THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

ENHANCED ANALYSIS OF SOLAR UTILITY AT PENN STATE USING TRADE SPACE VISUALIZATION

EGOR IVANOV
SPRING 2017

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Mechanical Engineering
with honors in Mechanical Engineering

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ABSTRACT

The primary purpose of this thesis is to examine the viability of developing a 2.5 MW solar energy conversion system to increase solar utility for Penn State and relevant stakeholders. The thesis also aims to demonstrate the value of trade space visualization in analyzing large data sets and the effects of several parameters on certain outputs. System Advisor Model (SAM) has been used to develop performance and financial models for diverse renewable energy systems, but is unable to effectively visualize large sets of parametric data. The Trade Space Visualizer (ATSV) developed by the Applied Research Laboratory at Penn State, was used to more effectively analyze such data sets and develop accurate conclusions. The thesis first examines the effects of varied technological parameters associated with the solar modules, inverters, and batteries on the performance and economics of the system. Next, the effects of local electricity rates and energy policies on system economics are analyzed. Finally, grants and incentives are considered to view the effects that they have on the economic viability of the overall system. The results show that varying technological parameters such as modules, inverters, and batteries has little effect on the outputs of the system. The variance of these parameters alone is unable to generate a positive net present value and justify the development of the system. On the contrary, electricity prices and incentives have a major effect on the economic value of the system. If electricity prices in the State College area experience a significant spike, or Penn State receives rebates or incentives exceeding $0.13/kWh, Penn State can begin to generate a positive net present value on the system with a payback period of less than 10 years.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would first off like to thank Dr. Jeffrey Brownson for welcoming me to his solar research team as a mechanical engineering student. Dr. Brownson has provided endless time and support to help me obtain all of the necessary background and resources I needed to succeed in both the technical and literary components of my thesis project. I would also like to thank Dr. Meghan Hoskins and the rest of the solar team for helping me surpass any obstacles I encountered throughout my research. Dr. Hoskins and the resources provided by the Applied Research Laboratory were vital for the development of clear and effective visual representations of the collected data. Additionally, accurate models and simulations could not have been developed without the help of Mike Prinkey and the Penn State Office of the Physical Plant (OPP). Hence, I would like to thank Mike for supporting our research and providing us with the necessary resources associated with Penn State's energy use. I would also like to contribute this paper to Mike and the OPP so that this research can be further developed as electricity rates and energy policies continue to change. Finally, I would like to thank my parents and sister for their endless support throughout the last twenty-two years for without them, none of this would have been possible.

Chapter 1

Introduction

The Pennsylvania State University is a public, land-grant institution. Penn State's University Park Campus is located in State College in central Pennsylvania and has a population of 46,000 students [1]. In order to accommodate all students, faculty, and staff, the University Park campus contains about 260 facilities that use over two million British thermal units (BTUs) of energy per year [2]. This energy is generated using commodities including oil, natural gas, coal, and hydropower to provide services such as heating, hot water, and electricity. Electricity, which is currently purchased from outside suppliers, makes up approximately 30% of Penn State's energy portfolio [3]. Throughout this research, the costs at which Penn State currently purchases its electricity are explored and analyzed with the aim to decrease these costs by maximizing solar utility for Penn State and relevant stakeholders. In this case, solar utility is the preference for solar goods and services needed to provide power, heat, light, food, etc. [4]. The primary client for the solar project will be the Office of the Physical Plant (OPP) at Penn State, but additional stakeholders include all of those affected by the project (i.e. students, faculty, engineers, community members, etc.).

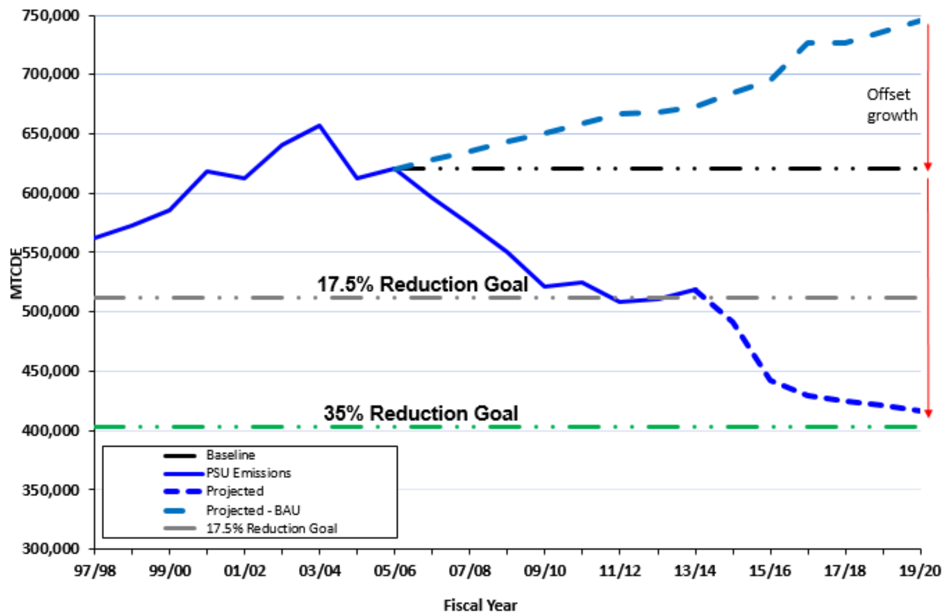

Figure 1.1. Penn State's greenhouse gas emission reduction strategy includes goals to reduce its 2005 emission levels by 35% by 2020**.**

Through the development of a community-scale energy solar conversion system, Penn State can diversify its energy portfolio and reduce carbon emissions. Penn State has established a target to reduce its carbon emissions to 35% of its 2005 emissions by 2020 (Figure 1.1). The success of this goal will require additional use of renewable energy sources, such as solar energy. Penn State has already reduced emissions by about 18% by switching to natural gas steam plants and partnering with the Mahoning Creek Hydroelectric Facility which supplies 8% of Penn State's energy [3]. This research seeks to establish justification and support for the development of a 2.5 megawatt (MW) photovoltaic (PV) energy conversion system to add to Penn State's renewable energy portfolio.

Chapter 2

Background

2.1 Energy History

2.1.1 Pennsylvania

Solar energy in Pennsylvania currently produces less than 1% of the state's net electricity generation [5]. However, according to a study by NREL, solar PV is capable of offsetting 34.5% of all electricity sold in the state in 2013 [6]. Hence, the number of utility-solar installations gradually continues to increase as multiple programs have been developed with the aim to expand the amount of solar deployment throughout Pennsylvania through funding and incentives. These programs are summarized in Table 2.1 [7].

Table 2.1. Programs to stimulate the growth of solar energy in Pennsylvania include the Solar Energy Program, AEPS Alternative Energy Program, The Pensylvania Sunshine Solar Program, and Finding Pennsylvania's Solar Future.

Program	*Years*	*Description*
Solar Energy Program	2008-Present	Loans for component manufacturers of solar energy generation equipment up to $40,000 for every new job created within three years after approval of the loan.
AEPS Alternative Energy Credit Program	2004-2021	Requires 0.5 percent of electricity be supplied from solar PV systems by 2021.
Pennsylvania Sunshine Solar Program	2009-2013	The Pennsylvania Department of Environmental Protection (DEP) was allocated $100 million to provide loans, grants, reimbursement or rebates to individuals or small businesses to help fund solar energy projects in Pennsylvania.
Finding Pennsylvania's Solar Future	2017-2019	State policy aimed to increase the amount of in-state electricity sales that come from in-state solar energy generation to 10% by 2019.

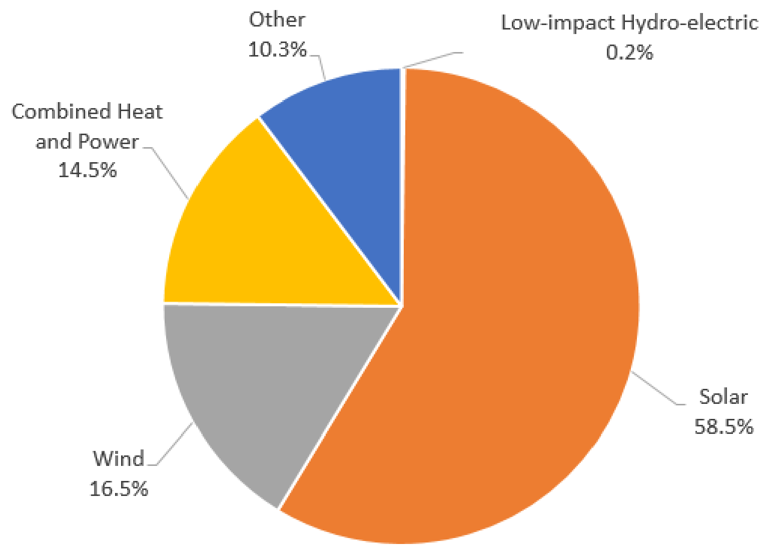

Figure 2.1. Pennsylvania's clean energy sector currently employs more than 66,000 workers, which is greater than the 59,100 employed in the oil and gas industry. Of the 66,000 workers employed, 58.5% of these workers are in the solar industry [8].

The development of solar and other renewable energy sources has also allowed for significant job growth in the energy sector in Pennsylvania. According to Clean Jobs Pennsylvania, the clean energy sector in Pennsylvania employed more than 66,000 workers at 5,900 businesses and establishments in 2015. This represents a 15% increase over the number of clean energy jobs in the state in 2014, with the solar industry leading the way in job growth. As shown in Figure 2.1, nearly 60% of Pennsylvania's renewable energy workforce was employed in the solar industry [8]. With nearly 40,000 employees in the solar industry, solar alone provides almost as many jobs as the oil and gas industry. Based on reports by the Department of Labor and Industry and the U.S. Energy Information Administration, there were an estimated 52,500 employees in natural gas jobs and just 6,600 jobs in coal in Pennsylvania in 2015 [9].

Solar growth was especially stimulated in Pennsylvania due to the establishment of the Pennsylvania Sunshine Program in 2008. In 2008, Pennsylvania had less than 3 MW of (PV) installed capacity. With the Sunshine Program, the Pennsylvania Department of Environmental Protection (DEP) was allocated $100 million to provide loans, grants, reimbursement or rebates to individuals or small businesses to help fund solar energy projects in Pennsylvania. This resulted in a significant spike in solar growth from 2009 to 2013 as evidenced in Figure 2.2. By the end of 2013, Pennsylvania had approximately 200 MW of PV systems installed [10].

After funding for the program expired in 2013, solar growth again began to slow in the following years. As other incentives and programs were established, however, solar capacity still increased by 25% in 2015 (Figure 2.2) as Pennsylvania added 13 MW of installed capacity during 2016 [11]. Pennsylvania now generates 273 MW of solar energy which ranks the state 16th in the country in solar PV installed capacity. However, of this installed capacity, only 22 MW are generated by utility-scale operations. Over the next 5 years, Pennsylvania is expected to install another 572 MW of solar electric capacity as solar PV system prices have decreased 66% since 2010 and continue to drop at a steady rate [11].

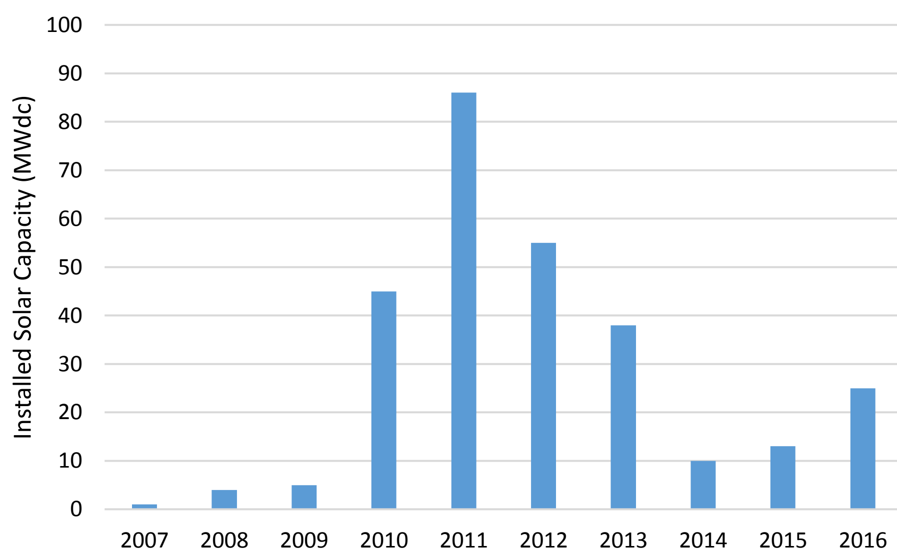

Figure 2.2. Annual solar installations in Pennsylvania experienced a spike between 2010 and 2013 due to the Sunshine Solar Program [10].

Table 2.2. Counties in the Philadelphia area lead the way in installed solar capacity due to higher electricity prices. Counties in Central and Western Pennsylvania have much smaller installed capacities due to lower electricity prices [12].

Solar Generating Capacity (MW)	*Installations*	*County*	*Region*
47.02	963	Lancaster	Pennsylvania Piedmont
20.88	839	Chester	Delaware Valley
16.24	831	Montgomery	Delaware Valley
15.11	733	Bucks	Delaware Valley
15.01	452	York	Pennsylvania Piedmont
14.21	425	Berks	Pennsylvania Piedmont
13.31	67	Carbon	The Poconos
12.30	255	Northampton	Pennsylvania Piedmont
9.25	233	Philadelphia	Delaware Valley
8.32	295	Cumberland	Pennsylvania Piedmont
3.67	281	Delaware	Delaware Valley

Central Pennsylvania and the Centre County area have experienced a significant lack of growth in solar as evidenced in Table 2.2 and Figure 2.3. Table 2.2 demonstrates that the leading counties in solar installations and solar capacity are primarily focused in the Delaware Valley and Pennsylvania Piedmont regions, which surround Philadelphia in the southeastern part of Pennsylvania. As shown in Figure 2.3, the western counties of Pennsylvania also lack solar installations, as Allegheny County (Pittsburgh and the surrounding area) is the only county in western Pennsylvania that appears in the top 20 counties for power generated by solar (number 19 in the state). Central Pennsylvania clearly has even less solar installations as seen in Figure 2.3, with less solar installers available in the area. This lack of growth in solar capacity is primarily due to economic reasons and the varying prices of electricity. Throughout highly populated areas such as Philadelphia, Pittsburgh, and the surrounding regions, the demand for energy is much higher, which also causes traditional electricity prices to increase. Likewise, areas with low energy demand, such as Centre County, have access to lower electricity prices from the grid. In order to make solar energy projects viable in these areas, the electricity prices produced from the solar projects must be lower than or equal to the cost of electricity from the grid.

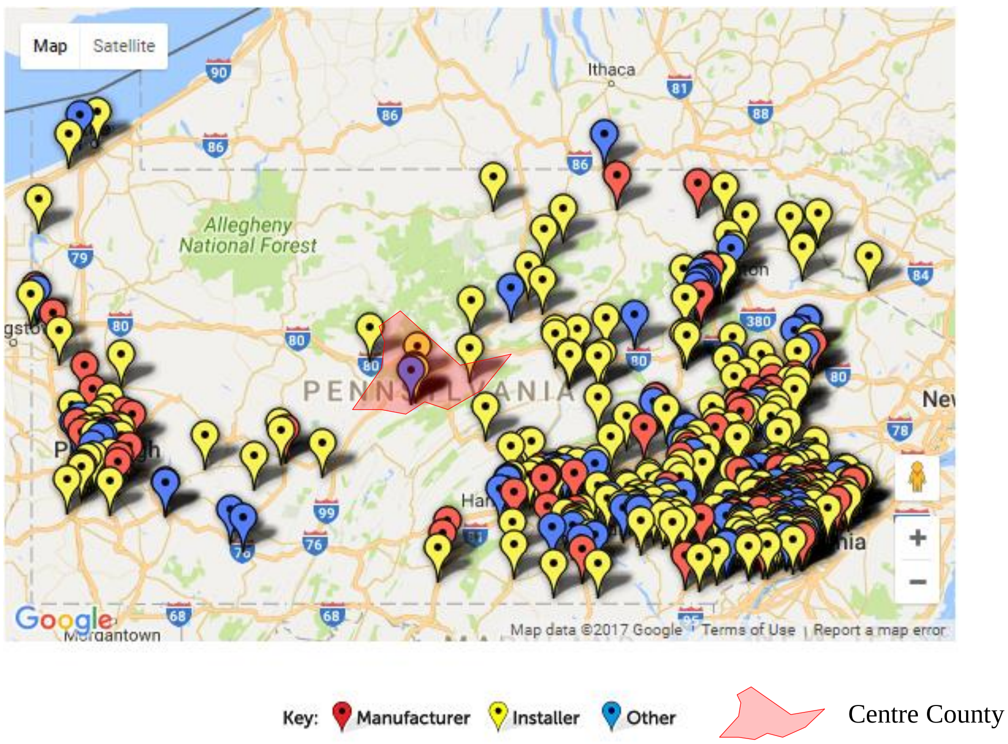

Figure 2.3. Significantly less solar manufacturers and installers are located in the Centre County area where electricity prices are low relative to areas with more congestion [11].

2.1.2 Centre County

Penn State University is located in the borough of State College in Centre County, Pennsylvania. As seen in Figure 2.3, Centre County and central Pennsylvania in general have an extremely small amount of solar capacity relative to the rest of the state. However, based on simulations in SAM, it can be shown that the irradiation throughout Pennsylvania is relatively stable and there is no significant gap in energy generation capability between Pittsburgh and Philadelphia despite their geographical differences (Figures 2.4 and 2.5). These graphs are based on Typical Meteorological Year (TMY) data sets which provide hourly meteorological values in order to establish the conditions at a specific location over a long period of time (e.g. 30 years) [13]. Since the meteorological data varies in each location, each location experiences different levels of irradiation and is able to generate different levels of energy.

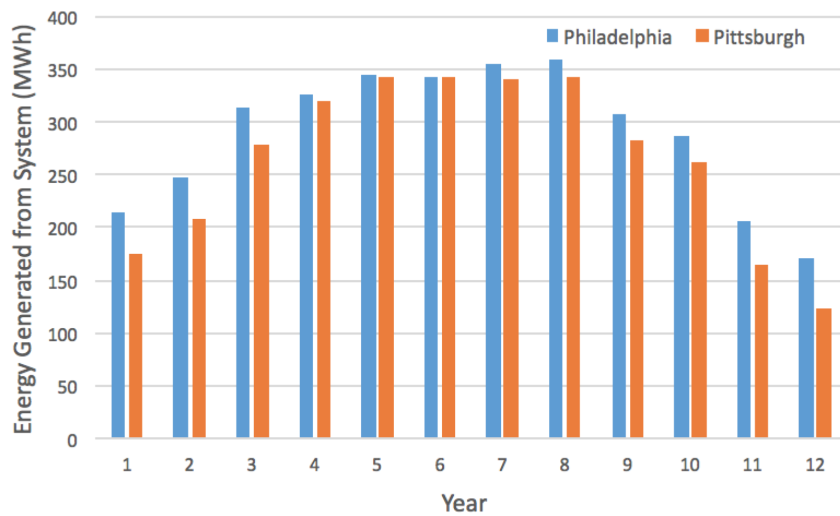

Figure 2.4. The monthly energy generated in Philadelphia is between 0-15% greater than the monthly energy generated in Pittsburgh.

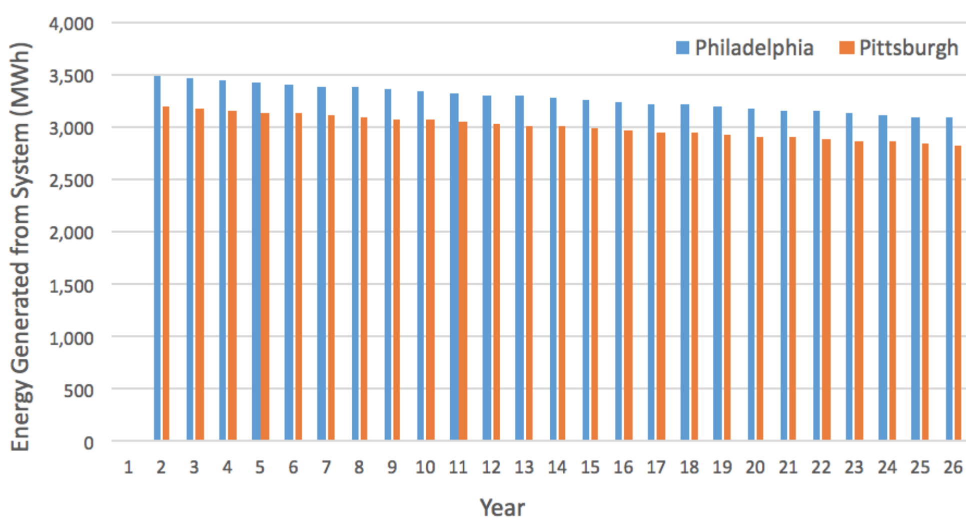

Figure 2.5. The annual energy generated in Philadelphia is about 8% greater than the annual energy generated in Pittsburgh.

2.2 Energy Policy

Energy policy has a major effect on the viability of establishing a 2.5 MW solar energy conversion system at Penn State. With changing state and national government regulations, the price of the solar to the customer is also constantly changing. The Pennsylvania Public Utility Commission (PUC) has been actively implementing the Alternative Portfolio Standards Act (AEPS), which was designed to encourage the development of alternative energy sources in Pennsylvania. Finding Pennsylvania's Solar Future seeks to exceed AEPS's goals for solar development and establish a plan to stimulate the growth of solar in Pennsylvania throughout the next decade. This plan includes further incentivizing solar through Solar Renewable Energy Credits (SRECs) and taxing strategies. Incentives based on capacity and production, as well as tax credits, can help stakeholders more effectively finance a solar project.

2.2.1 Alternative Portfolio Standards Act (AEPS)

AEPS was enacted in Pennsylvania Act 213 as a way to stimulate economic development in Pennsylvania by increasing the mix of alternative electricity generation. AEPS requires that 18 percent of the electricity supplied by Pennsylvania's electric distribution companies and generation suppliers come from alternative energy resources by 2021. AEPS has also established a solar carve-out which requires that 0.5 percent of electricity be supplied from solar PV systems.

AEPS and the PUC have certain limitations on generation capacity, which limit Penn State in the size of the solar system it can develop. Penn State is considered a customer-generator, which is a small, non-utility producer of electricity that is net metered and connected to the distribution system. Customer-generators have a capacity of less than 50 kW for a residential service or less than 3 MW at other customer-service locations. Hence, the maximum size solar system that Penn State can develop is 3 MW.

AEPS also issues alternative energy credits (AECs) to electricity generators, which serves an additional incentive to Penn State. An AEC is created each time an energy generator produces 1 MWh of electricity. This AEC can then be sold or traded for additional revenue to help finance the project [14].

2.2.2 Finding Pennsylvania's Solar Future

Finding Pennsylvania's Solar Future is a 2017-2019 statewide planning project led by the DEP Office of Pollution and Energy Assistance (OPPEA) which aims to equip Pennsylvania to produce more solar energy by 2030. The project seeks to exceed the current AEPS goal of generating 0.5% of Pennsylvania's energy from solar PV systems, and set additional goals beyond 2021. These include achieving 10% of Pennsylvania's retail electricity sales (10-15 GW) from in-state solar production by 2030 [5].

2.2.3 Solar Renewable Energy (SRECs)

If Penn State were to establish a solar energy conversion system, it would receive an SREC, which is the corresponding AEC for solar systems, for each MWh of energy generated. These SRECs can then be sold or traded in order to help Penn State generate revenue and fund the solar project. Unfortunately, Pennsylvania's low SREC prices provide little incentive to enter the solar market and establish solar systems. Pennsylvania and Ohio are the only two SREC states that still allows solar systems located outside of the respective state to register for and participate in their

SREC markets. Along with the solar boom from 2010 to 2013, this has caused Pennsylvania's SREC market to become severely over-supplied which causes SREC prices to remain low. A potential solution to the low prices would be to restrict access to Pennsylvania's SRECs from out-of-state energy generators.

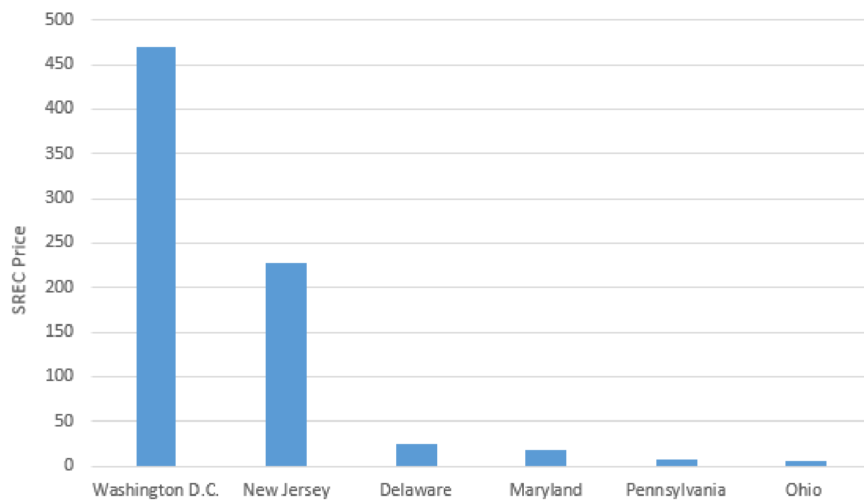

Figure 2.6. Pennsylvania and Ohio have the lowest SREC prices ($7 and $6) relative to other states, while Washington D.C. and New Jersey have SREC prices of $470 and $225, respectively. Multiple bills have been proposed to help Pennsylvania operate like its neighbors by closing the Pennsylvania borders to restrict SREC purchases to in-state projects. These include HB 1580, which was proposed in 2011, but did not pass, and HB 2040, which was proposed in 2016 and is currently in the process of being passed. If passed successfully, Pennsylvania could see a spike in SREC prices, which would create added incentives for Penn State to develop its 2.5 MW solar PV system [15].

2.3 Electricity Pricing

Penn State operates under a complex electricity pricing structure which is composed of various inputs and variables. Penn State participates in the PJM Interconnection regulation market, while purchasing electricity directly from its local distribution company, West Penn Power. The all-in energy price that Penn State pays includes unit costs which vary based on demand, along with other costs such as demand charges and non-energy components (capacity, transmission, ancillaries, REC's, etc.).

2.3.1 PJM Market Costs

PJM, the regional transmission organization (RTO) in Pennsylvania, uses locational marginal pricing (LMP) to set prices for the purchase and sale of energy in the PJM market. The LMP refers to the price of energy in the location in which the power is received or delivered at a specific point in time. The LMP varies depending on demand and congestion. Hence, when demand for electricity is very high (on-peak hours), the market and grid experience congestion, causing spikes in the LMP. As shown in Figure 2.7, these spikes typically occur in the morning and in the evening, around 8 AM and between 6 and 8 PM.

Figure 2.8 also shows that electricity prices vary by season. Prices tend to be higher during the winter and summer months when temperatures are more extreme, so additional electricity is required for heating or cooling.

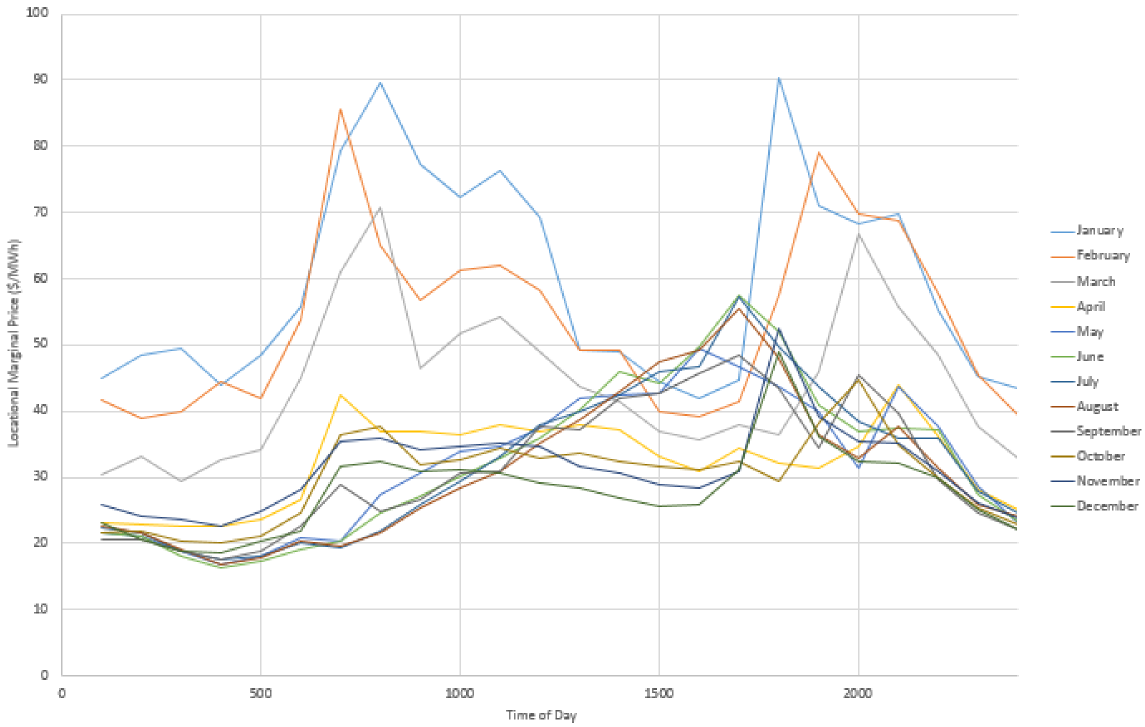

Figure 2.7. Based on PJM data, LMPs vary depending on the hour of the day and the time of the year. Maximum LMP prices occur during the winter months of December, January, and February and during peak hours (8 AM-10 PM).

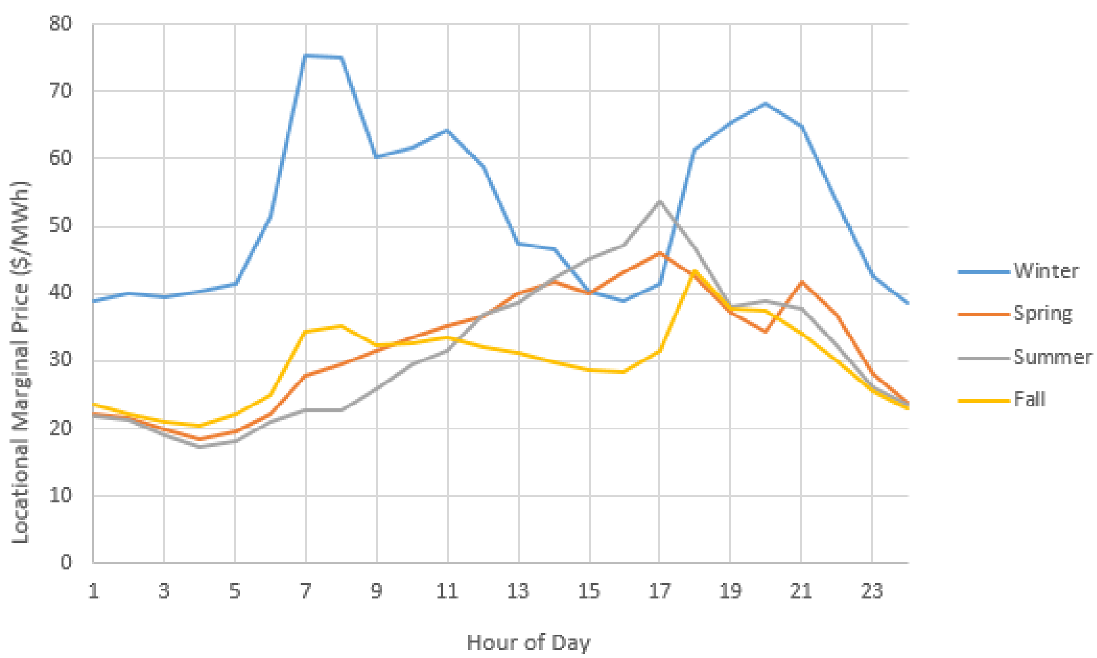

Figure 2.8. Based on PJM data, LMP's are highest during the winter and summer months.

2.3.2 Penn State Block Pricing

Penn State pays a unit cost per MWh of electricity that it purchases from West Penn Power. Based on past costs, the predicted unit costs during on-peak (8 AM to 10 PM) and off-peak (10 PM to 7 AM) hours for 2018 are displayed in Table 2.3. This indicates that the rates increase in January and corresponding winter months, while electricity prices are lower in the spring and fall months.

Table 2.3. In 2018, Penn State's unit electricity costs are expected to vary between $31.05-$52.75 per MWh during on-peak hours and between $21.15-$42.30 per MWh during off-peak hours.

	On-Peak	***Off-Peak***
January	$52.75	$42.30
February	$48.80	$39.10
March	$38.75	$29.75
April	$33.25	$24.75
May	$33.50	$21.35
June	$34.35	$21.35
July	$42.05	$24.40
August	$38.00	$22.05
September	$31.75	$21.20
October	$31.10	$21.15
November	$31.05	$21.90
December	$33.75	$25.75

2.3.3 Penn State Demand Charges

In addition to a unit charge, Penn State is charged an additional demand charge for using large amounts of energy. This demand charge is determined by finding the maximum amount of energy used in any given period of 15 minutes of each week. The greatest 15-minute energy loads from each of the four weeks in a month are then averaged and the average is multiplied by a set demand charge of $2.93. The monthly energy load used in Penn State's demand charge calculations can be seen in Figure 2.9 [16].

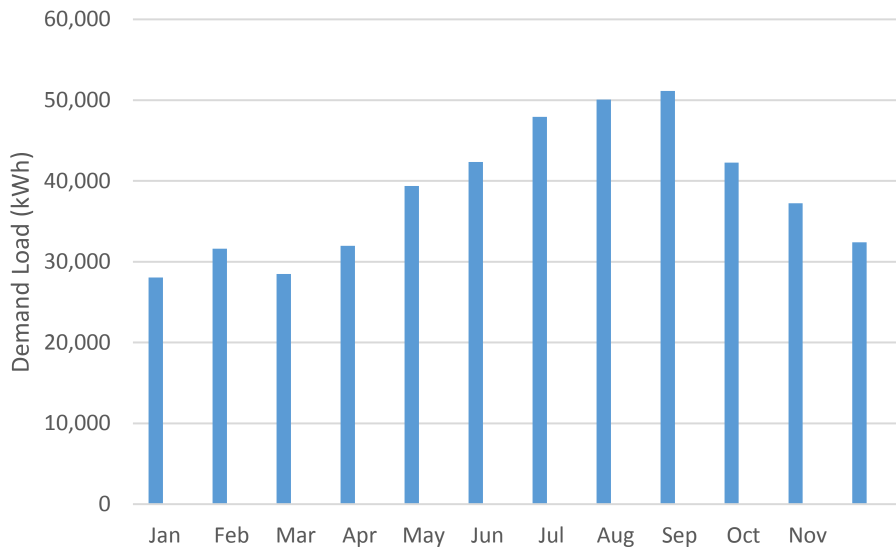

Figure 2.9. Penn State's demand loads for each month in 2016 are displayed in the chart. The demand load is the maximum weekly energy used in a 15-minute period averaged monthly [16]**.**

2.4 Locale

The utility of a solar energy conversion system strongly depends on the locale of the system. The locale is composed of several parameters, which refer to an address in time and place where energy resources are needed. These parameters include: the location, placement, climate region, time horizon, and frequency of the resource [17]. While Penn State plans to install a 2.5 MW solar farm at either the University Park Campus or in Rock Springs (Figure 2.10), it must consider all of the other design parameters associated with locale. The design of the locale will also be influenced by stakeholders, local economy, and local policy which have been discussed in earlier sections

2.4.1 Address

Penn State is considering installing a solar PV farm to supply energy to its University Park campus and the local community. Hence, the energy conversion system must be installed in a location with sufficient area and the capability to connect to the grid. The potential locations include University Park and Rock Springs, Pennsylvania as shown in Figure 2.10.

Figure 2.10. Potential locations for 2.5 MW solar PV farm include University Park and Rock Springs.

2.4.2 Climate Regime

Penn State University is located in the Northeast region of the United States, which means that it experiences four distinct seasons, or climate regimes. This can complicate the understanding of the locale, since the locale is divided into four smaller locales depending on the time of year. In other words, each climactic regime can be treated as a different geographical place throughout the year. The regimes can vary significantly in terms of relative humidity, wind speeds and size of weather cells, and emergent cloud behaviors [17].

Pennsylvania often experiences cold and snowy winters. According to U.S. Climate Data, State College, Pennsylvania experiences about 45 inches of snow per year [18], which could result in added cloud coverage and shading during the winter months. Otherwise, the position of Penn State is very adequate for producing solar energy. In fact, cold, sunny weather maximizes the performance of solar panels as they function more efficiently in low temperature conditions, similarly to other forms of electronics. Also, State College is located far north of the equator (2822 miles), which means that it will experience longer days in the summer months to make up for the shorter days during the winter months.

The average temperatures in State College and the corresponding irradiance throughout the duration of the year are shown in Figures 2.11 and 2.12. Figure 2.12 displays the Plane of Array (POA) Total Radiation in State College throughout the year.

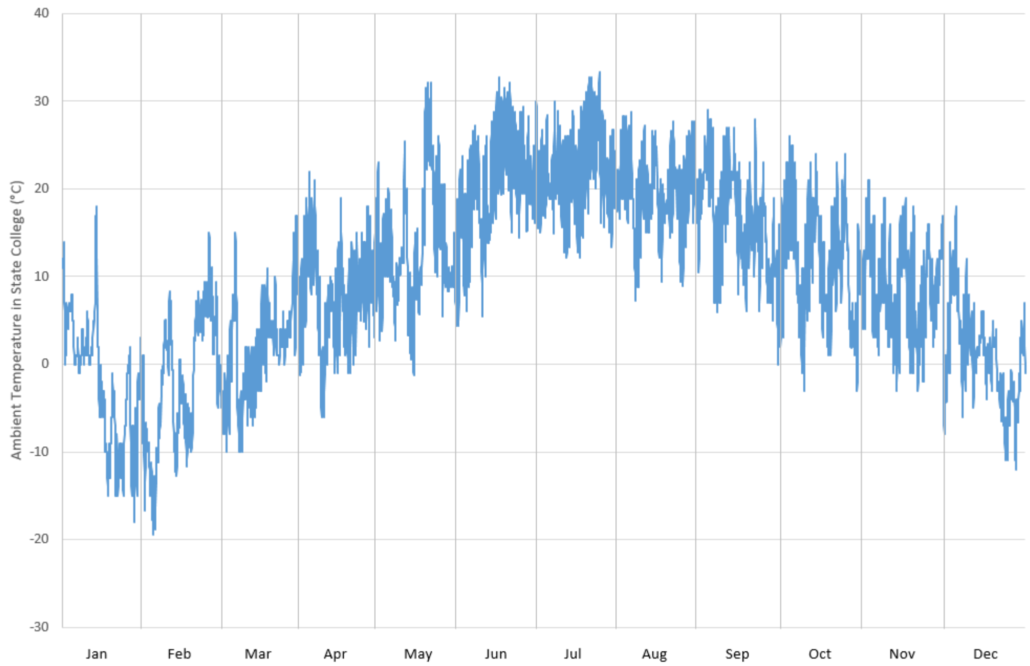

Figure 2.11. The temperatures during each hour of the day throughout the year were extracted using the State College TMY data set from SAM. The gridlines separate data for each individual month.

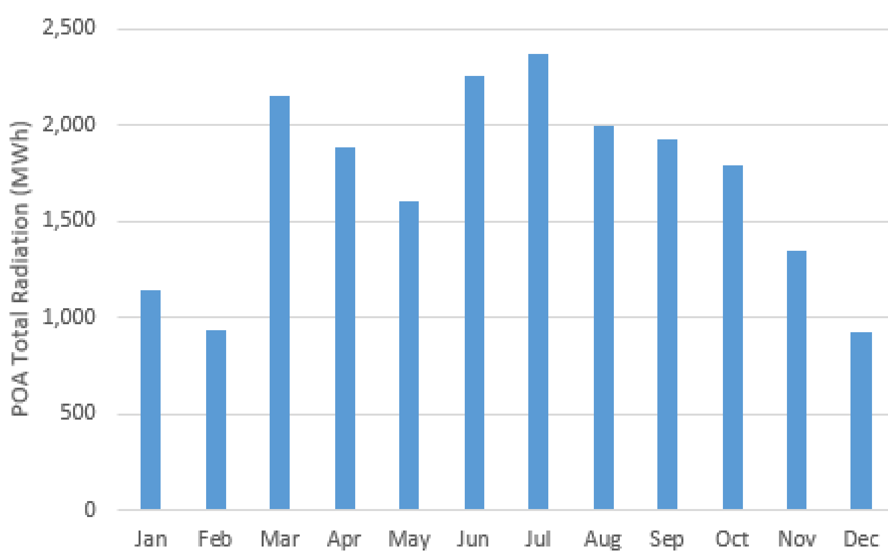

Figure 2.12. The Plane of Array (POA) Total Radiation during each month of the year is shown. The POA total radiation is composed of the POA beam component (direct normal irradiance adjusted for angle of incidence), POA ground-reflected component (radiation hitting the surface that is reflected off the ground), and POA sky-diffuse component (radiation that has been scattered from the direct solar beam). Hence, the POA total radiation depends on sun position, array orientation, direct and diffuse irradiance components, ground surface reflectivity, and shading [17].

2.5 Photovoltaics

2.5.1 Cost

PV systems are able to provide low costs relative to other forms of renewable energy, especially when applied in commercial operations. Figure 2.13 shows that after installation, a PV system between 1 to 10 MW generally offers the lowest price per kilowatt to the client or stakeholder. Additionally, the price of PV panels has been gradually decreasing over time with improvements in technology and manufacturing processes. According to SEIA, the installation cost of PV panels has decreased by about 60% since 2010 and continues to fall. Likewise, the price of an overall solar electric system has dropped by about 50% since 2010 [19].

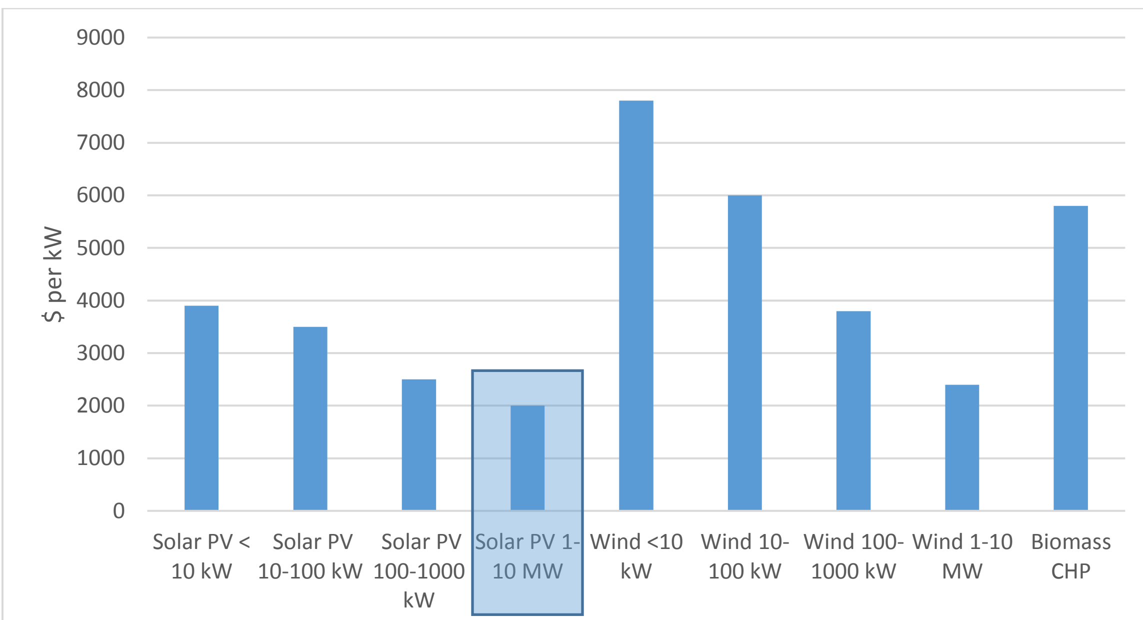

Figure 2.13. Relative to other forms of energy, Solar PV arrays from 1-10 MW are able to provide the lowest capital cost ($/kW) to the stakeholder [19].

2.5.2 Lifetime

In addition to cost, solar PVs have an advantage over other renewable technologies in terms of lifetime. Solar panels require little maintenance and adjustment after installation, and therefore can last between 25 to 40 years until replacement is required. The comparison to other forms of renewable technologies can be seen in Table 2.4.

Table 2.4. The table provides the average lifetimes of common renewable energy technologies according to NREL. These values can vary from the values shown, but the lifetimes presented are considered accurate for a first pass screen of economic viability [19].

System Useful Life	*Years*
Solar PV	25 to 40
Wind	20
Biomass Combined Heat and Power	20 to 30
Biomass Heat	10 to 25
Solar Thermal Systems	30 to 40
Geothermal Heat Pump	20

2.6 Energy Storage

The addition of energy storage to Penn State's solar energy conversion system can have a tremendous impact on the overall financials of the system. Without energy storage, the energy generated from the PV arrays must be immediately used or distributed to the grid. However, a large-scale energy storage system would allow Penn State to store energy generated from the solar system or external sources and use or sell electricity during peak pricing hours.

2.6.1 Services

The Rocky Mountain Institute suggests that a battery system installed behind the meter is able to provide up to 13 fundamental electricity services to three different stakeholder groups. A behind the meter based energy storage system can provide Independent System Operator (ISO) and Regional Transmission Organization (RTO) services, as well as customer and utility services. Energy storage systems can support ISOs/RTOs through providing services such as frequency regulation, voltage support, and black start, which provide consistent and reliable electricity across an entire power grid or region. Batteries can also impact utility services by reducing peak loads and utility investments. In behind the meter systems, batteries will provide the client, or customer, with additional services such as increased PV self-consumption, reduced demand charges, and backup power [20].

The primary services that Penn State University can utilize to generate revenue and reduce utility costs are load shifting and frequency regulation. Load shifting is the idea of shifting energy usage from the grid from one period of time to another. Electricity is typically purchased and stored in the battery during off-peak hours when electricity prices are at a minimum. The battery is then discharged during peak hours when electricity prices are at a maximum to reduce utility prices if discharging to buildings or to generate revenue if discharging back into the grid.

Frequency regulation becomes valuable when there is a sudden gap between power generation and demand on the grid. In this case, the grid frequency moves away from its nominal value and more electricity can be supplied than demanded. Hence, electricity prices tend to decrease as the utility companies must sell the excess electricity to stabilize grid frequency [21]. Penn State can utilize frequency regulation to charge its battery during gaps between power generation and demand when electricity prices dip. This electricity can then be discharged during peak hours when electricity prices are highest.

2.6.2 Technologies

The primary types of batteries used in the energy industry and solar applications are sodium sulphur, lithium-ion, advanced lead-acid, and nickel-cadmium batteries. While sodium sulphur batteries have been the commonplace in the industry in the past, lithium-ion technologies continue to get cheaper and more applicable in large-scale operations. According to The International Renewable Energy Agency (IRENA), the capacity of battery storage is expected to increase sevenfold throughout the next six years, with the ability to generate about 18 million dollars in revenue worldwide. Figure 2.14 demonstrates that lithium-ion technologies will lead the industry as approximately 75% of batteries installed in recent years have employed lithium-ion technologies [22].

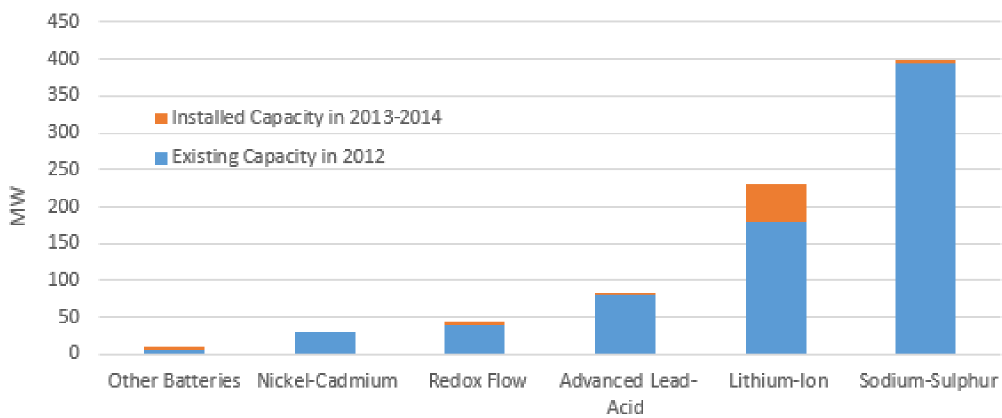

Figure 2.14. Lithium-ion battery systems have experienced the greatest increase in installed capacity in recent years, while sodium-sulphur were much more common in past applications [22].

The price of lithium-ion batteries continues to fall as technologies improve. Mckinsey has performed a detailed, bottom-up “should-cost” model to estimate how automotive lithium-ion battery prices will evolve through 2025. The study predicts that the price of a complete lithium-ion battery pack could fall from its current price of $500 to $600 dollars per kilowatt hour to about $200 per kilowatt hour by 2020. By 2025, the price per kilowatt hour is expected to fall even more to a price of $160 per kWh [23].

2.6.3 Lifetime

Lithium-ion batteries have an advantage to other types of batteries, such as lead-acid, because they do not suffer from “sudden-death” failure. Instead, lithium-ion batteries gradually decrease in performance throughout their service life. Hence, the end of life for a lithium-ion battery is typically defined as a reduction in initial capacity between 20 to 30 percent or a significant increase in impedance [24].

The calendar life of a battery can vary greatly between 1 and 20 years depending on the state of charge (SOC), or how much charge is kept in the battery, and the battery’s operating temperature. As evidenced by Figure 2.15, the battery should be maintained in a cool environment with minimum temperatures and avoid being charged to 100% capacity.

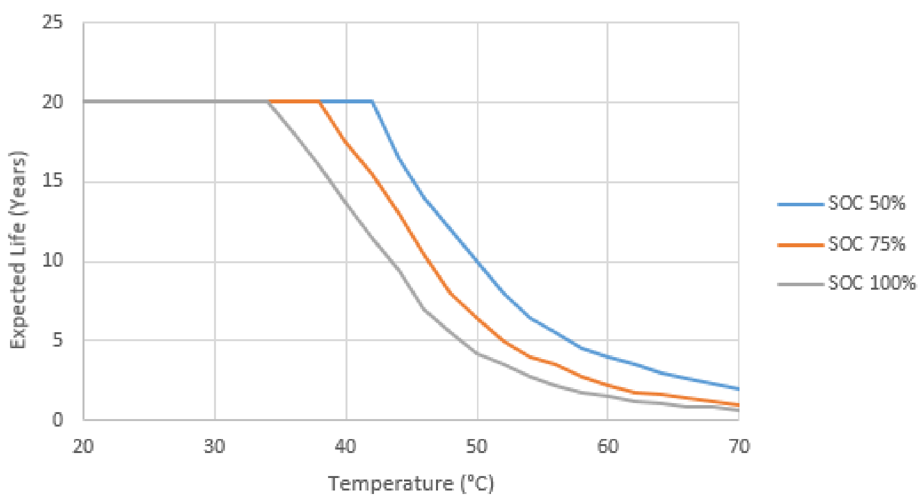

Figure 2.15. Lithium-ion batteries are expected to last longest when they operate at a temperature below 40 degrees Celsius and avoid being charged to full capacity [24].

The lifetime of a battery can also be analyzed by the number of discharge cycles that the battery can achieve before the its end of life (EOL). If a battery is discharged a greater amount, such as 80 to 100 percent during each cycle, the lifetime of the battery is expected to be significantly lower as shown in Figure 2.16.

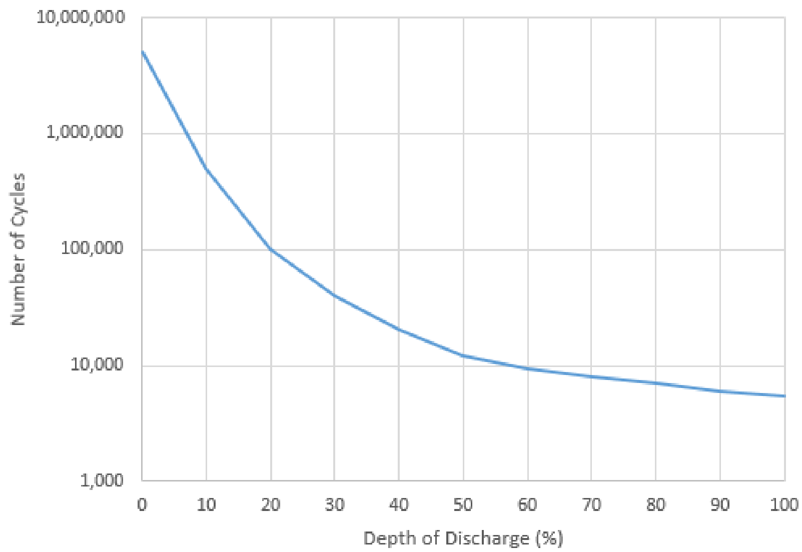

Figure 2.16. Battery cycle life decreases with increasing depth of discharge. Depth of discharge is the percent of energy capacity delivered from the battery during each discharge cycle [25]

2.7 Inverters

Inverters are valuable system elements used for power conditioning in solar systems of any scale. Inverters are necessary in every solar system as they convert the direct current (DC) that is generated by the solar panels to alternating current (AC), which is used by the grid and a majority of appliances. While the efficiency of commercial inverters can still vary, most available inverter models are now very efficient (over 95% conversion efficiency), able to reduce conversion losses to a minimum of about 5% [26].

2.7.1 Types of Inverters

There are three primary types of inverters that are commonly used in solar systems. The first most prevalent type of inverter system is a central inverter. Central inverters are typically mounted on a floor or ground and range in power capacity from 50 kW to over 1 MW. In the United States, central inverters are available in two voltage categories, 600 V and 1000 V. However, since Penn State plans to develop a utility-scale solar project, it would require the larger rated inverters. Central inverters are different from other types of inverters as the DC power produced from each string of panels runs to combiner boxes to combine with the power from the other strings (Figure 2.17). Then the DC power runs through the central inverter where power is converted to AC in a single stage.

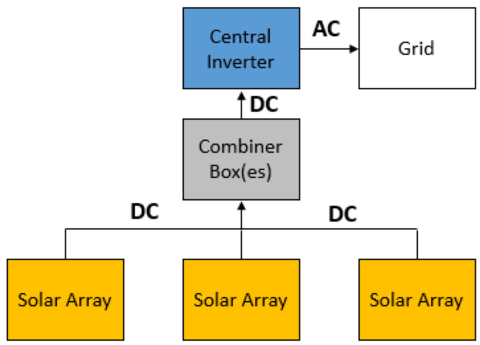

Figure 2.17. In a central inverter system, the DC power from each string of solar panels runs to a combiner box or boxes to combine with power from the other strings. Then, all of this DC power is sent through a single central inverter where it is converter to AC power and distributed to the grid or commercial appliances [27]

String inverters are another common form of inverters, which function similarly to central inverters. In a string inverter, each string of solar panels is connected to an individual inverter which transforms the DC electricity to AC electricity (Figure 2.18). Then, the AC electricity is distributed to the grid or used on-site. While central inverters may have lower capital costs and greater overall efficiencies, string inverters have several advantages in terms of functionality. First of all, fewer arrays are impacted by the failure of a single inverter since several inverters are connected to smaller groups of solar arrays. Also, string inverters can be more effective in systems that include different array angles and orientations since each inverter can operate at the optimum voltage required to generate maximum power output from a certain array.

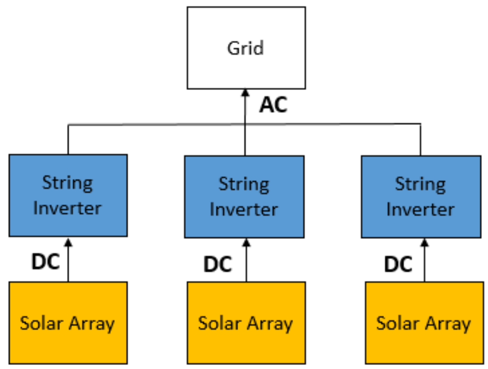

Figure 2.18. In a string inverter system, each inverter is connected to a string (array) or solar panels. Each array delivers DC power to an individual inverter where the power is then converted to AC and delivered to grid or commercial appliances [27]

Microinverters are much different from standard central and string inverters. These are very small inverters that are typically rated around 200 W. In microinverter systems, there is a small inverter on the back of each panel, which transforms the electricity from DC to AC for that individual panel (Figure 2.19). The AC electricity is then combined with that of the other panels in the system and sent to the grid. The primary advantage of microinverters is that if a single panel or inverter fails, the remaining components of the system will continue to function normally. On the other hand, if a component of the system in a central or string inverter fails, the entire system will go offline.

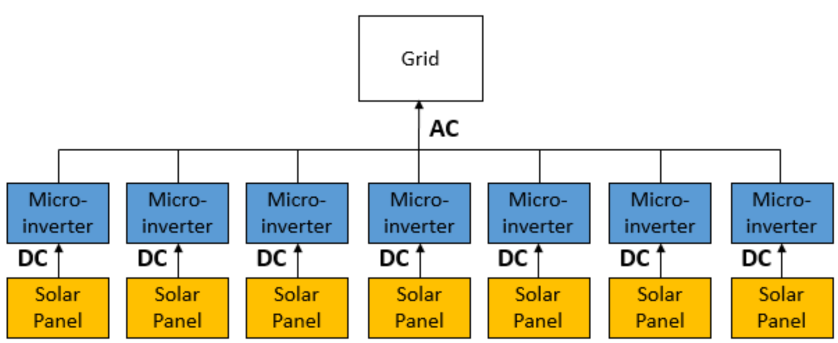

Figure 2.19. Microinverters operate similarly to string inverters, except a small inverter is attached to each individual solar panel. This way, if a single solar panel or inverter fails, the remainder of the system can continue to function [28].

2.5.2 Inverter Lifetime and Costs

The price of inverters can serve as the major differing factor in PV system cost of ownership. As discussed in Appendix A, NREL estimates the average installed costs of inverters to be \$0.13/Wdc or about \$0.17/Wac. While this already accounts for about 6% of the overall cost of the system, inverters can influence system costs even more due to replacements or repairs.

When customers invest in PV systems, they typically expect between 25 to 30 years of energy production from the system since panels are expected to last between 25 to 40 years with little maintenance required. However, inverters have lifetimes on the order of 15 years or less with inverter warranties between 5 and 10 years in length. Hence, maintenance and replacement of inverters can significantly add to the cost of the overall system. According to a Fronius study, traditional string inverters and micro-inverters have extended cost factors of 1.19 and 1.26, respectively [29]. These extended cost factor represent how much more a system will cost over its lifetime based on the type of inverter selected.

Chapter 3

Experimental Methods

3.1 System Advisor Model

The System Advisor Model (SAM) is a performance and financial model used to facilitate decision making for various renewable energy projects. SAM is able to accurately project performance and energy costs for grid-connected power projects based on a wide set of inputs specified by the user. These inputs include the project's location, the type of equipment in the system (e.g. modules, batteries, inverters, etc.), the cost of installing and operating the system, and financial and incentive assumptions.

3.1.1 Detailed PV Commercial Project

This research focuses on the development of a commercial level, detailed PV system. The SAM tool allows the user to input individual module and inverter details, along with details for an integrated energy storage system. Since the project is a commercial project, it is assumed that Penn State will fully finance the project through either a loan or cash payment. In this case, Penn State can also continue to buy and sell electricity at retail rates and displace purchases of power from the grid. For the commercial project, SAM calculates the performance of the system, along with various financial metrics such as, the project's levelized cost of energy, net present value, and payback period. These metrics can be better understood through Appendix A, System Financials.

Location and Resource

The location and resource tab of SAM establishes the locale of the project. SAM makes it easy to select a weather file to represent the locale and solar resource in a certain location, specifically, State College, PA (Figure 3.1).

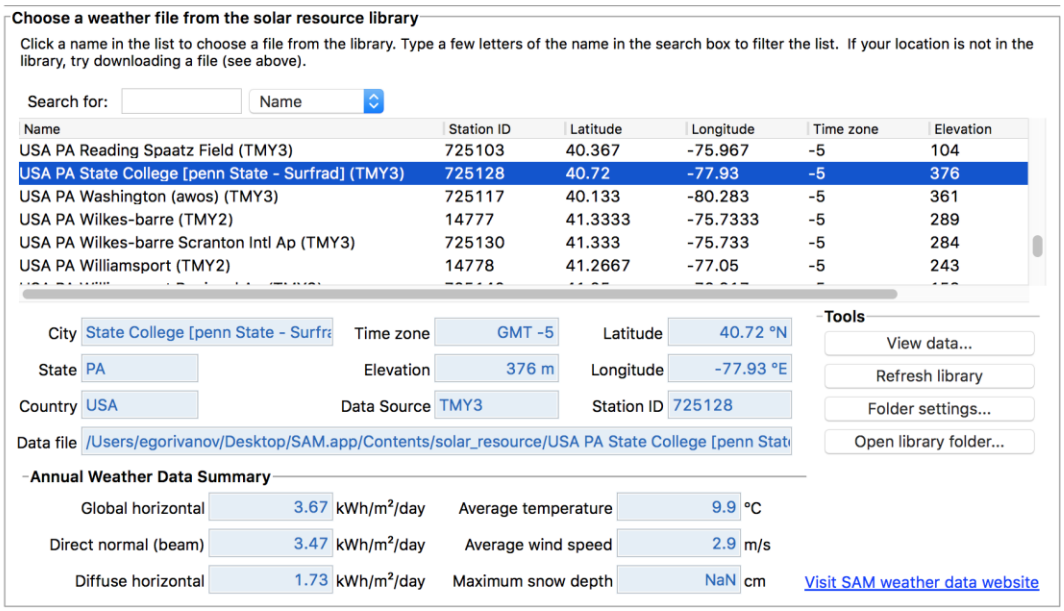

Figure 3.1. The locale in SAM was selected as State College, PA, which allows SAM to apply all TMY data associated with this locale to the corresponding simulations.

Module

SAM provides multiple options for selecting the module design to use in a project. Users can manually input the module specifications, or use data from one of the thousands of commercially available models for which SAM has data stored. For this research, automatically generated data from one of the modules available in the SAM system is used. This will provide the module's efficiency, output power, voltages, currents, and temperature coefficients which will be automatically corrected for in SAM.

Inverter

Similar to the modules, SAM allows the user to select from a long list of inverters which provide the necessary inputs, including efficiency, power, current, and voltage. If necessary, inputs can be manually applied as well.

System Design

The System Design Tab allows the user to establish any sizing and configuration constraints as necessary. Based on parametric analyses as discussed at the end of Section 3.1, it was determined that the optimum tilt for the system is about 35 degrees, while the optimum azimuth angle is approximately 180 degrees. Likewise, the optimum DC to AC ratio was determined to be about 1.10 as shown in Section 4.1. Hence, these inputs were established along with the desired array size of 2.5 megawatts.

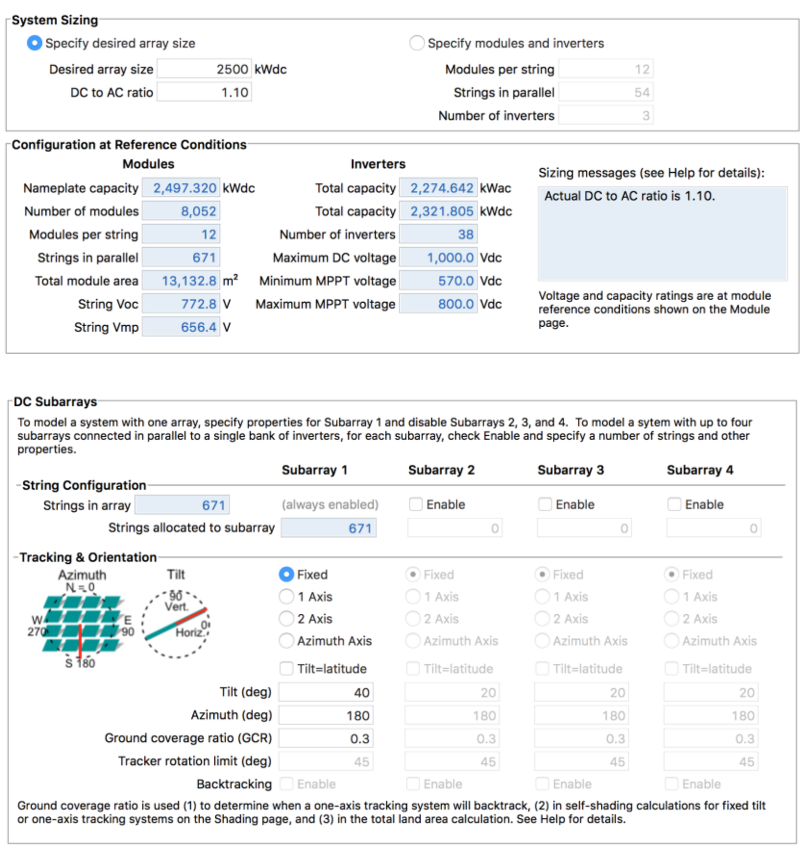

Figure 3.2. The system design inputs were varied in SAM to account for a 2.5 MW system with a DC to AC ratio of 1.10.

Battery Storage

Battery storage is a complex component of SAM which allows the user to integrate an energy storage system with the renewable energy system. Here, the user can establish the desired characteristics of the battery such as the size, chemistry, voltage properties, and current properties. Additionally, the user can use a peak shaving, automatic, or manual dispatch model for the battery. A manual dispatch model based on Penn State's electricity prices in order to maximize the effect of load shifting and frequency regulation was created. The manual dispatch model used in the simulations is shown in Figure 3.3.

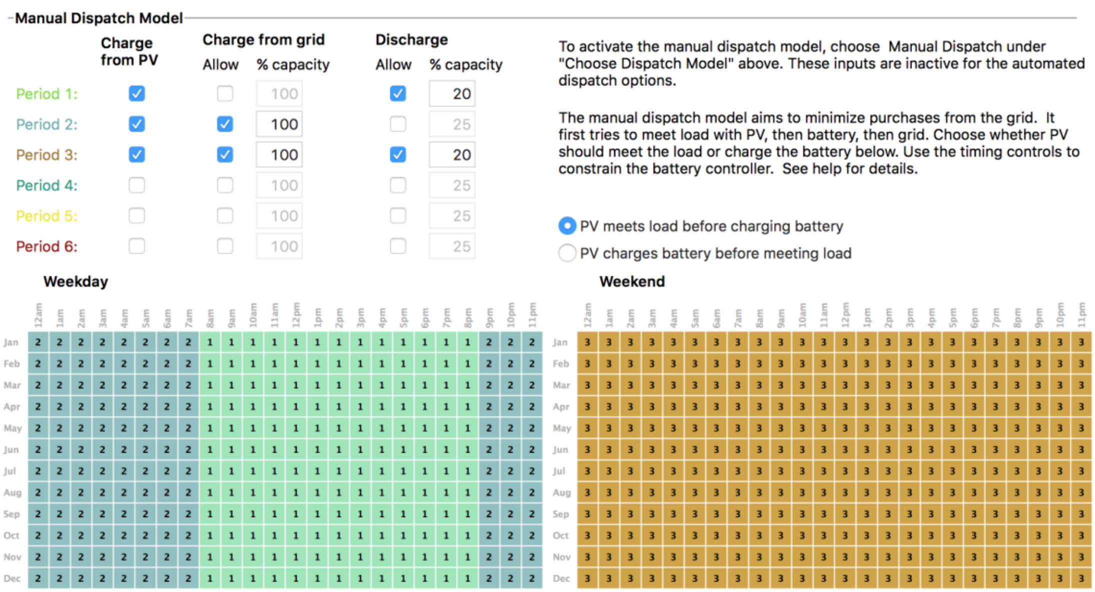

Figure 3.3. A manual energy storage dispatch model was developed in SAM to accurately depict the dispatch under which the battery would perform based on Penn State electricity prices and load data**.**

System Costs and Financial Parameters

These sections allow the user to manually input any costs or financial parameters associated with the system. See Appendix A for details on any of these costs or parameters.

Electricity Rates

The electricity rate structure has a major effect on the success of the system since the Electricity Rates page determines how the retail electricity customer is compensated for electricity generated by the renewable enrgy system. This tab allows the SAM user to establish a metering system as well as the rate structure to be used for customer (Penn State). In this case, a single meter option with monthly rollover credits was used. Hence, in months that the system produces more electricity than the total monthly load, credits in kWh will apply to the following months electric bill. This effect can significantly reduce the total monthly energy bill for that month.

Since an energy storage system will also be in effect, an accurate rate structure of energy rates and demand charges should be established. This way, the battery can capitalize upon load-shifting and frequency regulation, purchasing electricity when it is cheapest, and selling it back to the grid when it is most expensive. The structures that were used in the corresponding simulations can be seen Section 4.3.

Parametric Analysis

Throughout this research, SAM's Parametric Analysis tool was used extensively to develop large data sets which were later analyzed using ATSV and Microsoft Excel. Parametric analyses make it possible show the relationship between one or more input values and selected output values, or results. While SAM can generate graphs to display these relationships, the graphs are not effective for analyzing large data sets, as shown in Section 3.2. Instead, the results from SAM's parametric analyses were exported to a text-based CSV file, and further analyzed using ATSV.

3.2 Applied Research Laboratory Trade Space Visualizer

The data generated in SAM for the specific solar system was further analyzed using the ARL Trade Space Visualizer (ATSV), which was developed by the Applied Research Laboratory (ARL) at Penn State to aid complex decision making. Throughout the research, the ATSV was used to explore single and multi-dimensional data sets and analyze relationships between different parameters and features.

3.2.1 Trade Space Exploration

ATSV helps users utilize a method of design selection that allows the user to form design preferences while exploring the trade space and searching for the best design. Additionally, the user is able to exploit any knowledge gained throughout the trade space exploration by focusing future searches to more select regions of data. This iterative design process is based on the idea of a sequential decision process that increases the detail of modeling and analysis while decreasing the space of alternatives considered [30]. As seen in future analyses using ATSV, the design space, or set of parameters, is very broad at the beginning of the analysis process. As the design develops, however, the design space narrows as designs that are guaranteed to not be the choice set of the final model are removed from the trade space. This process gradually continues until a single design is selected after considerable detailed analysis.

3.2.2 ATSV Capabilities

ATSV includes various tools to display and analyze trade space data. While current energy system analysis tools are very limited in their ability to effectively display large data sets, ATSV allows users to visualize large data sets and explore trade-offs among parameters. The ATSV interface allows users to plot multi-dimensional data using 3D glyph plots, 2D scatter plots, 2D scatter matrices, parallel coordinates, and histogram plots. Also, users can filter data and designs using brushing tools, preference shading, and Pareto frontiers to eliminate undesired designs or highlight preferred designs.

3.2.3 ATSV for Design of Solar PV Systems

Throughout this research, ATSV was used extensively to analyze the tradeoffs between system inputs and demonstrate their effects on overall system performance and financials. Examining Figure 3.4 shows that SAM is unable to effectively display the effects of multi-dimensional data on a desired output. In this figure, four different battery parameters were varied to examine the effects on the NPV of the system. Hence, 300 individual systems were developed using a parametric analysis and compared using SAM. However, the data was extremely cluttered and indecipherable. The data was extracted from SAM and further analyzed using the ATSV tools.

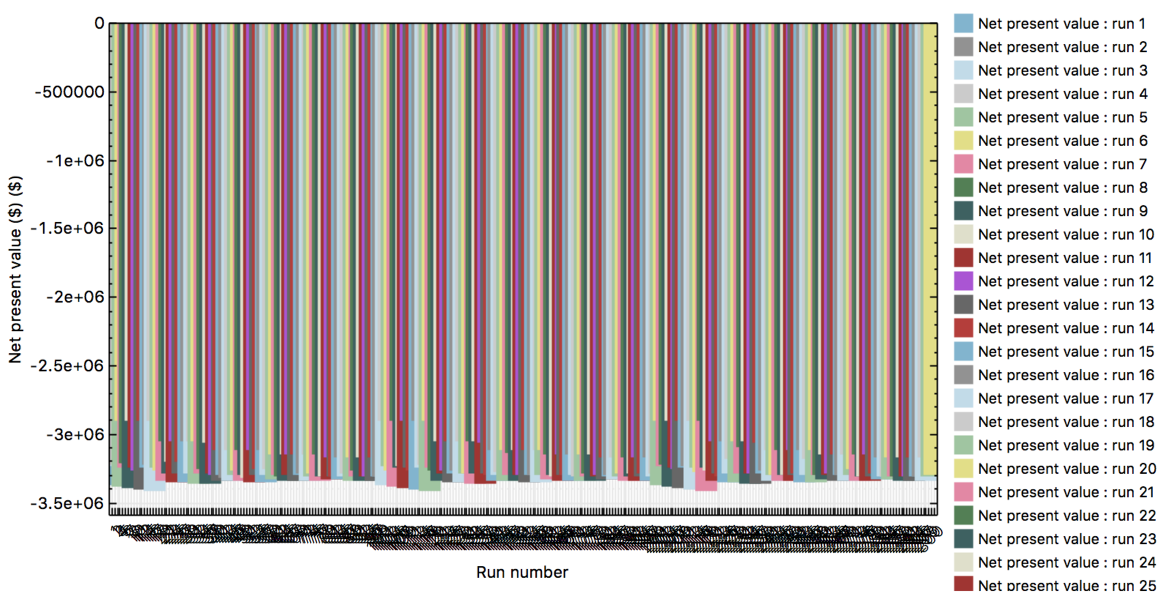

Figure 3.4. SAM's visualization models are still extremely underdeveloped and do not allow the user to effectively view the trade-offs between inputs on a selected output.

ATSV allows the user to plot all of the data points in a trade space quickly, creating a more effective visual representation of the data (Figure 3.5). Analysis of the effects of more than two parameters using a 3D glyph plot can be completed using ATSV. Using ATSV, the user is able to change the size, color, or style of data points based on different inputs, as well. For example, in Figure 3.5, a different colored point is used for each C-rate of charge that was tested, while a different sized point is used for each cell capacity tested.

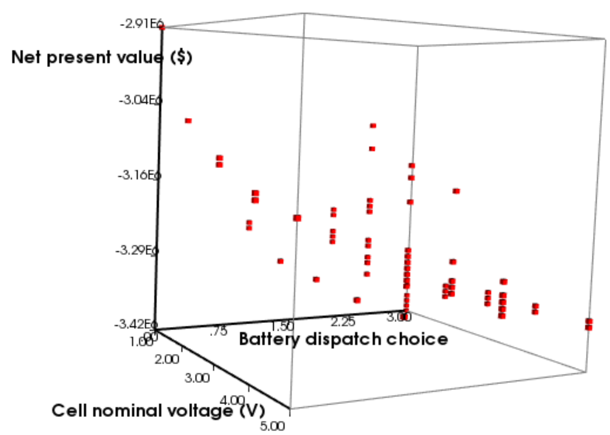

Figure 3.5. ATSV is able to offer a much more effective visualization method for parametric analyses**.**

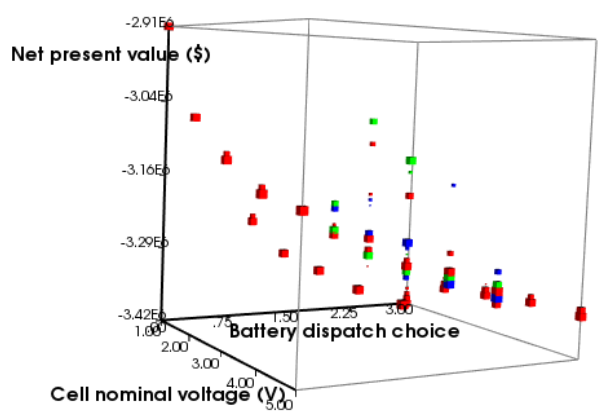

Figure 3.6. ATSV allows users to vary designs by color and size in order to analyze the effects of multiple inputs and parameters at once**.** In the figure, the size of the data points is varied based on the cell capacity, while the color of the data points is varied based on the max c-rate of charge.

3.2.3 Brushing

ATSV's brushing tool is extremely useful when the user would like to analyze a more specific data set or demonstrate the effects of individual parameters. Figure 3.7 demonstrates the use of brushing to highlight the trends between input and output parameters by limiting the data being displayed. In each of the four plots in Figure 3.7, only the single input parameter shown on the x-axis was varied, while all other parameters were held constant using brushing. This helped the user quickly identify which parameters have the greatest effects on the desired output. As shown in Figure 3.8, brushing was utilized to remove undesired values from the plot area, which was then rescaled to view the remaining points more adequately.

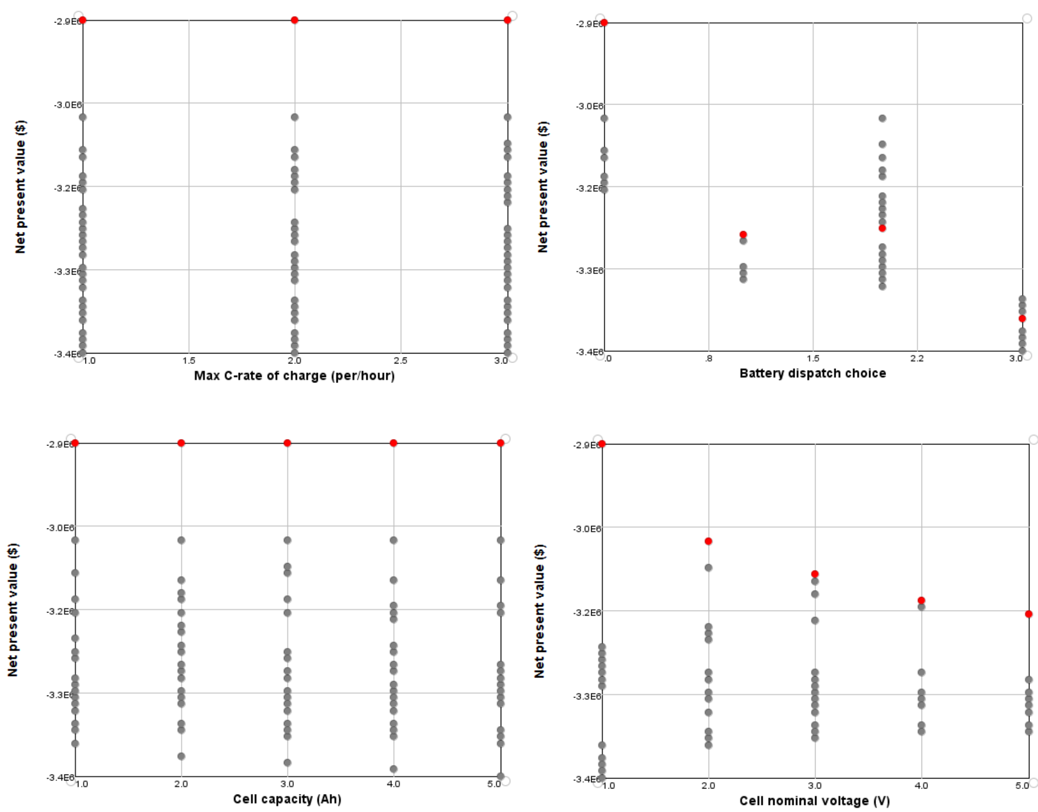

Figure 3.7. Brushing can be used in ATSV to vary the amount of data displayed by adjusting analysis criteria and establishing control values. In the figure, the red points are used to analyze trends in the data and identify the parameters which have an effect on NPV. Hence, the red points represent points where all other inputs except the variable (parameter shown on x-axis) were held constant.

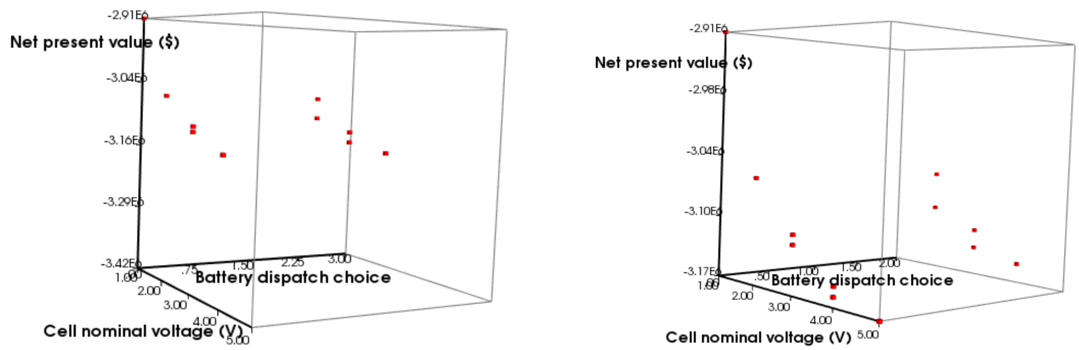

Figure 3.8. Brushing in ATSV can be used to reduce the displayed data sets to desired designs for more effective analysis.

3.2.4 Preference Shading

In addition to brushing, ATSV allows the user to apply preferences and visualize the most preferred designs using those preferences. The user can visualize their preferred points by specifying their preference to maximize or minimize certain parameters. The data set is ranked from best to worst based on the preferences established, as seen in Figure 3.9. In Figure 3.9, only the preference for net present value was maximized, so the upper-most point, is also represented as the "best" point by ATSV.

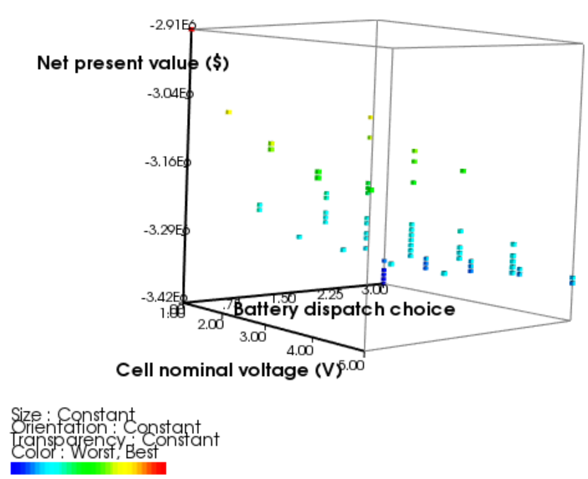

Figure 3.9. Preference shading in ATSV can be used to visualize a preference to maximize or minimize one or multiple parameters. Then, the best and worst designs can be highlighted in the trade space.

Chapter 4

Results

4.1 Preliminary Results

In order to begin designing a system for Penn State, SAM and ATSV were used to determine the effects of some standard parameters on the performance and financials a solar system at Penn State. These include the orientation of the solar panels, the DC to AC ratio, along with several other inputs.

4.1.1 Effect of Solar Panel Orientation

It can be determined that the optimum tilt of solar panels for energy generation in State College, PA is between 30 and 40 degrees (Figure 4.1), with the maximum energy generated at a tilt of 35 degrees (of angles included in simulation). Also, the maximum energy generation occurs at an azimuth angle of 180 degrees, which means that it is ideal for solar panels in the Northern Hemisphere to be facing directly due south. The accuracy of these simulations can be confirmed by the NREL paper by Christensen and Barker summarizing the effects of tilt and azimuth on annual incident solar radiation in different U.S. locations. Based on Christensen and Barker's analyses, the optimum angle of tilt for a south-facing surface at a latitude of 40 degrees is between 30 and 40 degrees [31]. It can be seen in Figure 4.1 that the tilt and azimuth angles have little effect on the overall energy production as first year energy production ranges between 1000 and 1300 kWh regardless of tilt and azimuth angle.

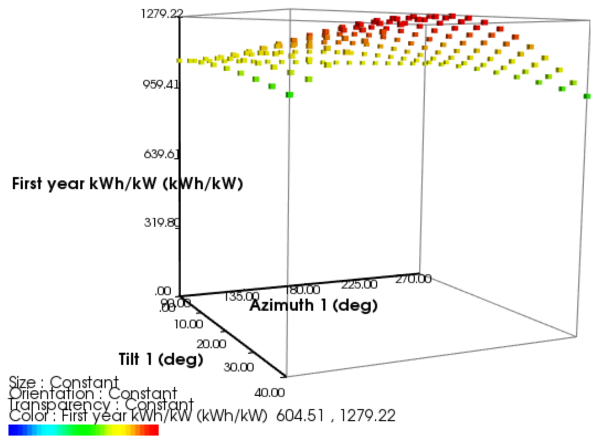

Figure 4.1. Using SAM parametric analysis and ATSV visualization, it was found that the optimum azimuth angle for the solar PV system is 180 degrees (facing due south), while the optimum angle of tilt is approximately 35 degrees**.**

4.1.2 Effect of DC to AC Ratio on Annual Energy Generation

The DC to AC ratio is an important parameter to consider before designing a solar system as it is the array-to-inverter ratio of the system. Using SAM and ATSV, it was found that the optimum DC to AC ratio of a 2.5 MW system at Penn State is between 1 and 1.2. For simplicity, future simulations used a DC to AC ratio of 1.1, which means that the power rating of the solar array is 1.1 times the power output of the inverter.

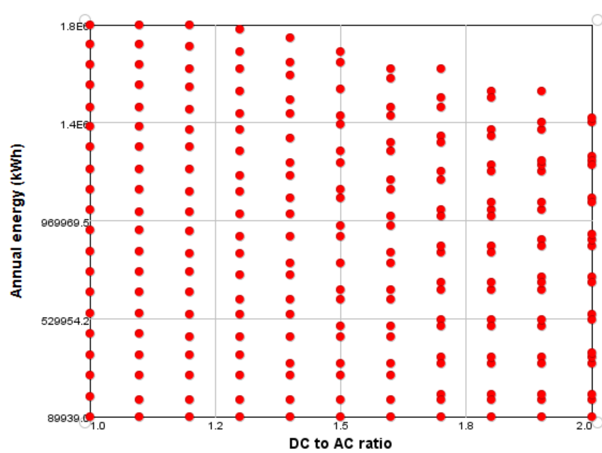

Figure 4.2. Using SAM parametric analysis and ATSV visualization models, it was found that the optimum DC to AC ratio of the system is between 1.0 to 1.2.

4.2 Effects of Module, Inverter, and Battery Parameters on Performance and Financial Metrics

4.2.1 Module

In order to test whether the specific solar PV array used in our simulations has an effect on the outputs of the system, basic parametric simulations were developed in SAM. As shown in Table 4.1, SAM does not recognize the difference between different solar PV modules in terms of the effect they have on the overall energy generated or the net present value of the system. Each module generated the same amount of energy per year and produced similar values of NPV and LCOE. Hence, the SunPower SPR-E19-310-COM was used as a standard module for all future simulations.

Table 4.1. The effects of different commercial PV modules on annual energy, NPV, and LCOE were tested. It was found that SAM does not generate different output values for different commercial modules, so a standard module was used in all future simulations

Module name	*Annual energy (kWh)*	*Net present value ($)*	*Real LCOE (cents/kWh)*
SunPower SPR-210-BLK [2007 (E)]	3.25E+06	-2.95E+06	10.37
Advent Solar Ventura 210 [2008]	3.25E+06	-2.95E+06	10.37
Advent Solar Ventura 215 [2009]	3.25E+06	-2.95E+06	10.37
Aleo S16 180 [2007 (E)]	3.25E+06	-2.95E+06	10.37
AstroPower APX-140 [2002 (E)]	3.25E+06	-2.95E+06	10.37
AstroPower APX-40 [2002 (E)]	3.25E+06	-2.95E+06	10.37
BP Solar BP3110 [2006 (E)]	3.25E+06	-2.95E+06	10.37
BP Solar BP3115 [2006 (E)]	3.25E+06	-2.95E+06	10.37
BP Solar BP3180N [2010]	3.25E+06	-2.95E+06	10.37
BP Solar BP3232G [2010]	3.25E+06	-2.95E+06	10.37
BP Solar BP380J Module [2009]	3.25E+06	-2.95E+06	10.37
BP Solar BP380J Module [2009 (E)]	3.25E+06	-2.95E+06	10.37
Canadian Solar CS5P-220M [2009]	3.25E+06	-2.95E+06	10.37
Evergreen ES-180-RL-T Module [2008]	3.25E+06	-2.95E+06	10.37
Evergreen ES-180-RL-T Module [2008 (E)]	3.25E+06	-2.95E+06	10.37
Kyocera Solar KC130TM [2008 (E)]	3.25E+06	-2.95E+06	10.37
Kyocera Solar KC35 [2003 (E)]	3.25E+06	-2.95E+06	10.37

4.2.2 Inverter

String Inverters vs. Micro-Inverters

As discussed in Section 2.7, inverters incur a major capital cost to the overall system. In attempt to drive the cost of the system down, while improving system performance, various inverter inputs and parameters were considered and the results were compared.

Performance and financial metrics were developed for the two primary types of inverters, string inverters and micro-inverters. As calculated by SAM, string inverters have a total DC power loss of 4.44, while micro-inverters have a power loss of 2.49. Hence, micro-inverters were expected to perform slightly better than string inverters. However, since micro-inverters have a higher cost than string-inverters, a cost of $0.13/W was used for the string-inverters, while a cost of $0.15/W was used for the micro-inverters. Based on these inputs (Table 4.2), the results presented nearly identical outputs for the two different systems as displayed in Table 4.3. Regardless of the inverter type, the system still has an extremely negative net present value which makes it difficult to validate the feasibility of the project to the stakeholders.

Table 4.2. The inputs varied for string inverters and micro-inverters include the DC Power Loss and the Capital Cost of the inverter.

	String Inverter	*Micro-Inverter*
DC Power Loss (%)	4.44	2.49
Capital Cost ($/KW)	0.13	0.15

Table 4.3. Analysis of string inverter outputs vs. micro-inverter outputs presents similar results for both inverter types.

Metric	Value	Metric	Value
Annual energy (year 1)	3,203,740 kWh	Annual energy (year 1)	3,267,019 kWh
Capacity factor (year 1)	14.6%	Capacity factor (year 1)	14.9%
Energy yield (year 1)	1,283 kWh/kW	Energy yield (year 1)	1,308 kWh/kW
Performance ratio (year 1)	0.83	Performance ratio (year 1)	0.85
Battery efficiency	0.00%	Battery efficiency	0.00%
Levelized COE (nominal)	8.14 ¢/kWh	Levelized COE (nominal)	8.04 ¢/kWh
Levelized COE (real)	5.88 ¢/kWh	Levelized COE (real)	5.81 ¢/kWh
Electricity bill without system (year 1)	$8,755,982	Electricity bill without system (year 1)	$8,755,982
Electricity bill with system (year 1)	$8,586,079	Electricity bill with system (year 1)	$8,582,777
Net savings with system (year 1)	$169,903	Net savings with system (year 1)	$173,205
Net present value	$-1,218,866	Net present value	$-1,208,110
Payback period	NaN	Payback period	NaN
Net capital cost	$5,368,439	Net capital cost	$5,420,058
Equity	$0	Equity	$0
Debt	$5,368,439	Debt	$5,420,058

Comparison of Commercial Inverters

Using the "Inverter CEC Database" in SAM provides the ability to select specific commercial inverters to use in the overall system design. Using a parametric analysis, a set of 544 inverter models developed in the past 5 years were tested in a controlled system. The performance (energy generated) and net present value of each system were then analyzed using the ATSV. Each individual system is represented as a data point in Figure 4.3. While several outliers existed, a majority of the systems showed little variation in performance or financials regardless of the commercial inverter selected. In general, the net present value varied between -$1.3 million and -$1.2 million. Likewise, performance only varies between 3.1 MWh and 3.3 MWh per year. As shown in Figures 4.4 and 4.5, an optimum system was identified using the ATSV plot, which is the SolarEdge Technologies: SE5000. Nevertheless, the results confirm that the inverter type does not have a major effect on the overall system performance and financials, especially when there is such a negative net present value. Varying solely the inverter model used in the system will not generate a positive net present value as desired.

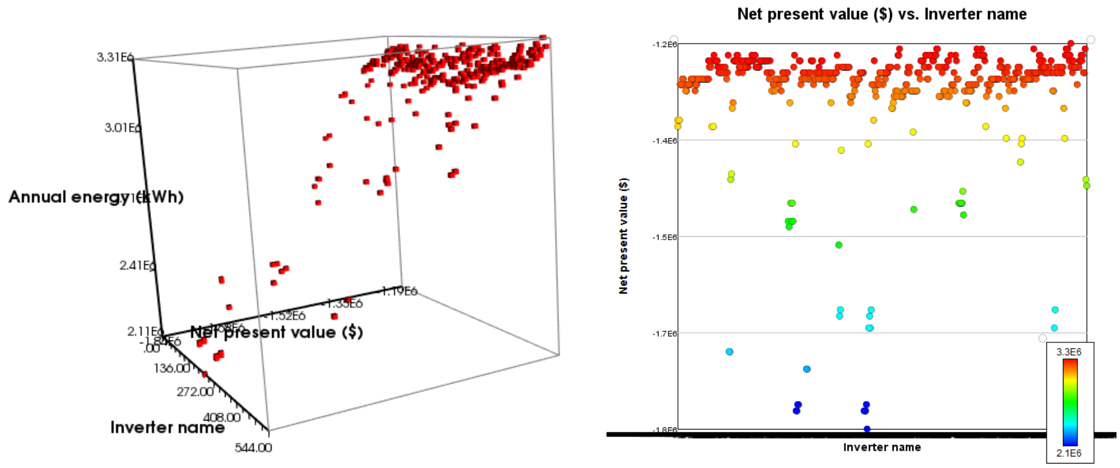

Figure 4.3. ATSV was used to compare the NPV and energy generated of systems with different commercial inverters. The data was analyzed using a 3D glyph plot (left), as well as a 2D plot (right) in which the color of the points corresponds to the annual energy generated.

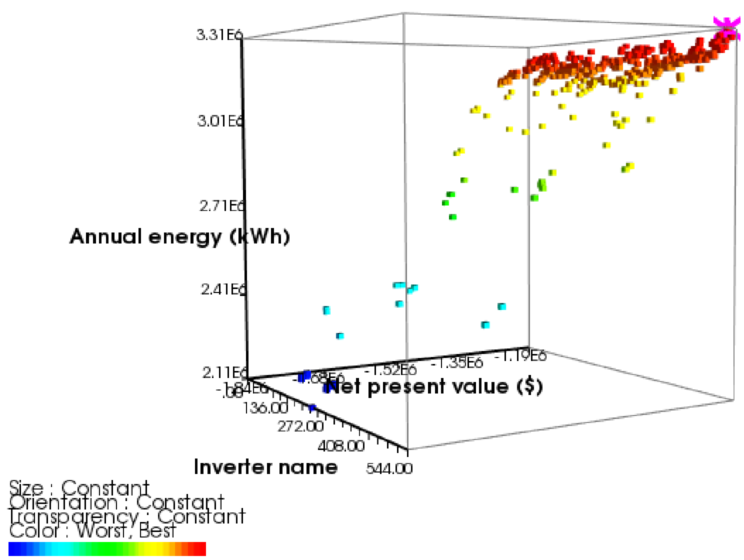

Figure 4.4. Preference shading was used to maximize preference for annual energy and NPV and the optimum inverter was identified as shown.

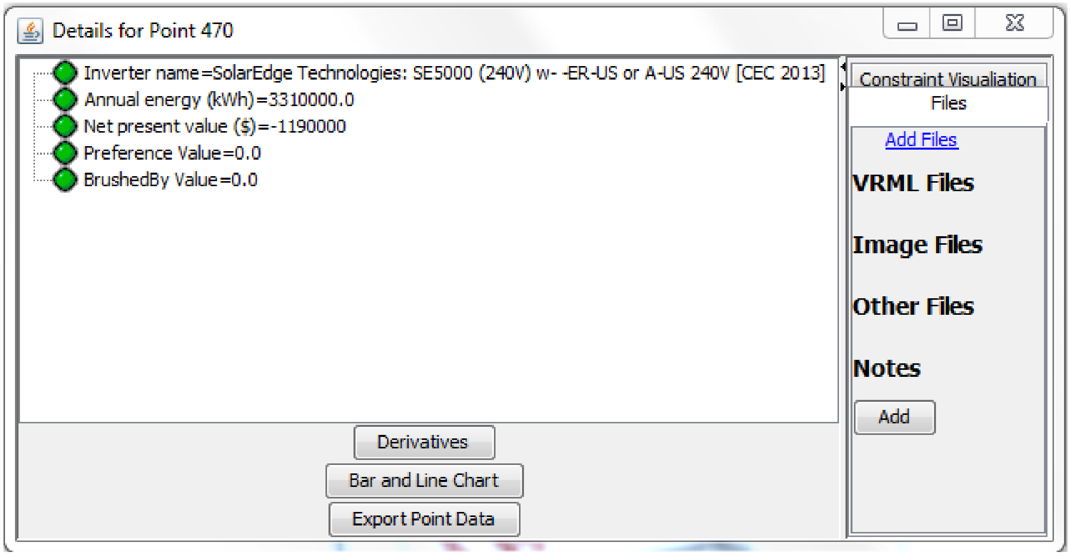

Figure 4.5. Optimum inverter from those tested was the SolarEdge Technologies: SE5000 inverter.

4.2.3 Battery Storage

A 2 MW battery was added to the system to examine the potential for load shifting and frequency regulation at Penn State, as discussed in Section 2.6. The battery's dispatch model was developed based on the electricity prices established by the OPP at Penn State. During on-peak hours, the battery would only charge from the PV system, and it would be allowed to discharge as necessary. During off-peak hours, the battery would be allowed to charge from both the grid and the PV system, since electricity prices are at a minimum during these times. Since weekends operate on off-peak prices at all times, the battery would be allowed to charge from both the PV array and the grid, and discharge at any time on weekends. Also, since it is damaging to the battery to discharge the full capacity at any time, the battery would only be allowed to discharge to 20 percent capacity. An example of this model can be seen in Figure 4.6.

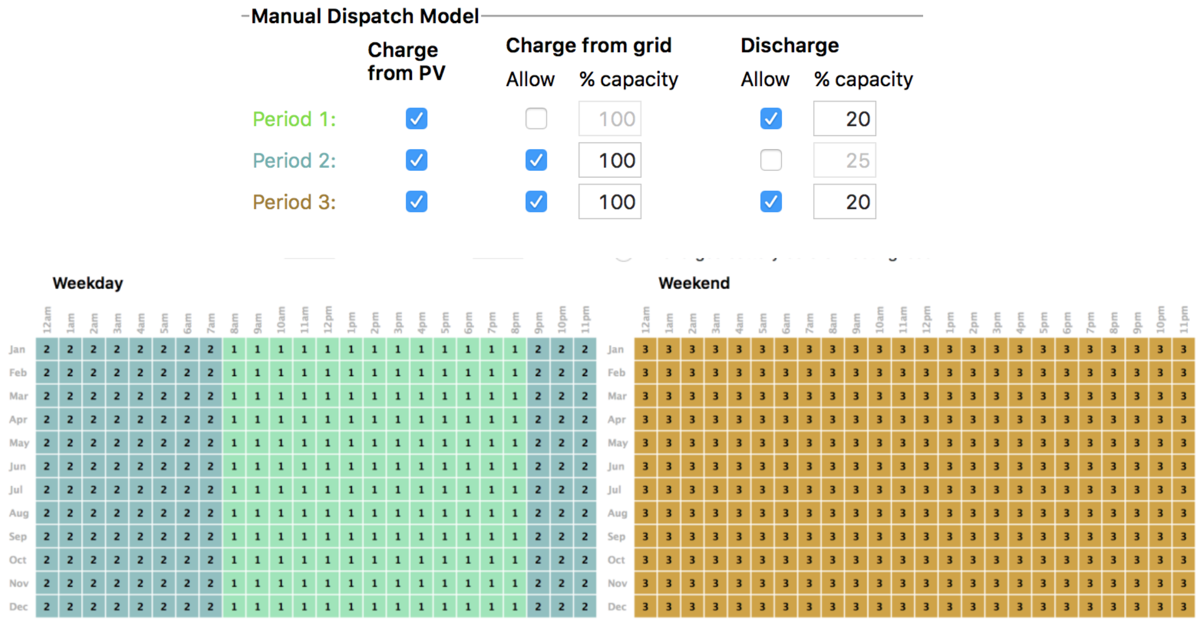

Figure 4.6. Manual dispatch model developed for energy storage based on Penn State electricity prices.

Using a 2 MW energy storage system with the dispatch model in Figure 4.6, it was found that the overall system provided a lower (more negative) NPV than a system without energy storage capability. This could be due to the large added capital cost associated with the battery system, along with small or negligent added benefit. The results from a 2.5 megawatt PV system combined with a 2 megawatt energy storage system can be seen in Table 4.4.

Table 4.4. System performance and financial results when energy storage system is enabled.

Metric	Value
Annual energy (year 1)	3,240,552 kWh
Capacity factor (year 1)	14.8%
Energy yield (year 1)	1,296 kWh/kW
Performance ratio (year 1)	0.84
Battery efficiency	97.60%
Levelized COE (nominal)	14.56 ¢/kWh
Levelized COE (real)	11.51 ¢/kWh
Electricity bill without system (year 1)	$8,755,982
Electricity bill with system (year 1)	$8,584,562
Net savings with system (year 1)	$171,420
Net present value	$-3,343,032
Payback period	NaN
Net capital cost	$6,613,984
Equity	$0
Debt	$6,613,984

In order to test whether it would be possible to improve overall system performance and NPV using energy storage, several battery parameters were varied and the effects were observed. It was found that the parameters with the greatest effect on the system were the dispatch model used and the nominal voltage of the cells. Figure 4.7 indicates that when holding all other values constant, the cell capacity and maximum C-rate of the battery do not have an effect on the NPV of the system. Based on this figure, it can also be found that optimum dispatch model is the manual dispatch based off of Penn State's electricity pricing structure model (represented as "0" in graphs). Also, the optimum nominal voltage of each cell was found as 1 V. However, even with the optimum rate structure and voltage enabled, the PV and battery system is still not able to achieve a positive net present value. In fact, the greatest NPV found using energy storage was still -$2.91 million (Figure 4.8), which is relatively similar to the value obtained without energy storage as seen in Table 4.15.

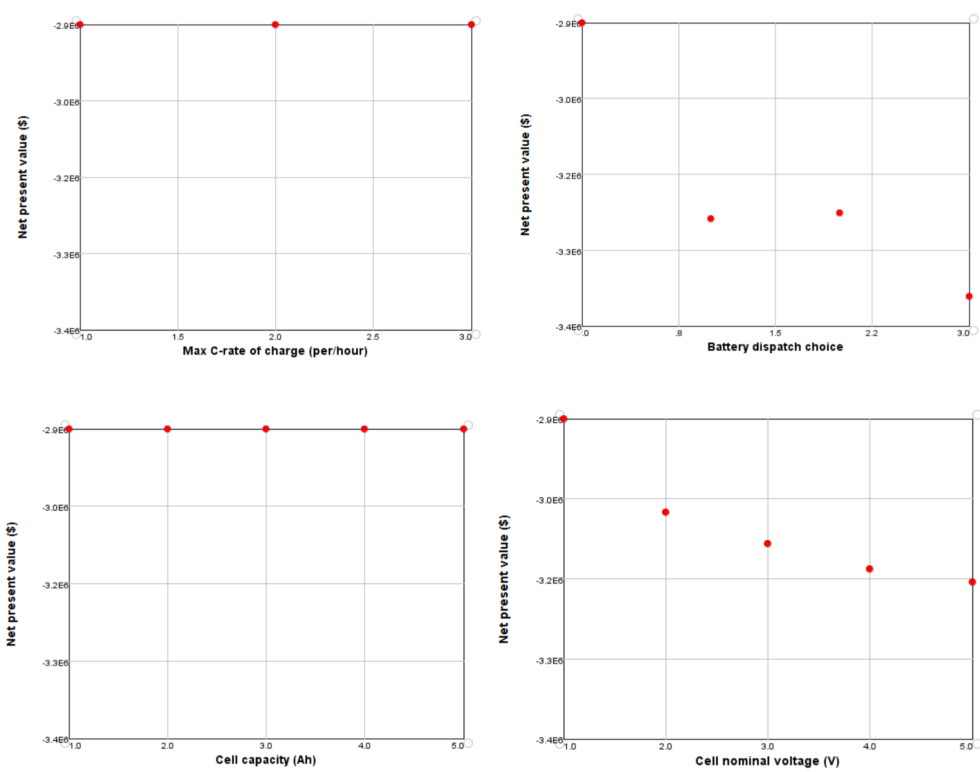

Figure 4.7. Effects of individual battery parameters on overall system NPV were observed. The battery dispatch model and nominal voltage were found to affect the NPV, while the C-rate and cell capacity did not.

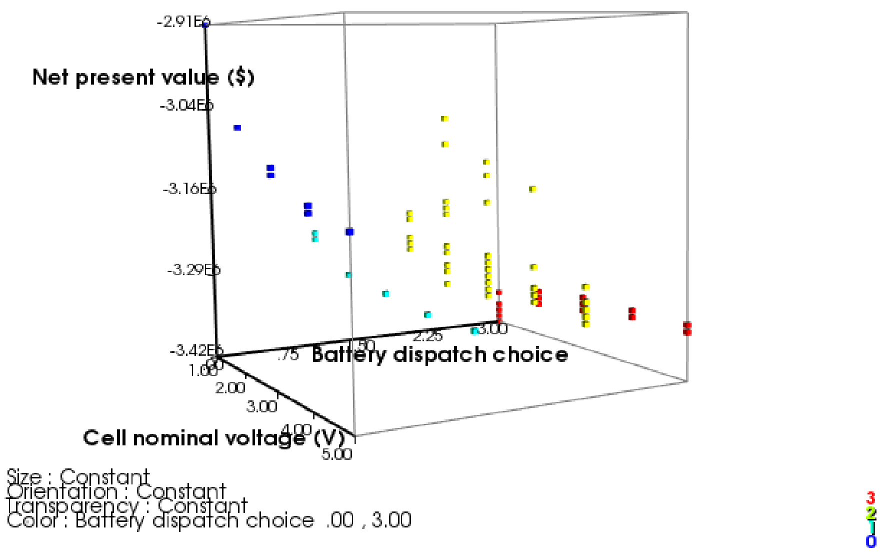

Figure 4.8. All potential systems including batteries are shown in a 3D trade space. Since only the nominal voltage and battery dispatch choice affected the NPV of the parameters tested, these are displayed on the x and z axes. The points are also colored according to the dispatch model used, where "0" represents the manual dispatch model in Figure 4.6.

4.3 Effect of Electricity Prices on System Performance and Financials

Throughout this research, simulations were ran using multiple electricity rate structures in order to determine the effect of electricity prices on the overall system's financial metrics. As explained in Section 2.3, Penn State operates on a complex electricity rate structure in which electricity prices vary with demand. These prices also vary due to multiple external factors such as population and congestion in the specific location. Hence, three viable rate structures were explored in order to better understand the effect of electricity prices on the viability of developing a solar energy conversion system for Penn State.

4.3.1 Penn State Electric Load

In order to generate accurate simulations to depict how much Penn State will pay for energy with and without a solar energy conversion system, Penn State's electric load data had to be entered into SAM. Penn State's 2016 hourly energy consumption was obtained from the Office of the Physical Plant in the format presented in Table 4.5 This data was input into SAM's electric load page as shown in Figures 4.9 and 4.10.

Table 4.5. The table shows an example of Penn State's hourly power load for January 1, 2016. Penn State's power usage was imported into SAM using hourly power load data for the entire year of 2016

Timestamp	*Power Imported (kW)*
2016-01-01 00:00:00	18,247.90
2016-01-01 01:00:00	18,268.83
2016-01-01 02:00:00	18,377.88
2016-01-01 03:00:00	18,181.05
2016-01-01 04:00:00	18,357.16
2016-01-01 05:00:00	18,337.55
2016-01-01 06:00:00	18,762.73
2016-01-01 07:00:00	19,482.37
2016-01-01 08:00:00	18,946.52
2016-01-01 09:00:00	19,120.91
2016-01-01 10:00:00	19,125.56
2016-01-01 11:00:00	18,906.46
2016-01-01 12:00:00	19,050.81
2016-01-01 13:00:00	19,277.16
2016-01-01 14:00:00	18,891.57
2016-01-01 15:00:00	19,119.75
2016-01-01 16:00:00	18,871.23
2016-01-01 17:00:00	18,886.67
2016-01-01 18:00:00	19,364.54
2016-01-01 19:00:00	19,386.31
2016-01-01 20:00:00	19,120.18
2016-01-01 21:00:00	18,792.72
2016-01-01 22:00:00	18,698.23
2016-01-01 23:00:00	18,530.14

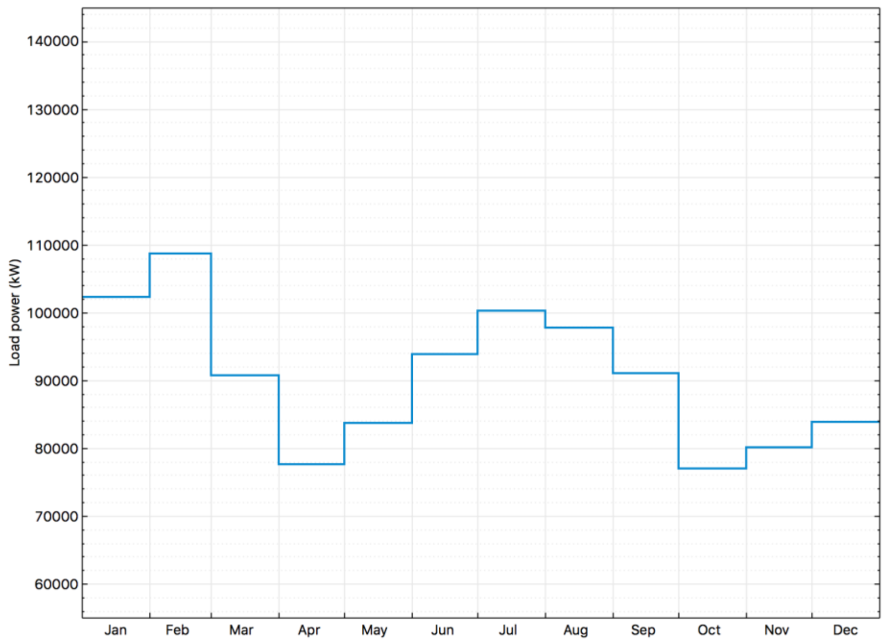

Figure 4.9. The figure displays average monthly values of load power (kW) used by Penn State in 2016.

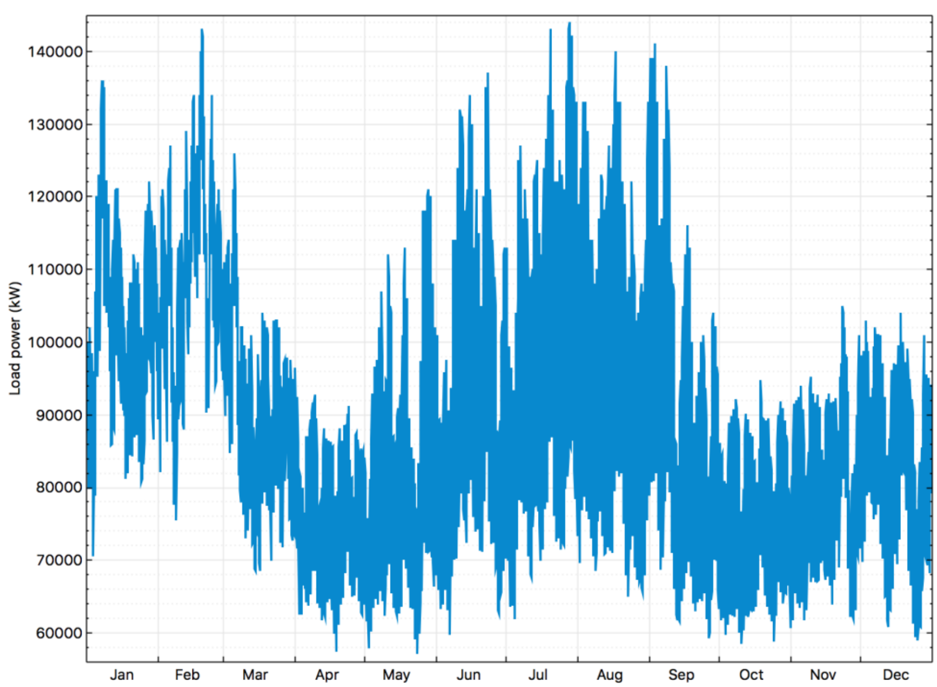

Figure 4.10. The figure displays the hourly power load data for Penn State used to generate the average monthly values shown in Figure 4.9.

4.3.2 PJM Locational Marginal Prices

The first set of simulations utilized a rate structure based on the LMPs presented by PJM, which can be seen in Figure 2.7. Since these are only the base costs of energy, the LMPs were scaled by a value of 2 in order to account for the additional prices included in the all-in hourly cost of energy that Penn State pays. Then, an average price was obtained for each season during on-peak and off-peak hours. These prices are shown in Table 4.6. The rate structure in the table, along with the demand structure in Table 4.7, were input as the electricity rates in SAM and the performance and financial metrics using this electricity structure were measured. The rate structure as it appears in SAM can be seen in Table 4.8 and Figure 4.11, while a summary of the results from this simulation can be seen in Table 4.9.

Table 4.6. The table displays the on-peak and off-peak PJM prices per season scaled for SAM. In this case, the average seasonal LMP prices were scaled by a factor of 2 in order to account for the additional energy fees that Penn State pays

	On-Peak ($/MWh)	*Off-Peak ($/MWh)*
Winter	115.97	86.03
Spring	74.89	47.34
Summer	74.48	44.54
Fall	67.07	47.27

Table 4.7. The average demand charge for Penn State obtained from the OPP is \$2.93/kW. The peak demands that Penn State experiences in each month are also displayed in the table.

Month	Tier	Peak (kW)	Charge ($/kW)
Jan	1	28000	2.93
Feb	1	31600	2.93
Mar	1	28474	2.93
Apr	1	31988	2.93
May	1	39376	2.93
Jun	1	42331	2.93
Jul	1	47934	2.93
Aug	1	50068	2.93
Sep	1	51140	2.93
Oct	1	42285	2.93
Nov	1	37228	2.93
Dec	1	32390	2.93

Table 4.8. The on-peak and off-peak prices for each season were inputted into SAM as individual periods as shown in the table.

Period	Tier	Max. Usage	Max. Usage Units	Buy ($/kWh)	Sell ($/kWh)
1	1	1e+38	kWh	0.086	0.086
2	1	1e+38	kWh	0.116	0.116
3	1	1e+38	kWh	0.048	0.048
4	1	1e+38	kWh	0.074	0.074
5	1	1e+38	kWh	0.066	0.066

Weekday

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
Feb	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
Mar	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
Apr	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3
May	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3
Jun	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3
Jul	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3
Aug	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3
Sep	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3
Oct	3	3	3	3	3	3	3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3	3
Nov	3	3	3	3	3	3	3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3	3
Dec	3	3	3	3	3	3	3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	3	3

Figure 4.11. The electricity rate structure using scaled PJM LMP prices is displayed as it appears in SAM. Since the off-peak hours during the fall, spring, and summer months were nearly identical, these were grouped into a single price of \$0.048/kWh. Similarly, the on-peak and off-peak prices during the spring and summer months were nearly identical, so these were grouped as a single price of \$0.074/kWh.

Table 4.9. The results based on electricity prices scaled from PJM LMP prices generate a negative net present value, along with a real LCOE of 9.20 ¢/kWh.

Metric	Value
Annual energy (year 1)	3,246,746 kWh
Capacity factor (year 1)	14.8%
Energy yield (year 1)	1,299 kWh/kW
Performance ratio (year 1)	0.84
Battery efficiency	0.00%
Levelized COE (nominal)	11.66 ¢/kWh
Levelized COE (real)	9.20 ¢/kWh
Electricity bill without system (year 1)	$637,264
Electricity bill with system (year 1)	$366,947
Net savings with system (year 1)	$270,316
Net present value	$-1,600,083
Payback period	NaN
Net capital cost	$5,373,772
Equity	$0
Debt	$5,373,772

4.3.3 OpenEI Prices

A second analysis was performed using a slightly different electricity rate structure. OpenEI is an open access storage place of rate structure information from various utilities throughout the United States. Hence, rate structures from OpenEI are used as the default structures when performing simulations. The OpenEI rate structure used in this specific simulation is the structure for large, general service clients with a minimum usage of 400 kW.

Unlike the previous rate structure which includes on-peak and off-peak hours throughout the entire year, the OpenEI data only has on-peak hours during the summer months. Also, instead of lasting from 8 AM to 10 PM, peak hours only last from 12 PM to 8 PM during the summer months. The appearance of this structure in SAM is shown in Table 4.10 and Figure 4.12, while the results from the simulations can be seen in Table 4.11.

Table 4.10. The OpenEI on-peak and off-peak prices for each season were inputted into SAM as individual periods as shown in the table.

Period	Tier	Max. Usage	Max. Usage Units	Buy ($/kWh)	Sell ($/kWh)
1	1	1e+38	kWh	0.0739362	0.078462
2	1	1e+38	kWh	0.133654	0.066502

Weekday

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Apr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
May	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Jun	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1
Jul	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1
Aug	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1
Sep	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Oct	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 4.12. Electricity rate structure using OpenEI pricing shows that the electricity prices only vary during the on-peak hours (12 PM-8 PM) according to the table above.

Table 4.11 The results based on the OpenEI electricity prices generate a negative net present value, along with a real LCOE of 9.00 ¢/kWh, which is an improvement from the results based on the scaled LMP PJM prices.

Metric	Value
Annual energy (year 1)	3,247,579 kWh
Capacity factor (year 1)	14.8%
Energy yield (year 1)	1,299 kWh/kW
Performance ratio (year 1)	0.84
Battery efficiency	0.00%
Levelized COE (nominal)	11.67 ¢/kWh
Levelized COE (real)	9.00 ¢/kWh
Electricity bill without system (year 1)	$18,904,000
Electricity bill with system (year 1)	$18,640,524
Net savings with system (year 1)	$263,476
Net present value	$-1,654,757
Payback period	NaN
Net capital cost	$5,373,772
Equity	$0
Debt	$5,373,772

4.3.4 OPP Electricity Pricing Structure

The most accurate pricing structure was obtained from the OPP at Penn State and includes on-peak and off-peak block pricing plus an additional charge for all non-energy costs.

Table 4.12. The table displays the on-peak and off-peak prices per season as provided by the OPP at Penn State.

	On-Peak ($/MWh)	*Off-Peak ($/MWh)*
Winter	64.70	55.60
Spring	52.20	42.00
Summer	56.70	42.40
Fall	50.70	42.80

The appearance of this rate structure in SAM is shown in Table 4.13 and Figure 4.13, while the results are shown in Table 4.14. As you can see, the hourly prices are much lower than in previous simulations, which results in an even more negative NPV. Hence, when Penn State is already paying such low prices for electricity from the grid, a solar energy generation system is not financially justifiable for the stakeholders.

Table 4.13. The on-peak and off-peak prices for each season were inputted into SAM as individual periods as shown in the table.

Period	Tier	Max. Usage	Max. Usage Units	Buy ($/kWh)	Sell ($/kWh)
1	1	1e+38	kWh	0.0647	0.0647
2	1	1e+38	kWh	0.0522	0.0522
3	1	1e+38	kWh	0.0567	0.0567
4	1	1e+38	kWh	0.0507	0.0507
5	0	1e+38	kWh	0.0556	0.0556
6	0	1e+38	kWh	0.042	0.042
7	0	1e+38	kWh	0.0424	0.0424
8	0	1e+38	kWh	0.0428	0.0428

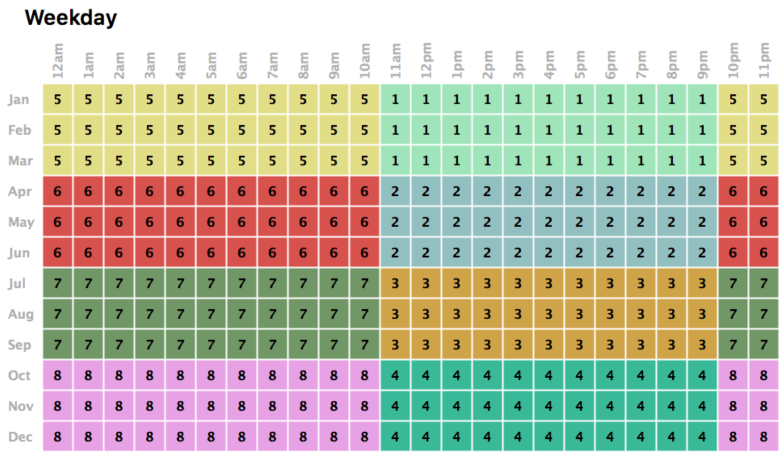

Figure 4.13. The electricity rate structure using Penn State electricity pricing from OPP shows that a different electricity price was used during on-peak and off-peak times for each season.

Table 4.14. The results based on the Penn State's accurate electricity prices generate a significantly negative net present value and greater cost of energy, which shows that this electricity pricing structure is the least effective for the development of a solar system.

Metric	Value
Annual energy (year 1)	3,245,299 kWh
Capacity factor (year 1)	14.8%
Energy yield (year 1)	1,298 kWh/kW
Performance ratio (year 1)	0.84
Battery efficiency	0.00%
Levelized COE (nominal)	13.11 ¢/kWh
Levelized COE (real)	10.37 ¢/kWh
Electricity bill without system (year 1)	$11,728,838
Electricity bill with system (year 1)	$11,565,967
Net savings with system (year 1)	$162,871
Net present value	$-2,948,284
Payback period	NaN
Net capital cost	$5,373,772
Equity	$0
Debt	$5,373,772

4.3.5 Summary

Based on the simulations, it is shown that the electricity rate structure has the major effect on the financial metrics of the system. The values of NPV and LCOE are compared in Table 4.15 in order to demonstrate this. At lower electricity prices, such as those provided by the OPP, the system is restricted from generating a positive NPV since the system cannot generate electricity at a lower cost than that which the customer already pays for electricity.

Table 4.15. Comparing the NPV and LCOE generated by different electricity rate structures, it was found that lower electricity prices result in a more negative NPV and a lower LCOE.

	Scaled PJM Prices	***OpenEI Prices***	***Penn State OPP Prices***
NPV ($)	-1,600,083	-1,654,757	-2,948,284
Real LCOE (¢/kWh)	9.20	9.00	10.37

In order to confirm our results, several simulations were developed in which only a consistent cost of electricity was varied. In other words, a certain unit cost of electricity (e.g. 10 ¢/kWh) was maintained for each hour of the year. This unit cost was varied between 0 ¢/kWh to 20 ¢/kWh, and the effects on LCOE and NPV were observed. Figure 4.14. shows that a positive NPV and reasonable payback period are only generated when the unit cost of electricity exceeds 15.8 ¢/kWh. This is extremely unlikely to occur in the State College area unless a sharp spike in electricity demand is experienced. Hence, other factors must be considered in order justify the viability of a 2.5 MW solar energy conversion system at Penn State.

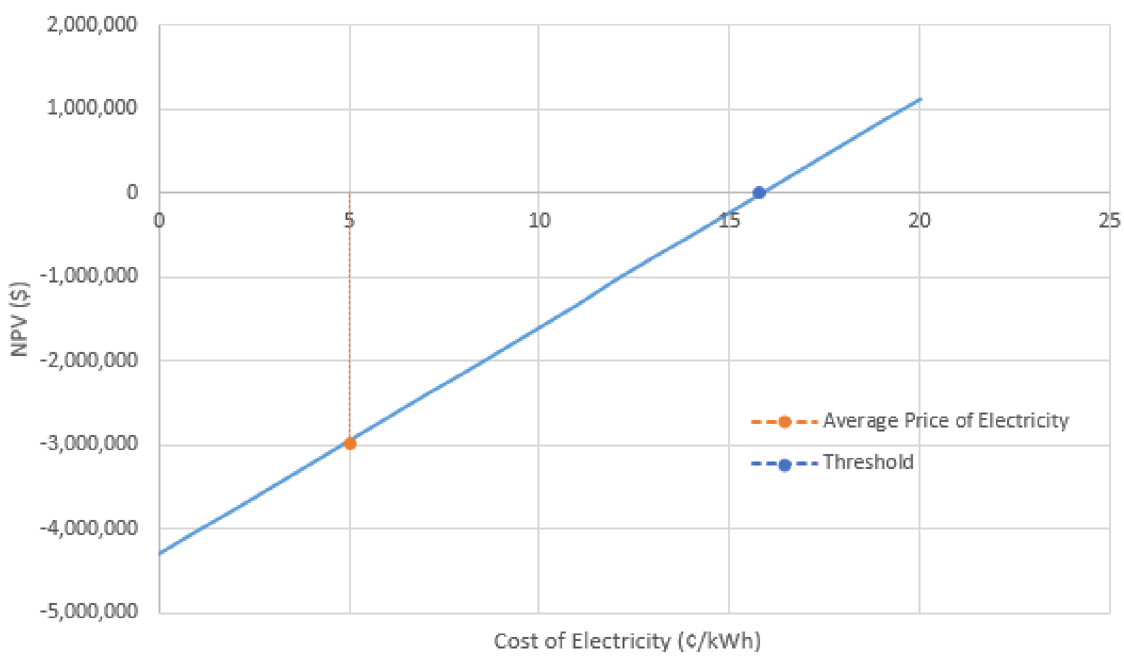

Figure 4.14. Without any discount rates or added incentives, an average electricity cost of 15.8 ¢/kWh is needed in order to generate a positive NPV using the aforementioned 2.5 MW solar energy conversion system

4.4 Effect of Incentives on System Financials

There are various monetary incentives which can be applied to the development of renewable energy systems. Since these incentives are consistently changing due to governmental regulations and external factors, it makes sense to consider the effect of such variations on the financial metrics of a solar system at Penn State.

4.4.1 Federal Investment Tax Credits

Penn State is considered a tax exempt entity, which means that it cannot receive any federal tax credits on systems or infrastructure that it installs on its own. However, the federal government currently offers a solar Investment Tax Credit (ITC), which is a 30 percent tax credit for solar systems installed on residential and commercial properties. Therefore, if Penn State outsourced the development of a solar system to a solar utility company or developer, the developer would have an incentive to lower the cost of the system to Penn State based on the tax credits it would receive. If this tax credit is applied in SAM, it is found that the NPV increases by 43%.

4.4.2 SREC Price

As discussed in Section 2.2, generators of solar energy are also able to receive solar renewable energy credits (SRECs) based on production levels. Currently Penn State would receive $7/MWh or $0.007/kWh based on Pennsylvania's SREC prices. However, as discussed earlier, Pennsylvania has planned to close its SREC borders to utilities outside of the state. This could result in a significant increase in SREC prices, which would contribute to a much more profitable investment. As shown in Figure 2.6, Washington, D.C. has an SREC price of $470/MWh or $0.47/KWh, while other states such as New Jersey also have prices above $100/MWh.

In 2010, Pennsylvania's SREC prices hovered above $300 in 2010, and with a change in the government regulation, SREC prices could return to high levels. As shown in Figure 4.15, Penn State would begin to generate a positive NPV as long as SREC prices are above $140/MWh or $0.14/kWh.

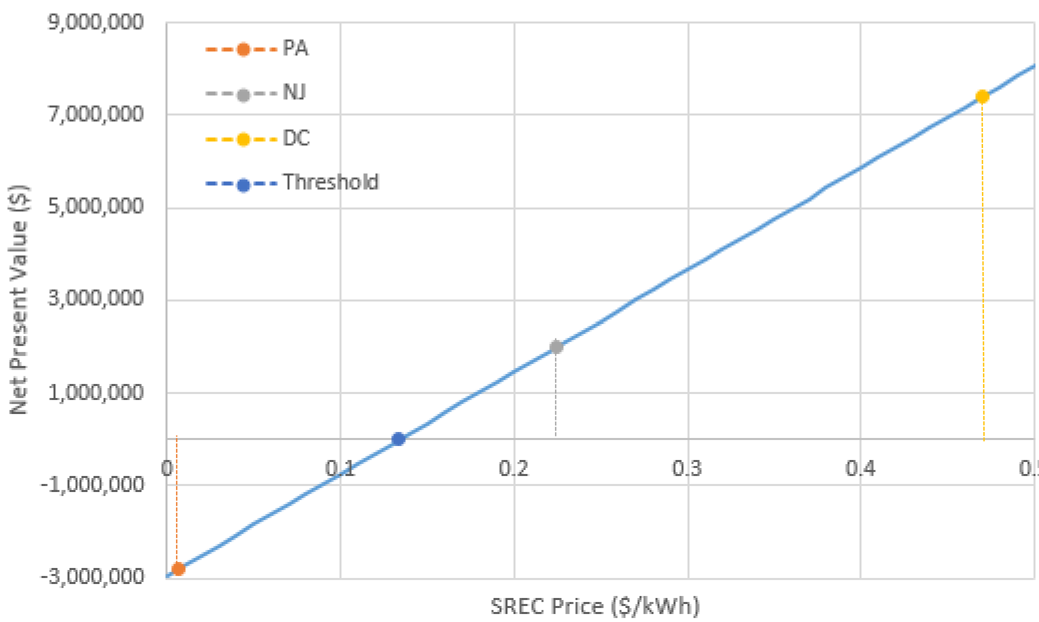

Figure 4.15. The figure shows the effect of SREC prices on the NPV of a 2.5 MW solar energy conversion system at Penn State using pricing obtained from OPP. Currently, the SREC in Pennsylvania is just $0.007/kWh, generating an NPV of -$2.8 million. If this price exceeds $0.140/kWh, Penn State can begin to generate a positive NPV using the system described. If the SREC price reaches that of New Jersey, Penn State would generate a positive NPV of approximately $2.0 million using the system.

4.4.3 Additional Incentives

While incentives due to investment tax credits and SRECs alone are able to increase the value of the solar system, the combination of tax credits and SRECs, along with additional incentives could certainly justify the development of a solar energy conversion system for Penn State. In the past, programs such as the Solar Energy Incentives Program and the Sunshine Solar Program offered rebates that varied between $1/W to $3/W for commercial systems. Figures 4.16 and 4.17 indicate that if such values of capacity based incentives (CBI) are combined with a tax incentive and SRECs (PBI), then over 75% of systems analyzed will generate a positive NPV and hence justify the development of the solar energy conversion system.

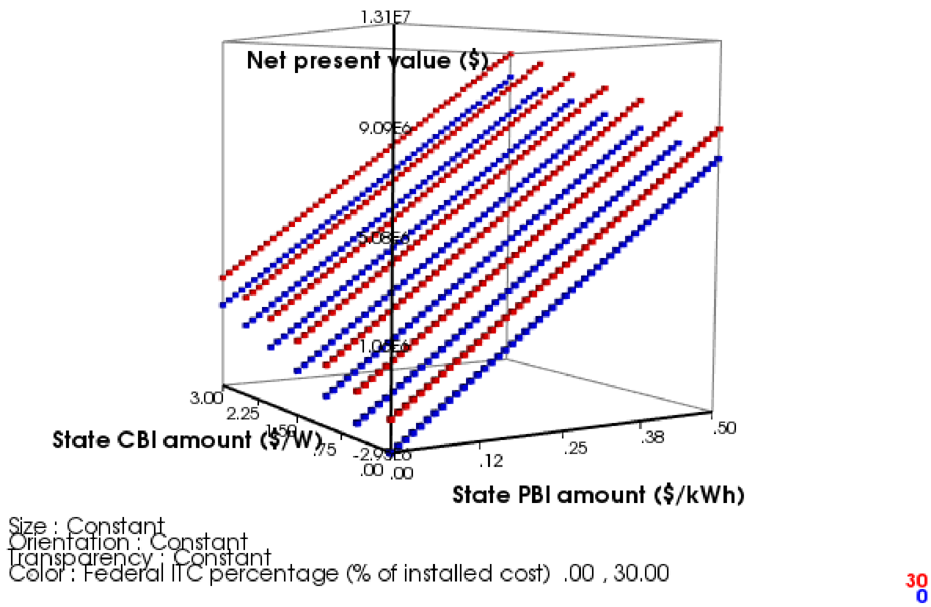

Figure 4.16. The figure shows the combined effect of capacity based incentives, performance based incentives, and tax incentives on NPV.

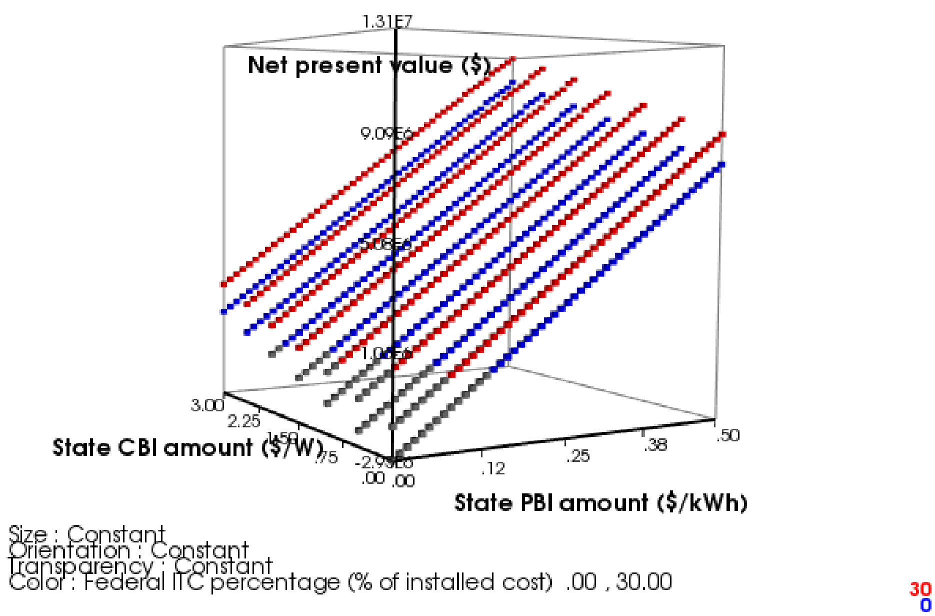

Figure 4.17. If all negative NPVs are shaded, it was found that over 75% of systems are still able to generate a positive NPV using a combination of incentives and federal tax credits.

Chapter 5

Conclusion

Throughout this research, the necessary parameters for Penn State to develop an economically viable 2.5 MW solar PV energy conversion system were explored. It was found that a solar PV system is currently unable to provide electricity to the stakeholders at a price below that of which Penn State currently pays. The 2.5 MW system which was analyzed throughout the research is able to provide a minimum levelized cost of energy of 10.37 ¢/kWh, while Penn State currently only pays between 3 and 7 ¢/kWh for electricity from the grid. Hence, Penn State is unable to achieve a positive NPV with the system unless parameters other than those associated with the technical components of the PV module, inverter, and energy storage system are varied.

It was found that the development of a 2.5 MW system can become economically feasible if several situations are to occur. The most unlikely situation would be a spike in electricity prices in Pennsylvania and the Centre County area. Currently, Penn State only pays an average of 5 ¢/kWh of electricity. Without any additional incentives or discount rates, Penn State will only begin to generate a positive NPV if this price reaches its threshold value of 15.8 ¢/kWh. This could occur if the State College area experiences an increase in congestion and electricity demand, or if the supply of electricity in the area drastically decreases.

Additionally, the system could experience a positive net present value if incentives or rebates are applied to Penn State's solar project. A bill has been developed to close Pennsylvania's SREC borders, which could result in a spike in Pennsylvania's SREC price. An increase in SREC prices in Pennsylvania would allow Penn State to more efficiently finance the solar PV project. Penn

State currently would only receive $7/MWh of energy generated by the system. However, it was found that if this price exceeds $140/MWh, the system would generate a positive net present value with a payback period of just 8 years. Based on changing government policies, Pennsylvania could also adapt a new solar rebate program in the next few year, which could further contribute to the funding of a solar project at Penn State.

While current electricity rate structures and incentives provide unfavorable economic conditions, Penn State and the OPP can take multiple actions to justify the development of a 2.5 MW solar array. First of all, the SREC prices should continue to be monitored, as prices can shift due to economic policies and external factors. If this price exceeds $140/MWh and remains above this price, the project will prove to be economically favorable. Additionally, stakeholders, such as students and faculty should seek to obtain a grant to help fund the project and reduce the capital costs and payback period associated with the system.

While Penn State cannot immediately generate positive economic value from the development of a community-scale solar energy conversion system, the system could present other benefits for the University. Penn State would diversify its energy portfolio by receiving electricity from another source of renewable energy. Additionally, the development of a solar PV system would decrease Penn State's greenhouse gas emissions creating a positive social and environmental impact.

Appendix A

System Financials

The total cost of a solar energy conversion system depends on multiple parameters, including capital costs (direct and indirect), operation and maintenance costs, and any taxes or incentives applied to the project. The system costs can be most effectively evaluated throughout a project's lifetime using the levelized cost of energy (LCOE) and net present value (NPV).

Direct Capital Costs

The direct capital costs represent expenses for all specific components installation services that apply in year zero of the cash flow.

Module ($/Wdc or $/Unit)

For a flat plate PV model, the module cost is the total physical cost of all of the PV panels installed in the system. This cost can be expressed as the dollars per unit or dollars per DC Watt:

- Dollars per DC watt multiplied by the capacity of the system (e.g., 2,500 kWdc)
- Dollars per unit multiplied by the total modules (e.g., 800 modules)

Inverter ($/Wac or $/Unit)

The cost of inverters in the system is expressed in dollars per AC Watt or dollars per inverter:

- Dollars per AC watt multiplied by the total inverter capacity (e.g., 2,300 kWac)
- Dollars per unit multiplied by the total number of inverters (e.g., 40)

Miscellaneous Costs

Additional costs typically included in the direct cost category for a PV system include: tracking equipment, balance of system, installation labor, installer margin and overhead. If a battery is included in the system, the direct capital cost of the battery along with any installation costs are also included in the direct costs. Additionally, a contingency cost is usually added to account for any expected uncertainties in the direct cost estimates.

Total Direct Cost ($)

The total direct cost of the system can be determined as the sum of the module, inverter, balance of the system, installation labor, installer margin, overhead costs, contingency costs, and any additional costs such as a battery.

Indirect Capital Costs

The indirect capital costs include any costs which cannot be identified with specific pieces of equipment or installation services. These include costs such as permitting and environmental studies, engineering, grid interconnection, and land and land preparation costs.

Total Installed Costs

The total installed cost of the system is the sum of all system expenses due to investments in year zero of the project's cash flow. This cost is used to establish loan amounts and debt interest payments based on local, state, and federal incentives established in Chapter 2. The total installed costs are typically referenced using the overall value ($) or the total cost per capacity ($/Wdc or $/kW).

Operation and Maintenance Costs

The operation and maintenance costs annual expenditures on equipment and services throughout the lifetime of the system. Hence, the operations and maintenance costs are all costs that are reported in the project cash flow after production has initiated in Years 1 and later. These costs can be established as a fixed annual cost that remains consistent in each year of production, or vary from year to year due to expenses such as component replacements or specific operations.

Operation and maintenance costs can increase annually based on a specified escalation rate, or they will increase based on the annual inflation rate if the escalation rate is zero.

Levelized Cost of Energy (LCOE)

The LCOE is the total cost of installing and operating a solar project expressed in dollars per kilowatt-hour ($/kWh) generated by the system over its lifetime. Assuming that the solar system will meet all or part of certain building's electric load, the LCOE is comparable to the $/kWh retail electricity rate representing the cost of the alternative option to meet all the building's load by purchasing electricity from the grid. Hence, to be economically viable, the project's LCOE must be equal to or less than the average retail electric rate. The current average retail electric rate for Penn State is about $0.06/kWh.

A project's equivalent annual cost (C_n) is the product of the LCOE and the quantity of electricity generated by the system in that year (Q_n):

$$C_n = Q_n \text{ x } LCOE$$

In order to effectively calculate the LCOE, the total lifecycle cost (TLCC) must first be established as the present value of project costs over its life (N) at discount rate (d):

$$TLCC = \sum_{n=0}^{N} \frac{C_n}{(1+d)^n} \quad = \quad \sum_{n=1}^{N} \frac{Q_n \times LCOE}{(1+d)^n}$$

Hence, the LCOE can be expressed as:

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}}$$

Nominal LCOE

The nominal LCOE is the value of the LCOE when using current dollar value which does not account for inflation. The nominal LCOE should only be used for short-term analyses when inflation is not a factor. Adding the project's initial capital costs (C_0) to the equation, the nominal LCOE can be calculated as:

$$\text{Nominal LCOE} = \frac{-C_0 - \frac{\sum_{n=1}^{N} C_{AfterTax,n}}{(1 - d_{nominal})^n}}{\frac{\sum_{n=1}^{N} Q_n}{(1 - d_{nominal})^n}}$$

Real LCOE

The real LCOE is simply the LCOE adjusted for inflation, or the constant dollar value for LCOE. This value is useful for long-term analyses in order to account for many years of inflation over the project's lifetime. Adding the project's initial capital costs (C_0) to the equation, the real LCOE can be calculated as:

$$\text{Real LCOE} = \frac{-C_0 - \frac{\sum_{n=1}^{N} C_{AfterTax,n}}{(1 - d_{nominal})^n}}{\frac{\sum_{n=1}^{N} Q_n}{(1 - d_{real})^n}}$$

Net Present Value (NPV)

A project's net present value (NPV) measures the profit or loss that a system is capable of generating. In other words, the NPV depicts the economic feasibility of a project based on the revenue and cost of the project. Typically, a positive NPV indicates an economically feasible project, while a negative NPV indicates an economically infeasible project. The NPV (nominal) can be calculated as the present value of the cash flow after tax:

$$\text{NPV} = \sum_{n=0}^{N} \frac{C_{AfterTax,n}}{(1 + d_{nominal})^n}$$

Payback Period

The payback period is the critical time period in years that it takes for a project to begin generating savings based on the project's cash flows. Hence, it is the time that it takes for the project to break even and the revenue generated from the project to outweigh the costs. For Year Zero, the cash flow can be represented as the incentives, which include investment-based incentives (IBI) and capacity-based incentives (CBI), minus the total installed cost of the system:

$$\begin{aligned} Year\ Zero = {} & Total\ IBI \\ & + Total\ CBI \\ & - Total\ Installed\ Cost \end{aligned}$$

For every year after Year Zero, the cash flow can be represented as:

$$
\begin{aligned}
\textit{Year } n>0 = {} & \textit{Energy Value} \times (1 - \textit{Effective Tax Rate}) \\
& + \textit{State Tax Savings} \\
& + \textit{Federal Tax Savings} \\
& + \textit{Total PBI} \\
& - \textit{Debt Interest Payment} \times \textit{Effective Tax Rate} \\
& - \textit{Total Operating Expenses}
\end{aligned}
$$

In this equation, the total PBI represents production-based incentives and the effective tax rate is a number that accounts for the federal and state income tax rates:

$$\textit{Effective Tax Rate} = \textit{Federal Tax Rate} \times (1 - \textit{State Tax Rate}) + \textit{State Tax Rate}$$

REFERENCES

[1] "Penn State at a Glance." [Online]. Available: https://stats.psu.edu/. [Accessed: 26-Jan-2017].

[2] M. Prinkey, "PSU Building Benchmark UP."

[3] "Sustainability Guidebook," Penn State Sustainability Institute, 2014.

[4] Jeffrey Brownson, *EME 810: Solar Resource Assessment and Economics*. 2016.

[5] "Finding Pennsylvania's Solar Future," 2017. [Online]. Available: http://www.dep.pa.gov/Business/Energy/OfficeofPollutionPrevention/Pages/Finding-Pennsylvania%E2%80%99s-Solar-Future.aspx. [Accessed: 27-Jan-2017].

[6] Pieter Gagnon, Robert Margolis, Jennifer Melius, Caleb Phillips, and Ryan Elmore, "Rooftop Solar Photovoltaic Technical Potential in the United State: A Detailed Assessment," National Renewable Energy Laboratory, Technical Report, Jan. 2016.

[7] "Pennsylvania Solar Rebates and Incentives," *The Clean Energy Authority*. [Online]. Available: http://www.cleanenergyauthority.com/solar-rebates-and-incentives/pennsylvania/. [Accessed: 27-Jan-2017].

[8] Philip Jordan *et al.*, "Clean Jobs Pennsylvania," Environmental Entrepreneurs (E2), Keystone Energy Efficiency Alliance, Jul. 2016.

[9] "Marcellus Shale Update," Pennsylvania Department of Labor and Industry, 2016.

[10] Tom Corbett and Dana K. Aunkst, "The Pennsylvania Sunshine Program," PA DEP, Nov. 2014.

[11] "Solar Spotlight: Pennsylvania," SEIA, Jun. 2015.

[12] "Top 10 Counties for Solar in Pennsylvania | Paradise Energy Solutions." [Online]. Available: https://www.paradisesolarenergy.com/solar-counties-pa/. [Accessed: 02-Mar-2017].

[13] S. Wilcox and W. Marion, "Users Manual for TMY3 Data Sets," NREL, May 2008.

[14] "Alternative Energy and Economic Development in Pennsylvania," Public Utility Commission Bureau.

[15] "Pennsylvania SRECs," *Flett Exchange*. .

[16] M. Prinkey, "PSU Electric Budget."

[17] J. R. S. Brownson, *Solar energy conversion systems*, First edition. Oxford, UK ; Waltham, MA, USA: Academic Press, 2014.

[18] "Climate State College - Pennsylvania and Weather averages State College." [Online]. Available: http://www.usclimatedata.com/climate/state-college/pennsylvania/united-states/uspa2543. [Accessed: 02-Mar-2017].

[19] "NREL: Energy Analysis - Energy Technology Cost and Performance Data." [Online]. Available: http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html. [Accessed: 02-Mar-2017].

[20] Garrett Fitzgerald, James Mandel, Jesse Morris, and Herve Touati, "The Economics of Battery Energy Storage," Rocky Mountain Institute, Oct. 2015.

[21] cleanhorizon, "Frequency regulation: the need for fast responding assets and the 'mileage' case in the USA. | CleanHorizon Blog." .

[22] Ruud Kempener and Eric Borden, "Battery Storage for Renewables: Market Status and Technology Outlook," IRENA, 2015.

[23] R. Hensley, J. Newman, and M. Rogers, "Battery technology charges ahead | McKinsey & Company." [Online]. Available: http://www.mckinsey.com/business-

functions/sustainability-and-resource-productivity/our-insights/battery-technology-charges-ahead. [Accessed: 02-Mar-2017].

[24] "The Global Market for Lithium Ion Batteries for Vehicles Is Expected to Total $221 Billion from 2015 to 2024," *Navigant Research*, 17-Feb-2016. [Online]. Available: https://www.navigantresearch.com/newsroom/the-global-market-for-lithium-ion-batteries-for-vehicles-is-expected-to-total-221-billion-from-2015-to-2024. [Accessed: 02-Mar-2017].

[25] "li_ion_battery_life__TechnicalSheet_en_0514_Protected (2).pdf." .

[26] Mark Fedkin and John A. Dutton, *Utility Solar Power and Concentration*. .

[27] "String vs. Central Inverters: Choosing the Right Inverter for your Solar System," *The Solar Report « Cenergy Power - Solar Energy News and Information*, 09-Jan-2014.

[28] "Micro-inverters vs. string inverters for solar PV - Renewable Energy Focus." [Online]. Available: http://www.renewableenergyfocus.com/view/10472/micro-inverters-vs-string-inverters-for-solar-pv/. [Accessed: 02-Mar-2017].

[29] Brian Lydic, "Sustainability for the PV Industry: Field Service," Fronius.

[30] Simon W. Miller, Timothy W. Simpson, and Michael A. Yukish, "Design as a Sequential Design Process," ASME, 2015.

[31] Craig Christensen and G. Barker, "Effects of Tilt and Azimuth on Annual Incident Solar Radiation for United States Locations," NREL, 1998.

[32] Donald Chung, Carolyn Davidson, Ran Fu, Kristen Ardani, and Robert Margolis, "U.S. Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential, Commercial, and Utility-Scale Systems," National Renewable Energy Laboratory, Technical Report, Sep. 2015.

ACADEMIC VITA

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EDUCATION

The Pennsylvania State University — **University Park, PA**
Schreyer Honors College — Expected May 2017
B.S. Mechanical Engineering, Minor in Spanish

Charles III University of Madrid — **Madrid, Spain**
Study Abroad: IES Engineering, Architecture, and Science — Jan. 2016 – May 2016

PROFESSIONAL EXPERIENCE

MOTIVA Enterprises LLC (Shell Oil Company) — **New Orleans, LA**
Production Team Support Engineering Intern — Jun. 2016 – Aug. 2016

- Investigated 305 pumps across site for faults and potential hazards according to design requirements
- Analyzed 97 defective pumps and designed field packages to reduce future turnaround time by 25%
- Streamlined repair process to save $50K on maintenance-outage costs per pump replacement
- Designed safety protocols that were presented to all 1,200 employees to reduce risk of injury

Shell Oil Company — **Pittsburgh, PA**
Completion & Well Intervention Intern — May 2015 – Aug. 2015

- Developed a smaller casing design to reduce drilling and completion costs by $110K per well
- Built total landed cost model to analyze a $2M re-fracture project for potential areas of savings
- Utilized incident analysis methods to effectively communicate risk assessments to all employees
- Gained invaluable hands-on experience through observing drilling and completion field operations

General Electric Transportation — **Erie, PA**
Advanced Manufacturing Intern — May 2014 – Aug. 2014

- Investigated and resolved part tracking issues on shop floor to reduce tracking errors by 20%
- Refined scrap process to increase productivity and improve organization on shop floor
- Led daily meetings with shop floor personnel to ensure smooth operations
- Performed physical inventory to confirm accuracy of record keeping throughout the shop

THESIS RESEARCH

Solar Energy Research — **University Park, PA**
Earth and Mineral Sciences Energy Institute — Jan. 2014 – Present

- Developing data visualization tool to analyze trade-offs in photovoltaic systems
- Seeking to identify optimum practices and designs for Penn State's 2.5 megawatt solar energy project
- Exploring the potential of lithium-ion energy storage for load shifting and frequency regulation services

LEADERSHIP EXPERIENCE

The Schreyer Consulting Group — **University Park, PA**
Corporate Events Chair & Career Development Chair — Oct. 2014 – Jan. 2016

- Coordinated 9 workshops with alumni and firms to prepare students for consulting careers
- Organized two treks to corporate offices in Washington DC and NYC for over 20 students

BP Ultimate Field Trip Competition — **Houston, TX**
Team Leader — Oct. 2014 – Apr. 2015

- Devised solution to reduce amount of water consumed in hydraulic fracturing by up to 95%
- Received first place in campus finals at Penn State University
- Presented technical poster and informational video to BP executives at the national finals

Penn State Formula SAE — **University Park, PA**
Brake Team Assistant Lead — Oct. 2013 – May 2014

- Redesigned vehicle's brake pedal, rotors, and pads to improve braking performance
- Worked with suspension team to improve steering and driving stability

VOLUNTEER

Penn State IFC/Panhellenic Dance Marathon — **University Park, PA**
Sigma Chi Fraternity — Jan. 2014 – Present

- Participated in canning and other philanthropic events to raise money for THON
- Raised over $200K for pediatric cancer for three consecutive years with Alpha Omicron Pi

SKILLS

Language: English (Native), Russian (Native), Spanish (Conversational)
Computer: MATLAB, SolidWorks, Microsoft Office, System Advisor Model (SAM), Proficy
Athletics: Member of Penn State Club Tennis Travel Team, PIAA State Semi-Finalist (Tennis)