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An Economic Analysis of the Solar Energy Potential at Lake Forest College

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An Economic Analysis of the Solar Energy Potential at Lake Forest College

Abstract
The energy industry is evolving towards renewable energy. This study examines the potential of solar energy for electricity usage on the campus of Lake Forest College through both a technical and market analysis. A solar panel was installed on the roof of Carnegie Hall, a large building in the central campus area, for a period of twelve weeks. In addition, regression analysis on the total output of the solar panel in relation to cloud coverage, solar intensity, average temperature, and hours of daylight led to more extensive analysis on the technical potential of solar energy on the campus. The economic analysis contributed by the photovoltaic solar cell system was determined in terms of the energy savings and monetary payback. The results of this investigation concluded that a small portion of the school's electricity needs can be met by the use of solar energy.

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An Economic Analysis of the Solar Energy Potential at Lake Forest College

by

Jennifer McTague

May 1, 2017

The report of the investigation undertaken as a Senior Thesis, to carry two courses of credit in the Department of Economics, Business and Finance and the Department of Environmental Studies

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Krebs Provost and Dean of the Faculty

Jeffrey Sundberg, Chairperson

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Abstract

The energy industry is evolving towards renewable energy. This study examines the potential of solar energy for electricity usage on the campus of Lake Forest College through both a technical and market analysis. A solar panel was installed on the roof of Carnegie Hall, a large building in the central campus area, for a period of twelve weeks. In addition, regression analysis on the total output of the solar panel in relation to cloud coverage, solar intensity, average temperature, and hours of daylight led to more extensive analysis on the technical potential of solar energy on the campus. The economic analysis contributed by the photovoltaic solar cell system was determined in terms of the energy savings and monetary payback. The results of this investigation concluded that a small portion of the school’s electricity needs can be met by the use of solar energy.
To my parents
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Introduction

Renewable energy is a clean and sustainable energy source generated through natural systems. The increased global awareness of the depletion of fossil fuels, their environmental costs, and the hazards associated with climate change, are driving efforts toward renewable energy. One concern, however, is the reliability of renewable energy sources since they are dependent on natural systems for their energy generation. Solar energy has become an attractive source of renewable energy given that it is noiseless and emits no carbon dioxide during operation. The energy received by the sun in one single year, if entirely captured and stored, would represent more than 6,000 years of total energy consumption; if we capture and distribute one-tenth of one percent of that energy, the global energy supply problem disappears.\(^1\) Solar energy, therefore, has the potential to displace fossil fuels.

The global environmental danger associated with the burning of fossil fuels for electricity has become a primary driving force for the transition to renewable energy sources. According to the U.S. Energy Information Administration (EIA), The United States currently uses fossil fuels to meet 81% of its total energy demand.\(^2\) Fossil fuels have been the traditional energy source due to their dense storage of energy and accessibility. In addition, fossil fuels are considered fast and cheap in comparison to renewables such as solar. One liter of gasoline can deliver 35 megajoules of energy, which is the amount of energy one square meter of land receives from the sun in roughly ten hours in the best conditions.\(^3\) However, it is important to understand that while fossil

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\(^2\) The Institute for Energy Research (IER). (2016).
\(^3\) IEA, Pg. 24
fuels are cheap and generate energy relatively quickly, solar energy will prove to be more sustainable and energy efficient in the long run.

Fossil fuels are a finite resource for energy that emit carbon dioxide and other greenhouse gases, contributing in large part to global climate change. Coal, oil, and natural gas reserves are expected to be used up by the end of this century. The most common products derived from oil are gasoline, heating oil, and aviation and diesel fuels; all found within the energy sector. Therefore, the energy industry is currently one of the largest contributors to climate change. According to the IEA, fossil reserves for oil are expected to be depleted in 46 years, natural gas in 58 years, and coal in approximately 150 years given the 2010 global consumption rates. In addition to the depletion of these resources, jobs in these areas are decreasing as well. According to the EDF report, the compound annual growth rate of employment in the fossil-fuel industry was -4.5% from 2012 to 2015. This comes to no surprise, as working in a coal mine or drilling for oil offshore are both dangerous and can have serious long-term health effects.

Fracking is the most recent method to extract fossil fuels. Fracking is the injection of high-pressure fluid into rocks deep underground thus releasing pockets of oil and natural gas. This is an impressive technology, but it’s also a technology that imposes large costs on the public. Fracking produces toxic and radioactive wastewater that contaminates drinking water. It also sends a shock through the earth’s crust that has led to many earthquakes and the heavy trucking required for fracking causes major damage on roads. Economist Paul Krugman argues that an industry imposing large costs on third

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4 IER. (2016)
5 IEA, Pg. 32
parties should be required to internalize those costs. That is, for the industry to pay for the damage it causes, treating that damage as a cost of production. Fracking, and any industry for that matter, should be held accountable for its impacts on the environment and the nation’s infrastructure. Fracking has grown in the United States due to the decrease in oil and natural gas prices, which occurs each time new reserves are discovered. The U.S. fracking revolution has caused natural gas prices to drop 47% compared to what the price would have been prior to the fracking revolution in 2013. Until the external costs of the environmental and infrastructure damages are internalized in the fracking industry, there will still be investments to prioritize cheap oil and natural gas.

While the United States consumes the most energy in the world, predominantly from fossil fuels, it does contain the third largest photovoltaic (PV) market in the world. Within the U.S., many states have created incentives for companies which implement a small fraction of their energy consumption from renewables.

An analysis of the solar energy potential at Lake Forest College requires a look at the policies in place in Illinois. Illinois currently ranks twenty-fifth in the U.S. for total energy per capita, ninth in total energy production, and fourth in total carbon dioxide emissions. In fact, Illinois is one of the leading states for fossil fuel production and transportation, especially for crude oil and natural gas. Illinois’s location in the center of the country makes it an ideal production and transportation hub for the rest of the

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11 EIA. (2017)
country. While Illinois is ranked first in generating capacity and net electricity generation for nuclear power, development in renewable energy sources is minimal.\(^\text{12}\) There are currently seven nuclear plants operating in Illinois, with a 24-hour monitoring system in and around each reactor site.\(^\text{13}\) While Illinois leads the country in nuclear energy, they fall short in forms of renewable energy such as solar and wind. Making a switch to renewables will therefore require significant changes from Illinois lawmakers. In fact, Illinois recently passed the Future Energy Jobs Act to provide funding towards clean energy, ensuring job growth, investments, cleaner air, and savings on electricity bills.\(^\text{14}\)

From a national perspective, the 2017 Energy and Employment Report suggests that the solar industry now employs more people than coal, oil, and gas combined.\(^\text{15}\) Given the current federal administration’s goal to increase jobs, there is no question that they need to move away from fossil fuels and focus their attention on renewable energy. Renewable energy will become the standard in the future due in part to its current growth as well as its environmental benefits.

Currently, the United States is far behind other countries in solar energy development. As early as in 2000, solar markets in Japan and Germany alone were responsible for 40% of global photovoltaic (PV) installations.\(^\text{16}\) While the United States has access to cheap fossil fuel sources, the potential for solar energy development is large. The yearly amount of energy received from the sun is far greater than the total

\(^{12}\) EIA. (2017)
\(^{15}\) Varinsky, D. (2017)
estimated by fossil fuel resources.\textsuperscript{17} Therefore, as fossil fuels become depleted over time, the need to transition to solar energy will occur based on economic sustainability in addition to the environmental benefits. We already know that the global PV market grew by 40% in 2009, and nearly 135% in 2010.\textsuperscript{18} Additionally, electricity is more easily decarbonized than other fuels, thus it is set to play an important role in a world struggling to reduce its energy-related carbon dioxide emissions, further enhancing energy security.\textsuperscript{19} While fossil fuels may continue to be used for heating and other methods of energy use in the near term, electricity can easily be generated using solar technology.

There is competition among carbon-free and renewable energy resources. Currently, the largest competitors to PV solar energy are wind, hydropower, and nuclear. Nuclear and hydropower energy have historically been the largest carbon-free resources in the United States, however the storage of nuclear waste has hazardous implications. The disasters at Fukushima and Three Mile Island are two examples of the environmental and health dangers associated with storing nuclear energy. Despite its dangerous implications, nuclear energy has no carbon dioxide emissions, which made it appealing in an energy industry dominated by fossil fuels. However, following these incidents, nuclear has become a less attractive method of generating energy Hydropower has the largest efficiency of any renewable energy resource, operating at around 56% efficiency.\textsuperscript{20} However, there is not much room to grow in the hydropower industry. Hydropower is limited to certain waterways, with dams already built in almost all potential locations. While hydropower has no carbon dioxide emissions as well, the environmental hazards

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\textsuperscript{17} IEA, Pg. 32 \\
\textsuperscript{18} IEA, Pg. 47 \\
\textsuperscript{19} IEA, Pg. 47 \\
\end{flushright}
are that it disrupts the local ecosystem by blocking minerals and species that would normally pass through the waterway.

Wind and solar are now becoming more dominant on the market, and for good reason. The United States is currently the world leader in wind energy production.\(^\text{21}\) This is due in part to the vast amount of flat lands in the Midwest. Wind energy is generated using wind turbines, and have reached a cumulative capacity in 2016 of over 75,000 megawatts (MW), enough to power over twenty million homes.\(^\text{22}\) The downside of wind energy is that turbines can only operate in certain wind conditions, unlike solar panels that operate under any sunlight conditions. Wind turbines have also led to many bird and bat fatalities, in addition to disrupting local migration patterns.\(^\text{23}\) In comparison to solar, the panels require non-renewable resources in their construction and require an extensive amount of land use depending on their location. However, while no source of energy comes without external costs, the risks associated with any renewable energy resource are far less than those caused by fossil fuels.

While solar energy has its limitations, it far exceeds the potential of any other renewable energy resource in terms of its energy resource. Solar energy, (and renewable energy in general), can help to decrease the amount of carbon dioxide (\(\text{CO}_2\)) in the atmosphere, which is one of the major contributors to climate change. Generating carbon-free electricity will not only eliminate carbon dioxide emissions from electricity generation, but will also help eliminate emissions resulting from direct fossil fuel consumption by the large consumers of electricity in the construction, industrial, and


\(^{23}\) American Bird Conservancy. (2017)
transport sectors of our economy.\textsuperscript{24} In addition, the decrease in carbon-based electricity costs will lower the overall cost of renewable energy, making it the preferred choice of energy generation.

This study provides an in-depth analysis on the solar energy potential at Lake Forest College. The hypotheses in this study look at the technical potential of the solar panel under normal conditions in Lake Forest, Illinois and a financial analysis of the impact to the college. Economic analysis of electricity generation is challenging due to the variation in cost, technology, plant size, time, and location.

The words energy and electricity will be used frequently in this paper, and it is important to distinguish the two. Energy is a source of power, which can come in the form of heat, electricity, or caloric intake. Electricity is a form of energy, and will be frequently referenced as energy throughout this paper. When discussing solar energy, solar electricity is referenced. Since energy prices fluctuate, an economic analysis one year might be inaccurate in the next. Therefore, this study provides a framework for an annual economic analysis of solar energy production at Lake Forest College.

\textsuperscript{24} IEA, Pg. 47
Chapter 1

The connection between the power of the sun as an energy source and the collection and storage of that energy for the use of electricity becomes the framework for understanding the potential of solar energy. This chapter discusses the source of solar energy, the physics of solar panels, and the current market for solar energy. In addition, this chapter provides an analysis of the current barriers to solar energy development and current strategies to overcome those barriers.

Solar Irradiance

The power of the sun is an essential resource that can be captured and used to create heat or electricity. Roughly 885 million terawatt-hours (TWh) of energy reach the earth’s surface in one year, which is 6,200 times the 2008 global commercial energy consumption. However, it is extremely difficult to collect and store that amount of energy. To lend perspective, it would take the sun approximately one and a half hours to produce enough energy to supply the entire annual global energy demand, and following the IEA’s Current Policies Scenario, it would take between two and seven hours to supply enough energy for the predicted energy consumption in 2035.

When considering the use of solar panels to harness this much energy, it is important to note that solar panels must logically be placed on land. It would take approximately 3.25 times longer to capture this energy if captured solely on land, however this is still a small fraction within a single day. While the technology is not in

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25 IEA, Pg. 31
26 IEA, Pg. 32
27 IEA, Pg. 32
place to make this a reality, solar energy is the most abundant source of renewable energy.

Solar irradiance is defined as the amount of power that the sun deposits per unit area that is directly exposed to sunlight.\(^{28}\) Radiation is the term used to define the amount of power through electromagnetic waves. Solar radiation is also defined as a flux (in kWh/m\(^2\)/y) of electromagnetic particles or photons.\(^{29}\) These photons are highly energetic, and enable photoreactions such as in photosynthesis in addition to generating conduction of electrons in semiconductors, enabling photovoltaic conversion of sunlight into electricity.\(^{30}\) The solar constant is the average amount of solar radiation received by the Earth’s atmosphere, per unit area, and is equal to 1,370 watts per square meter.\(^{31}\) However, only 57% of the total energy emitted by the sun reaches the Earth’s surface, due in part to the earth being a rotating globe rather than a flat, stationary surface.\(^{32}\) The rest of the sun’s radiation is either absorbed into the atmosphere or emitted back into space. Climate change has decreased the total solar irradiance by 4% since the 1950’s due to aerosols and possibly aircraft contrails.\(^{33}\) While the solar industry has a high technical potential, its efficiency and growth can be irreversibly affected by climate change.

The two types of solar radiation that reach the earth’s surface are direct radiation, which comes directly from the sun’s disks; and diffuse radiation. Diffuse radiation is directed towards the earth’s surface in all directions, comes indirectly, and does not cause shadows but can be reflected by ground surfaces.\(^{34}\) Both types of radiation vary by

\(^{28}\) IEA, Pg. 31
\(^{29}\) IEA, Pg. 34
\(^{30}\) IEA, Pg. 34
\(^{31}\) Retrieved from http://www.dictionary.com/browse/solar-constant
\(^{32}\) IEA, Pg. 31
\(^{33}\) IEA, Pg. 33
\(^{34}\) IEA, Pg. 38
altitude and latitude. The radiation is the highest at the equator where the sun’s rays hit the earth, and decreases towards the poles. All locations on earth receive the same 4,380 hours of daylight per non-leap year, however each location receives a different amount of energy within those hours.\(^{35}\) Both the solar intensity and hours of daylight are at their minimum at the winter solstice, and at their maximum at the summer solstice. This does not take into account weather patterns or annual cloud coverage. Solar irradiation varies little in the tropical areas near the equator, and becomes more varied towards the poles and higher altitudes. Therefore, the ideal location to place solar panels would be in areas with the highest solar irradiance per daylight hours and the maximum amount of clear skies. Deserts near the equator fit these two qualities. According to Image 1, the largest solar photovoltaic resource in the United States is in the southwest states of California, Arizona, and Nevada. The Chicagoland area is expected to receive between 4.0 and 5.0 kWh/m\(^2\)/day, in comparison to Arizona expecting greater than 6.5 kWh/m\(^2\)/day. Collecting this amount of solar radiation is dependent on the size and efficiency of the solar panels in use.

**Physics of Solar Technology**

Solar technology systems can take multiple forms. The most common forms are solar thermal systems and solar electric systems. These two systems use the energy of the sun in different ways.\(^{36}\) In this paper, the solar energy described will be based on a solar electric system, which is also known as a Photovoltaic System because it uses photons from the sun to create electricity.\(^{37}\) The performance of a photovoltaic (PV) panel is

\(^{35}\) IEA, Pg. 35
\(^{36}\) Miller, Pg. 13
\(^{37}\) Miller, Pg. 13
largely affected by its orientation to the sun and its tilt angle because both of these elements change the amount of solar energy received by the panel.\textsuperscript{38} The amount of power produced by a PV panel depends on the amount of sunlight it is exposed to.\textsuperscript{39} More sunlight means more power.

When calculating the angles and orientation of solar panels, it is important to recognize the different terminology. The angle at which the sun hits the panel is critical when placing the panel in specific locations. The zenith angle is the vertical angle of the sun in the sky, meaning that at sunrise and sunset the sun is at a zenith angle of 90 degrees.\textsuperscript{40} The solar azimuth angle is the horizontal angle between the sun and south, meaning that at solar noon the angle is zero degrees.\textsuperscript{41} East is measured negative, and west is measured positive. The surface azimuth angle is similar to the solar azimuth angle in that it is a horizontal angle; however, instead of the angle between the sun and the south, the surface azimuth angle is the measure of the solar panel and south. When the panel is facing due south, this angle is 0 degrees. The most important angle is the angle of incidence, which can only be calculated using the hour angle of the sun, the surface azimuth angle, the slope of the panel, and the latitude of the location.\textsuperscript{42} This is the angle between the sun and the angle of the panel. It is important to minimize this angle in order to have maximum efficiency of the solar panel. Figure 1 depicts these angles. Solar tracking systems are used to rotate the panel with the angle of the sun for maximum exposure.

\textsuperscript{39} Kacira, et al., Pg. 1267
\textsuperscript{40} TeachEngineering. (n.d). Photovoltaic efficiency: Solar angles and tracking systems.
\textsuperscript{41} TeachEngineering. (n.d).
\textsuperscript{42} TeachEngineering. (n.d).
Solar panels contain photovoltaic cells, hence their name. Photovoltaic cells are semiconductor devices that enable photons to “knock” electrons out of a molecular structure, leaving a freed electron and “hole” pair which diffuse in an electric field to separate contacts, generating direct current (DC) electricity. The rate of electricity usage is typically measured in watt-hours, typically kilowatt-hours (kWh) or for larger projects, gigawatt-hours (GWh). The two types of photovoltaic technology that are currently on the market include monocrystalline silicon-based photovoltaic cells and multi-crystalline silicon based photovoltaic cells, which are made out of a range of different semi-conductor materials. These panels can either be grid connected (centralized) or off-grid (decentralized) connected. The chemical makeup inside the solar panel is also critical for the panel’s efficiency. Solar cells made of mono-crystalline have better conversion efficiency than those made of multi-crystalline silicon. Solar panels typically last between twenty and twenty-five years before having to be replaced. Therefore, a cost benefit analysis of the panel is necessary in order to ensure profit on the project.

The Market for Solar Energy

Solar photovoltaic cells have been used in the United States since the mid-twentieth century with the initial purpose of supplying electricity to space satellites. Since then, the commercialization of solar energy has had its ups and downs. There was a

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43 IEA, Pg. 111
47 Timilsina, et al., Pg. 450
strong interest in solar technology in the 1970’s and 1980’s when the oil crisis made energy economics unstable; however, growth in solar technology declined when oil prices stabilized.\textsuperscript{48} In addition, there was a lack of policy support to move toward renewable energy sources.\textsuperscript{49} Since 2000 and the increasing awareness of the limitations of fossil fuels, the development of solar technology has increased steadily. Solar energy has become the fastest-growing energy sector for the past few years and is expected to reach competitiveness on a large scale in less than ten years.\textsuperscript{50} The increased awareness of the threats of global climate change in addition to declining oil and coal reserves have assisted in this growth. In addition to market growth, the specific technology has developed as well. The market originated with small-scale solar photovoltaic cells and has evolved to include large-scale photovoltaic systems that connect to the electricity grid.\textsuperscript{51} Globally installed PV capacity (both grid and off grid) has increased from roughly 1.4 GW in 2000 to 40 GW in 2010, corresponding to an average growth rate of 49%.\textsuperscript{52} According to the Solar Energy Industries Association, the U.S solar installation increased its market by 119% in 2016 with 74% of installations coming from utility-scale projects.\textsuperscript{53} In addition, a report published by the EDF Climate Corps in partnership with Meister found that solar and wind jobs are growing at a rate twelve times faster than the rest of the U.S. economy.\textsuperscript{54} This growth in renewable energy jobs is a signal that the U.S energy industry is becoming more sustainable. The EDF’s report also suggests that the cost of production for solar PV panels dropped 72% from 2010 to 2015, meaning solar

\begin{thebibliography}{99}
\bibitem{48} Timilsina, et al., Pg. 450
\bibitem{49} Timilsina, et al., Pg. 450
\bibitem{50} IEA, Pg. 23
\bibitem{51} Timilsina, et al., Pg. 450
\bibitem{52} Timilsina, et al., Pg. 451
\bibitem{54} Varinsky, D. (2017)
\end{thebibliography}
panels are becoming more cost competitive on the market.\textsuperscript{55} Putting these numbers into perspective, 60 million Americans currently live in areas where solar energy costs are competitive with retail energy prices.\textsuperscript{56} While not all households in these regions take advantage of competitive solar resources, it shows that there is substantial growth that can occur if people also understood the environmental dangers associated with their current energy generation systems. The economic boundaries of growth continue to be dependent on federal and state policies and government subsidies.

**Barriers to Solar Energy Development**

Timilsina, Kurdgelashvili, & Narbel conducted an analysis in 2012 which showed that climate change mitigation benefits would not be sufficient to make solar energy technologies environmentally attractive.\textsuperscript{57} The cost of energy is the driving force behind many decisions in the energy industry. If environmental factors were enough, renewable energy development would be much farther along than it is right now. Therefore, overcoming other barriers to solar energy development will make it more attractive and sustainable on the market.

The main technical barrier is the low conversion efficiency in PV solar panels. Most panels operate between 14 and 22\% efficiency, meaning that of the total amount of energy received by the sun, only a small portion gets converted into electricity.\textsuperscript{58} The majority is lost to heat in the conversion. In addition, there are performance limitations with batteries and inverters, and inadequate supplies of raw materials such as silicon for

\textsuperscript{55} Varinsky, D. (2017)
\textsuperscript{57} Timilsina, et al., Pg. 455
the development of the panels. All forms of solar energy generation are limited to times when sunlight is available. Transmission losses in the grid play a role in storing and transporting energy as well. A study conducted by Robert Fares concluded that battery systems actually increase energy consumption. While one of the benefits of storage is that it reduces power flows in the distribution grid, thus leading to utility infrastructure savings, there is energy lost every time a battery system charges and discharges. Therefore, it requires less energy to send the excess electricity back into the grid rather than storing it to use at a later time. There is also a concern with finding a safe disposal method for the batteries when they exceed their battery life.

Currently, when there is excess energy created by solar panels, it is sent back into the grid rather than being stored by a battery. There is research that argues that a typical battery system could reduce peak power demand by 8-32%; however, this comes at a tradeoff to the emissions produced. The researchers argue that the only way energy storage would reduce energy consumption and emissions is if it directly enables renewable energy such as solar. The tradeoff from using renewables instead of fossil fuels must be greater than the emissions created by the battery. Solar energy without being attached to a battery system is nondispatchable, meaning it cannot be turned on and off; it works when the sun is shining and does not work when there is no sun. Therefore, without a strong storage method, solar energy is unable to meet energy

59 Timilsina et al., Pg. 455
63 Fares, R., & Webber, M. (2016)
demands where there is little or no sun. Given the unpredictability of cloud cover, solar becomes too variable of a resource, making storage methods even more essential.

Another technical barrier to the growth of solar energy is the variability in grid systems. Many grid systems are outdated and will need to be updated to manage new functions, such as managing more variable supply, sending appropriate and timely price signals to producers and consumers, and managing demand loads.65 This is already seen in the evolution towards smart grids. Smart grids systems are the modern version of the current electric grid, and are constructed to withstand renewable developments such as solar and wind sources. Smart grid technologies include advanced sensors known as Phasor Measurement Units which allow operators to access grid stability, advanced digital meters which provide better information to consumers, and batteries which store excess energy to the grid, among other benefits.66 The Office of Delivery and Energy Reliability is currently working with public and private partners to develop this system in order to provide clean and reliable energy to consumers. Along with modernizing the grid system, creating interconnected grid systems between energy sources across the globe will help grow solar energy and other variable sources of energy.

Net metering is another strategy used to overcome the technical barrier by allowing households and commercial establishments to sell back excess electricity generated through solar panels back into the grid. In the United States alone, net metering programs are limited to renewable energy facilities up to ten kW in capacity.67 It can be argued that this limit is in place to protect traditional energy utility companies, and is an example of federal and state energy policy tied to economics.

65 IEA, Pg. 51
66 U.S. Department of Energy, 2017
67 Timilsina, et al., Pg. 460
Political or institutional barriers are some of the most prominent barriers to solar energy development. There is a lack of effective and appropriate legal regulation to encourage solar energy development.\(^6\)Government influence is therefore a large factor in the overall growth of solar energy. In many countries, governments have mandated energy transmission companies and electrical utilities provide energy transmission and/or the purchase of electricity from renewable energy sources.\(^6\) The difficulty with this type of policy in the current U.S. political and economic climate is that the traditional utility and energy transmission companies would lose their market power. Therefore, only a small portion of our energy needs at this time are able to come from renewable sources.

There are a limited number of strategies, however, that have been introduced in the U.S. to overcome the political and economic barriers inherent with solar energy development. As noted above, the main economic barrier with solar energy is that it is not yet cost competitive with fossil fuel resources. Many governments worldwide have approached this issue by supporting renewable energy development through fiscal, regulatory, and market incentives. Government subsidies are the main tool used to support solar development. In the U.S., a subsidy could come in the form of investment grants, capacity payments, output or production-based payments, or soft loans.\(^7\) However, the issue with subsidies is that while they encourage the development of solar technology in the short-term, they do not necessarily lead to the long-term sustainability of solar energy. As solar develops, subsidies would need to be reduced to ensure that solar can support itself on the market.

\(^6\) Timilsina, et al., Pg. 457  
\(^6\) Timilsina, et al., Pg. 460  
\(^7\) Timilsina, et al., Pg. 458
Currently, one of the primary methods used to help decrease the cost of solar energy in the U.S. is the feed-in-tariff (FIT). FIT refers to a premium, tariff, or payment to new and renewable energy technologies that are not yet cost competitive with conventional energy sources.\textsuperscript{71} It is based on the cost of the electricity produced, plus a profit for the producer, and aims to encourage investors to make long-term investments on these new technologies to ultimately drive down the cost.\textsuperscript{72} As solar develops, these tariffs would have to be slowly reduced in order to insure the long-term sustainability of solar energy in the market.

The Solar Investment Tax Credit (ITC) is another important federal policy mechanism designed to support the development of solar energy in the United States.\textsuperscript{73} It is a 30\% tax credit for solar systems on residential and commercial properties based on the amount of investment in solar property, which has helped annual solar installation grow by over 1,600\% since it was implemented in 2006, which corresponds to a compound annual growth rate of 76\%.\textsuperscript{74} Tax credits work as a one-time reduction in the consumer’s income tax. Initiatives like the ITC are great for the initial implementation of solar energy; however, for solar to be cost competitive in the market it must be able to be sustainable in the long run without the need for incentives.

There are economies of scale when it comes to individual solar panels in addition to large-scale solar projects. The overall efficiency of a solar panel depends on the manufacturer, with more efficient panels tending to be larger in size. In terms of economies of scale with efficiency, if one solar panel has a 21\% efficiency rating, and the

\textsuperscript{71} Timilsina, et al., Pg. 457
\textsuperscript{72} Timilsina, et al., Pg. 457
\textsuperscript{74} SEIA. (2017)
other has a 14% efficiency rating, the 21% efficient one will produce 50% more kWh of electricity under the same conditions.\textsuperscript{75} Economist Paul Krugman claims that solar energy prices adjusted for inflation are falling around 7% a year.\textsuperscript{76} The combination of these falling prices with an increase in solar projects is what has led to the large growth in solar energy in locations all over the world. This decrease in price has been the main driving force behind the large growth in solar projects.

Another method to analyze the market for solar energy is to look at technology costs. One way to measure the cost of solar energy is to look at the cost per unit of energy generated. This cost depends on the lifetime of solar panel at the panel’s location. For example, any given photovoltaic solar panel will produce more energy in Arizona or the Sahara Desert than in regions with higher latitudes such as San Francisco or Chicago.\textsuperscript{77} Therefore, estimates such as cost per unit of energy generated are difficult to generalize. Most of these types of analyses, therefore, are site specific. Overall cost reductions in solar energy will result in higher conversion efficiency of the panels, less and cheaper material consumption in the development of the panels, manufacturing innovations, mass production, and optimized system technology.\textsuperscript{78} Research and development, in addition to government subsidies and policy, can further change the course of the energy industry in favor of solar energy.

\textsuperscript{75} Aggarwal, V. (2016)
\textsuperscript{77} Baker, et. al., Pg. 411
\textsuperscript{78} Dincer, Pg. 715.
Chapter 2

This chapter analyzes the methods and results of the study. It includes a literature review of different studies that have inspired the researcher’s investigation and methods. In addition, this section introduces the application of findings in comparison to another local establishment using solar panels to gain another perspective of solar panel output throughout a year.

Literature Review

A number of studies, including Kacira et al. (2004), Chandrakar and Tiwari (2013), and Benghanem (2010) have analyzed the optimal tilt angle and orientation of a solar panel for maximum electricity output. Kacira, Simsek, Babur, and Demirkol observed differences in the tilt angle and orientation of a photovoltaic solar panel in relation to the total solar energy received. They observed two panels facing true south for a full calendar year in Sanliurfa, Turkey. The study found that the monthly optimum tilt angle for a photovoltaic panel changes throughout the year, thus determining that both the tilt angle and orientation have a significant impact on the amount of solar energy received by the solar panel. Higher tilt angles during fall and winter and lower tilt angles during the summer allow maximum radiation to be received by the panel. Changing the tilt angle seasonally is more efficient than daily or monthly. While the location of their study is vastly different than the location of this investigation, their findings regarding tilt angle and orientation can be applied to any location, including Lake Forest, Illinois.

Li and Lam (2007) analyzed the mathematic equations behind finding the optimum tilt angle and orientation for photovoltaic systems. They observed solar radiation and sky radiance data in Hong Kong throughout the 2004 calendar year, resulting in roughly 21,200 sets of ten-minute interval readings. They calculated the
incident solar radiation on various inclined surfaces facing different directions. They found that the peak annual total solar yield (kWh/m²) was 1575 kWh/m² at around 20 degrees oriented due south. Hong Kong’s latitude is 22.396 degrees North, which supports the notion to set a solar collector at the tilt angle of the latitude of the location to receive the maximum solar radiation. Therefore, both tilt angle and orientation play essential roles in determining the optimum output of the solar panel. In analyzing the efficiency of the panels, they found that the system conversion efficiency is highest in the winter months (December, January, and February) rather than in the summer months; however, the efficiency only differs from 9.3% to 8.8%. The energy output decreases when increasing the tilt angle above 20 degrees.

In terms of reduced emissions from switching from fossil fuels to solar panels, they found they could reduce the annual Carbon Dioxide (CO₂), Sulfur Dioxide (SO₂), and Nitrous Oxide (NOₓ), and particulates by 102, 0.31, 0.17, and 0.013 kilograms (kg), respectively, per unit square meter of a PV panel installed at the optimum angle to generate electricity in Hong Kong. Therefore, they found that the environmental impacts of switching to solar energy are significant.

From a financial viewpoint, they calculated the annual payback at each orientation and tilt based on the total installation cost and average commercial electricity tariff. They found that the shortest monetary payback for the optimum tilt angle at 20 degrees due south was roughly 78 years, compared to 163 years when the panel was facing east. According to Li and Lam, this finding is consistent with the monocrystalline silicon PV system located in Edinburgh, Scotland. They predicted that with the expected rise in energy prices in the future, the monetary payback period would drop rapidly.79

79 Li, D. H. W. & Lam T. N. T. Pg 8
Timilsina et al. (2012) looked at the economics behind the solar energy industry. Their findings support the notion that although there has been a large drop in capital cost associated with solar and an increase in fossil fuel prices, solar energy technologies are not yet competitive with conventional technologies for electricity production. They predict that the share of solar energy in the global energy supply mix could exceed 10% in 2050. This will take combined improvements in financial, technical, and institutional sectors. They argue that the current growth in the solar industry is largely due to policy mechanisms, and the solar industry will need to see new strategies for the next few decades to increase development worldwide. There needs to be a large shift in political will toward renewable energy in order to ensure this progress for the long term.

**Kohl Children’s Museum Data**

To gain a full understanding of the application of solar energy in the area near Lake Forest, Illinois, the researcher contacted a local establishment that has used solar panels for several years. The Kohl Children’s Museum in Glenview, Illinois installed 219 solar panels on their roof in July, 2010. Since then, they have produced 426 Megawatt-hours (MWh), supplying an estimated 7% of their electricity needs. With the installation of LED lighting and system management, they have further reduced their total electricity usage by 24%. During the timeframe of this investigation, the solar panels on the roof of the museum produced a total of 9.58 MWh of energy, compared to a total of 5.315 kWh produced by the panel at Lake Forest College. The solar panels at Kohl Children’s Museum are flush-mounted on the roof, which is slanted at a 20 degree angle.

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80 Timilsina, et al., Pg. 450
81 Timilsina, et al., Pg. 450
82 As of March 2nd, 2017
and azimuthally oriented at 16.5 degrees, meaning the panels are facing southeast. A view of the solar panels on the museum rooftop is shown in Image 2. They have not specifically tracked the payback of the panels; however, Curt Adams, Vice President of Operations at the museum, has estimated a twenty-year payback. While the percentage of solar energy generated by the museum is only a fraction of their total energy needs, this represents a significant example of the feasibility of solar energy in relation to other energy efficiency strategies in use there, such as LED lighting.

The software used to monitor the panels factors in an annual degradation factor into the production estimate of the system. This factor is the percentage to reduce the estimate each year to account for the aging of the PV modules, and is equal to 0.5%. Solar panels will decrease in efficiency over time, which is crucial to understand when evaluating a project. The weather conditions on the panel may also play a role in its efficiency over time.

**Hypothesis**

This study examines two main hypotheses. The initial hypothesis is that there is technical potential to capture significant solar energy at Lake Forest College. Given that there is frequent sun exposure, solar energy can be utilized as a method to generate electricity for the college. This hypothesis is supported by the findings by Li and Lam (2007), which claim that there is solar energy potential in all areas of the world, varying by location and by the tilt and orientation of the panel. By setting the panel to the optimal tilt and orientation of Lake Forest College, the researcher predicted that solar energy could be generated using a solar panel.

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83 Li, D. H. W., & Lam T. N. T. Pg. 6-7
The second hypothesis of this study is that it will be difficult to capture enough solar energy at Lake Forest College to make it financially sustainable as the school’s only energy source. While solar energy as an industry is becoming more cost competitive, it is still too variable of a resource and requires installation and ongoing maintenance costs, which would make it financially unsustainable on a large scale for a small, private liberal arts college located in the Midwest. Therefore, it is predicted that only a portion of the campus’s total energy needs could benefit from the use of solar energy.

**Data**

This study aims to understand the impact of weather on solar energy production in Lake Forest, Illinois. The dependent variable in this study is the daily output of the solar panel in kilowatt-hours. The independent variables in this study included the NASA cloud coverage ratio, date, solar intensity, average temperature, high temperature, low temperature, sunrise, sunset, and hours of daylight.

The NASA cloud coverage ratio, or cloud fraction index, measures the total surface of cloud coverage relative to the portion of Earth not covered by cloud.\(^{84}\) This ratio is given per day at differing latitude and longitudes. The MODIS Cloud Mask product (MOD 35) is used daily to create a cloud mask that applies field of view spectral tests to each pixel, relying on thresholds for different surface types (ocean, desert, land, etc.), and indicates shadows affecting the scene.\(^{85}\) The cloud ratio is calculated using five-by-five kilometer cloud mask pixels, then dividing by twenty-five. The latitude and longitude of Lake Forest is roughly 42.2 degrees north, and -87.84 degrees east. However, the closest latitude and longitude for Lake Forest that were included in this study.

\(^{84}\) Nasa Cloud Fraction Index.

\(^{85}\) Nasa Cloud Fraction Index.
dataset were 42.25 degrees north and -87.75 degrees east. A potential issue with this dataset is that it gives one reading per day. Therefore, the ratio for cloud coverage for the day may not accurately represent the exact cloud coverage throughout the day.

The solar irradiance data was taken from a data set in the 2017 Solar Electricity Handbook.\textsuperscript{86} Solar irradiance is measured in kWh/m\textsuperscript{2}/day. The settings were set to the closet location to Lake Forest, which is Highland Park, Illinois, facing directly south at the optimal year-round tilt angle (which is 48 degrees). One reading was assigned per month based on these credentials. The high, low, and average temperature readings per day were taken from weatherunderground.com. Lake Forest was not included as a location in this dataset, so the readings were taken from the closest location to Lake Forest, which was a weather station in Northbrook, Illinois, just nine miles south of Lake Forest. The sunrise and sunset times were received from the U.S. Naval Observatory Rise and Set for the sun data set for Lake Forest, Illinois in 2016 and 2017, respectively. Hours of daylight per day were calculated by finding the difference between the time of sunset and time of sunrise.

**Methods**

This study was performed using one GrapeSolar\textsuperscript{®} polycrystalline photovoltaic solar panel. The panel was placed on the roof of Carnegie Hall, a large building in the central campus area, facing directly south based on research which concluded the optimum orientation was to face the panel due south. Carnegie Hall was chosen based on the accessibility to an open rooftop. The dimensions of the panel were 665mm by 620mm. Give that the solar constant was 1,370 W/m\textsuperscript{2}, the panel was estimated to

\textsuperscript{86} Retrieved from http://solarelectricityhandbook.com/solar-irradiance.html
generate 321.96 Watts at 100% efficiency. With a maximum output of 50 Watts, the panel was expected to operate at approximately 15.5% efficiency.

The panel was set to a 42 degree tilt to match the latitude of Lake Forest, which is approximately 42 degrees north. The panel was placed in an area without shadows for optimal sunlight exposure. Two weighted bags of sand were placed on the back ends of the stand to keep the solar panel stationary. According to the specifications, the panel is capable of withstanding up to 50lbs/ft² of wind and snow load, which made it possible to use the panel in the winter with frequent snow build up.

The electrical parameters of the solar panel are shown in Table 1. The maximum output was 50 watts (W), the maximum power voltage of the panel was 17.5 volts (V), and the maximum power current was 2.86 amps (A). The solar panel was connected to a resistor with seven ohms and a Fluke 8845A Digital Multimeter. The purpose of the resistor was to extract power from the solar panel, with the goal of finding a measure of resistance that would be closely compatible to the maximum output, voltage, and current. Given the electrical parameters, the resistance of the solar panel calculated to be roughly 6.1 ohms. Using six ohms for this experiment ran the risk of exceeding the maximum specifications and damaging the solar panel, so utilizing more resistance was the ideal solution to this potential problem. Given its specifications, seven ohms was compatible with drawing the maximum power from the solar panel. The resistors were placed in a metal casing that lifted them off the surface of the roof with a cover on top to protect them from weather damage. The direction of the current (I) through the set-up is shown in Figure 2.

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87 According to Ohm’s Law, resistance is equal to voltage divided by current.
A Pasco Model ‘91 function generator was attached to the multimeter to create time intervals of the readings. The function generator controls the rate at which the voltage and current are read by the digital multimeter. The multimeter and function generator were both placed in a cooler to protect them from snow and rain. A small incision was made in the side of the cooler to allow the wires to attach. A weighted sand bag and a tarp were placed over the cooler to protect it from rain and snow. The generator was set to 0.05 Hertz (hz), which is equal to 200 second intervals. Readings of both amps and volts were taken separately every 200 seconds. The multimeter was set to take 6,048 readings per week, resulting in a total of 3,024 samples per week. A set-up diagram is shown in Figure 3 and a picture of the set-up on the roof is shown in Image 3.

The readings were saved onto a patriot USB drive that was used to transfer the data to an Excel spreadsheet. The amp and volt readings per sample were multiplied together to produce total output in Watts, which was later converted into kWh for the comparison to the campus energy bills. This was calculated by summing every sample’s watt output throughout the day, then multiplying that total by 200 to represent the time interval of 200 seconds, and then dividing by 3,600,000, which is the conversion from Watt-seconds to Kilowatt-hours.

Readings were collected between December 8th, 2016 and March 2nd, 2017, and represent limitations in the timeframe to completing this investigation. Some daily readings were lost due to snow cover, in addition to the building shutting off its power supply between December 22nd and December 28th. These limitations have been noted in the weekly readings shown in Figure 4. Snow cover was not brushed off during weekly readings due to the desire to make this study as realistic as possible for the weather patterns in Lake Forest, Illinois during winter months. However, the snow was brushed off after the first week of readings to allow for more data collection the following week.
In addition, strong winds blew the solar panel over on February 13th, and the data was lost from that day until it was restored on February 16th. In total, there were 72 days with total kWh output readings.

**Descriptive Statistics**

Table 2 contains the descriptive statistics for the dataset. The mean total output of kWh was 0.0680, with a standard deviation of 0.875. The temperature ranged from -8 degrees Fahrenheit (°F) as the low temperature to 69°F as the high temperature, averaging 29.7569 °F. The minimum hours of daylight was 9.01 hours, which is consistent with the winter solstice on December 21st. The mean hours of daylight was 9.8252, with a standard deviation of 0.7127. At the summer solstice in the northern hemisphere, Lake Forest experiences roughly 15.26 hours of daylight, which is a 6.18 hour difference compared to the winter solstice.  

The cloud coverage ratio ranges from 0 to 1, where 0 is no cloud cover and 1 is complete cloud cover. The mean cloud coverage ratio was 0.7781, meaning that the average cloud coverage over Lake Forest from December through March was 77.8% with a standard deviation of 0.3486. A potential error with the cloud coverage ratio was that NASA provided one estimate per day; therefore there was no way to track when the cloud coverage specifically occurred. For example, it could be completely cloudy until noon one day, and then clear up in the afternoon, and still receive the same cloud coverage ratio as another day where it was partly cloudy all day. An hourly estimate would provide a more accurate reading of the cloud coverage.

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88 U.S. Naval Observatory Rise and Set for the Sun for 2016.
The efficiency variable is a unitless measure of the panel’s efficiency each day. The mean daily efficiency was 1.032 with a standard deviation of 0.8288. There are many factors that contribute to the panel’s efficiency, which will be further explained in the results section.

**Identification Strategy**

The model in this study is a mechanism, where there is one dependent variable with many independent variables that multiply rather than add. The time of sunlight and sunset were removed from this model because hours of daylight provide a more descriptive look at the effects. The model used in this study is written as $E = e*A*I*L*(1-C)$, where “E” is equal to the total output of the panel that day measured in kWh, “e” is the panel efficiency (unitless), “A” is the area of the panel measured in m², “I” represents the solar intensity that day in kW/m², “L” is the amount of daylight that day in hours, and “C” represents the cloud coverage ratio that day. The panel efficiency each day was found by multiplying $A*I*L*(1-C)$ and then dividing that value into “E”. Therefore, with $E$ representing total daily kWh output, and $A*I*L*(1-C)$ representing the daily inputs. The regression model is presented below.

$$Total\ Daily\ kWh\ Output = \beta_0 + \beta_1 Daily\ Inputs$$

All of the variables were of interest in this model; however, the variables of most interest were the cloud coverage ratio, hours of daylight, and solar intensity, given that this study was performed in the winter months where sunlight exposure was the lowest. For all the days where cloud coverage equaled 1, meaning total cloud coverage, the variable was changed to 0.98 in order to show the effects of the other variables being

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89 Unitless, where $C=1$ corresponds to total cloud cover
multiplied. It is expected that there would be a high correlation between the inputs and
the daily kWh output of the solar panel.

Results

The regression results are presented in Table 3. A correlation coefficient was run
between the inputs value and E, resulting in a coefficient of 0.8375, symbolizing a high,
positive correlation. This finding is consistent with the 2007 findings by Li and Lam
given that sunlight exposure is a highly significant predictor of kWh output, and is
reduced by cloud coverage.90

There is a large variation in the daily efficiency of the panel, which could
potentially be the result of many different factors. One potential reason could be the daily
temperature, given that temperature and solar intensity are not the same thing. The panel
is not always facing the sun since there is no tracking system, however this should be a
constant effect since the panel was not moved. Pfister, et al. concluded that that while
there are cases in which cloud coverage increases the amount of solar radiation reaching
earth’s surface, cloud coverage reduces incoming solar radiation from the sun by more
than 10% for two thirds of the year.91 Therefore, there is potential that cloud coverage
may have in fact increased the solar intensity on the panel, which could be a potential
reason for the solar panel producing kWh output on days in which the cloud coverage
ratio was 1. This finding could be a contributing factor, however the problem here is for
mismeasurement in the data. According to the data, a cloud coverage ratio of 1
symbolizes complete cloud cover and no sunlight, however this is not what actually
happens. Sunlight is still able to penetrate through the clouds otherwise there would be

90 Li, D. H. W., & Lam, T. N. T. Pg. 8
91 Pfister, et. al. Pg. 1433
complete darkness. So, even when the ratio claims that there is complete cloud cover, the panel still receives a small fraction of sunlight. In addition, the conditions are not exactly measured. This is why the panel efficiency has a mean of 1.032, or 103% because it is not expected to receive any sunlight on days where the cloud coverage ratio is 1, resulting in the panel operating in efficiencies greater than 100%. Figure 6 shows a graph comparing the panel efficiency to cloud coverage. Based on a visual analysis, it is evident that the panel functions at an efficiency greater than 1 when the cloud coverage is 1. The panel operates at around 15% otherwise, which is consistent with the specifications of the panel. The cloud coverage ratio should be a point in time variable, however it provides one value for the entire day.

Temperature was not included in the regression, however a graph depicting the relationship between daily temperature and panel efficiency is presented in Figure 7. The graph has two best fit lines because the quadratic formula shows the maximum is at 39.4ºF. Therefore, it can be predicted that the solar panel’s efficiency increases with temperature up to around 40ºF, and then decreases with higher temperatures.

In total, the amount of kWh produced by the solar panel in December, 2016, was 0.5258 kWh, increasing to a total of 1.3651 kWh in January, 2017, and increasing further to 3.2791 kWh in February, 2017. It is important to note that there was at least a week of lost data in each of these months, so the total monthly output should be higher than these values.

A graph depicting the daily kWh output of the panel used in this investigation is shown in Figure 5. As noted previously, there are gaps in this graph due to snow cover and technical difficulties. The kWh produced by the panel increased day by day, which supported the findings in the regression analysis that solar intensity and cloud coverage are statistically significant predictors of kWh output. Cloud coverage, which has a
negative correlation, decreases heading into the summer months, and solar intensity, which has a positive correlation, increases. These findings are therefore consistent with other research.

Given that data from Lake Forest College was collected for only three months, data from the Kohl Children’s Museum’s was used in comparison to see if the data shared similar trends and to corroborate the findings of this investigation. The museum’s average daily per-panel kWh output was used. Figure 8 depicts the comparison with data from Lake Forest College. Through a visual analysis, it is evident that both the Lake Forest panel and the museum’s panels shared a similar trend. All panels experienced a minimum output during the winter solstice, and output increased as the days approached the summer solstice. It is important to note, however, that the museum’s panels had a different orientation and tilt compared to the Lake Forest panel, which may have led to slight variations between the datasets. As supported by the findings by Li and Lam, even the slightest change in tilt or orientation can lead to drastic changes in the solar panel’s output. Even so, the trend between the museum and Lake Forest datasets was similar enough that confident predictions using the museum’s data from other dates can be made, as noted in Chapter 3.

On average, the output of the solar panel at Lake Forest College produced 15.19% of the total daily output per panel at the museum. On some days, the Lake Forest solar panel produced up to 40% of what the museum was outputting, and on other days the panel produced just 1% of a panel at the museum. A potential reason for this extreme variation could be due in part to cloud cover, as well as the difference in angle and tilt of the panels at the museum versus the panel at Lake Forest College. Given that the Lake Forest panel had a similar trend to the museum’s panels, these data were used to predict the year-round output expected for the Lake Forest panel. The museum’s daily output per
panel from January 1st, 2016 through March 2nd, 2017 are shown in Figure 9. Using the museum’s data as a framework for this analysis, it was predicted that the Lake Forest solar panel would have outputted roughly 0.2 kWh per day in June, 2016, or 5.5118 kWh total for the month. Figure 10 depicts the year-round daily predictions using these ratios. The output would likely peak near the solar solstice on June 21 where sunlight exposure would be the strongest, along with the longest amount of daylight exposure.
Chapter 3

In this chapter, the findings of this investigation of Lake Forest College electricity consumption are summarized. As energy prices are consistently fluctuating, this section provides a strategy to calculating the number of solar panels needed to supply the college’s various electricity needs. This section analyzes the number of solar panels needed using the GrapeSolar® 50W Polycrystalline Photovoltaic Module as the reference, with acknowledgement of larger and more efficient panels. The main question this chapter examines is the amount of solar energy that can supplement, if not replace, the energy demand at Lake Forest College.

Electricity Usage on Campus

The total campus monthly electricity bill was collected for each month from December, 2011 through December, 2016. For each month, the number of days, total kWh measured, total energy charges, total utility (delivery) charges, total current charges, and price per kWh were recorded. In addition, the specific total kWh usage of Nollen Hall and the Donnelley and Lee Library were also recorded monthly to provide additional analysis for buildings with different functions on campus. Lake Forest College currently receives its energy supply through MidAmerican Energy. The energy comes primarily from a coal plant in Iowa. Although the energy is currently supplied through fossil fuels, there is an additional monthly charge of $0.00103 per kWh for the renewable energy compliance requirement. In addition, there are two small charges under the categories of utility charges for environmental cost recovery adjustment and for energy efficiency programs. Although indirect, a small portion of the Lake Forest College monthly electricity bill currently goes towards sustainable initiatives.
The total monthly electricity cost is broken down into energy and utility charges. Taxes and fees are included in the utility charge. The total energy usage cost consumes between 65-80% of the total monthly bill. The energy cost and utility cost have a positive correlation, meaning that when the energy cost increases the utility cost increases. While the total electricity consumed by the college increases in the summer, the annual bill has decreased slightly since 2012, with a drop in the price per kWh charge as the primary reason. In 2011 and 2012, the price per kWh was $0.056 cents. This value dropped to $0.035 in 2013, and has stayed at that rate since. To best compare the solar panel output to the energy bills, the energy charges separate from the utility charges were analyzed, as it is a more direct measurement of the total kWh used per month.

The number of panels needed was calculated using the daily energy demand from the college divided by the daily energy produced by the panel. Ideally, it would be most beneficial to the college to calculate the year-round demand for solar energy. This calculation is impractical, however, due to the information available. Therefore, a more practical approach would be to look at seasonality issues in regards to the solar energy potential on campus by calculating the peak usage in the summer compared to the peak usage in the winter. It is important to note that the panel used in this study was considered small while maintaining a “normal” efficiency rating. There are larger solar panels on the market with up to 285W output, which can produce a significantly larger amount of energy under the same conditions. While the cost for these panels would increase, the total savings from kWh would offset this cost. A more in-depth analysis of the types of panels on the market will be discussed later in this chapter.

It is unknown how much electricity the solar panel would produce in the summer. However, it is possible to predict summer energy demand by comparing the winter data collected by the Lake Forest College panel used in this investigation to the
output of the panels at the Kohl Children’s Museum, and then using a conversion ratio to compare the Lake Forest data to the museum’s summer data. Once this is determined, the data can then be compared to the college’s monthly electricity bill.

Using information from the Lake Forest College utility bills from 2011-2016, on average, the highest electricity consumption occurs in September, and the lowest in February, respectively, with a monthly difference of roughly 20,000 kWh between the two. This is to be expected, given that in September the hours of daylight are decreasing, which requires more need for lighting along with a substantial amount of air conditioning. February, on the other hand, has an increasing amount of sunlight exposure, requiring less lighting, without the need for air conditioning. However, during the timeframe of this investigation, from December, 2016 through February, 2017, the kWh demand surprisingly increased each month, with the February energy consumption the largest of the three months. The data in this investigation did not reveal any explanation for this change in energy consumption. A potential explanation could be a series of unseasonally warm days in February that required air conditioning units to be turned on.

A graph comparing the campus electricity usage in relation to the solar panel output is shown in Figure 11. Based on the data, there is a similar increase in kWh demand and kWh output by the solar panel. This finding shows that as the campus increases its energy demand, solar panels have the capacity to meet that demand. The increase in solar intensity per month plays a large role in this calculation. As a preliminary analysis, the total savings of the output from 219 solar panels at the Kohl Children’s Museum was calculated as the hypothetical output. Given that the museum is only 18 miles south of the college, the readings would not see significant variation under the same conditions. For the 2016 calendar year, the solar panels at the museum produced a total of 61,728 kWh. The college consumed 8,952,147 kWh of electricity in 2016, so if
the same number of panels in use at the museum were installed at Lake Forest College, the total 2016 Lake Forest electric bill would have offset by at least 0.6%. The total cost of each solar panel was unknown, otherwise a cost benefit analysis would have been performed to see how much this would cost the college. Given that less than one percent of the total bill would be offset by 219 solar panels, the practicality of offsetting the campus electricity needs completely with solar is very low at this time.

The average total energy bill at the college in February, 2017 was $75,018.65, while the average total bill in September, 2016 was $81,693.78. February averaged a total of 710,073 kWh with September averaging a total of 940,842.4 kWh. The solar panel produced a total of 3.2791 kWh in February. The solar intensity in September for a panel in Lake Forest facing due south at a near 48 degree tilt was 4.91 kWh/m²/day. The solar panel produced, on average, 15.19% of the daily output per panel compared to those at the museum. This percentile was then applied to the rest of the year to predict the year-round kWh values for the Lake Forest panel. The total output for the museum’s solar panels increased by 72.9% from September, 2016 to February, 2017. Based on the predictions made using the Kohl Children’s Museum data, the total kWh output for the Lake Forest panel in September, 2016 was expected to be approximately 4.493 kWh. It is important to note that this is a loosely predicted value, given that there were days missing from the Lake Forest dataset due to snow cover, strong winds, and a power outage. Therefore, based on these predicted values, to completely offset campus energy needs in February, the college would need 216,545 solar panels installed. In September, the college would need to have 209,402 solar panels installed. It may appear to be an error that there are less solar panels needed in September when the electricity demand is

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higher; however, the solar intensity increases after January at a rate much quicker than the campus electricity usage, thus providing more power to the solar panel. Valuing the solar panels at $60.00 each, this would cost the college $12,992,700. With an average annual electricity bill of $778,125.93, it would take nearly seventeen years to recover all the purchase and installation costs, without discounting. The college would be better off investing in other strategies to reduce energy costs, or limiting solar energy to a smaller portion of the total campus electricity consumption.

Since it is financially unfeasible to provide the entire campus with solar energy, the next step is to analyze what fraction of the total energy bill solar energy can offset and still be cost efficient. Ideally, the solar panels would be monitored year-round for multiple years. If the necessary data was available, a more accurate depiction of the solar potential at Lake Forest would allow the college to make better decisions regarding the installation of solar panels on campus.

The Donnelley and Lee Library, renovated in 2004, consumes between 11% and 15% of the total monthly campus kilowatt hour usage, which equates to roughly 7% of the total monthly energy cost of the campus when factoring in utility charges. The library consumes a larger portion of the total energy consumption in the summer months, due primarily to an increase in the use of air conditioning. The library averaged a total of 66,420 kWh in electricity usage for February and a total of 129,210 kWh for September over the past five years. Analyzing the total number of solar panels needed to cover the electricity usage of the library would result in 20,257 panels in February and 28,759 panels in September. In this scenario, the number of 50W solar panels needed for the library increases from February to September, which is different compared to the larger scale need to power the whole campus. This number is still impractical, due to there being larger and more efficient panels on the market.
The panels at the museum averaged a total of 281.8 kWh each for the 2016 calendar year. The Donnelley and Lee Library consumed a total of 1,156,289 kWh in 2016. Therefore, using the museum’s larger panels in place of the small one used in this study, it would take an estimated 4,104 panels to meet the library’s 2016 electricity demand. This is still a large number of panels, however it is evident that the efficiency and size of the panel plays a major role in its efficiency and output.

Nollen Hall, a residence hall on campus, was also analyzed in contrast to the library’s energy demands. Nollen Hall consumes around 4% of the total monthly kWh usage across campus, and roughly 2% of the total bill when factoring in utility charges. Nollen Hall is one of three residential buildings on campus that is air conditioned, which plays a significant role in its electricity consumption in the summer months. On average, Nollen Hall consumed a total of 25,325 kWh in February, and a total of 39,026 kWh in September. Therefore, 7,723 50W panels would be needed to meet this demand in February, and 8,686 50W panels in September.

Nollen Hall consumed a total of 311,431 kWh in the 2016 calendar year. Using the solar panels at the museum as a reference, it would take an estimated 1,106 solar panels to meet this demand. The size of each of these panels is unknown, however the next question is determining whether there is enough roof space for 1,106 solar panels. With even more efficient panels, less panels would be required to meet this energy demand, which would reduce the amount of roof space needed.

A valuable question to analyze is whether it is more practical to have a large amount of solar panels to meet the summer demand, or just enough to cover the smaller demand in the winter. The ideal locations to install solar panels at Lake Forest College are either on rooftops or on street lamps facing due south with full sky exposure. Rooftops with ample sun exposure include the Donnelley and Lee Library, Young Hall,
the Mohr Student Center, Moore Hall, the Sports Center, and the Ice Rink. The panels would need to be set at an angle of 42 degrees for optimum energy production if they were installed as stationary panels. Laying the panels flat on the flat rooftops risk reducing maximum sunlight exposure throughout the day. The ideal set up would be to have a photovoltaic system of panels that rotate with the sun, and where the panel tilt is altered seasonally. Given that the solar panel used in this study was not the most efficient panel on the market, it would be in the best interest of Lake Forest College to invest in panels with a higher efficiency rating so that fewer panels would be needed. The amount of rooftop space needed would also be reduced, streamlining maintenance. While it is possible to calculate the number of solar panels that could hypothetically fit within the rooftop space and then extend the analysis into energy collection and usage, such speculation leads to more questions regarding the structure of the rooftops and how much weight could be supported once the number of panels is increased.

Given that the panel used in this study was meant to be used as a recreational panel rather than a rooftop panel, the numbers in this analysis are much higher than they would be using the more efficient and larger panels currently on the market. It is difficult to analyze the daily efficiency of those panels, which is why this study provides a framework to approach analyzing the efficacy of solar energy at Lake Forest College. The most efficient solar panels on the market are SunPower solar panels, which operate at around 19% efficiency and are estimated to provide 70% more energy than a conventional panel (such as the one used in this study) over the first 25 years.\footnote{Better solar products. (2017). Retrieved from the SunPower website} If these panels were installed at Lake Forest College, the number of panels needed would greatly reduce as well as an enormous increase in the energy output of those panels. So, while
installing 50W solar panels to offset the electricity bill at the college is impractical, installing larger and more efficient panels may prove to be an effective way to offset the electricity bill and provide the college substantial savings.

Additionally, consideration of energy storage methods would be needed if the solar panels produced excess energy during the day. The complexities of energy storage systems is another critical factor in the finding that solar energy should be a supplement to the total campus energy source, but not its only source. Even if enough solar energy was accessible and financially feasible to meet all the energy demands at Lake Forest College, fossil fuels would theoretically still need to be purchased by the college in order to maintain buildings when sun exposure is low and/or when storage capacities have been depleted. If a battery system was not feasible, any excess solar energy produced could be sent back into the grid system, providing the college some additional profit.

**Alternatives to Generating Solar Energy**

While it is impractical to offset the college’s energy consumption completely with solar energy, other strategies could be used to minimize energy use on campus to reduce total energy costs. As an example, the 20% decrease in energy consumption through LED lighting and system management at the Kohl Children’s Museum proved that this was a practical and cost efficient alternative to reducing overall energy consumption. Such lighting improvements could be made across Lake Forest College.

There is too much variation in solar energy for the college to rely solely upon it for its energy needs. As noted earlier, this is one of the major challenges with any renewable energy source. However, solar energy can be effectively used today on a smaller scale by providing electricity to street lamps or other small appliances across campus, even if the source is not directly connected to the grid. The 50W solar panel used
in this study is primarily designed to stand alone and be used for RV’s, small appliances, emergency backups, and electric fences. There are larger scale solar panels on the market that are designed to work in systems with higher efficiencies and peak output that would be better suited to offset the campus’s energy needs.

**Conclusion**

This study was conducted to analyze the potential for solar energy to meet the college’s energy needs. While this analysis has shown that energy demand, consumption, and storage is a complex problem, the study provided a framework for analysis of related questions. Solar energy at this time is a practical source for supplemental electricity on campus; however, it is only cost-efficient on a small scale. Solar energy remains too variable a resource to rely solely upon it for electricity needs.

Additional analysis on the electricity consumed by the Donnelley and Lee Library and Nollen Hall provided an alternative method to thinking about reducing the energy use on campus. The data from Nollen Hall, as a residential building on campus, helps to answer the questions regarding the per student impact on the overall electricity demand at the college.

The primary hypothesis of this investigation that solar energy had technical potential at Lake Forest College is supported by these findings. However, the current extent to which solar energy usage and storage is technically possible is not sufficient enough to be implemented on a large scale across the campus and be cost-efficient. The actual year-round input and output of solar panels on campus need to be analyzed rather than using comparative predictions of those values.

However, the college can further decrease its energy consumption, and therefore the cost of their monthly energy bill, by implementing other energy efficient initiatives
such as LED lighting and improving system management. Switching to renewable energy sources will eventually become cost effective and efficient for the college. This will likely happen when fossil fuels are depleted enough that their cost makes solar and other renewables the cheaper option.

**Limitations and Future Studies**

There were many limitations to this study. The most obvious limitation was the timeframe in which this study was conducted. Solar intensity is the strongest and cloud coverage is the lowest in the summer months; however, this study was conducted in the winter months when solar intensity was at its weakest and cloud coverage was at its highest. Therefore, providing estimates of year-round solar panel output was difficult. Further questions led into analyzing rooftop space and durability in relation to how many solar panels would technically be possible for installation across the campus.

An interesting future study would involve analyzing electricity usage on campus in regard to the total number of students, faculty, and staff on campus. Determining the amount of energy consumed per student, faculty, and/or staff member would provide the college important information when considering enrollment parameters and per capita costs.
References


## Appendix

### Tables

#### Table 1.
Electrical Parameters for GrapeSolar® PV Module

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Type</td>
<td>GS-STAR-50W</td>
</tr>
<tr>
<td>Max Peak Power ($P_{\text{max}}$)</td>
<td>50W</td>
</tr>
<tr>
<td>Maximum Power Point Voltage ($V_{\text{mpp}}$)</td>
<td>17.5V</td>
</tr>
<tr>
<td>Maximum Power Point Current ($I_{\text{mpp}}$)</td>
<td>2.86A</td>
</tr>
<tr>
<td>Open Circuit Voltage ($V_{\text{oc}}$)</td>
<td>22.0V</td>
</tr>
<tr>
<td>Short Circuit Current ($I_{\text{sc}}$)</td>
<td>3.17A</td>
</tr>
<tr>
<td>Normal Operating Cell Temperature (NOTC)</td>
<td>45±2°C</td>
</tr>
<tr>
<td>Module Dimensions (LxWxT)</td>
<td>665mm x 620mm x 35mm</td>
</tr>
<tr>
<td>Weight</td>
<td>4.8kg (10.58 lbs)</td>
</tr>
<tr>
<td>Max System Voltage</td>
<td>1000V</td>
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<tr>
<td>Fuse Rating</td>
<td>10A</td>
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<tr>
<td>Fire Rating</td>
<td>Class C</td>
</tr>
<tr>
<td>Field Wiring</td>
<td>Copper only, 12 AWG min.</td>
</tr>
<tr>
<td></td>
<td>Insulated for 90°C min.</td>
</tr>
</tbody>
</table>

Source: GrapeSolar® PV Module
<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output in kWh</td>
<td>0.0680</td>
<td>0.0875</td>
<td>0</td>
<td>0.2827</td>
</tr>
<tr>
<td>Cloud Coverage Ratio</td>
<td>0.7781</td>
<td>0.3486</td>
<td>0</td>
<td>1</td>
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<tr>
<td>Solar Intensity</td>
<td>3.2892</td>
<td>0.4187</td>
<td>2.82</td>
<td>4.4</td>
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<tr>
<td>High Temperature</td>
<td>37.0417</td>
<td>14.2349</td>
<td>8</td>
<td>69</td>
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<tr>
<td>Hours of Daylight</td>
<td>9.8252</td>
<td>0.7127</td>
<td>9.01</td>
<td>11.3</td>
</tr>
<tr>
<td>Efficiency</td>
<td>1.032</td>
<td>0.8288</td>
<td>0.0243</td>
<td>3.3169</td>
</tr>
</tbody>
</table>

Number of Observations: 72 (67 for efficiency due to days with snow cover)
Source: Author’s self-collected data
Table 3.
Regressions Results on Daily kWh Output

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Inputs</td>
<td>0.0301(^A)</td>
<td>(0.00235)</td>
</tr>
<tr>
<td>Constant</td>
<td>0.3362(^A)</td>
<td>(0.0063)</td>
</tr>
</tbody>
</table>

Number of Observations: 72 days

R\(^2\) Value: 0.7012

Y-Variable: The total energy output produced by the solar panel in kilowatt-hours (kWh)

Note: Superscript \(^A\) represent statistical significance at the 1% level
Note: Standard errors are below the estimated coefficients
Note: The constant is as economically important as the daily inputs

Source: Author
Figures

Figure 1.
Solar Angles

Note: Power resistors with a total of 7 ohm resistance.
Note: “A” represents the ammeter, “V” represents the voltmeter, “I” represents the current in amps.
Source: Author
Figure 3.
Set-Up Diagram for the Experiment

Note: The function generator controls the rate at which the voltage and current are read by the digital multimeter
Source: Author
Note: Snow cover on the panel from 12/10/16 through 12/15/16. The snow was scraped off for the following week’s readings.

Note: Snow cover on the panel from 12/16/16 through 12/20/16. The snow melted away naturally, it was not cleared off.
Note: No data was recorded during week 3. The power to Carnegie Hall was shut off at some point between 12/22/16 and 12/28/16, thus erasing all readings during that time frame.
Note: Strong winds blew the solar panel over on 2/13/17, resulting in lost data until the solar panel was retrieved on 2/16/17.
Source: Author
Figure 5.
Solar Panel Daily kWh Output

Source: Author
Figure 6.
Panel Efficiency vs. Cloud Coverage

Source: Author
Figure 7.
Panel Efficiency vs. Daily High Temperature

Panel Efficiency vs. Daily High Temperature
(best fit lines below and above 40 degrees)

Source: Author
Figure 8.
Daily kWh Output

Source: Author
Figure 9.
Daily kWh Output for Kohl Children’s Museum

Source: Author
Figure 10.
Daily kWh Output for Museum and Solar Panel

Source: Author
Figure 11.
Campus kWh Demand vs. Solar Panel kWh Output

Note: Data was lost from 12/10/16-12/5/16, 12/22/16-12/18/16, and 2/12/17-2/16/17
Source: Author
Images

Image 1.
Photovoltaic Resource of the U.S.

Source: National Renewable Energy Laboratory (NREL).
Image 2.
Bird’s Eye View of Kohl Children’s Museum

Note: The rooftop is slanted at a 20 degree angle.
Note: The surface azimuth angle is 16.5 degrees.
Source: Google Maps
Image 3.
Set-Up of Solar Panel

Source: Author