DC MICROGRID AND RENEWABLE ENERGY MODEL DEVELOPMENT FOR IMPROVING SUSTAINABILITY OF ELECTRIC POWER SYSTEMS

by

Andrew R. Bulman

Bachelor of Science, University of Pittsburgh, 2014

Submitted to the Graduate Faculty of

The Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2017

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

This thesis was presented

by

Andrew R. Bulman

It was defended on

March 23, 2017

and approved by

Gregory F. Reed, PhD, Professor, Department of Electrical and Computer Engineering

Zhi-Hong Mao, PhD, Associate Professor, Department of Electrical and Computer Engineering

Brandon M. Grainger, PhD, Research Assistant Professor, Department of Electrical and Computer Engineering

Thesis Advisor: Gregory F. Reed, PhD, Professor, Department of Electrical and Computer Engineering

Copyright © by Andrew R. Bulman

2017

DC MICROGRID AND RENEWABLE ENERGY MODEL DEVELOPMENT FOR IMPROVING SUSTAINABILITY OF ELECTRIC POWER SYSTEMS

Andrew R. Bulman, M.S.

University of Pittsburgh, 2017

As renewable energy becomes more prevalent throughout the electric utility industry there is an increasing interest in recreating the industry with sustainability goals in mind. One goal is to have 100% of power generated from renewable sources, such as wind and solar energy. However, targeting 100% generation creates technical and economic obstacles for the industry. Microgrids may provide solutions to the some of the challenges, but their applications have been limited thus far due to case availability and modeling difficulties in regards to optimizing the systems economically, environmentally, and technically.

This thesis examines a DC-based microgrid located at a trucking facility in Pittsburgh, PA by creating the system in a microgrid modeling software called HOMER. The simulations were completed to better understand the effect microgrids have on resiliency and sustainability by analyzing the economic, environmental, and technical impacts of the system. This paper also shows how microgrids are currently being investigated by communities and the social benefits that microgrids can provide if deployed optimally.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

I would like to my friends and family that helped me defend my master's thesis in electrical engineering this semester. First of all, my amazing fiancée, Holly Matyas, supported me constantly through a tiring semester of both working and research. She has helped me stay focused, but helped remind me to also enjoy the time, even though it was stressful. My parents have always supportive of my decision in life, and they were both encouraging about me deciding to go to graduate school. They would always ask me about school even though they have no particular interest in the electrical industry and their interest in my work means a lot to me.

I never could have made it through graduate school without the support of my peers. Ansel Barchowksy and Chris Scioscia, in particular, gave me technical advice that helped me understand core aspects of my research. Patrick Lewis provided emotional support, friendship and mentorship throughout the entire program. Alvaro Cardoza was always an encouraging, positive role-model that helped make research fun. Thanks to everyone else in the graduate student group: Hashim Al-Hassan, Joseph Petti, Santino Graziani, Jacob Friedrich, Rui Hu, Matthieu Bertin, and Samantha Morello.

I would also like to thank my advisor, Dr. Gregory Reed, for encouraging me to attend graduate school and providing me advice throughout my time as a graduate student. I will never forget our first conversation where I expressed interest, but uncertainty, in the electric power industry and he offered me an opportunity to do research in his graduate research group. His experiences and resources have allowed for me to be exposed to things that most graduate students would not have the opportunity to experience. Ultimately, the exposure I got from these programs led to me being able to get an internship and a full-time job with Duquense Light, so I am very thankful for the opportunity to have been his student during graduate school. Dr. Brandon Grainger was also very helpful getting me started with research and figure out what areas I was most interested in. He also provided advice throughout my entire time in graduate school. I want to thank Dr. Zhi-Hong Mao for agreeing to be on my committee, along with Dr. Reed and Dr. Grainger, and for exposing me to his expertise in the control field in the classroom. Dr. Katrina Kelly and Michael Rooney from the Center for Energy also provided a lot of critical insight and guidance for the work of this paper.

I would also like to thank my managers at Duquesne Light, Jason Harchick and Greg Rymarowicz, for being flexible with my schedule during my last semester of graduate school. They have been extremely supportive of me finishing my degree and it is much appreciated.

LIST OF ABBREVIATIONS

DOE	Department of Energy
CO2	Carbon Dioxide
EIA	U.S. Energy Information Administration
EPA	Environmental Protection Agency
ZEB	Zero-Net-Energy Buildings
AC	Alternating Current
DC	Direct Current
NREL	U.S. National Renewable Energy Laboratory
HOMER	Hybrid Optimization of Multiple Energy Resources
PUC	Pennsylvania Utility Commission
ROI	Return on Investment
EIS	Energy Independent Solutions
KEPCO	Korea Electric Power Corporation

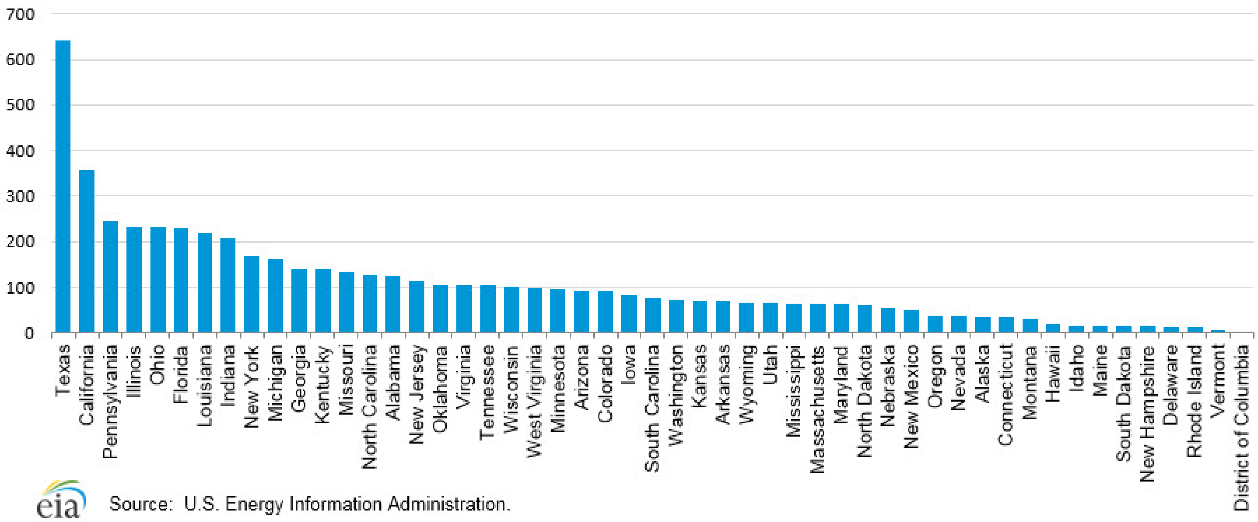
1.0 INTRODUCTION

According to the City of Pittsburgh, sustainability means “operating in such a way that we lessen our impact on the environment, while finding ways to save money, improve the services we provide to citizens, and grow the economy. It also means living our lives in such a way that we do not diminish the ability of future generations to also produce and thrive.” According to the Pittsburgh Mayor, Bill Peduto, one of the goals of Pittsburgh is to be a leader in sustainability locally, nationally and globally [1]. One major aspect of sustainability that needs to be strongly considered by cities looking to be leaders in this area is electric power. Electricity has become a basic necessity in modern society and is largely undergoing an industry-wide transformation. Because of this there are many pressures in the electric industry to recognize the opportunity to transform the industry with goals of long-term sustainability in mind [2].

Presently, renewable energy sources, such as solar energy and wind power, are key aspects of realizing long-term sustainability goals because these sources have small impacts on the global environment, are readily available and are naturally replenished. These characteristics of renewable energy have the potential to provide environmental, economic and social benefits all across the world. Ideally, the goal would be to have power entirely generated by naturally replenishing resources that have no carbon footprint and there are social pressures from organizations, like The Solutions Project, to transition to 100 percent clean, renewable energy

[3]. However, targeting 100 percent renewable energy for the electric industry creates technical and economic obstacles that need to be addressed before these targets are achievable. One potential way to mitigate some of the renewable energy obstacles is to construct microgrids throughout the electric industry. According to the Department of Energy (DOE), a microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode [4]. Microgrid research has been limited thus far due to case availability and modeling difficulties that come with needing to economically, environmentally and technically optimize a system. This paper uses a microgrid modeling software to model a local Pittsburgh company's facility to provide further evaluation of these difficulties and to provide a better understanding of the effects that microgrids have on resiliency and sustainability.

Electricity also plays a crucial role in all aspects of the global political economy, including as both the source of power behind our homes and hospitals, but also as a main contributor to greenhouse gas emissions. In 2015, emissions of carbon dioxide (CO2) by the U.S. electric power sector were 1,925 million metric tons, or about 37% of the total U.S. energy-related CO2 emissions of 5,271 million metric tons [5]. According to the U.S. Energy Information Administration (EIA), in 2014, Pennsylvania was the state with the third highest CO2 emissions as shown in Figure 1 [6]. Additionally, the Environmental Protection Agency (EPA) mandated Pennsylvania to cut its carbon dioxide emissions by approximately 32% by 2030, which may need to involve high renewable penetration in the state [7]. Microgrids in particular, can play an effective role in helping a city to overcome its carbon emissions reductions. This paper will analyze the estimated carbon emissions from a local Pittsburgh company using a microgrid software to understand the impacts renewables have on microgrids.



Source: U.S. Energy Information Administration.

Figure 1. Energy-related Emissions by State, 2014 [6]

In current times, many renewable energy projects are only constructed if there is a favorable return on investment (ROI). For energy projects, ROI analysis tends to focus on the payback period – the number of years it takes for the savings to cover the initial investment and the customer seems a positive cash flow [8]. However, for microgrids the ROI should not be as simple as the savings from the electric bill because that does not consider the full value of a micrgrid. This paper will highlight some of the non-economic benefits provided by microgrids such as reliability, sustainability and security. A feasibility study completed by a local Pittsburgh community is investigated in this paper and shows how communities are currently evaluating microgrid and other renewable energy projects.

The Department of Energy (DOE) has broken down the energy industry into three major market sectors – residential, commercial and utility-scale [9]. These sectors are defined differently throughout the industry, but this paper will assume the size for residential-scale is approximately 10kW or less. Additionally, commercial is defined between 10kW and 1mW and utility-scale is above 1mW. The differences in sizes of the sectors can have a major effect on implementing the technology. For example, the cost can be significantly different when comparing residential versus utility-scale solar panels installations. Figure 2 shows monthly averages for PV installations compiled by the National Renewable Energy Laboratory since 2004 for residential and utility-scale applications [10]. This paper will investigate the effects from different scale projects using the local Pittsburgh company as a basis.

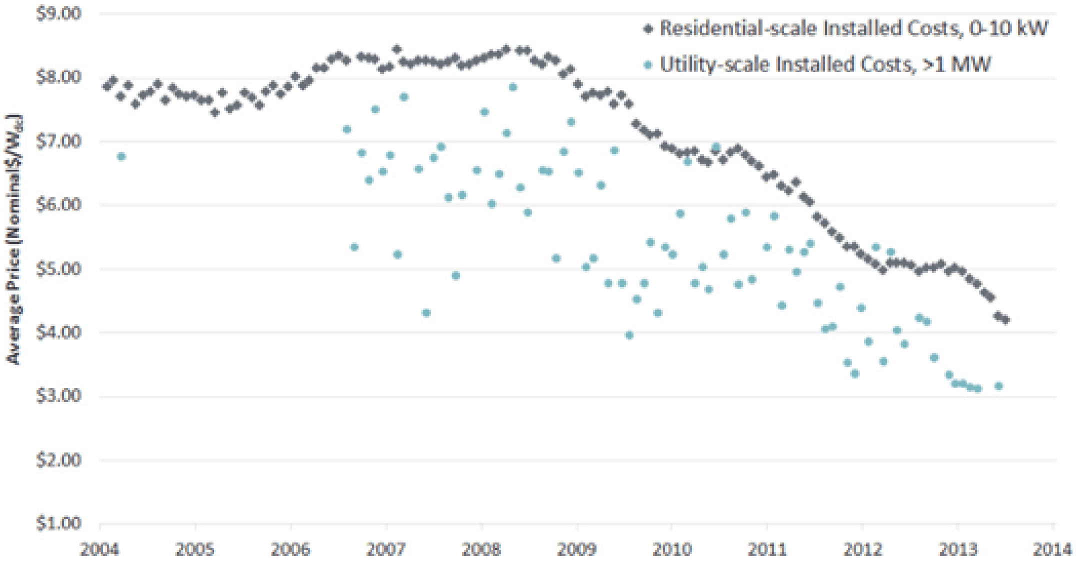


Figure 2. NREL PV Monthly Averages [10]

2.0 PITT OHIO DC MICROGRID

2.1 PITT OHIO OVERVIEW AND ARCHITECTURE

2.1.1 Pitt Ohio Background

DC infrastructure is becoming increasingly prevalent in transmission and distribution applications, including naval vessels [11], LED lighting, data centers [12], and telecommunication systems [13]-[14]. The maturation of the technology has begun to allow more commercial users to transition to DC systems. One benefit of using DC systems is the ease of integrating renewables into power systems. Using renewables in power systems are a primary way to create zero-net-energy buildings (ZEBs) – buildings that cleanly generate more energy than they use. There is a large movement pushing for all new commercial buildings to be ZEBs by 2030, but improving the energy efficiency of existing commercial buildings is a more complicated task because of the existing lighting systems, mechanical and heating, ventilation and air-conditioning (HVAC) systems that will need to be renovated for energy retrofits [12]. In order to evaluate the plausibility of improving existing buildings, alternating current (AC) and direct current (DC) based architectures of interconnecting renewable based generation with nonlinear, dynamic loads must be studied and integrated with ease. This work presents the development of a large scale demonstration project of a 380Vdc based DC microgrid at a distribution center for a regional shipping company. Integrating photovoltaic panels, a wind turbine, battery storage, and LED lighting loads, the system presents a step forward in adoption of DC technologies in commercial enterprises.

In this paper, the activities regarding the development of a DC based microgrid at the Pitt Ohio trucking facility in Cheswick, PA are described. The goal of this program was to create a viable system architecture for integrating the existing AC power system with renewable energy resources (50 kW of solar power and 5 kW of wind power) distributed through a 380 Vdc backbone to promote future research in sustainable power solutions.

2.1.2 Drivers of DC Technology within Microgrid Applications

In order to keep up with growing demand from consumers, there is a growing focus on developing solutions to make the nation’s electric grid more flexible, reliable and efficient. Due to policy pressures to also mitigate the carbon impact of the electricity sector, while at the same time maintaining low-costs for consumers makes the operation and development of the electric grid increasingly difficult. Although there has been substantial pressure on utilities to move towards electric generation that comes from clean energy resources, the current architecture of the electric grid itself still presents significant opportunities for improving the resiliency and sustainability of existing electrical systems. One possible method to meet these targets is through the implementation of microgrids. Microgrids are localized grids that can disconnect from the existing power grid and operate autonomously.

Operating separately from the grid is an advantage for the current electric grid system because using microgrids reduces the strain on and vulnerability of the electric grid [12]. In recent years, there have been significant research efforts toward developing solutions to incorporate microgrids to the grid at a distribution and commercial level. Many key technologies have been developed for 380 Vdc systems and are aiding in the commercialization of 380 Vdc microgrid systems [15]. They also aid the integration of renewable resources (wind and solar), which are inherently DC based resources or contain a DC conversion path through their electrical architecture. This increases the appeal of producing DC microgrid systems because wasteful conversion stages can be eliminated [15], [16]. For example, in a standard solar system, DC power is generated by the panels and is inverted to AC power to be distributed throughout the building. Then, the AC power is converted back to DC for the different loads in the building. These conversions lead to losses that are estimated to be about 15% of the solar energy produced [12]. Research has also shown that the cable losses associated with DC power can be decreased by around 36.6% compared to an AC system [17].

There have been many studies showing the benefits of DC power, but most of these studies thus far rely on a traditional optimization formula that estimates the most optimal voltage configurations. Understanding the benefits of various voltage levels is important because different voltage levels will affect the system efficiency, cost and safety [16]. Over the past decade, 380 Vdc has been becoming more popular worldwide because of the expected energy and space savings associated with this specific voltage level currently [13]. Table 1 highlights some of the commercial uses of 380 Vdc worldwide. There are ETSI standards being implemented for telecom and data center applications that specify a voltage range from 260 Vdc to 400 Vdc and 380 Vdc is becoming a popular choice within the range because of the high achievable efficiency (efficiency improvements of 2% for the frontend converter of a system) [17]. The efficiency is enhanced because the power electronics can be optimized at a higher performance level. The DC Components and Grid (DCC+G) project also showed that there were less electronics and cost in the more efficient system than a similar AC system [17]. Additionally, the simpler configuration inherent to a 380 Vdc system compared to a standard AC power system increases the reliability and reduces the area of the system by approximately 31% [13].

Table 1. 380 Vdc Installations Worldwide (Select List) [13]

World Location	Voltage Level
Telecom Operator (Canada)	380 Vdc
SAP (USA)	380 Vdc
Intel Corporation (USA)	380 Vdc
Stanford University (USA)	380 Vdc
Nextek (USA)	380 Vdc
Syracuse University (USA)	380 Vdc
Duke Energy (USA)	380 Vdc
Steel Orca (USA)	380 Vdc
Norway	350 / 380 Vdc
Sweden	350 / 380 Vdc
ABB (Switzerland)	350 / 380 Vdc
Telecom Operator (China)	240 / 380 Vdc
IBM (India / Singapore)	380 Vdc
Korea	300 / 380 Vdc
NTT Group (Japan)	380 Vdc

Many key technologies have been developed for 380 Vdc systems and are aiding in the commercialization of 380 Vdc microgrid systems [15]. These technologies focus on achieving high efficiency, stability, and safety. However, one of the drawbacks of DC microgrids that limits their commercial viability is the challenge of cost-effectively integrating them with the current AC grid. In recent years, there have been significant research efforts toward developing solutions to incorporate microgrids to the grid at a distribution and commercial level. At the same time, evaluating the benefits of microgrids are technically difficult as the tools for systematically evaluating simultaneous performance metrics requires an optimization formula across both environmental and technical dimensions. The case-study of Pit Ohio analyzed further in this paper shows how optimizing across both environmental and technical dimensions have helped develop an economically efficient microgrid.

2.1.3 Pitt Ohio and the Use of a DC Microgrid

Pitt Ohio Trucking is a transportation solutions provider based in Pittsburgh, PA committed to promoting sustainability. All trucking companies understand that the nature of their business has an impact on the environment. Pitt Ohio continuously pledges to improve the environmental and social sustainability performance of their business. One of the company's sustainability efforts was to create the region's first 55,000 square foot, LEED-certified trucking terminal in Cheswick, PA (Harmar Township) composed of 100 dock doors, 150 LED lights, natural light panels, CNG tractors, and electronic forklifts. The terminal is found in Figure 3.

Pitt Ohio additionally strives to promote the Pittsburgh region as pioneers of the electric power industry. Pitt Ohio partnered with the University of Pittsburgh and other local Pittsburgh manufacturers including Adam Solar Resources, Aquion Energy, BDA Engineering Inc., Eaton, PCTI, Sargent Electric Company, Universal Electric, and WindStax to retrofit the existing terminal with a DC distribution feed to integrate a variety of renewables and serve the terminal lighting load.

Figure 3. Pitt Ohio – Harmar Distribution Facility

The project to be discussed was the first commercial installation in Pittsburgh to incorporate some of these new 380 Vdc technologies, the first microgrid that coordinates both solar power and wind power with the utility feed to serve the existing load, and show that a DC microgrid can be cost effective.

2.1.4 DC Microgrid Design for the Pitt Ohio Trucking Terminal

The purpose of the microgrid project was to power a 33.4 kW lighting load, a 2.5 kW DC test load, and a 2.5 kW AC test load from 50.4 kW of solar power (180 panels) and 5 kW of wind power with the capability of disconnecting from the bulk grid. Current microgrid trends have primarily focused upon solar power coupled with battery storage as the major source of renewable generation. Here, the coordination of wind power, solar power, and energy storage on a DC distribution bus within a commercial facility is a new facet for the technological community.

A one-line diagram of the DC microgrid is provided in Table 2 and Figure 4 provides the details for all the components composing the system.

Table 2. DC Microgrid System Components

Item	Manufacturer	Ratings	Quantity
Photovoltaic Panels	Solar World	280 W, I_{sc} - 9.71 A, V_{oc} - 39.5 V	180
vBoost 600 DC to DC Converter	eIQ energy	600 W, output voltage of 380 Vdc	90
Rectifier	Emerson	480 Vac to 380 Vdc, 50 kW	1
Wind Turbine	WindStax	5 kW	1
Wind Turbine Battery	Aqueon	2.4 kW	4
Wind Turbine Boost Converter	Eltek	48 Vdc to 380 Vdc	1
Battery Storage System	Aqueon	75 kWh	5
Lighting Load Inverter	PCTI	380 Vdc to 480 Vac, 40 kW	1
Test Room Inverter	PCTI	380 Vdc to 108 Vac, 2.5 kW	1
Feeder Busway	Universal Electric	380 Vdc, 225 A	30 ft

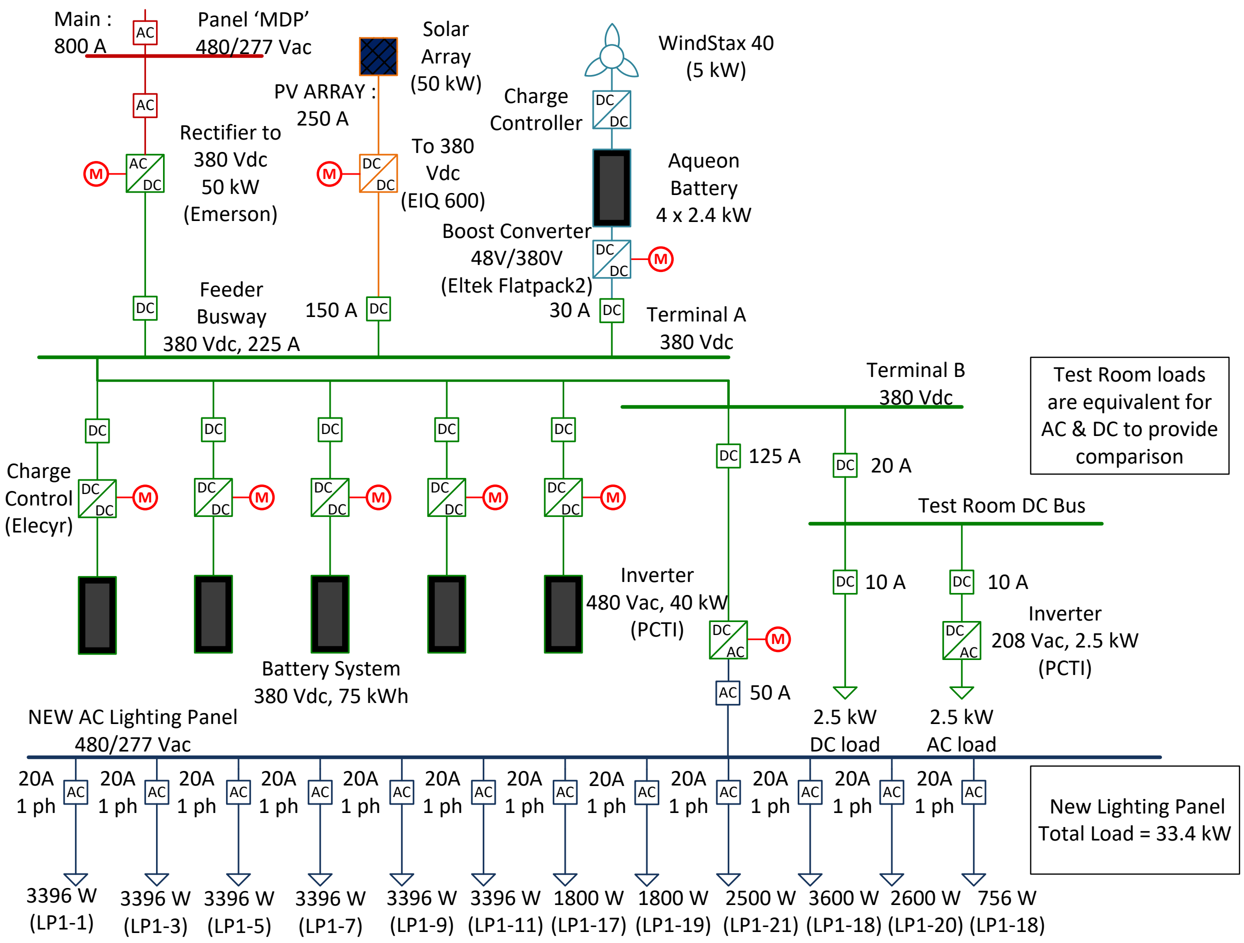


Figure 4. DC Microgrid One-Line Diagram

The outputs from the solar array (orange; Voc - 39.5 V; Isc – 9.71 A, 16.70% efficient panels) were stepped up to 380 Vdc using vBoost 600 DC to DC converters, [18], and fed to Terminal A, where the energy can be stored in the battery system rated for 75 kWh. Similarly, the output from the wind turbine was fed to a battery system composed of 4, 2.4 kW Aquion battery stacks using a DC to DC charge controller.

The 380 Vdc, 75 kWh battery system has two unidirectional connections to the bus so that charging and discharging could be controlled independently. Also, the unidirectional connections were necessary because the magnetic breakers used on the bus were polarized. Each connection has a controlled bypass which limits current for pre-charging the bus or for slow charging when the batteries are initially very low or high. Ethernet is used for each of the battery stacks to communicate between each other and ensures that enough stacks are turned ON when charging to avoid overload current.

Both 40 kW and 2.5 kW inverters were manufactured locally to convert the 380 Vdc to 208 Vac required for the lighting load and programmable 2.5 kW AC and DC loads both found in the test room. The test room DC bus architecture is slightly more elaborate compared to the state-of-the-art, [17], because, now, system dynamics from the renewable resources will impact system measurements when comparisons between the DC circuit and AC circuit are developed. The facility operates 24 hours a day. Hence, the solar and wind generation is coordinated with the utility supply to ensure all load is met during the day and battery system discharges at night to maintain power to the lighting load. Currently, the utility smooths the variance in the delivered solar power during the day and the wind energy supplements the utility supply at night. On sunny days in Pittsburgh, the generated solar power is only supplied to the load with no aid from the onsite wind generation or utility supply. On cloudy days, the utility supply and wind supplement the available solar generation. The latter comments reflect the steady-state milestones of the system. In the case of a system failure or low bus voltage condition, a transfer switch is programmed to allow utility power to supply all system loads and stabilize the bus voltage. The primary setting is for the system to be operating continuously on available renewable energy.

To ensure the wind and solar systems were properly sized, expected renewable generation performance profiles were developed. A weather station was used to provide on-site readings for 18 months to confirm the monthly distribution patterns. Additionally, the weather station was used to provide detailed information on how the wind speed and direction was typically distributed at the installation site. The readings on-site confirmed regional reports that the area has above-mean wind speeds. The annual mean wind speed was found to be 3.92 m/s. A wind rose was created using the meteorological data from Pittsburgh to show the wind speed and direction and is shown in Figure 5. Figure 6 shows the WindStax vertical axis wind turbine installation on the outer edge of the facility plot.

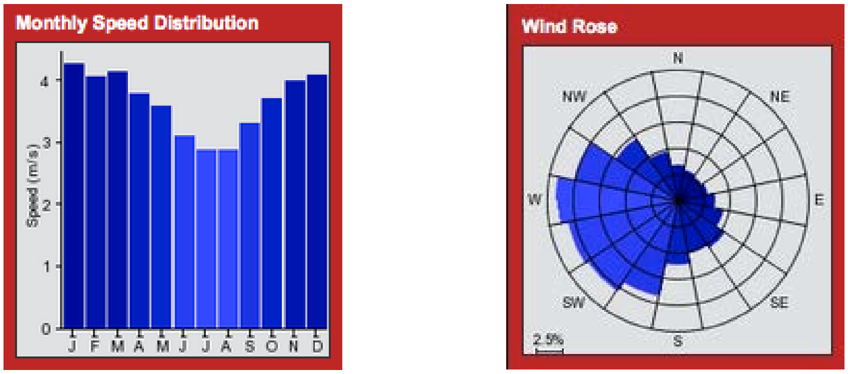


Figure 5. Monthly Speed Distribution and Wind Rose Profile for Site

Figure 6. 5kW WindStax Vertical Axis Wind Turbine Installation

Similarly, estimates were determined for the photovoltaic system based on the specific location of the facility. The panels would be facing 190º on a 2/12 pitched roof with an array tilt of 9.46º. The system losses and converter efficiency were specified at 14% and 96%, respectively. Using these figures and monthly solar radiation statistics from the area, the vendor estimated that 180 solar panels would produce approximately 58,320 kWh per year. Figure 7 shows the solar panels on the roof of the facility.

Figure 7. 50kW Photovoltaic System Installation

The system architecture is constructed primarily around the renewable sources and loads being connected to a 380Vdc bus. Because the 75kWh battery bank cannot limit the amount of power they can absorb, it was necessary for the power sources to be current controlled. This was completed for the PV system by using the vBoost modules, which operate as charge controllers on the common bus. They operate at a voltage slightly above the DC bus voltage and maintain the voltage while limiting current to control the output voltage. For the wind system, the boost converter limits the current and controls the output voltage. Similarly, the rectifier is used for limiting the current and controlling the output voltage for the connection to the AC grid. The loads connected to the main DC bus pull power until the low voltage threshold has been met.

Figure 8 provides a view of the control room where the 380 Vdc bus distributes all renewable power to the panel load and where measurements of the sources and loads can be taken. At the time that this article is being written, the engineering team has been commissioning the system and gathering preliminary measurements. As evidenced by Figure 9, when the solar system energizes, the DC bus voltage increases from 380 Vdc and remains at 400-407 Vdc compared to when the solar power is not utilized at night. Recall that the lighting load at the terminal operates every day for 24 hours. This higher system voltage operation is triggering the alarm within the rectifier when the solar photovoltaic system is supplying power to the load. This is one of the smaller challenges experienced during the commissioning process of the overall architecture. Thus far in the commissioning stages, the team has successfully run a 24 hour continuous test and weekend long continuous test to ensure proper operation of all equipment in the facility.

Figure 8. Electrical Equipment within the Pitt Ohio Harmar Facility

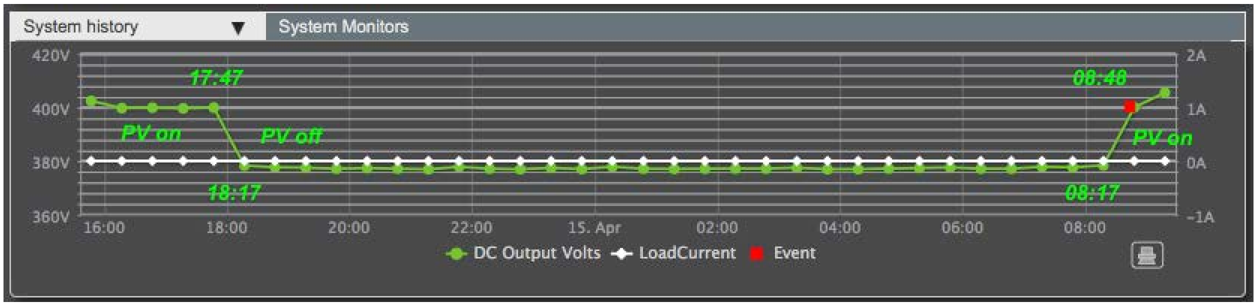


Figure 9. DC Bus Voltage Measurement under Preliminary Commissioning Tests

2.2 PITT OHIO DC MICROGRID HOMER MODELING

2.2.1 Homer Background and System Modeling

To analyze various impacts of the system, the entire Pitt Ohio Harmar facility was modeled in a microgrid computer software called HOMER (Hybrid Optimization of Multiple Energy Resources). HOMER was developed by U.S. National Renewable Energy Laboratory (NREL) to compare microgrid technologies and optimize microgrid systems. The software is designed to optimize the system across both environmental and economic dimensions and to estimate the cost of the installation based on component and technology inputs to the model. For this system the inputs to the model were the grid, electric load for the facility, PV array, and wind turbine. Additionally, the location of the facility was input so that the proper solar irradiance and wind speed data were used for the area. Figure 10 shows the GPS location of the Pitt Ohio Harmar Facility.

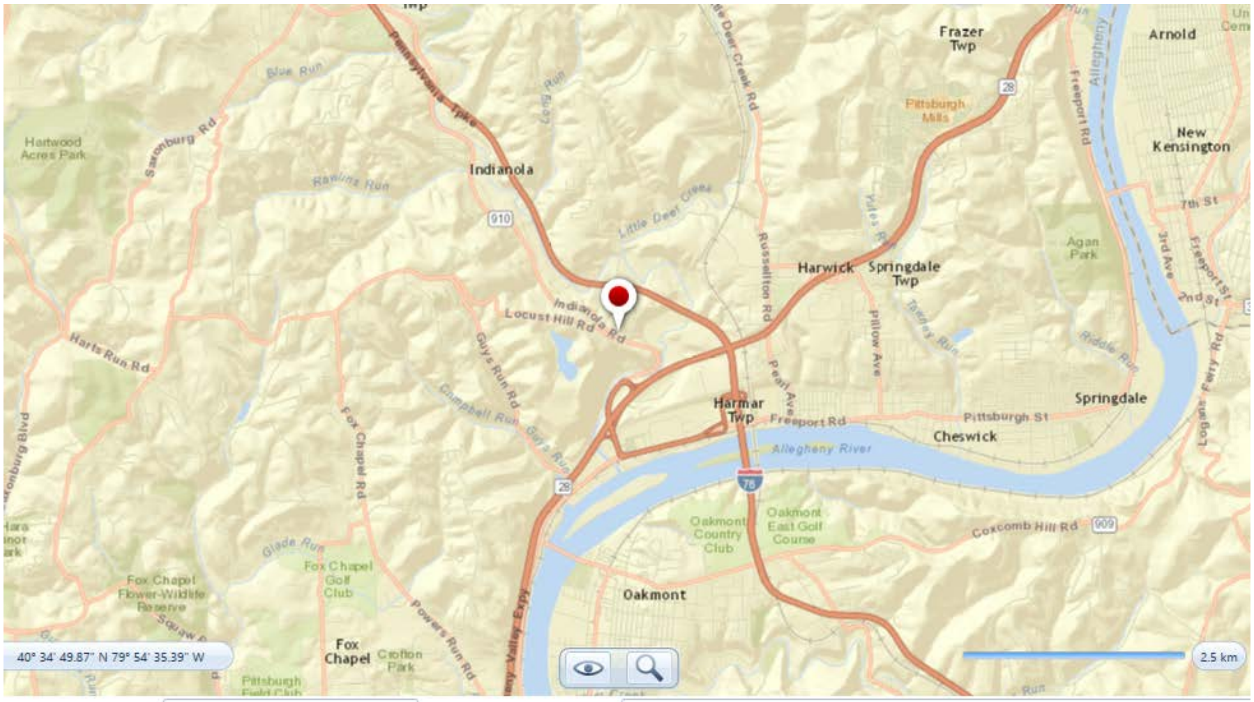


Figure 10. Location of Pitt Ohio Harmar Facility

The grid was modeled by using the power price from the grid from electric utility data provided by Pitt Ohio for the Harmar facility. For this system the power price was 0.072 $/kWh. The electric load for the facility was also modeled using the electric utility data. The inputs for the electric load were the peak month of January and the average load of the facility, which was approximately 4500 kWh/d. A generic flat plate 1 kW PV array was used to model the PV for the system and the cost of the array was the only input. The cost used was $2.7/w, which was the price of the solar for the Pitt Ohio installation. It should be noted that HOMER's library does not include a vertical axis wind turbine, so a component was created using the power curve of a 1.2 kW vertical axis turbine created by Windspire and is shown in Figure 11 [19].

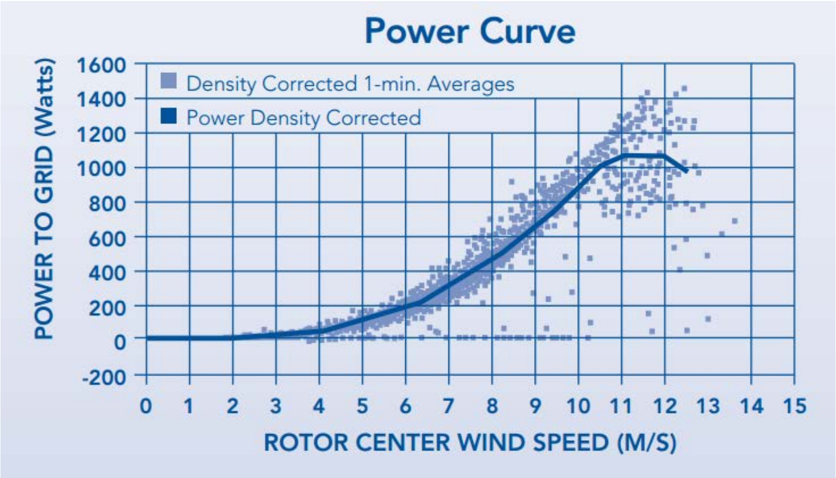


Figure 11. 1.2 kW Windspire Vertical Axis Turbine Power Curve [19]

To recreate the same system as shown in Figure 4 the electric load was selected to be an AC load and the PV array and Wind turbines were selected as DC inputs. The one-line of the homer model is shown in Figure 12.

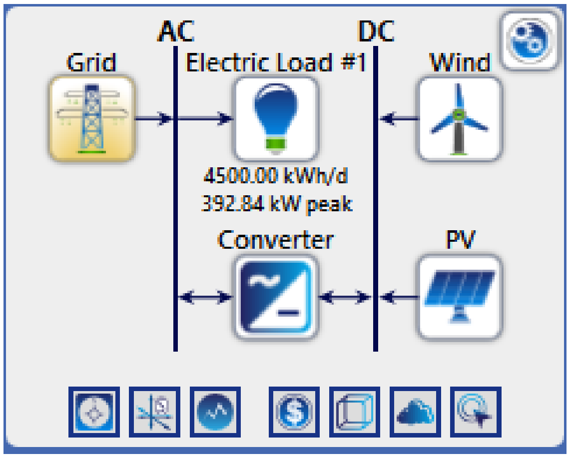


Figure 12. HOMER DC Microgrid One-Line Diagram

2.2.2 Homer Model Validation

The main variable that was used to test the system was a minimum renewable fraction (%) constraint on the system. The purpose of using that variable was to force Homer to create a system with a certain percentage of the load being powered by renewables. Because the total load of the facility is approximately 150 kW, the expected percentage of renewables for the facility is approximately 30%. The 30% comes from the 50kW solar array and 5kW wind turbine. When the minimum renewable fraction was set to 30% for the system, the result was that Homer optimized the PV array to be approximately 55.7 kW. This result is about what is expected for this model since the 5kW of wind turbine was experimental and not the optimal design of the system from a cost perspective. In addition, the cost of the PV was approximated to be $150,000 in the Homer model, which was slightly lower than the expected cost of around $135,000 for 50kW. Before the PV array was installed at the facility, it was estimated that the kWh per year would be between 55,000 to 60,000 based on the solar radiation at the site location [20]. In Homer, the kWh produced from the 55.7 kW array was approximately 65,000 kWh. It was expected that this number would be slightly higher than the estimated value because of the additional 5kW of PV instead of wind power. To check the validity of the wind model the PV array was taken out of the model and a system with just 5kW of solar was created. In this model Homer estimated that the wind turbines would produce approximately 7,000kWh. The wind turbines installed at the facility are estimated to produce around 18,000kWh at 12.5m/s average wind speed. The average wind speed in the Harmar area is closer to 4m/s as shown in Figure 5, so this drastically lower production from the wind speed was to be expected. In the next section, a sensitivity analysis is performed on the validated model to test the effects of changing the bus types for the inputs (PV Array and Wind Turbines) and the electrical load.

2.2.3 Homer Model Technical Evaluation

One of the difficulties in understanding the benefits of renewables in power systems is from the intermittency and unpredictability of renewables and the uncertainty in regards to efficiency of the conversion processes from AC to DC and DC to AC. In this section, some of these challenges are addressed by testing the renewables inputs and electrical load on different electrical buses with the validated Homer model. The base case for this system was for the renewables to be on the DC bus and the electrical load to be on the AC bus and this can be seen in Figure 12. To analyze trends that occur with these technical changes, eight new cases were created from the base case. For each of the cases only one variable was changed so that trends could be observed at this facility. The eight technical cases simulated in Homer are shown in Table 3.

Table 3. Eight Technical Cases Analyzed in Homer

Case Number	Renewable Generation	Renewable Bus	Electrical Load Bus
1	Solar, No Wind	DC	AC
2	Solar, No Wind	AC	AC
3	Solar, No Wind	DC	DC
4	Solar, No Wind	AC	DC
5	Wind, No Solar	DC	AC
6	Wind, No Solar	AC	AC
7	Wind, No Solar	DC	DC
8	Wind, No Solar	AC	DC

For each of the eight cases the minimum renewable fraction was altered from 0% to 100% to test the effects of increasing renewables on the system. For this analysis it was assumed that the cost of the renewables scaled linearly and was not altered based on the size of the system.

For case 1, the system was developed with only a PV array on the DC bus and the electrical load on the AC bus as shown in Figure 13. This case was unique because the converter acted as an inverter to power the load and the results of these simulations are shown in Figure 14. In this scenario a DC/DC converter is used at the PV panels before the power is converted at the inverter. The load could be powered directly from the grid when necessary.

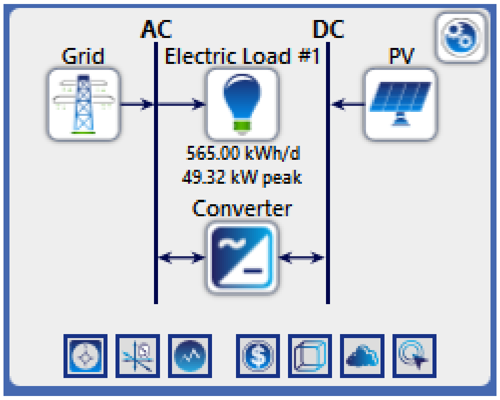


Figure 13. Homer One-Line for Case 1 - DC Solar and AC Load

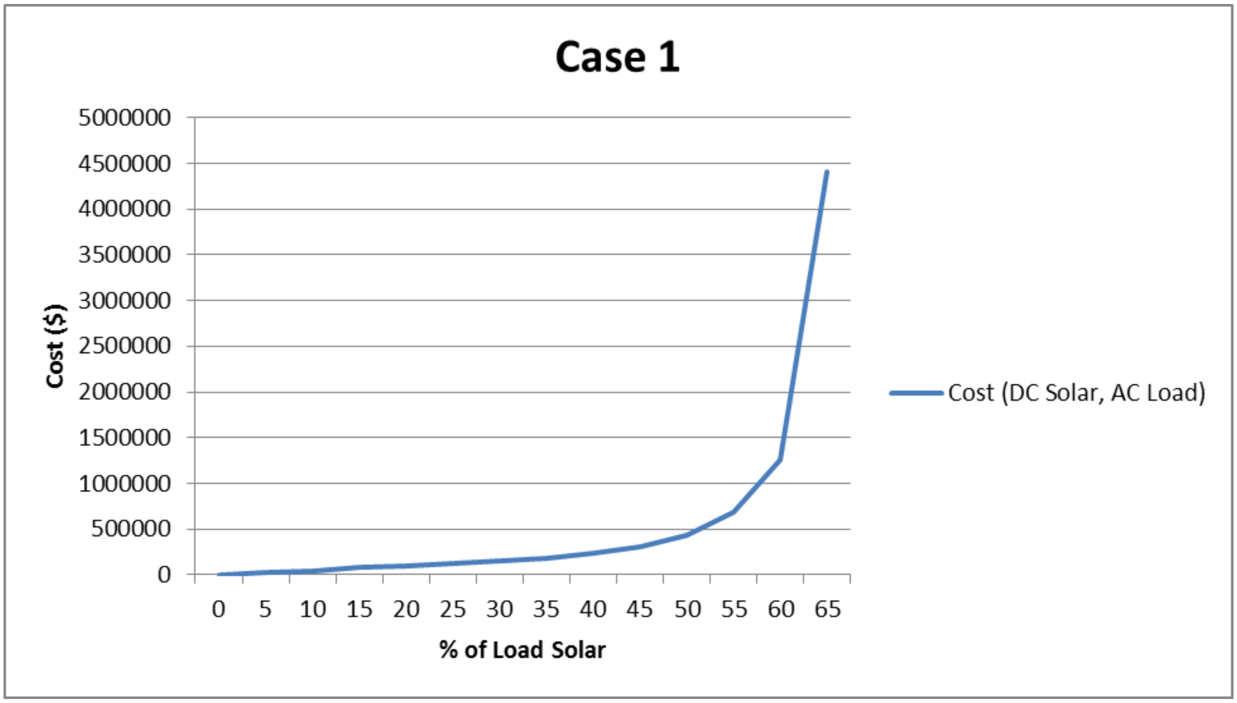


Figure 14. Simulation Results for Case 1 – DC Solar and AC Load

For case 2, the system was developed with only a PV array on the AC bus and the electrical load on the AC bus as shown in Figure 15. This case was unique because the energy from the PV array can be used directly to power the AC load and the results of these simulations are shown in Figure 16. The power would only need to be inverted at the PV panels before being fed to the load in this scenario and the system converter was not required because the load could be powered directly from the grid when necessary.

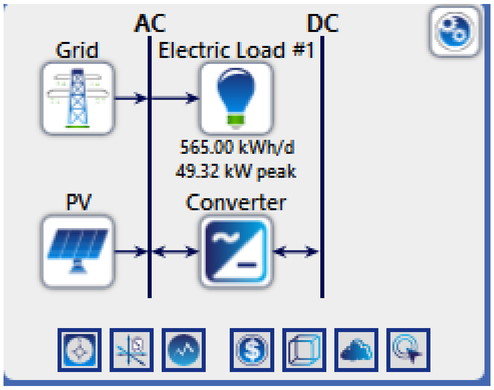


Figure 15. Homer One-Line for Case 2 – AC Solar and AC Load

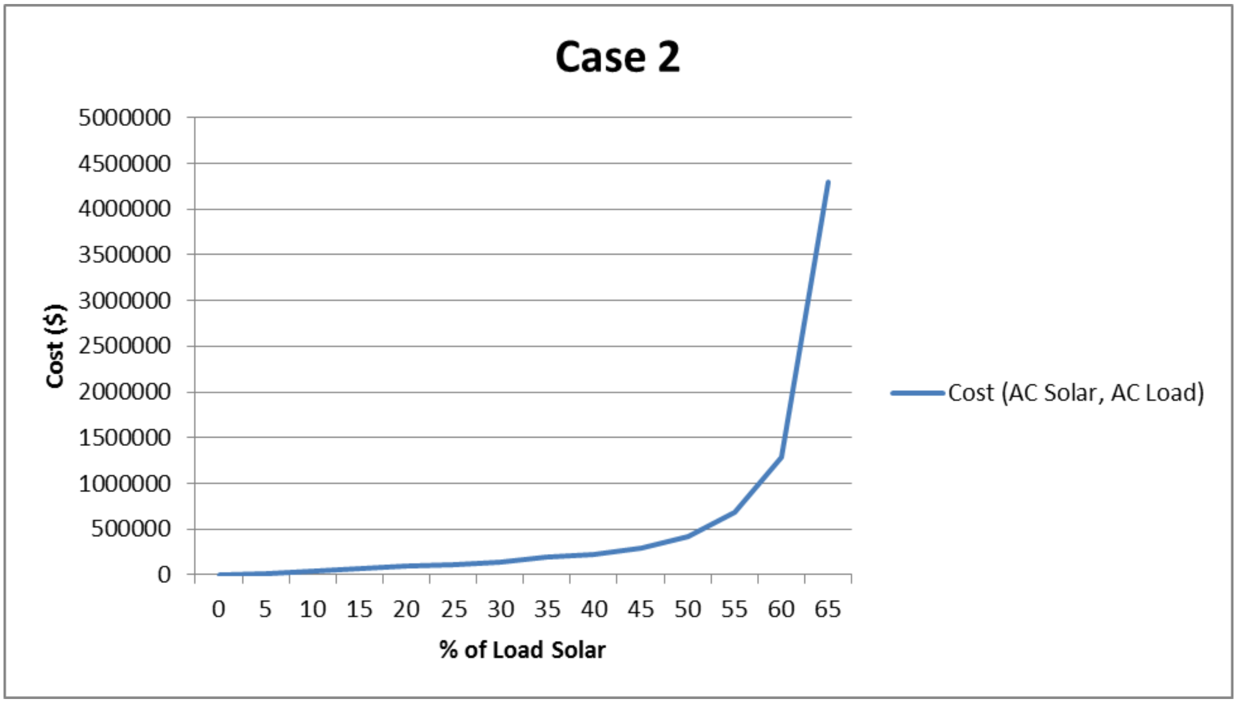


Figure 16. Simulation Results for Case 2 – AC Solar and AC Load

For case 3, the system was developed with only a PV array on the DC bus and the electrical load on the DC bus as shown in Figure 17. This case was unique because the energy from the PV array can be used directly to power the DC load and the results of these simulations are shown in Figure 18. Only a DC/DC converter at the PV panels is necessary to power the load in this scenario. The system converter was only required so that the load could be powered from the grid when necessary.

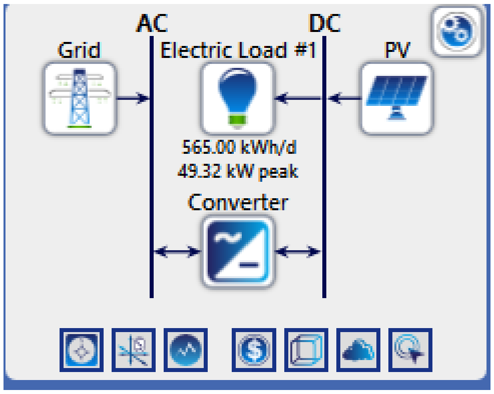


Figure 17. Homer One-Line for Case 3 – DC Solar and DC Load

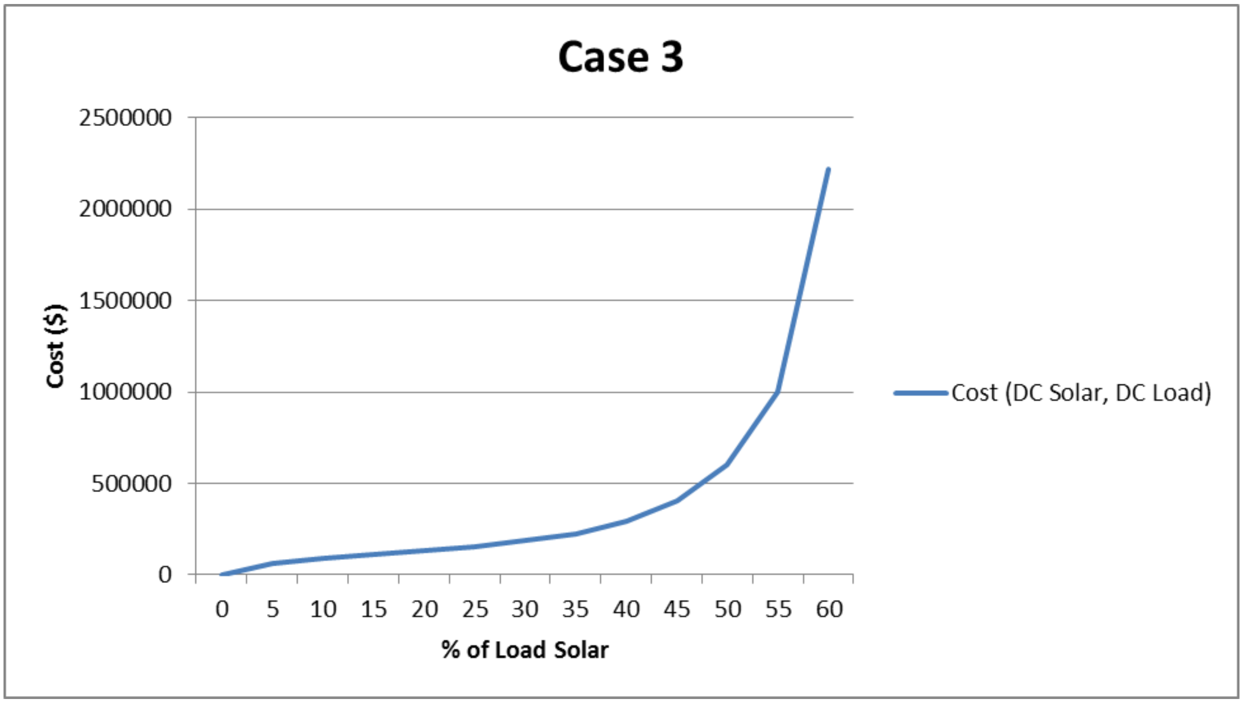


Figure 18. Simulation Results for Case 3 – DC Solar and DC Load

For case 4, the system was developed with only a PV array on the DC bus and the electrical load on the AC bus as shown in Figure 19. This case was unique because the converter acted as a rectifier to power the load and the results of these simulations are shown in Figure 20. The system converter was required so that the load could be powered from the grid when necessary.

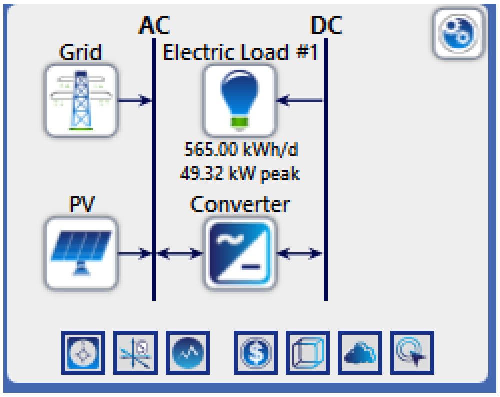


Figure 19. Homer One-Line for Case 4 – AC Solar and DC Load

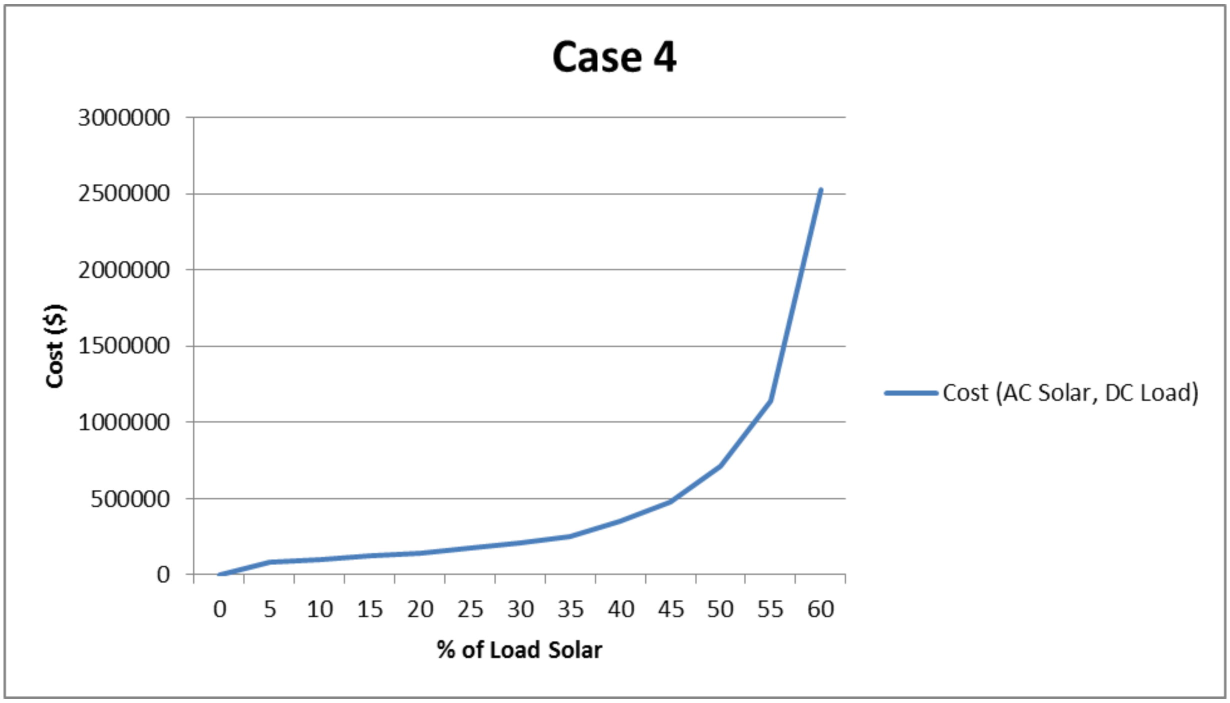


Figure 20. Simulation Results for Case 4 – AC Solar and DC Load

Figure 21 shows the four cases on the same plot and highlights that the results are different, but have similar trends. This is especially true for the cases that share the same electrical bus for the load. The cases with the load on the DC bus being more expensive than the cases with the load on the AC bus because the grid was connected to the AC bus. However, this assumed the same converters for each case. In many scenarios, the correct converter needed for these systems does not exist for practical applications currently and would be extremely hard to model correctly in Homer because costs are unknown. As more converters are designed, especially for the DC conversions, the model could be updated and the results would likely produce different results.

The cost for all four cases begins to grow exponentially as the percentage of the load generated by renewable energy increases. Generally, it is assumed that the cost of adding additionally solar panels to a project would increase the cost linearly with the number of panels. Because the simulation was being constrained by the minimum renewable fraction the intermittency from the solar irradiation data affects the results. When a higher percentage of the load was required to be generated from renewables the affects from weather and sunlight have a greater impact on the simulation results. More solar panels were required to ensure that the minimum percentage of renewables was reached.

Constraining the system with minimum renewable fraction is a practicable constraint because many states are mandating utilities and new buildings to generate certain percentage of electricity from renewable sources [21]. In Pennsylvania, the renewable mandate is for 18% of electricity produced to be from renewable sources [21]. Understanding the effects of percentage-based requirements on power systems is essential for cities, like Pittsburgh, and states to hit their renewable goals. There is a lack of awareness about the exponential growth of cost as the renewable percentage increases.

However, renewable energy is not only produced through solar energy. The Pennsylvania Utility Commission (PUC) recognizes PV energy, solar-thermal, energy, wind, low-impact hydro, geothermal, biomass, biologically-derived methane gas, coal-mine methane and fuel cells as eligible renewable sources [21]. This study also analyzed wind energy because it was also a component of the installation at Pitt Ohio’s Harmar facility.

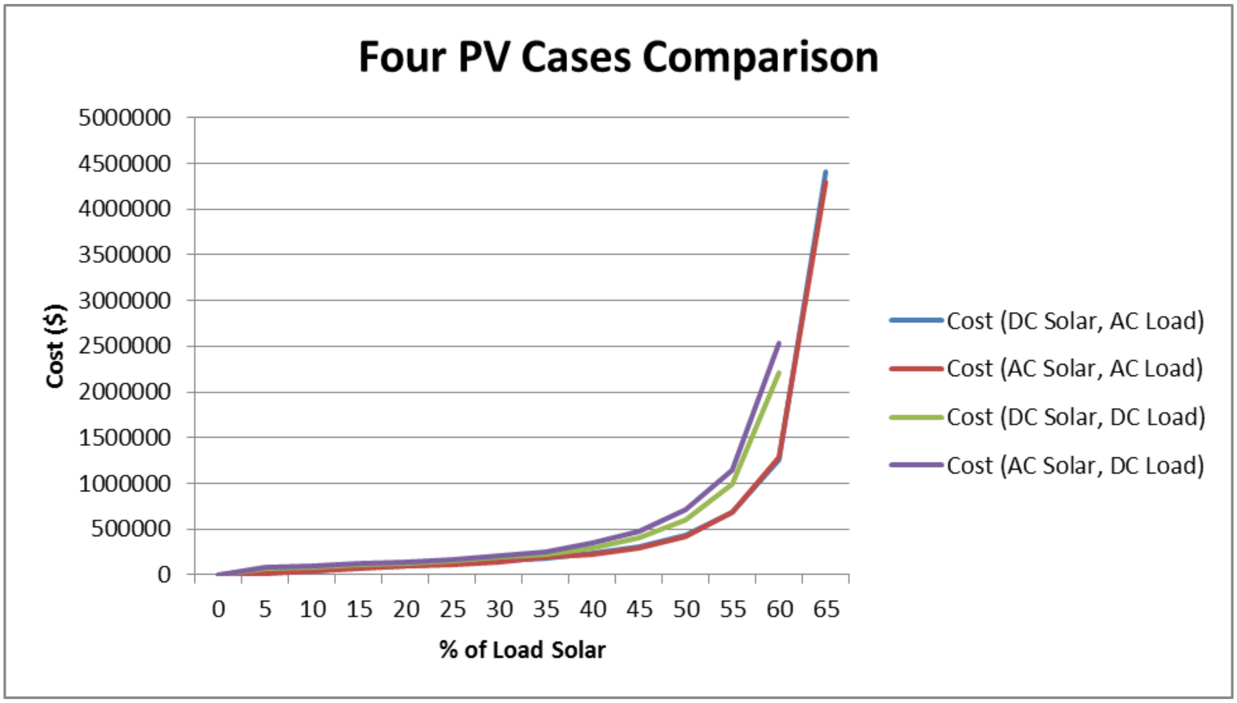


Figure 21. Simulation Results for Four PV Cases

The next four cases of the Homer simulation focused on wind power being the sole renewable source to the facility. For case 5, the system was developed with only wind turbines on the DC bus and the electrical load on the AC bus as shown in Figure 22. This case was unique because the converter acted as an inverter to power the load and the results of these simulations are shown in Figure 23. In this scenario, an AC/DC converter and DC/DC converter are used at the wind turbines before the power is converted at the inverter. The load could be powered directly from the grid when necessary.

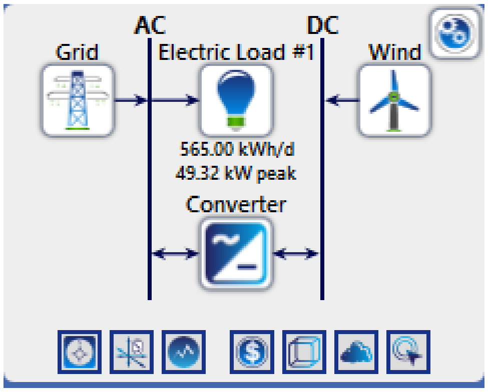


Figure 22. Homer One-Line for Case 5 – DC Wind and AC Load

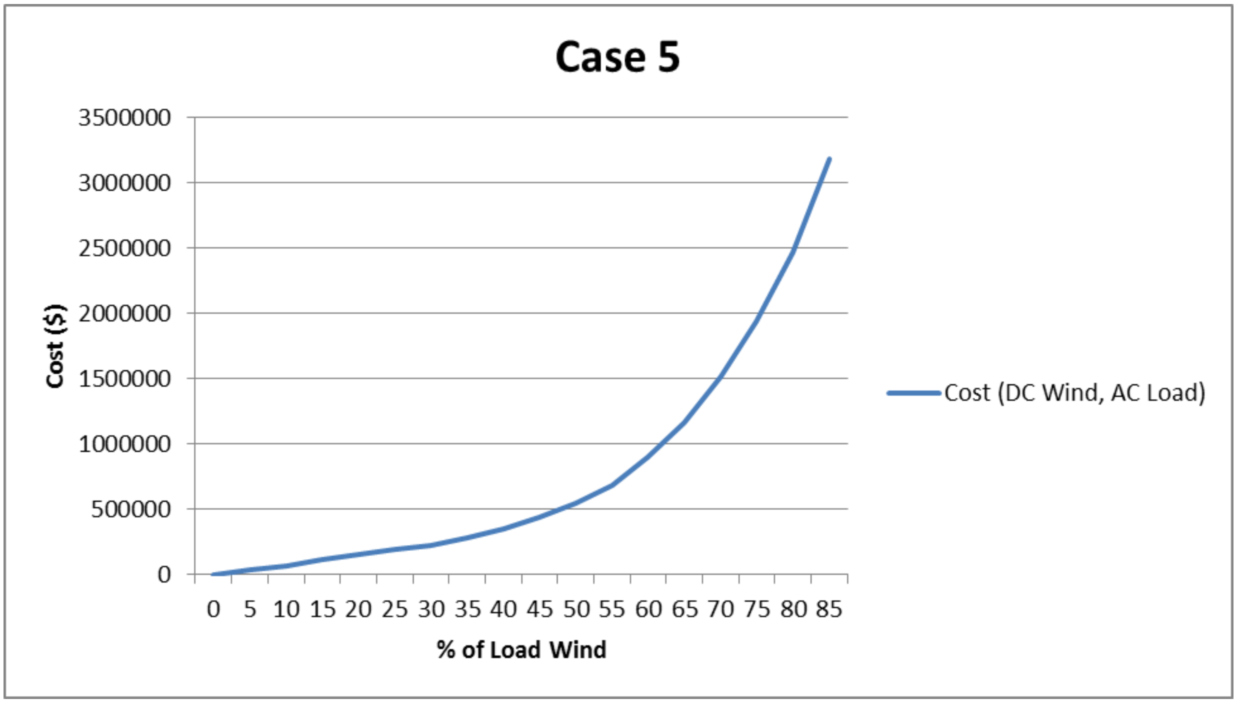


Figure 23. Simulation Results for Case 5 – DC Wind and AC Load

For case 6, the system was developed with only wind turbines on the AC bus and the electrical load on the AC bus as shown in Figure 24. This case was unique because the energy from the wind turbines can be used directly to power the AC load and the results of these simulations are shown in Figure 25. The power would be input directly from the AC output of the wind turbines to the AC load and the system converter was not required because the load could be powered directly from the grid when necessary.

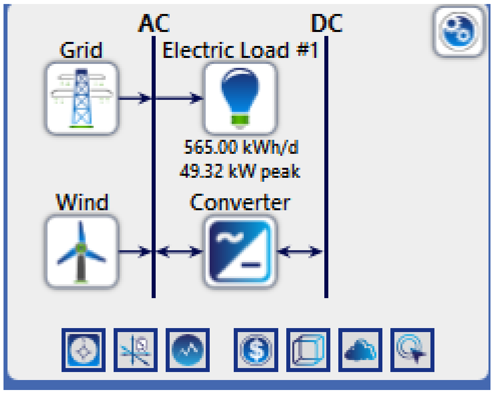


Figure 24. Homer One-Line for Case 6 – AC Wind and AC Load

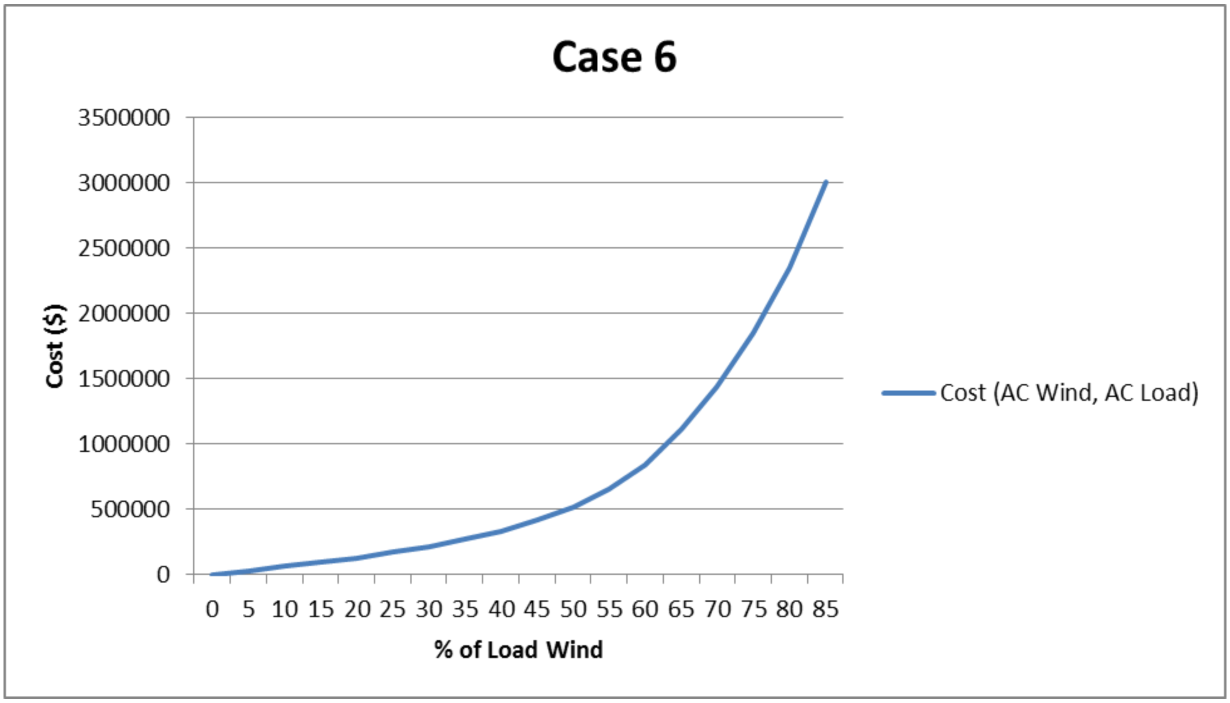


Figure 25. Homer Simulation for Case 6 – AC Wind and AC Load

For case 7, the system was developed with only wind turbines on the DC bus and the electrical load on the DC bus as shown in Figure 26. This case was unique because the energy from the wind turbines can be used directly to power the AC load and the results of these simulations are shown in Figure 27. Only an AC/DC converter at the wind turbines was necessary to power the load in this scenario. The system converter was only required so that the load could be powered from the grid when necessary.

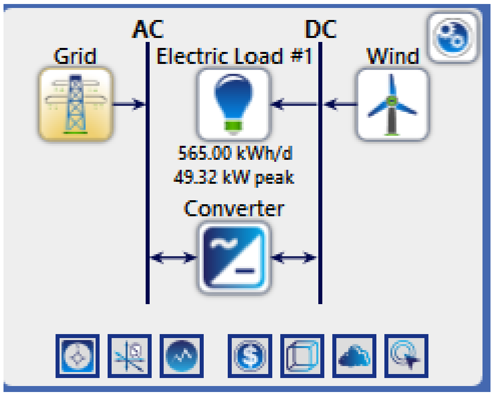


Figure 26. Homer One-Line for Case 7 – DC Wind and DC Load

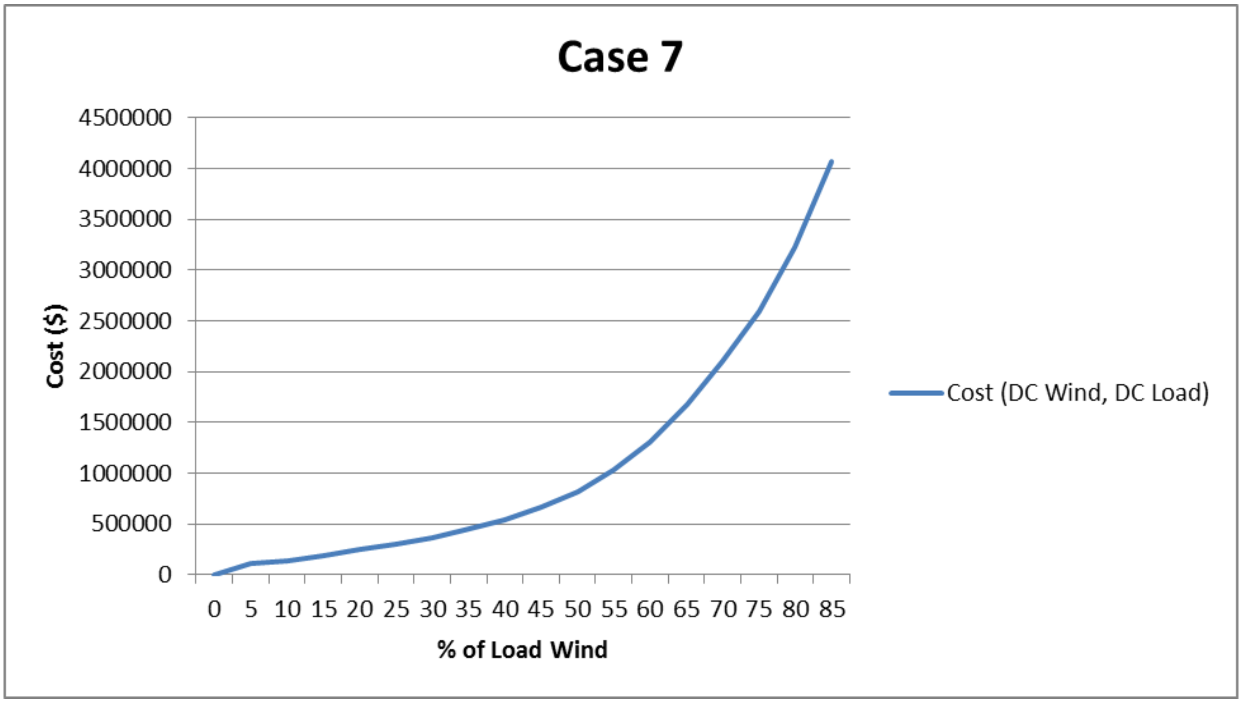


Figure 27. Homer Simulation for Case 7 – DC Wind and DC Load

For case 8, the system was developed with only wind turbines on the DC bus and the electrical load on the AC bus as shown in Figure 28. This case was unique because the converter acted as a rectifier to power the load from the wind turbines and grid and the results of these simulations are shown in Figure 29. The system converter was required so that the load could be powered from the grid when necessary.

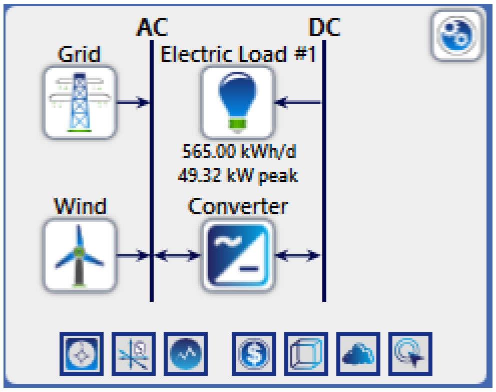


Figure 28. Homer One-Line for Case 8 – AC Wind and DC Load

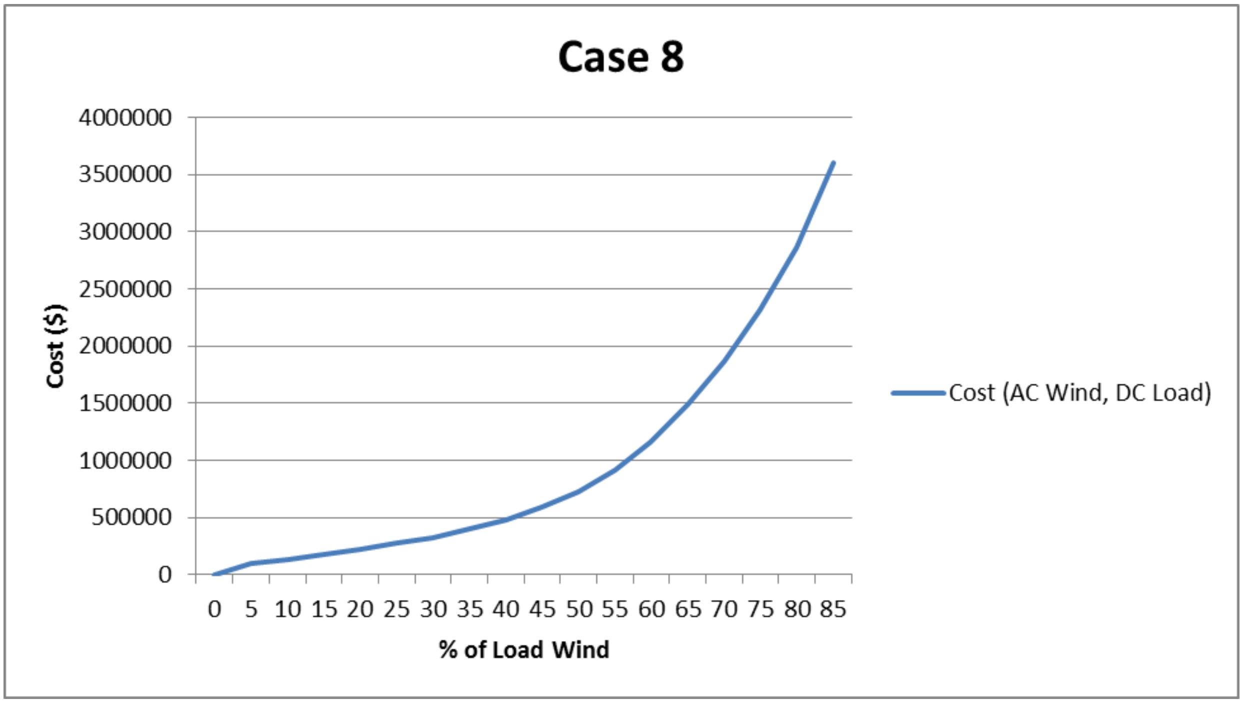


Figure 29. Homer Simulation for Case 8 – AC Wind and DC Load

Figure 30 shows the four cases for wind generation on the same plot. Similarly to the solar plot the plot highlights that the results are different, but have similar trends for all the cases. This still holds true for the cases that share the same electrical bus for the load. Similarly to the PV cases, the cases with the load on the DC bus being more expensive than the cases with the load on the AC bus because the grid was connected to the AC bus. However, this assumed the same converters for each case. In many scenarios, the correct converter needed for these systems does not exist for practical applications currently and would be extremely hard to model correctly in Homer because costs are unknown. As more converters are designed, especially for the DC conversions, the model could be updated and the results would likely produce different results.

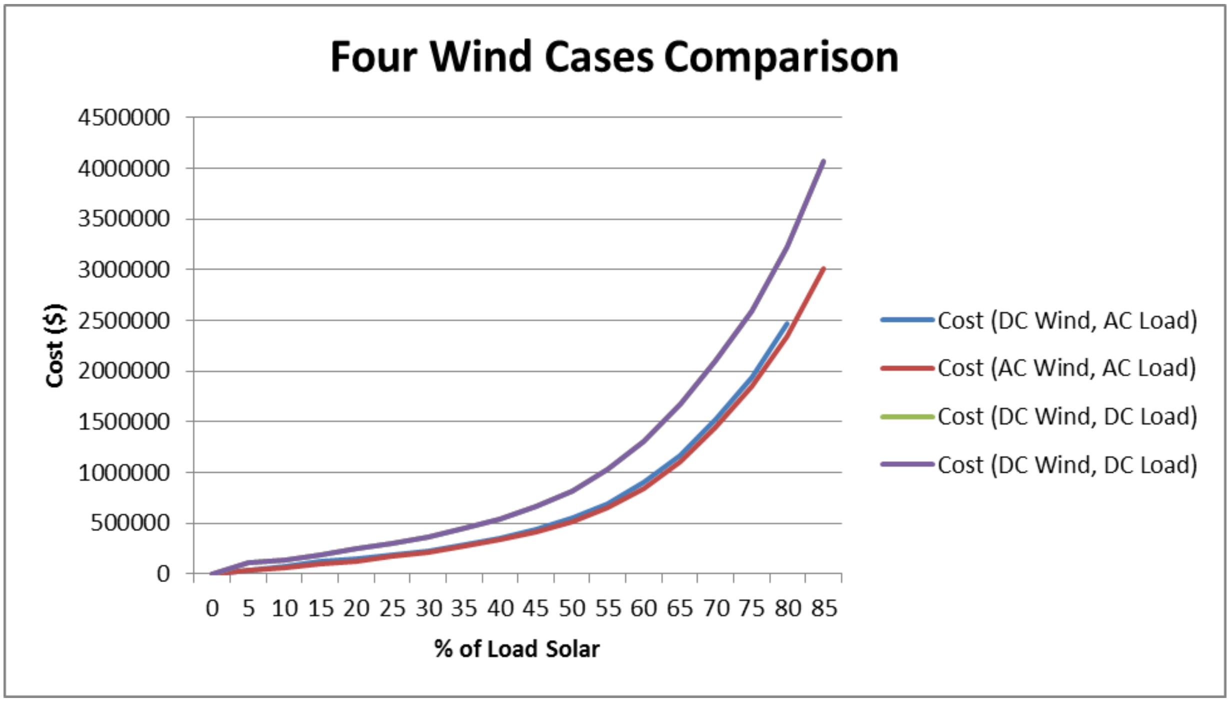


Figure 30. Simulation Results for Four Wind Cases

The cost of the four wind scenarios still increase exponentially as the percentage of renewables covering the load increased. However, the wind scenarios had lower exponential growth than the solar scenarios. All eight cases are shown in Figure 31 to highlight the difference in exponential growth between the solar and wind Homer simulation cases. This result made sense because wind turbines have intermittency issues due to wind speed, but this effect is not as drastic as the unpredictability of sunlight and cloud coverage that both affect solar panels.

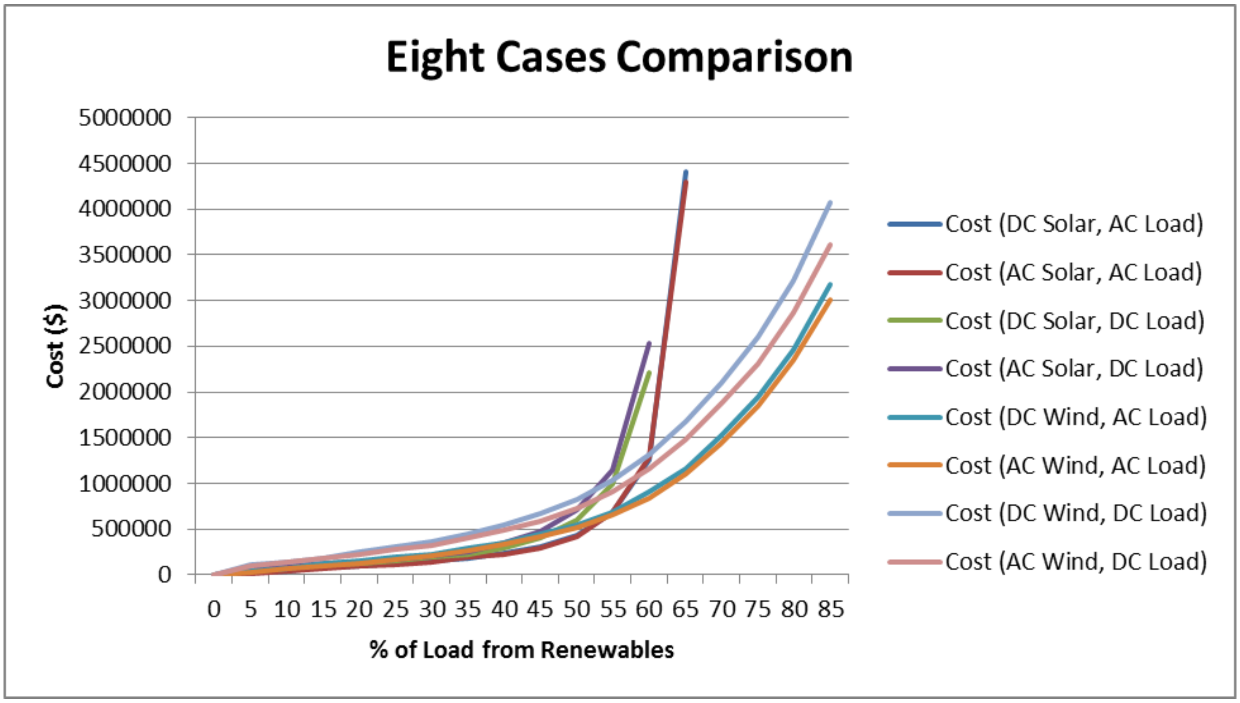


Figure 31. Simulation Results for all Eight Cases

Figure 32 shows just two cases for DC sources of renewable energy and AC load so that the differences between solar and wind could be analyzed. This plot emphasizes that the cost of solar is cheaper than wind in scenarios where the percentage of the load powered by renewables is between 55% to 60%. In projects that are required to power a higher percentage of the load from renewables it would be economically beneficial to consider wind power.

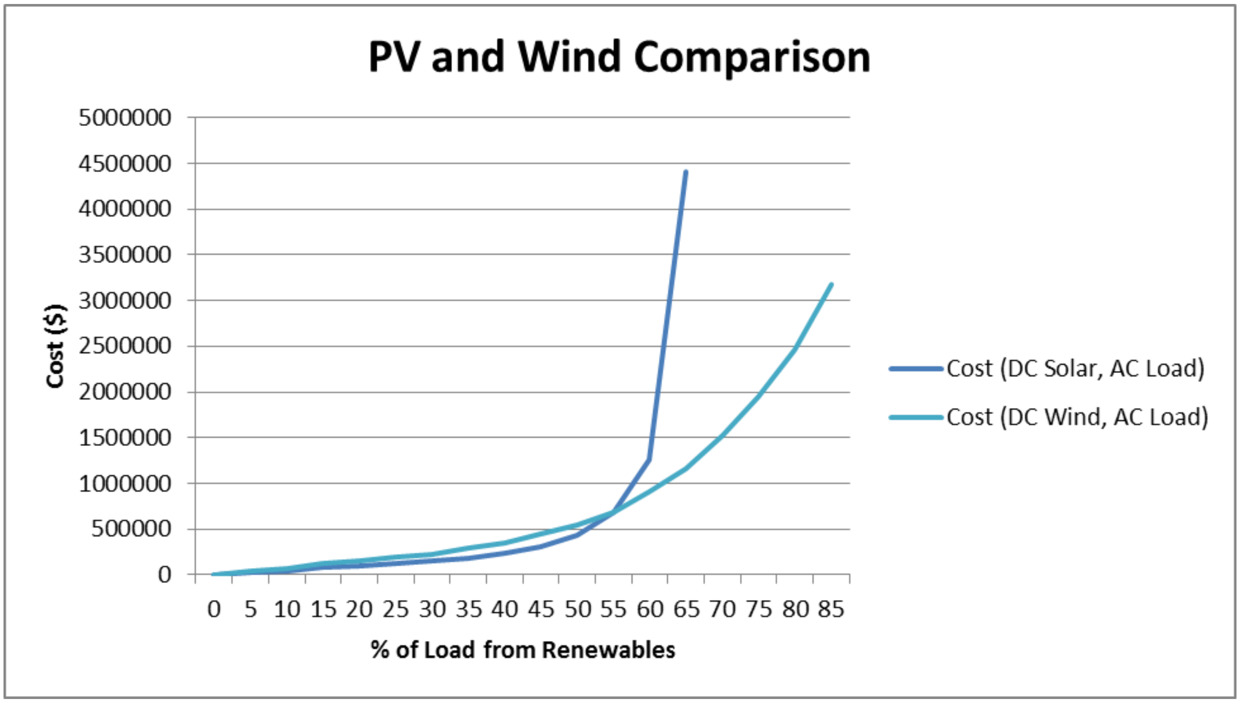


Figure 32. Simulation Results of DC Sources and AC Load

Another consideration for renewable projects is to understand the impact of battery energy storage technologies. Battery storage was not implemented in the Homer model due to the complexity of optimizing within the model, but battery storage could be an effective solution to the intermittency problems from renewable sources [22]. There are many characteristics of battery energy storage that make implementing batteries into a renewable project complex, such as the cycle time, storage response time and back-up time. These characteristics will change depending on the application of the battery system. For example, intermittent renewable sources and utility scale power systems require different battery storage characteristics and must be optimized for the particular application [22].

The work in this section was exploring various technical configurations of renewable power systems by using a Homer model of the Pitt Ohio Harmar facility as a base model. The base model was a system with approximately 50kW of solar panels and 5 kW of wind turbines and a grid backup when the renewables were not providing enough power. Both of the renewable sources were input on the DC bus. Also, the load for the facility was modeled from the electric utility data provided by Pitt Ohio and modeled on the AC bus. Eight different configurations evaluated by changing the electrical bus of the renewable sources and the load. The outputs generated from Homer for the case studies were the overall cost of the systems so that trends could be observed for the different configurations. It was observed that the overall cost of the systems grew exponentially as the minimum renewable fraction increased due to the intermittency of the renewable sources. The next portion of the paper uses the same Homer model to analyze some of the environmental impacts of renewable power systems.

2.2.4 Homer Model Environmental Evaluation

This section analyzes the carbon dioxide emissions from the eight case studies performed in Homer in the last section. For each of the eight case studies the carbon emissions of the system were generated in Homer. Homer calculates the total amount of each pollutant produced annually by the power system in kg/year and for this system the source of the pollutant was power generated the grid. It was expected that the amount of carbon dioxide emissions would decrease linearly with the amount of renewables installed in the system. Figure 33 shows that this expectation was correct and that the carbon emissions of the systems could be reduced by approximately 75%. Homer was unable to reduce the emissions by 100% because the amount of solar required for the minimum solar fraction of 70% to 100% did not provide any feasible solutions. A feasible solution in Homer is when the simulations are able to converge based on the inputs and constraints. For these simulations, Homer was unable to meet the minimum solar fraction for the system because the cost was extremely expensive for the size of the system.

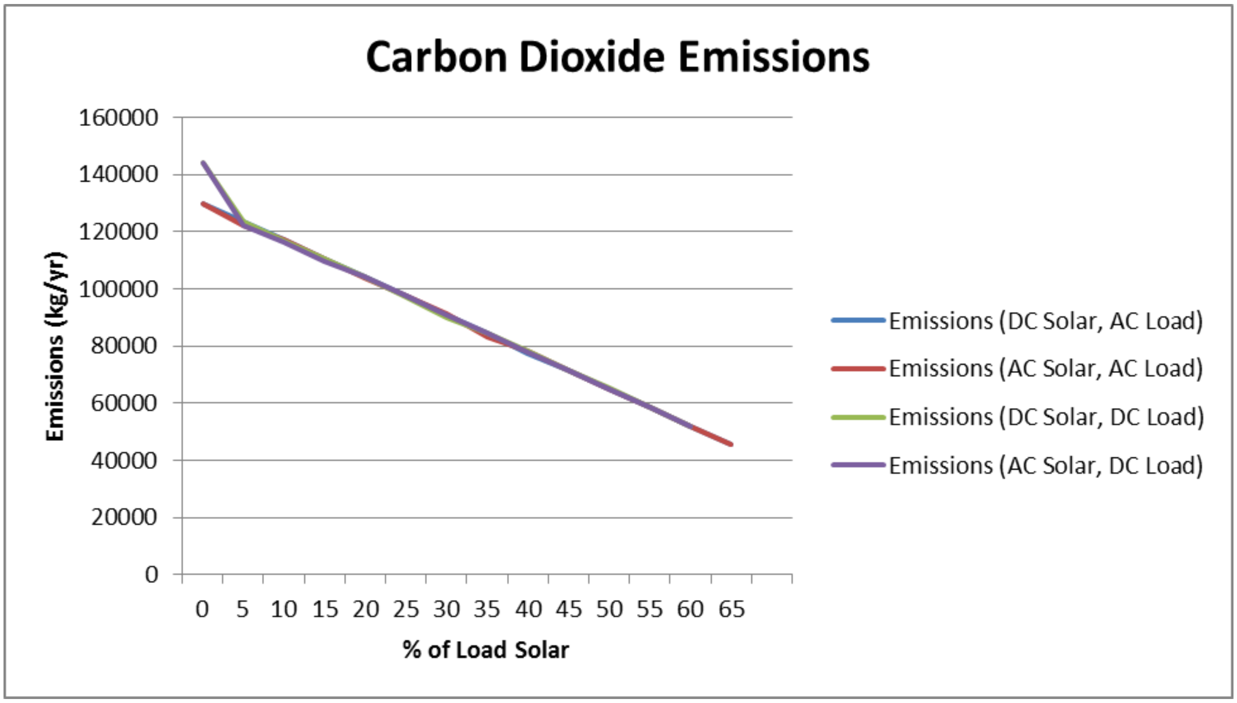


Figure 33. Carbon Dioxide Emissions for PV Homer Cases

Although the reduction of carbon dioxide emissions scaled linearly with the amount of solar, this analysis failed to capture the cost component of the increasing percentage of renewable covering the load. The previous section highlighted that the cost of the renewables begins to grow exponentially as the percentage of renewables increased and this has a significant effect on lowering the emissions of the power systems. The cost to reduce emissions also grows exponentially as the minimum renewable fraction increases and this is shown in Figure 34.

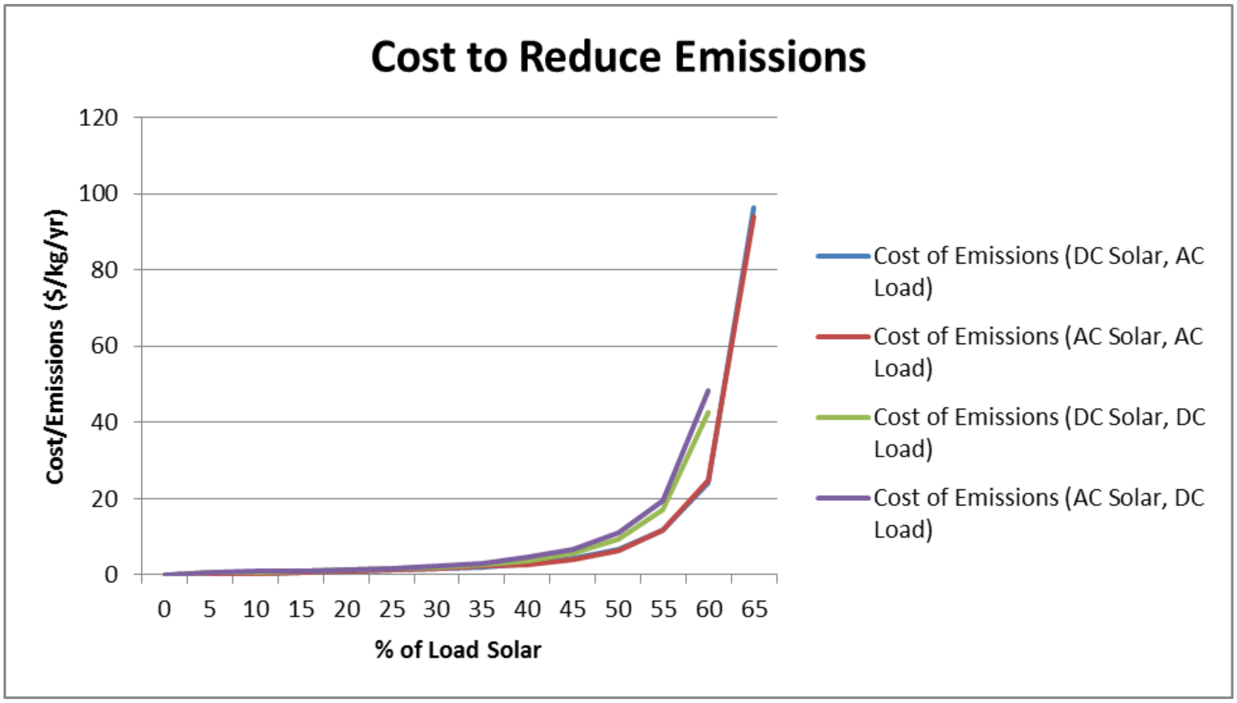
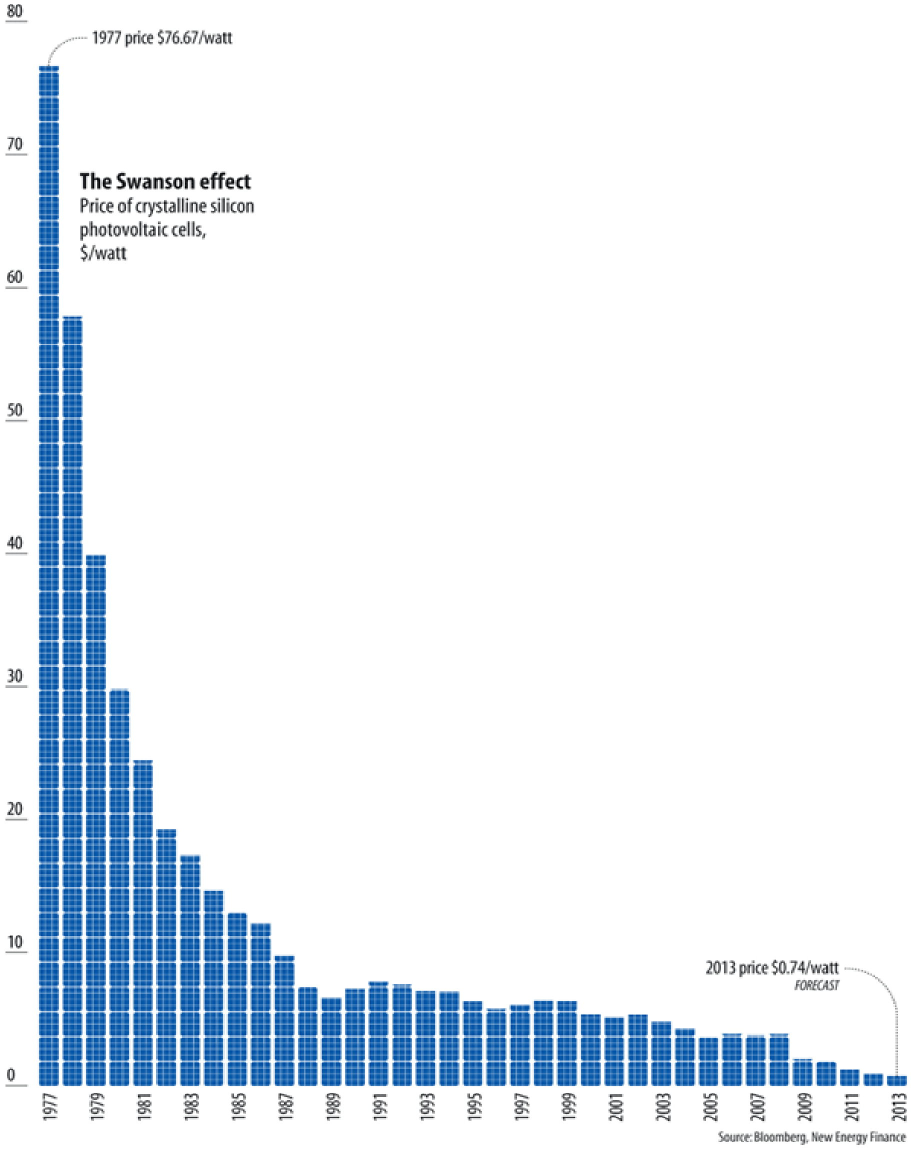


Figure 34. Cost to Reduce Carbon Dioxide Emissions for PV Homer Cases

The cost to reduce emissions for systems like the Pitt Ohio facility are important to understand because there could ways to optimize the system to reduce emissions in a cost effective way. With the pressures to become less dependent on fossil fuels and push toward 100 percent renewable it is important to understand the challenges with using renewable energy. It is essential to investigate the technical, environmental and economic aspects of renewable energy systems.

2.2.5 Homer Model Economic Evaluation

Solar energy is becoming more prevalent in the United States as the cost of crystalline silicon and photovoltaic cells has continuously decreased. The effect of the solar technology on the cost of solar panels is known as the Swanson effect, which is named after the founder of SunPower [23]. Figure 35 shows the Swanson effect chart and emphasizes the decreasing cost of solar energy since 1977 [23]. With the decreasing cost, more renewable energy systems like the Pitt Ohio Harmar facility are being installed around the country. This section of the paper uses the same Homer model to analyze the effects of decreasing cost of solar panels on the base case.



Source: Bloomberg, New Energy Finance

Figure 35. The Swanson Effect Chart from 1977 to 2013 [23]

To observe the effects of decreasing cost on the overall system, the cost per kW of solar was altered to three different pricing points. The original cost point was the actual installed cost for the solar and was $2.70/watt. The other two points were tested assuming that the price of crystalline silicon and photovoltaic cells would continue to decrease over time, so they were chosen to be $2.00/watt and $1.00/watt. Figure 36 provides the chart created for the three cost cases and shows the different exponential curve when the price of solar panels changed.

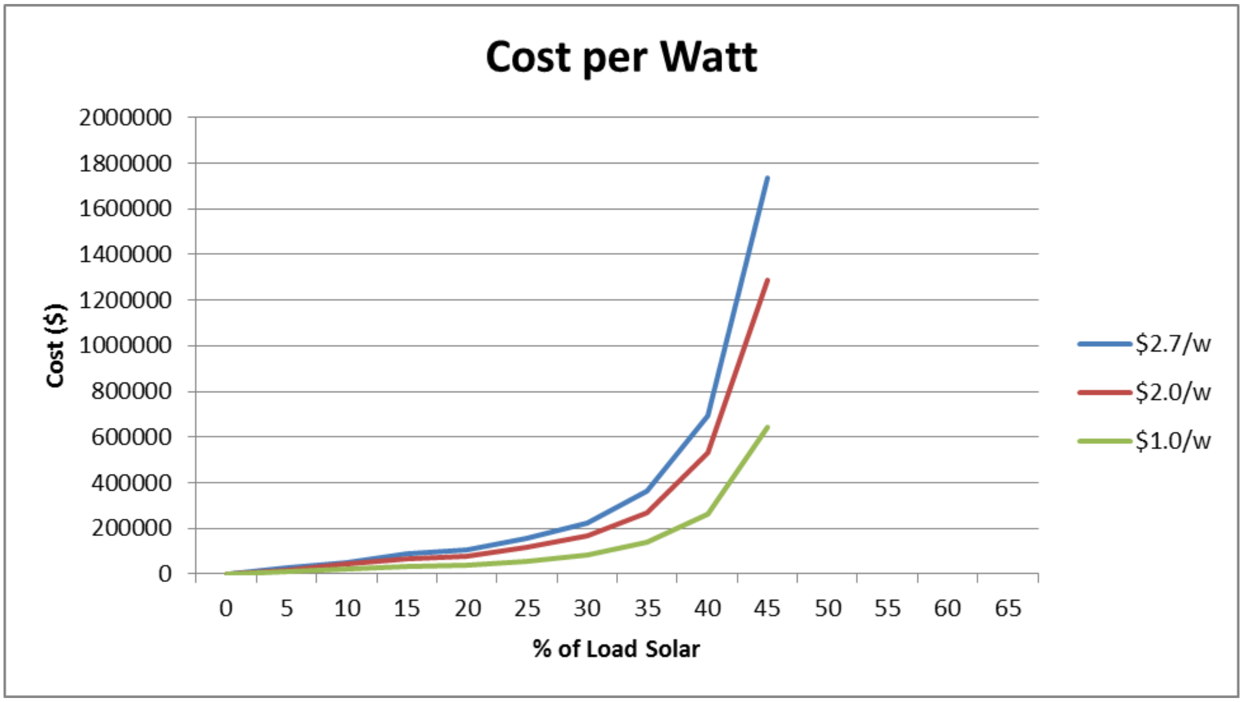


Figure 36. Homer Results for Cost per Watt Simulations

These results were what would be expected for the cost of the overall system as the price for solar energy dropped because the cases with more expensive solar had the most expensive overall system as well. Even though these results were not surprising, the information presented in the chart still represents a challenge with renewable energy projects because choosing the optimal time to build these projects will require additional work. As the Swanson effect showed, the cost of solar energy continues to decrease and so this information illustrates that the overall cost of the systems would also decrease. This leaves companies, utilities and communities interested in renewable energy systems with decisions of how long to wait before building this type of system. This section of the paper used the base Homer model to look at the overall system cost because the cost of solar is expected to continue to decline.

2.3 PITT OHIO ELECTRIC UTILITY DATA ANALYSIS

This section of the paper analyzes the electric utility data provided by Pitt Ohio before and after the installation of the renewable energy systems. For this analysis, it was assumed that there were no other changes to the facility that would have an impact on the data. The data supplied included the total kWh used and total charges from the utility on a monthly basis from approximately when the facility was constructed in December of 2014 through November of 2016. This data was used to gain an understanding on the cost reductions that the renewable energy systems had on the electric utility bill.

To quantify the cost reduction the total charges from the utility company the first twelve months and second twelve months were determined. These twelve months were approximately the years 2015 and 2016, but the information provided did not have all the information necessary to provide a direct comparison of directly 2015 and 2016. The months being used are December 2014 to November 2015 and December 2015 to November 2016. The facility did not have any renewable energy sources installed in 2015, so the total charge is made up of the total load of the facility during the year. In 2016, the solar panels and wind turbine were installed and connected to the electric system of the facility, so the data included the reductions that accrued from the renewable sources during the year. Both of the 50kW of solar power and the 5kW wind turbine were installed approximately in November of 2015, which is approximately the separation point between the twelve month comparisons being used for this analysis. Comparing the two years showed that the total charges to Pitt Ohio from the utility company were reduced by over 7% between 2015 and 2016. This cost reduction also excludes the battery storage solution that was installed at the Pitt Ohio Harmar facility. The battery system was not installed at the time the electric utility data was provided because there were problems with the initial batteries that were purchased for the installation. Battery storage would need to be incorporated into the analysis before an accurate return on investment (ROI) could be determined for the renewable system. A reduction of 7% on the total charges of the electric utility bill from just the renewable energy sources is a significant reduction on the electric bill at a commercial-level.

3.0 TRENDS IN RENEWABLE ENERGY MICROGRIDS

The Pitt Ohio Harmar facility microgrid installation was considered as a small commercial-scale in this paper. However, there is considerable interest from other parts of the industry besides businesses such as residents, utility companies and communities. This chapter will discuss current strategies for assessing microgrids for communities by studying a local Pittsburgh borough's microgrid feasibility study. Furthermore, this chapter of the paper will analyze some of the trends that can be taken from the Pitt Ohio renewable system and be applied to a utility scale microgrid.

3.1 COMMUNITY SCALE MICROGRIDS

Communities around the United States are beginning to understand that the country's power systems are old and outdated in many cases. Most of the power systems were designed decades ago to deliver electricity in bulk from large power plants over long distances to cities [24]. Communities are becoming interested in creating a cost-effective modern grid with renewable energy and locally sited generation. One organization leading the transition to a modern renewable grid is nonprofit organization called Clean Coalition and they are encouraging communities to invest in community microgrids that create more sustainable energy systems [24]. There are numerous benefits for installation of community microgrids including making the grid more reliable and secure , reducing dependence on inefficient and old generation and transmission infrastructure, and creating a foundation for modern, efficient grid operations [24].

Furthermore, the inclusion of renewable generation provides communities with social, technical, economic, and environmental advantages over the existing power grid. Social benefits for a community microgrid include promoting a stronger local economy because a microgrid can attract private investment and create jobs in the community. Increased reliability and power quality through advanced, intelligent technologies such as inverters are potential technical benefits. Because of battery storage elements, microgrids could provide communities with stable, affordable energy prices by reducing the impact from volatile fossil fuel prices. Finally, community microgrids can play a major factor in reducing greenhouse gas emissions through the use of renewable generation. Microgrids also provide opportunities to reduce the impact on the environment through other resources such as water [24].

This section of the paper, introduces a local Pittsburgh community that expressed interest in a community microgrid. The work discussed in this section is a feasibility study that was completed between the University of Pittsburgh and Millvale to analyze a potential site for a community microgrid. This feasibility highlights the current way that communities are investigating potential microgrids in their communities, which primarily revolves around the initial economic of a project. Some of the unique social and environmental benefits of a microgrid in Millvale are investigated in this section.

3.1.1 Millvale Ecodistrict Urban Solar Farm Background

Millvale is a borough in Allegheny County across the Allegheny River from Pittsburgh that is a food desert, has a history of flooding and has a strong interested in sustainability. Beginning in

2012, community members created goals to improve sustainable planning through the development of the Millvale Ecodistrict Pivot 1.0 Plan [25]. This plan selected three key areas to confront in the community – Food, Water and Energy. In regards to energy, Millvale has the goal of becoming more energy independent, primarily through energy conservation, in conjunction with solar and other renewable of energy [25]. Pivot 1.0 included solar installations at the Millvale Library and the Imagine building, as well as Phase 1 of the Millvale community center. The community members desire the Millvale Ecodistrict to contain the most energy-efficient buildings in the region to provide a low cost of living for residents and reduce their environmental impact [25].

In order to achieve the goals of the community, Pivot 2.0 was developed, which included investigating the feasibility of an urban solar farm and/or microgrid. Millvale partnered with the University of Pittsburgh to research the potential of installing an urban solar farm located in Millvale to further the energy independence of the community. The University of Pittsburgh was asked to take the lead in performing a feasibility study on a 1.459 acre site owned by Millvale that had potential to be the site of a solar farm. The available owned land is shown in Figure 37.

Figure 37. 1.459 Acre Site Owned by Millvale

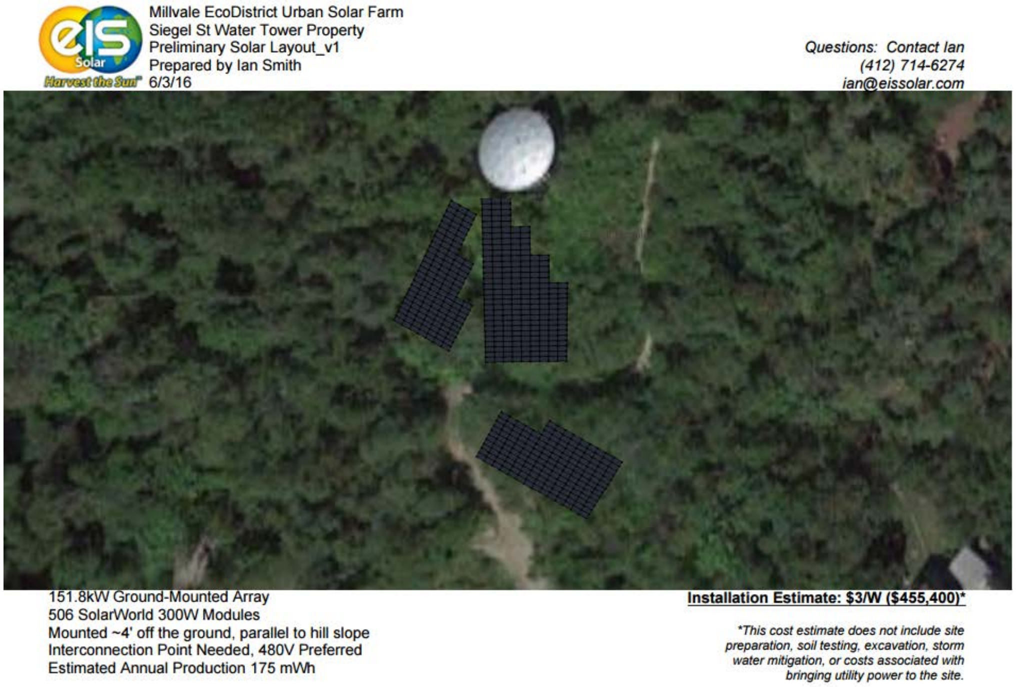
The feasibility study included researching:

- The solar potential of the site
- The civil and agricultural work necessary
- The costs and logistics with the utility company – Duquense Light Co.

This project provides a leadership opportunity for the University of Pittsburgh to use knowledge from related previous projects to promote renewable energy integration in the Pittsburgh region. Additionally, it provides the potential of a collaborative project between Millvale, the University of Pittsburgh and Duquesne Light in upcoming years.

3.1.2 Millvale Ecodistrict Urban Solar Farm Feasibility Study

There were three crucial aspects for the feasibility study that the University of Pittsburgh completed. These include researching solar integration, civil/agricultural site work and grid connectivity. For the solar, the University of Pittsburgh partnered with Energy Independent Solutions (EIS) to determine a realistic capacity of solar panels. EIS performed a study to estimate the possible capacity based on the site layout and the design challenges. Because of the topology of the hill certain areas of the land were avoided and a design was created for approximately 150 kW. Figure 38 below shows the preliminary layout for the solar panels that was determined:



Millvale EcoDistrict Urban Solar Farm
Siegel St Water Tower Property
Preliminary Solar Layout_v1
Prepared by Ian Smith
6/3/16

Questions: Contact Ian
(412) 714-6274
ian@eissolar.com

151.8kW Ground-Mounted Array
506 SolarWorld 300W Modules
Mounted ~4' off the ground, parallel to hill slope
Interconnection Point Needed, 480V Preferred
Estimated Annual Production 175 mWh

Installation Estimate: $3/W ($455,400)*

**This cost estimate does not include site preparation, soil testing, excavation, storm water mitigation, or costs associated with bringing utility power to the site.*

Figure 38. Preliminary Solar Layout

EIS Solar estimated that a system of this size would cost approximately $455,000 but that cost does not include the soil testing, other engineering and site prep work that may be required. Additionally, EIS Solar determined that the array would be raised off the ground by about 4’. This information is essential for the civil and agricultural site work for storm water mitigation techniques.

For the site to be ready for a solar farm installation there would be civil/agricultural site work that would be need to be completed including removal of trees and planting vegetation for storm water mitigation. Figure 39 shows the current state of the potential site including the hefty amount of vegetation in the area. Penn State Center Landscape Architects informed the University of Pittsburgh that vegetation could be planted beneath the solar panels to help with storm water mitigation. Additionally, it was suggested that an International Society of Arboriculture (ISA) certified arborist would be important to determine the cost of vegetation removal from the site. The Penn State Center has offices at the Energy Innovation Center (EIC) in Pittsburgh. The remaining civil/agricultural site work would have needed to be estimated by a construction firm.

Figure 39. Current State of Potential Solar Farm Site

It would be essential to connect a solar farm in Millvale to the grid upon completion and the University of Pittsburgh worked with Duquesne Light to understand the current electric grid infrastructure near the potential site and how an estimate to connect to the grid would be determined. To determine a realistic cost estimate of interconnection, Millvale would need to submit a formal interconnection request to Duquense Light with specific data about the location of the site, the size of the renewables and the load being supplied. The University of Pittsburgh and Duquesne Light also spoke about potential microgrid opportunities in Millvale; however, microgrid opportunities may not be cost effective in Millvale currently because the focus of microgrids is typically on critical infrastructure and places of emergency.

Because the complex area of the proposed site created a higher cost for the project than expected, other potential Millvale locations were considered so that the sustainable energy goals of the community could still be met. The other locations consider were Millvale Riverfront Park and the Millvale Community Center.

3.1.3 Millvale Ecodistrict Urban Solar Farm Impacts

Cost was a driving factor in a potential microgrid or urban solar farm in Millvale, but through the partnership between Millvale and the University of Pittsburgh it was understood that there are many other factors that should be incorporated into making a decision about potential projects. The economics of the project are fairly straight forward – there is a cost component of buying solar panels, installing solar panels and creating a solar ready site. However, the other factors are not typically as obvious as the economics and for Millvale there are environmental and social benefits to a renewable project in the community.

The community of Millvale faces a unique environmental challenge of flooding caused by streams in the area. The community has begun to build green storm water infrastructure, such as rain gardens at the Millvale Library and bioswales at Mt. Alvernia School, but there are plenty more opportunities for the community to change its identity past a flood community through a renewable energy project. A microgrid project, such as the one on the hillside plot of land, could provide an opportunity to not only create practical green storm water infrastructure, but also promote this mindset to the rest of the community. Incorporating storm water infrastructure would be important to a project in Millvale because it aligns with the goals of the community and is necessary for the project.

A renewable-based microgrid also would promote the goal of Millvale to become more energy independent. Not only would using renewable energy such as solar panels produce green energy, it would encourage residents to reduce their impact on environment through their own residential solar projects or changing their behavior to use less energy. Through the projects of the Millvale Ecodistrict Plan, the community has already been able to win three community energy efficiency competitions by reducing their energy usage by 8% in one year.

One of the other major concerns in the Millvale community is that there are safe locations for the residents during times of emergencies. The borough faces similar emergencies to other communities, such as extreme weather or blackouts, but they also face the flooding challenge that can leave residents without power or access to food. One of the benefits to building a microgrid in Millvale would be to create a safe place where the people of Millvale could be provided with power, shelter and food during the emergency situation.

3.1.4 Millvale Ecodistrict Urban Solar Farm Conclusions

This section analyzed a potential local renewable energy project in Millvale, Pennsylvania located just outside of Pittsburgh. In this feasibility study, some of the economic, environmental, and social impacts of the project were considered. However, the economic impact ultimately was the main emphasis in making the decision to forego a solar farm at the hillside location in Millvale. There was not a tool available to help quantify the non-economic impacts of a microgrid in this community.

3.2 UTILITY-SCALE MICROGRIDS

Electric utilities play a major role in the development and deployment of new technologies in the industry. Utilities have already begun investing heavily in renewable energy over the past few years and this is essential to meet long term sustainability goals in the industry. Utility-scale solar systems have become a large portion of the installed solar throughout the United States because of the ease they can connect to the high-voltage transmission lines of local utilities. It has been estimated that of the 20GW of installed solar systems installed in the United States, approximately 60% is made up of utility-scale projects. As microgrids become more prevalent around the country, there has been growing interest in utility-scale microgrids because of the increased resiliency and flexibility offered through a microgrid. A utility investing in microgrids has the potential to provide many benefits to the community including having a positive effect on sustainability and social impacts, such as job creation and social awareness. Additionally, microgrids offer a potential means to improve the security of power systems, which is currently a main concern for electric utilities.

One example of a utility-scale microgrid that was installed was a partnership between PowerStream and the Korea Electric Power Corporation (KEPCO) designed to provide several hours of backup power to around 400 customers in their system. In addition, one of the goals of the project was to use renewable power sources to reduce their carbon footprint and create a cleaner environment [26]. Similarly, a local Pittsburgh utility company, Duquense Light, is creating a microgrid at its Woods Run Facility with a capacity of approximately 2.6mW largely made up of natural gas and solar energy sources. The company is driven to construct their own microgrid to understand the technical, economic and regulatory issues with growing microgrid market [27]. To better understand utility-scale microgrids, this section will use the Homer model created for the Pitt Ohio Harmar facility and change the load to be a utility-scale system to observe the system.

3.2.1 Homer Model Utility-Scale Analysis

Similar to the other Homer models created in this paper, the base case was used to create the utility-scale model. To update the model, the electrical load was changed from the original 150kW load to approximately 2MW of load, which would characterize it in the utility-scale sector. In the same way as the previous section the minimum renewable fraction was altered from 0% to 100% to test the effects of increasing renewables on the utility-scale system. For this analysis it was assumed that the cost of the renewables scaled linearly and was not altered based on the size of the system. Furthermore, it was assumed that the cost of renewables was the same as in the commercial scale simulations, $2.70/w.

In this case, the system was created with solar panels on the DC bus and the electrical load connected to the grid. The results from the simulation were observed and plotted so that they could be compared to the commercial-scale results from Chapter 2.0 Figure 40 shows the plot comparing the two simulations created in Homer and the results appeared to support the expectations for this change in load. It was expected that the cost for the utility-scale system would begin to grow exponentially with a lower percentage of solar than the commercial-scale because of the variance in the energy produced from solar panels. Because there are more panels in a system of this size, the variance from the panels has a major impact at a lower percentage of the load being generated from renewables. Since more solar panels were required to ensure that the minimum percentage of renewables was reached, the cost increased dramatically much quicker than in the previous chapter.

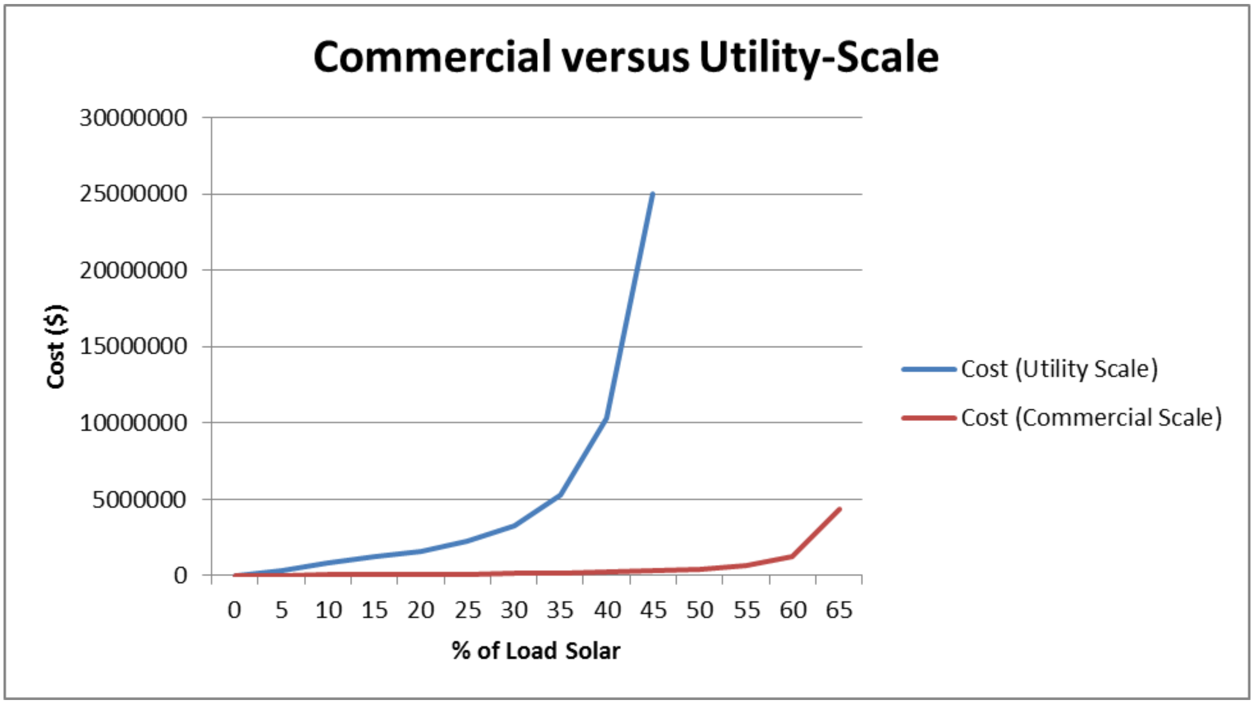


Figure 40. Homer Simulations for Commercial versus Utility-Scale

One aspect that was not considered in this paper, but could have potential impacts on results would be if the cost of buying large quantities of solar panels reduced the individual cost of panels. If this were the case then the differences between the two systems would not be as drastic, but would still be significant. According to the Solar Electric Power Association the national average for a solar panel in 2015 was approximately $3.50/watt and a breakdown for some the states are shown in Figure 41 [28]. When Solar companies buy panels in bulk they are generally able to buy solar panels at a much discounted rate. It has been approximated that buying panels in bulk can reduce the cost of single panels by 25% [28].

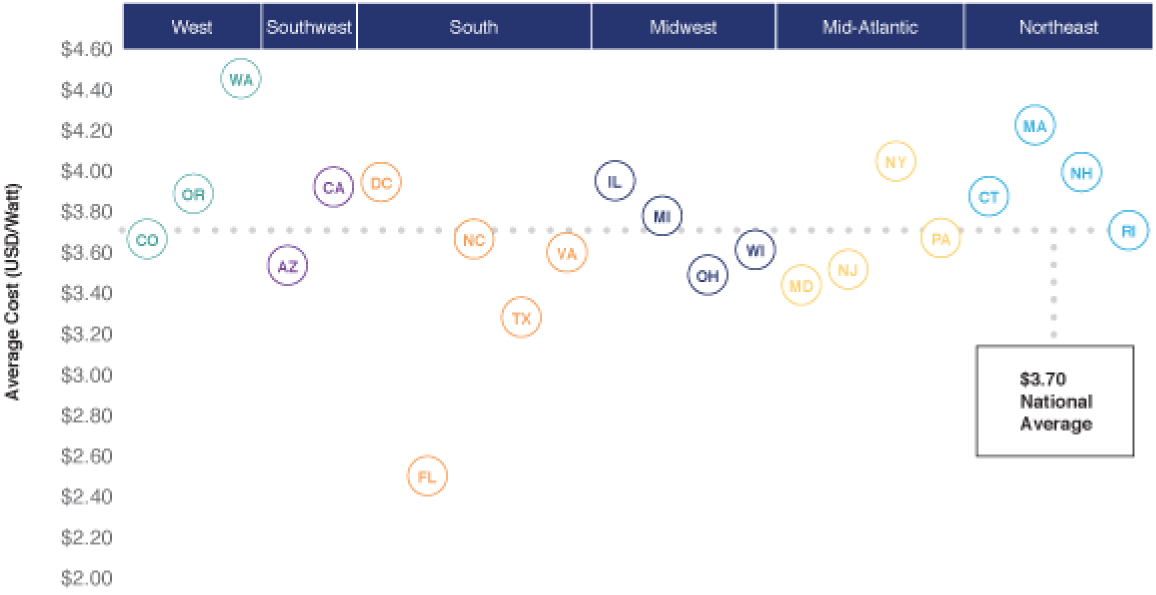


Figure 41. PV System Price Quotes from Selected States [28]

Similar to social benefits being hard to model for a community-scale microgrid, security is hard to quantify and model for a utility-scale microgrid. But security is a major concern in for electric utilities and should be taken into account when considering the long term sustainable goals in the industry. Security is a key feature of microgrids and factoring it into future ROIs would provide a closer understanding of the value from installing a microgrid.

4.0 CONCLUSION

There are many considerations that must be investigated when designing renewable energy projects, such as a microgrid. Using the Pitt Ohio DC microgrid as a basis for a microgrid model showed that creating systems of 100 percent renewable energy generation is much more expensive than expected due to the variability of the sun and wind. Analyzing the electric utility bills from the DC microgrid showed that renewables have a positive effect on the energy bills, but an accurate return on investment cannot be developed until the battery energy storage systems were installed and data was collected. Additionally, a feasibility study for a potential solar farm and microgrid in a local Pittsburgh borough was investigated and highlighted that these types of projects will not be considered with the current standards for ROI. There are benefits that microgrids provide that are not being fully considered when analyzing the ROI of renewable energy projects. One of the challenges for creating new standards for ROI is that the industry is unsure of how to quantify the benefits of reliability and security. Additionally, there is not currently software that allows for the evaluation of some of the impacts of microgrids such as social benefits. All of these factors should be considered if long term sustainability goals are going to be met in the future. This work is important to understand for utilities, companies and communities interested in microgrids and other general sustainability projects.

4.1.1 Future Work

There is still much work that needs to be completed to gain a better understanding of the impacts of microgrids and how they should be evaluated. In future iterations of this work battery storage should be implemented in the Pitt Ohio Harmar facility homer model and the electric utility bill economic analysis. When utilities, companies, or communities are creating future microgrid projects, there are many factors that should be considered to create the optimal system. This includes optimizing the amount of renewable generation sources and the amount of battery energy storage, which should also take into account the falling cost of renewables and battery energy storage over time. Additionally, optimizing the technical layout of the systems, such as which components should be DC versus AC, will be important in future projects. It is essential that the industry rethinks the current standards of return on investments when considering sustainability.

BIBLIOGRAPHY

[1] U. Greening, “About us Message from our Mayor Office of Sustainability,” pp. 2–3, 2017.

[2] P. Kundur, “Sustainable Electric Power Systems in the 21st Century,” *IEEE*.

[3] “The Solutions Project,” 2017. [Online]. Available: http://thesolutionsproject.org/.

[4] DOE, “Microgrid Definitions.” [Online]. Available: https://building-microgrid.lbl.gov/microgrid-definitions.

[5] U.S. EIA, “How much of U . S . carbon dioxide emissions are associated with electricity generation ?,” 2016. [Online]. Available: http://www.eia.gov/tools/faqs/faq.cfm?id=77&t=11.

[6] U.S. Energy Information Administration, “Energy-Related Carbon Dioxide Emissions at the State Level, 2000-2013,” *U.S. Dep. fo Energy*, no. October, pp. 18–19, 2015.

[7] S. Phillips, “Pittsburgh Hosts Hearing on EPA’s New Greenhouse Gas Proposals,” 2014. [Online]. Available: https://stateimpact.npr.org/pennsylvania/2014/07/31/pittsburgh-hosts-hearing-on-epas-new-greenhouse-gas-proposals/.

[8] Siemens, “How Microgrids Can Achieve Maximum Return on Investment (ROI): The Role of the Advanced Microgrid Controller,” p. 16, 2016.

[9] A. Goodrich, T. James, and M. Woodhouse, “Residential, Commercial, and Utility-Scale Photovoltaic (PV) System Prices in the United States: Current Drivers and Cost-Reduction Opportunities,” *Tech. Rep. NREL*, no. February, p. 64, 2012.

[10] “Utility-Scale Vs Residential-Scale PV – Which Is Most Cost-Effective?,” *Engerati*, 2015. [Online]. Available: https://www.engerati.com/article/utility-scale-vs-residential-scale-pv-—-which-most-cost-effective.

[11] G. F. Reed, B. M. Grainger, A. R. Sparacino, and Z.-H. Zhi-Hong Mao, “Ship to Grid: Medium-Voltage DC Concepts in Theory and Practice,” *IEEE Power Energy Mag.*, vol. 10, no. 6, pp. 70–79, Nov. 2012.

[12] B. T. Patterson, “DC, Come Home: DC Microgrids and the Birth of the "Enernet",” *IEEE Power Energy Mag.*, vol. 10, no. 6, pp. 60–69, Nov. 2012.

[13] J. Inamori, H. Hoshi, T. Tanaka, T. Babasaki, and K. Hirose, “380-VDC power distribution system for 4-MW-scale cloud facility,” in *2014 IEEE 36th International Telecommunications Energy Conference (INTELEC)*, 2014, pp. 1–8.

[14] S. Whaite, B. Grainger, and A. Kwasinski, “Power Quality in DC Power Distribution Systems and Microgrids,” *Energies*, vol. 8, no. 5, 2015.

[15] D. Fregosi, S. Ravula, D. Brhlik, J. Saussele, S. Frank, E. Bonnema, J. Scheib, and E. Wilson, “A comparative study of DC and AC microgrids in commercial buildings across different climates and operating profiles,” in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, 2015, pp. 159–164.

[16] S. Anand and B. G. Fernandes, “Optimal voltage level for DC microgrids,” in *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 3034–3039.

[17] R. Weiss, L. Ott, and U. Boeke, “Energy Efficient Low-Voltage DC-Grids for Commercial Buildings.”

[18] I. Q. Energy, “Wired vBoost System,” 2012.

[19] W. Specifications and S. Kw, “Windspire Wind Turbine Specifications.” .

[20] R. H. Rd, “Pitt Ohio Solar Production Estimate,” no. 180.

[21] I. for E. Research, *The Status of Renewable Electricity Mandates in the States*. 2011.

[22] N. Ertugrul, “Battery Storage Technologies, Applications and Trend in Renewable Energy,” pp. 420–425, 2016.

[23] G. Carr, “Sunny uplands Alternative energy will no longer be alternative,” *Econ.*, p. 21566414, 2012.

[24] “Community Microgrids.” [Online]. Available: http://www.clean-coalition.org/our-work/community-microgrids/.

[25] C. Mondor, A. Rosenblum, C. Guignon, and E. Hughes, “Millvale EcoDistrict Pivot 2.0,” no. January, 2016.

[26] E. Wood, “Utility - Scale Microgrid from PowerStream & KEPCO Up and Running,” vol. 2, pp. 1–2, 2017.

[27] B. D. Moore and P. Post, “Duquesne Light moves forward on microgrid project Join the conversation :,” pp. 2–7, 2017.

[28] Z. Shahan, "What Is The Current Cost Of Solar Panels?," *Clean Tech.*, pp. 1–14, 2014.