administration and facilities department further

investigate this matter by contacting local solar companies and obtaining cost estimates for arrays. We found that the following locations are currently suitable for array installation: Boynton Lot, East Hall Garage, Gateway Garage, Gordon Library, Sports and Recreation Center, and East Hall. We also recommend that arrays be placed on the following buildings when their rooftops are renovated: Salisbury Labs, Morgan Hall, Daniels Hall, Campus Center, and Institute Hall.

The recommendations are listed in order of descending net present value. Therefore, if there is not enough capital to finance every array, those with the highest net present value should be prioritized. Finally, we recommend further investigation into other buildings on campus, such as Atwater-Kent, which may be able to support PV arrays. We do not recommend an array on Fuller Labs. While our model indicates that such an array would still be profitable, its negative net present value means that it is a slightly sub-par financial investment. However, given a large enough budget for sustainability initiatives, a PV array on Fuller Labs may still be worthwhile for the environmental benefits.

The estimates from solar companies ought to contain the cost of equipment and installation, based on the module and inverter models they recommend. They should also consider the optimal azimuth and tilt of the array to provide the greatest financial benefit for the university.

When obtaining estimates from solar companies, WPI should consider both purchasing the array and a PPA. While our models found that purchasing was the most profitable option, the range of potential PPA prices and uncertainties in our estimates could alter that conclusion. If the profits under a PPA approach that of purchasing the array, it may be the better option due to the lack of a capital expenditure by WPI. Similarly, if the university wishes to offset the initial costs of the array, we recommend investigating a capital lease. Our models showed that the capital lease was more profitable than a twenty-five year loan and would distribute the array's cost over seven years.

We recommend that WPI investigate battery storage in the future

Our research indicated that WPI stands to significantly reduce the cost of its electricity bill through peak shaving using batteries. However, we also discovered that energy storage technologies are still in early stages of market development, and are expected to be both cheaper and more technologically advanced in the near future. We recommend that WPI formally investigate installing battery storage to supplement the PV arrays in approximately five years. We learned through conversations with solar companies that existing arrays can be easily retrofitted to incorporate batteries, so they do not need to be installed simultaneously. As an added benefit, the addition of battery storage would increase the value of state financial incentives for the array.

As part of this future investigation, we recommend that WPI subscribe to the National Grid Energy Profiler service. This program is relatively inexpensive and would provide historical and current electricity load data for WPI's campus. The data would be invaluable for determining the savings batteries would incur on peak demand charges. In conjunction to the profiler, we recommend that WPI re-implement the work done by the master qualifying project, *The Analysis of WPI's Power Grid in Worcester, Massachusetts*. This project collected electricity load data from the

campus buildings submetered under the powerhouse and stored them in a spreadsheet. However, the historical data has been erased and current data is not being collected and stored. This data would increase the accuracy of the analysis done by the energy profiler.

5.3 Technology and Society

It is difficult to avoid self-bias when investigating technologies that better society

As we worked on our project, we constantly had to struggle with the fact that the technologies we were investigating might not serve WPI's best interests. It was evident that PV arrays and, to a lesser extent, battery storage were environmentally beneficial. However, WPI's primary responsibility is not to the environment, but to its stakeholders, students and researchers. Our initial goal was to completely offset the campus's electricity usage with renewables, something we quickly found was impossible due to WPI's geographical location and high energy usage. We were also very eager to investigate battery storage to reduce WPI's electrical bills through peak-shaving.

It was disappointing to learn that batteries were not yet viable on a commercial scale. One of our greatest regrets is that we had to rely on outside sources for this conclusion as we were unable to gather electrical load information to accurately model battery storage. Furthermore, it was only after our financial analysis that we discovered that PV arrays would not only benefit the environment, but also generate profit for the university. Before this analysis was complete, we feared that we might have to recommend against investing in renewables.

It is important to quickly and rigorously define the objectives of the project

One of our greatest challenges was establishing a plan for the project in order to know what work needed to be done. As we progressed, we better defined the scope of our project, and our efforts became more focused and efficient. In retrospect, we should have spent more time researching in the early stages of the project. Specifically, we should have examined more case studies at other universities to aid us in defining our projects scope and objectives. The information from these studies would have allowed us to work more effectively throughout the project.

Aggressively pursue data that is important to the project

One of our project goals was to analyze battery storage in conjunction with PV arrays. We were largely unable to meet this goal due to our inability to obtain high-resolution electrical load data for the campus. In retrospect, a more insistent approach might have yielded us that data. We learned of its existence early in our research, but did not promptly pursue all avenues in obtaining it. It was only later that we discovered that the load information from buildings connected to the powerhouse had been erased. Our subsequent requests for access to the National Grid Energy Profiler were too late in the process to be successful.

5.4 Suggestions for Future Research

Green Revolving Fund

To pay for the aforementioned renewable energy technologies and future sustainability projects, we recommend that future project groups and the sustainability department investigate the establishment of a green revolving fund. A green revolving fund is an internally created investment managed by a committee of various stakeholder groups including students, faculty, and administrators, or through the finance, facilities, and sustainability offices. These funds typically finance projects and efforts including energy efficiency, waste reduction, facility improvements, and renewable energy implementation. The cost savings and profits generated through these programs and investments could fund future projects, creating a cycle of sustainability efforts to reduce the institution's environmental impact (Indvik, Foley, & Orłowski, 2013).

Integration of Renewable Technologies with Educational Efforts

Beyond the environmental and financial impact, another benefit of implementing PV arrays on campus is an educational one. One of the academic goals of the sustainability report is "Achieving social justice and meet basic human needs in sustainable global development through integration with academic programs". A solar PV array could also help meet this goal by providing an educational example of solar technology for engineering students (Orr, Tomaszewski, MacDonald, Pollin, & Engbring, 2013).

Future classes could incorporate studying the technologies into their curriculums. An updating electronic display could be placed in a prominent location on campus to show the current electricity output of the arrays. Additionally, WPI could have a dynamically updating website that displays the status of solar electricity generation in real-time.

There are a multitude of methods for utilizing renewable energy technologies to improve the experience of students at WPI. If these technologies are installed on campus, we recommend that future project groups investigate their educational benefits and develop a plan to expose WPI's community to those benefits.

5.5 Project Conclusion

The goal of this project was to determine the financial feasibility and environmental impact of PV arrays and battery storage on WPI's campus. We found that PV arrays were financially profitable and are valuable investments for the university. Additionally, they would aid in achieving WPI's sustainability objectives. We discovered that battery storage technology is expected to become significantly more efficient and less expensive in the next five years. We recommended that WPI formally investigate the installation of PV arrays at multiple locations on campus and that they similarly investigate battery storage in the near future. The implementation of our recommendations would advance WPI's commitment to benefiting society through science and technology.

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Appendix A:

Rooftop and Array Information

As part of our research for this report WPI facilities provided us with campus building rooftop information presented in Table 3. It details the rooftops' ages, material type, and when renovations are planned. As can be seen in Table 3, many rooftops on campus are past their expected replacement date. This fact severely limited the number of buildings at which we could recommend array installations. However, should rooftops renovations occur at those buildings, we recommend investigating the simultaneous installation of PV arrays. Our financial models showed profitability across the entire range of array sizes.

We modeled arrays using HelioScope based on GIS maps of WPI's campus. These models gave us an estimate of the DC power rating of the arrays, which we used as inputs for our financial calculations in SAM. Figures 19 and 20 show a sample two-page report generated from HelioScope. The rest of the reports can be found in the supplementary materials. Note that we used different system loss values to account for snow accumulation. The inputs we used for SAM were the Module DC Nameplate, Load Ratio, Tilt, and Azimuth. If the load ratio was below 1.00, we set it to the default of 1.10 to prevent significant system losses. While the specific PV module and inverter models were recommended to us by Doug Telepman, they will depend on market availability and the site conditions.

We set the Azimuth of the panels, their orientation with respect to the cardinal directions, in line with the edges of the buildings. While this technique reduces the individual efficiency of the panels, it allows more panels to be placed in the array. A previous project modelling a PV array on the library found that aligning the panels with the sides of the roof increased the fiscal savings from the array (Mayer, 2010).

As a final note, there has been recent construction on the roof of the Gordon Library, which was not shown in HelioScope's GIS maps during our modeling. Thus, the size of the array on the library will likely be smaller than our estimate.

The tilt of a solar panel is the angle it makes with the plane tangent to the Earth's surface. We set the tilt of the PV modules to 37° , approximately 5° lower than WPI's latitude. Our research (Rhodes, Upshaw, Cole, Holcomb, & Webber, 2014) suggested that this orientation optimizes a PV array's financial savings when compensating for the latitude and time-of-use electricity rates in Massachusetts.

To account for array losses due to snow accumulation, we referenced an NREL report (Ryberg & Freeman, 2015) which found losses of 4-10% in Massachusetts. We chose the center of this range as our default value and later performed a sensitivity analysis on the parameter.

The remainder of the arrays we modeled can be seen in Figures 21 and 22. We made many estimates for the size and height of roof obstructions to account for shading. Thus, it is almost certain that the layout and size of the arrays will be different than what a professional solar company would supply once a full site and solar survey is conducted.

Table 3: Rooftop material and age

Building	Use	Type	Building Age	Roof Age	Due To Replace	Material
Gordon Library	Academic	Flat	1967	2009	25yrs	Rockwell white hypalon rubber
Daniels Hall	Administrative/ Residence	Flat	1963	2004	20yrs	EPDM black rubber
Campus Center	Student Life	Flat	2000	2000	20yrs	045 EPDM black rubber
Ellsworth Apartments	Residence	Pitched	1973	1994	5-10yrs	Asphalt shingle
East Hall	Residence	Flat	2008	2008	25yrs	White hypalon rubber
Fuller Labs	Academic	Flat	1989	1988	3-5yrs	Ballast rubber
Gateway	Academic	Flat	2007	2007	25yrs	Black rubber
Goddard Hall	Academic	Flat	1965	2005	25yrs	White rubber roof
Institute Hall	Residence	Flat	1989	1975	1-5yrs	PVC rubber
Lee Street	Administrative	Flat	1886	2009	25yrs	EPDM black rubber
Morgan Hall/Wedge	Administrative/ Residence	Flat	1959/1976	1982	3-7yrs	Tar and gravel
Power House	Auxiliary	Flat	1894	2005	25yrs	EPDM black rubber
Project Center	Academic	Flat	1902	1980	2-5yrs	Smooth built up asphalt
Stoddard A	Residence	Flat	1970	1970	1-3yrs	Membrane insulation with rock
Stoddard B	Residence	Flat	1970	1970	1-3yrs	Membrane insulation with rock
Stoddard C	Residence	Flat	1970	1970	1-3yrs	Membrane insulation with rock
Stratton Hall	Academic	Flat	1894	1960	2-6yrs	Smooth asphalt
Alumni Gym	Administrative /Recreation	Flat	1916	1982	2012	Tar and gravel
Atwater Kent	Academic	Portion	1907	2006	25yrs	White hypalon rubber
Higgins Labs	Academic	Portion	1942	1996	10yrs	EPDM black rubber
Olin Hall	Academic	Portion	1959	1998	20yrs	Smooth asphalt
Washburn Shops	Academic	Portion	1868	1980	2-6yrs	mixed age and roof type
East Hall Garage	Parking		2008			
Gateway Garage	Parking		2007			
Salisbury Estates	Residence	Pitched		1948	1948	Slate
Sports and Rec Center	Administrative/ Recreation	Flat	2012	2012		

This table shows the ages, material makeup, and expected replacement date of buildings on campus. Note that this data was compiled in 2010 and certain entries may be out of date.

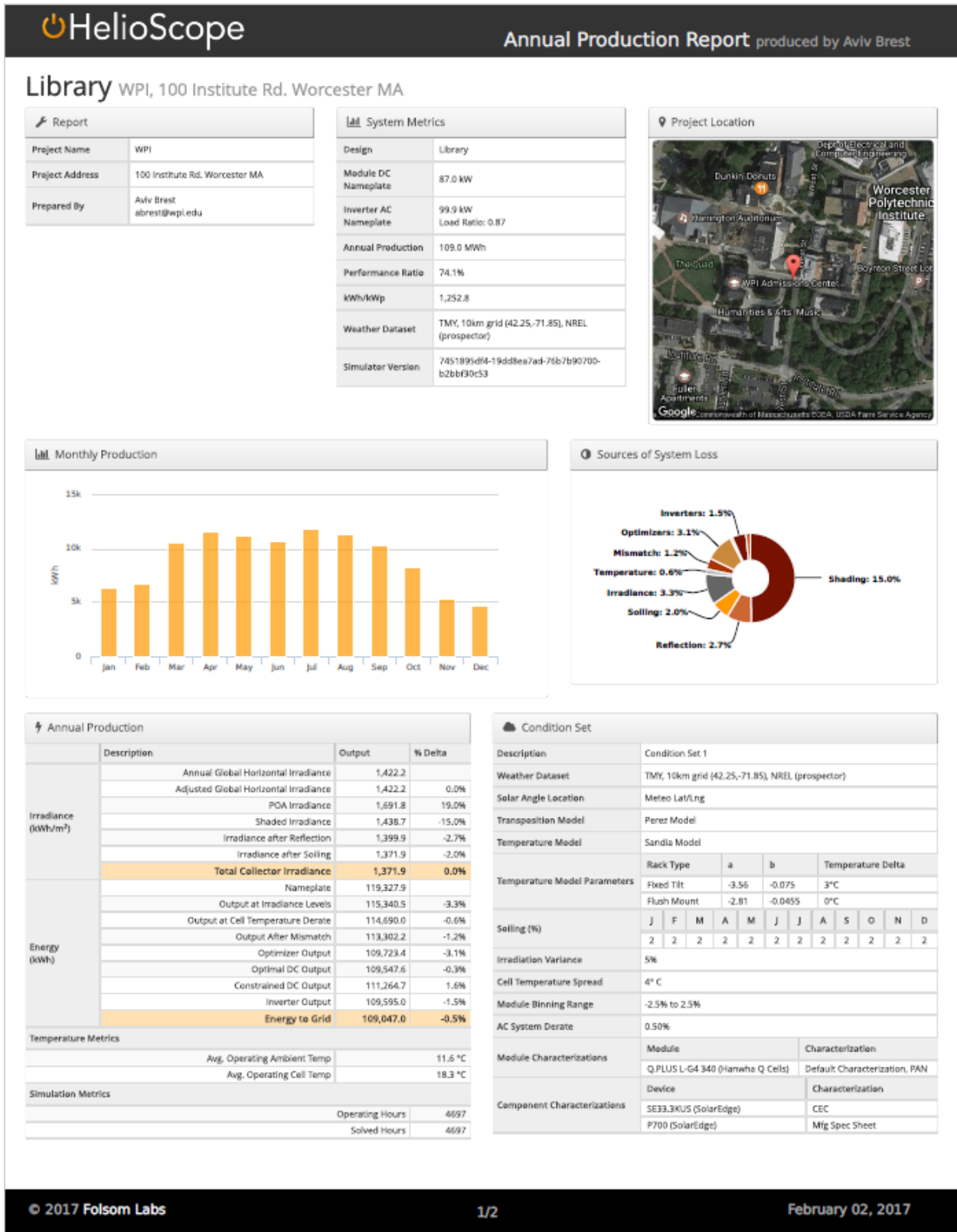


Figure 19: HelioScope report page 1. The first page of the HelioScope report for the Gordon Library.

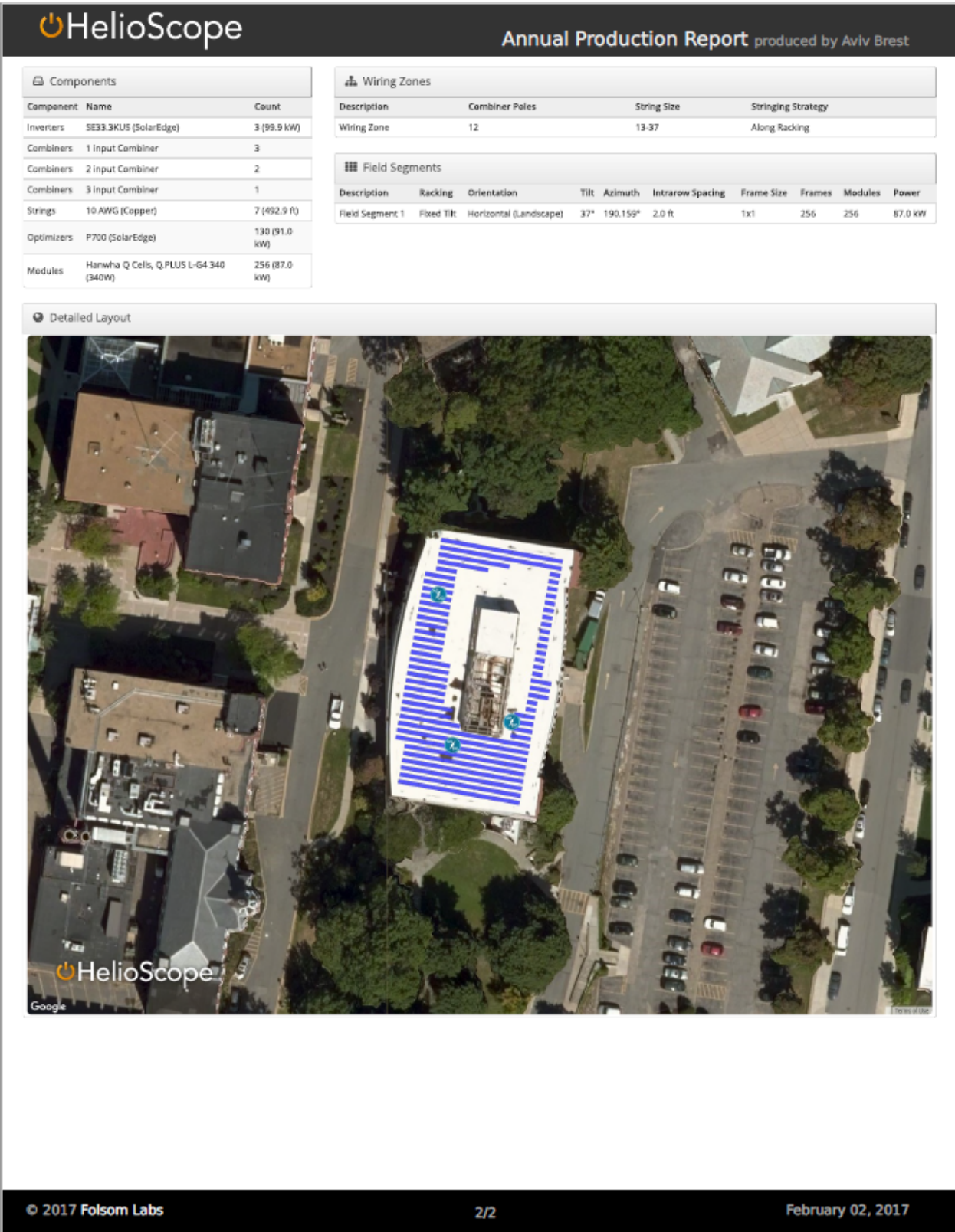
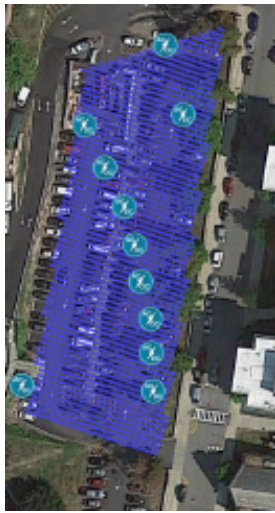


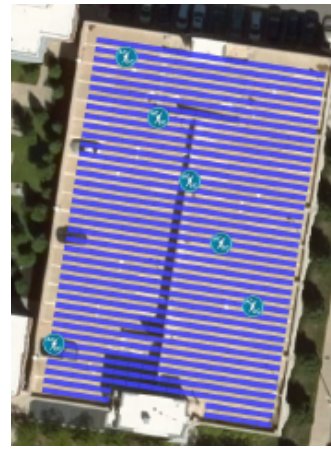
Figure 20: HelioScope report page 2. The second page of the HelioScope report for the Gordon Library.



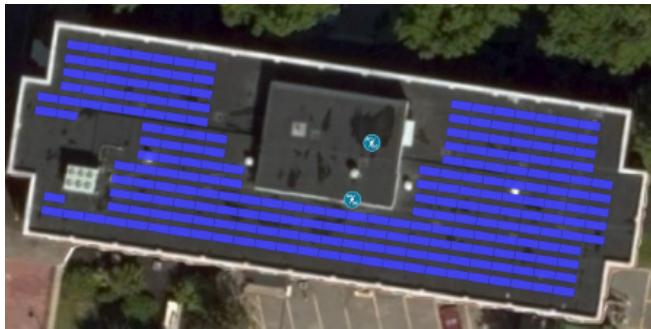
Boynton Lot



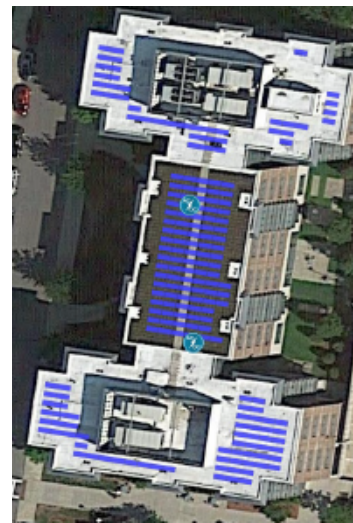
Campus Center



East Hall Garage

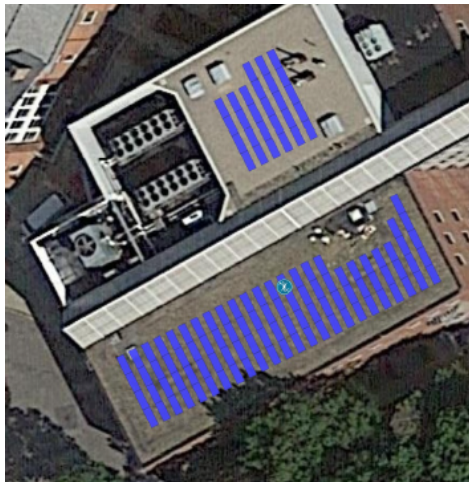


Daniels Hall

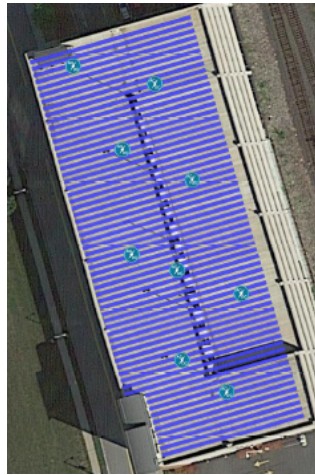


East Hall

Figure 21: Visual representation of proposed arrays (part 1)



Fuller Labs



Gateway Garage



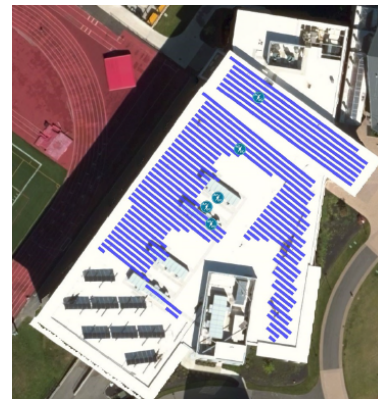
Institute Hall



Morgan Hall



Salisbury Labs



Sports and Recreation Center

Figure 22: Visual representation of proposed arrays (part 2). Note that the array for the Sports and Recreation Center is offset due to HelioScope changing between different GIS services when printing the report.

Appendix B:

SAM Parameters and Simulation Results

The following paragraphs describe and justify our SAM simulation inputs. We used default values except where we could find reliable sources which improved simulation accuracy.

We kept the inflation and real discount rates at the defaults of 2.5% and 5.5% respectively. According to SAM's documentation, that inflation rate was based on data from the U.S. Department of Labor's Bureau of Labor Statistics. In terms of the simulation, the inflation rate affects the system costs, incentives, and electricity rates. The real discount rate is the measure of the time value of money, the concept that a given amount of capital is worth more in the present than in the future due to its potential to increase itself. According to SAM's documentation, the financial outputs are highly dependent on the real discount rate. It continues by stating that this rate is highly subjective and that there is little concrete information published about its value.

For electrical cost inputs, we made several approximations. For arrays connected to the powerhouse, we calculated the rates for on and off-peak electrical usage for every month in \$/kWh, then took the averages in three-month sections, since SAM limits the number of inputs to nine. After calculating the rates, we noticed that while they varied between months, the standard deviation for the set was very low. We calculated the ratio of the standard deviation to the mean was approximately 0.6%. Thus we felt it was an adequate approximation to use the electricity rate data from a single month and apply it to the entire year. We chose the first month Nov-Dec 2015. It had the lowest electricity rates for the powerhouse, making our results more conservative.

Table 4 shows the cumulative after-tax cash flow in the 25th year of each proposed array under every financial model. Note that the same pattern holds for most arrays with our assumed conditions. The upfront purchase is the most profitable, followed by the capital lease, the twenty-five year loan, and finally the PPA.

The full SAM project files used to make these calculations can be found in the materials attached to this report. There is one project file per proposed array and within each file there are four tabs, one for each financial model.

Table 4: Cumulative cash flow of arrays

Array Location	Purchase	Capital Lease	Loan	PPA	Array Cost
Boynton Lot	2,009,654.70	1,815,149.30	1,292,045.20	872,116.30	927,371.00
Gateway Garage	1,620,334.60	1,463,588.00	1,042,031.40	675,851.20	747,343.00
East Hall Garage	1,224,146.60	1,113,301.53	851,322.60	412,894.38	464,442.00
Sports and Rec Center	661,719.80	568,795.90	318,885.72	328,494.56	443,046.00
Salisbury Labs	376,023.70	331,646.40	212,298.94	181,411.16	211,581.00
Gordon Library	327,248.80	287,812.50	181,753.14	159,445.28	188,024.00
Daniels Hall	273,555.60	239,513.60	147,961.05	135,267.35	162,306.00
East Hall	244,010.00	213,957.48	133,132.80	115,201.36	143,288.00
Morgan Hall	219,379.50	194,086.06	126,061.81	104,893.04	120,595.00
Campus Center	182,608.77	161,032.04	103,004.19	88,275.83	102,873.00
Fuller Labs	116,505.93	98,147.79	48,775.30	65,633.78	87,529.00
Institute Hall	48,719.04	42,237.07	24,804.29	24,746.57	30,905.00

This table shows the total expected profit from each array under every financial model and the array's cost. It is sorted in descending order of profit for the purchase model.

Appendix C:

Financial Incentives

This appendix details the financial incentives that apply to commercial PV arrays in Massachusetts. Under the upfront purchase, capital lease, and loan models, WPI would receive the financial incentives. However, as a nonprofit institution, WPI does not pay income or property taxes, and therefore does not receive any benefit from associated tax credit incentives. Under a PPA, the company owning the PV array would benefit from the incentives, and as a for-profit company, would be able to make use of the aforementioned tax credits.

Solar Massachusetts Renewable Target (SMART)

SMART is a feed-in tariff style program that is replacing SRECs and is scheduled to begin in January 2018. It rewards the owner of a PV array with a monetary payment per kWh of energy produced. The rate of this incentive varies based on a number of factors, including the array's power output, array type (building mounted, parking canopy, ect.), and the presence and size of energy storage. The details for the project are mostly finalized, but may change before implementation. They can be found in the presentation given by Judson in January 2017.

The initial clearing price for smaller arrays is based on a competitive bidding process for projects greater than 1 MW in size. Entities planning to build a PV array of this size will bid on the incentive rate, and then be ranked in according to their bid. The ceiling for the bids is set at \$0.15/kWh. For the first block, projects totaling 100 MW in capacity will be selected in order of increasing bid price. Once the 100 MW of projects has been selected, the highest bid among those projects is set as the clearance rate for all projects within that block. This rate then applies to smaller arrays as well.

Once the initial rate is set, it is multiplied by a factor based on the size of the array. Applicable factors for this report are 200% for projects less than 25 kW, 150% for projects ranging from 25 kW to 250 kW, and 125% for projects ranging from 250 kW to 500 kW. The term length of the incentive is set to 20 years for all arrays greater than 25 kW in size and 10 years for arrays of 25 kW or less.

In addition to the base rate multiplied by the size factor, certain adders will be applied based on the nature of the project. Applicable adders include \$0.02/kWh for building-mounted arrays and \$0.06/kWh for solar canopies. There is an additional adder for energy storage that is calculated based on the capacity related to building usage. This adder would apply to installed PV arrays once the battery storage is incorporated.

For behind-the-meter projects, which is what WPI would install, the final rate is constant throughout the incentive term, regardless of changes to energy prices. It is calculated by the following formula:

Behind the Meter Solar Tariff Generation Unit Compensation Rate = Capacity Based Rate + Adders - (Three year average of Volumetric Delivery Rates + Three year average of Basic Service Rate)

Renewable Energy Equipment Sales Tax Exemption

Massachusetts has exempted photovoltaic equipment from its state sales tax of 7% if the system is used for a residence's primary or auxiliary power generation. While this only applies in the residential sector, a similar exemption applies to nonprofit organizations, such as WPI.

Renewable Energy Credits (RECs)

Some states utilize a REC model of solar incentivizing, whereby the state government will award you with solar renewable energy credits, or SRECs, for a set amount of solar energy generated. Generators of renewable energy will sell or use the energy created, and then have the option of selling the RECs as well. In the United States one REC is created each time a qualified system generates 1 megawatt hour (MWh) of electricity (Hasic, 2011).

There is a market for these renewable energy credits as many state governments impose a requirement on electric supply companies that a certain percentage of energy generated must from renewable sources, which are: solar, wind, geothermal, hydro-power, biomass and biofuels, and hydrogen powered fuel cells (Hasic, 2011). This regulation is called a renewable portfolio standard or RPS. RECs are used as a sort of tracker, telling the government how much renewable energy has been generated. One way of meeting the state's RPS is to buy the REC's from other energy creators. Buying REC's encourages renewable energy generation, and promotes growth in the industry. The Massachusetts REC program is concluding at the end of 2017, and will be replaced with the SMART feed-in tariff program, which will provide a much more predictable incentive value.

Net Metering

For buildings that are connected to an existing grid infrastructure, the energy from the grid is still used as either the primary supplier of energy or as a backup source of energy during times of insufficient energy yield, depending on the size of the PV array and the electricity consumption of the building. In some jurisdictions, net metering policies are in place (Durkay, 2014) which mandate that the utility company credits the excess energy delivered from solar panels back to the energy producer. These credits offset the cost of using the grid's power, so even though the energy from the grid may not have been produced sustainably, its environmental impact has been effectively nullified. In many cases this strategy may be optimal because it requires no upfront investment in energy storage solutions. However, the proposed arrays at WPI are not expected to ever exceed the buildings energy demands, and thus net-metering is largely inapplicable for the university.