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MODELING THE RELIABILITY VALUE OF COMBINED HEAT AND POWER GENERATORS IN THE PJM INTERCONNECTION ZONE

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ABSTRACT

The United States is currently suffering from an outdated and unreliable electrical grid. Electricity blackouts have been estimated to cost American consumers $79 billion a year. Increasingly violent weather events and costly blackouts have regenerated an interest in analyzing reliability and determining a way to increase the strength of the power grid. Combined heat and power (CHP) is an efficient technology that can simultaneously power and heat a facility. The use of CHP as a backup source can provide reliability benefits and protect a business from economic loss due to a power outage. In this study, the private economic value of the reliability benefits of CHP is determined. The report focuses entirely on customers in the commercial and industrial sector. This paper analyzes the outcomes of 81 power outages in the PJM interconnection zone from 1990-2010. The economic loss from a blackout in the PJM zone is modelled using blackout duration values and estimated values of lost load for small and large commercial and industrial customers. The costs of installing and operating a CHP unit is then integrated into the model. The study seeks to answer two questions: On average what is the annual value of economic harm endured because of blackouts and how does this relate to CHP cost? Furthermore, what is the annual reliability value of CHP that will negate the capital cost of a 1 MW CHP system over its lifetime? The results show that CHP generators could provide $50,741,112 - $78,145,293/MW demand in benefits to small commercial and industrial businesses, and $4,330,658 - $6,931,782.11/MW demand in benefits to large commercial and industrial business over the entire 15 year lifetime of the CHP system. It is important to note that these values are heavily reliant on the values of lost load (VOLL) that are used in this study, and the results could be drastically different if these values were to be changed.
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LIST OF TERMS

Carbon Dioxide – CO₂
Combined Heat and Power – CHP
Commercial and Industrial – C/I
Disturbance Analysis Working Group – DAWG
Distributed Generation – DG
Energy Efficiency Resource Standards – EERS
Greenhouse Gas – GHG
Mega-watts – MW
Momentary Average Interruption Frequency Index - MAIFI
North American Electric Reliability Corporation – NERC
Probability Density Function – PDF
Renewable Portfolio Standard – RPS
Regional Transmission Organization – RTO
System Average Interruption Duration Index - SAIDI
System Average Interruption Frequency Index – SAIFI
Value of Lost Load – VOLL
Chapter 1: Introduction

1.1: Background

The establishment of reliable and efficient energy infrastructure is key to the stability of an industrialized nation. The maintenance and improvement of this infrastructure is equally important. Despite its position as a world economic power, the United States is burdened by an outdated and overly strained electrical grid. The majority of the modern day electrical grid was constructed in the 1890s (Smart Grid, 2013). Currently it is characterized by more than 300,000 miles of transmission lines connected to 9,200 electric generating plants with over 1 million mega-watts (MW) of capacity (Smart Grid, 2013). Although these numbers are impressive, the majority of these generating plants are large, centralized coal, natural gas, hydroelectric, or nuclear power plants. Figure 1.1 is a breakdown of the U.S. electricity generation by energy source created with data provided by the EIA (EIA, 2013).

Figure 1.1: U.S. Electricity Generation by Source (EIA)
The outdated and consolidated nature of this system produces an electrical grid that is unreliable, inefficient, and vulnerable to blackouts and intentional attack.

The United States’ electrical grid is rapidly reaching its maximum capacity and deteriorating with age. The strain on this system is expected to grow, as U.S. demand for electricity is projected to increase by 1.4% per year through 2020 (Rahman and Pipattanasomporn, 2009). It is estimated that electricity blackouts effect an average of 500,000 U.S. citizens per day (Industry Perspectives, 2013). These power interruptions are an inconvenience, but also can have severe economic impacts on commercial and industrial end-users. The annual economic cost of electricity blackouts is estimated to be $79 billion for U.S. electricity consumers (LaCommare and Eto, 2005). Additionally, studies indicate that the frequency of large blackouts are not decreasing with time (Hines, Apt and Talukdar, 2009). As energy demand rises, the costs of blackouts and number of citizens affected will grow.

The U.S. electrical grid can be unreliable for many reasons. However, there are numerous solutions that can be enacted to decrease blackout frequency and severity. The electrical grid is a complex system of generating plants, transmission wires, and distribution lines. The fundamental law of electrical power generation is that supply must always equal demand. When this balance does not hold equal, power interruptions occur. The majority of U.S. electricity generation comes from large fossil fuel or hydroelectric plants. These plants can be located miles away from the end-users consuming the electricity. Furthermore, increasingly outdated and inefficient power lines must carry the electricity from source to consumer. These power lines are often located above land, and are subject to destruction from violent weather, vandalism, and attack (Rahman and Pipattanasomporn, 2009).
Global climate change is also beginning to show implications of being a cause for blackouts. Increasingly warm summers, droughts, and rising sea levels are effecting the efficiency and output of power lines and electrical power plants (Koch, 2013). Climate change has arguably caused an increase in violent and unpredictable weather events. These storms cause damage to an already vulnerable transmission system. Super storm Sandy alone caused 8.5 million customers to be without power for days (Chittum, 2012).

There are several solutions that would increase the reliability of the U.S electrical grid and, in turn, decrease the frequency and economic cost of blackouts. Advocates have argued for the implementation of a smart grid. Essentially, a smart grid is a more high tech version of the current electrical power grid. In addition to the physical upgrade of transmission systems, the smart grid would also make for better communication between the independent system operator and the customer. This system would result in better matching of supply and demand and fewer blackouts. Customers would also be able to monitor their own electricity use and hopefully decrease their consumption (Smart Grid, 2013). Another technology, distributed generation (DG), is expected to be an important factor in future methods of power generation (Rahman and Pipattanasomporn, 2009). Combined heat and power (CHP) in particular offers significant benefits to end-users through increased efficiency, reliability, and reduced greenhouse gases. This report seeks to quantify the private economic savings that CHP could provide by mitigating the effects of blackouts.
1.2: Distributed Generation

Distributed Generation (DG) is the connected or stand-alone use of a small-scale (less than 10 MW) electricity generator that can be installed close to the point of consumption (Rahman and Pipattanasomporn, 2009). DG is not defined by one set type of power generators, but rather is the term that encompasses a variety of alternative energy technologies (Rahman and Pipattanasomporn, 2009). DG includes but is not limited to CHP, other reciprocating engines or combustion gas turbines, fuel cells, photovoltaics, micro turbines, and wind turbines. Also known as alternative energy sources, DG is a viable substitute for traditional fossil fuels.

DG systems are advantageous in that they can be connected close to the point of power consumption. In the event of a power failure, DG sources can continue running as a backup power source. Each different type of DG has advantages and disadvantages when compared to conventional power sources. For example, energy sources such as wind or solar can be intermittent and are therefore inconsistent. However, if solar is generated on-site, then the end-user can save on fuel costs and hedge against a power outage (provided it is during the day). Electricity supply from centralized power centers is prone to inconsistency and low efficiency. Electricity that is not lost during the power generation process can be lost by travelling several miles through power lines. Therefore, one can argue that on-site power generation is not only more efficient, but more cost-effective as well.

As the United States’ electricity grid becomes increasingly strained, the use of DG for power generation is becoming more common. In 2005, there were 28,744 distributed and disbursed generators installed in the United States (EIA, 2013). In 2011, there were 35,064 distributed and dispersed generators installed (EIA, 2013). Much of this growth has been fueled by the recent boom in the solar industry. The United States solar industry grew by 76% in 2012, and is
projected to continue at this pace into 2013 (SEIA, 2013). Non-conventional renewable technologies are certainly vital DG technologies. However, DG technologies that run off of more conventional fuels such as natural gas or fuel oil will help bridge the gap between old and new sources of power generation. In particular, this report focuses on the benefits that combined heat and power (CHP) could provide to the PJM Interconnection zone through increased reliability.

1.3: Introduction to Combined Heat and Power

The remainder of this report will focus on the installation of CHP generators for the purpose of reducing the economic costs of blackouts. The study will focus on the costs that small and large commercial and industrial (C/I) businesses experience from a blackout. CHP differs from conventional generators in many ways. A conventional generator uses a fuel source such as natural gas or diesel to produce electricity. CHP, also known as co-generation, is the simultaneous production of both electricity and heat. The CHP generator uses conventional fuels, commonly natural gas, to produce electricity. The generator then captures the waste heat from this process and uses that to heat the rest of the facility. Some generators can also convert the heat into cool air, and cool the building as well.

Combined heat and power is a form of distributed generation. The generators can easily be installed near or at the point of energy consumption. CHP does not connect to the electricity grid. Instead, these generators are connected directly to the supply of whatever fuel source the unit uses. In the United States, 72% of all CHP generators run off of natural gas (DOE and EPA, 2012). CHP generators are commonly installed in any building that has a large thermal load. In the United States, 87% of all CHP generators are located in manufacturing plants (DOE and EPA, 2012). CHP units run efficiently and reliably, and allow factories that cannot afford lost production hours to continue running during power outages. CHP is also used in other industries
as well. CHP units are ideal for schools, university campuses, hospitals, airports, and other large facilities that require reliable energy. Figure 1.2 shows the capacity of CHP in each industry sector.

**Figure 1.2: Existing CHP Capacity in the U.S.**

![Pie chart showing CHP capacity by industry sector](image)

(DOE and EPA, 2012)

CHP has been used in the United States for decades. Its implementation in the United States has been marked by periods of increased and decreased use. Since 2000, the installation of Combined Heat and Power generators has been on a decline. Figure 1.3 demonstrates the annual additions in GW of CHP since the year 2000.
Since the year 2005 the installation of CHP is noticeably low, not exceeding 1 GW per year. This steep decline can be attributed to uncertain gas prices, and the poor economic conditions leading up to, causing, and following the 2008 world financial crisis. Despite low fuel costs due to efficiency, CHP requires a relatively high capital cost. During times of low economic output it is difficult for both a small or large business to partake in large capital projects such as CHP installation.

Despite a recent decrease in the use of CHP nationwide, there are several factors that will support an increase in the technology in future years. Members of both the public and private sector are beginning to realize the benefits to be gained from CHP. Potential for the installation of CHP generators in existing commercial and industrial facilities could be 130 GW (DOE and EPA, 2012). Additionally, restrictions on greenhouse gas emissions (GHG) become more stringent every year. CHP decreases GHG emissions and is more reliable and affordable than
other clean energy sources such as solar or wind. A CHP generator can be installed anywhere from a basement to a shed outside of the facility. Wind turbines and PV farms must be placed strategically. Large amounts of money and time must be spent monitoring the wind and sun levels in a particular area before the project can be determined as economical. Furthermore CHP generators can be run 24/7 without interruption. They do not rely on a certain amount of wind or sun, or even the output of a centralized power generation station for operation.

The recent discovery of vast supplies of domestic natural gas and rapid innovation of hydraulic fracturing technology will also lead to a greater potential for CHP. The development of shale gas reserves such as the Marcellus Shale has rapidly increased the supply of natural gas in the United States. Since 2005, the supply of shale gas in the United States has risen by a factor of 14 (DOE and EPA, 2012). This increase in supply has lowered the cost of natural gas. CHP generators will be cheaper to run at these low prices. This paper analyzes the installation of CHP units by small and large C/I customers in the PJM interconnection zone. The proximity of the Marcellus Shale to this area is particularly important in analyzing the potential for CHP installation.

Policymakers are also beginning to see the value of CHP. On a federal level CHP is receiving a great deal of support. President Obama has called for the installation of 40 GW of new CHP capacity by the year 2020 (DOE and EPA, 2012). This increase in capacity would save energy users and taxpayers billions of dollars while also reducing CO₂ emissions by around 150 million tons per year (DOE and EPA, 2012). The United States has also recently seen an increase in the adoption of not only renewable energy resources, but energy efficiency practices as well. Many states are beginning to include energy efficient technologies in their renewable incentive programs. Figure 1.4 demonstrates the states that have adopted energy efficiency standards as of February 2013.
When combining each state’s Energy Efficiency Resource Standards (EERS) with their respective Renewable Energy Standards (RPS), 23 states include CHP as an eligible technology for incentives (DSIRE, 2013). Certain states such as California, New York, Massachusetts, New Jersey, and North Carolina have designed programs specifically for the purpose of incentivizing CHP (DSIRE, 2013). In the future, more states may adopt similar policies.

CHP has both economic and environmental benefits to an end-user. CHP generators are far more efficient than the separate generation of electricity and heat. The average efficiency of separately producing electricity and heat is around 45% (DOE and EPA, 2012). In comparison, a CHP generator runs at 65-75% efficiency (DOE and EPA, 2012). Increased efficiency leads to lower operating costs and reduced emissions. Figure 1.5 provides a visual representation of the efficiency benefits of CHP.
Combined Heat and Power is also more reliable than receiving power from conventional power plants or even from traditional renewable energy sources. As this paper will demonstrate, the economic losses that businesses and organizations experience from power interruptions are large. CHP is not connected to the electrical grid, and therefore can keep running during blackouts. Many businesses are aware of the frequency of these blackouts and have installed backup generators. However, these generators commonly run off of diesel, which can be more costly than natural gas and harmful to the environment. CHP runs cheaper, cleaner, and more reliably. CHP systems need less fuel to produce the same amount of output as a normal backup or primary generator. Therefore, they also emit less to produce the same amount of energy. Figure 1.6 represents the emission reductions that can be realized from CHP in comparison to conventional power generation:
1.4: Combined Heat and Power in the PJM Interconnection Zone

This study analyzes blackouts that occurred in the PJM Interconnection zone from 1990-2010. PJM Interconnection is referred to as a regional transmission organization (RTO). PJM Interconnection controls the flow of wholesale electricity in the areas over which it controls. The RTO has operations in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia (PJM, 2013). PJM has over 60 million customers throughout the area in which it covers (PJM, 2013). Figure 1.7 outlines the area that PJM Interconnection covers.
The scope of this report will focus on small and large C/I customers served in this area. Only power outages specific to this area are analyzed. This territory covers an area of the country that has high energy demand and many commercial and industrial facilities. Therefore, the PJM zone serves as an important market for CHP. This region has a large capacity of CHP already installed, and an even greater potential for installation.

The installed capacity of CHP in the PJM zone is significant. For the purpose of accuracy, this section will only analyze the amount of CHP in states that are completely controlled by PJM: Delaware, Maryland, New Jersey, Ohio, Pennsylvania, Virginia, Washington D.C. and West Virginia. The mid-Atlantic Clean Energy Application Center provides data on the CHP market in all PJM states except Ohio. There is currently a total of 11,803 MW of CHP capacity in the mid-
Atlantic (Mid-Atlantic Clean Energy Application Center, 2013). Adding Ohio, there is a total of 12,325 MW of existing CHP capacity in the PJM zone (EEA, 2013). The majority of this total capacity is located in the industrial sector. Although this capacity is large, the potential for CHP is even greater. The total estimated potential capacity for CHP in the PJM zone is 90,322 MW (Mid-Atlantic Clean Energy Application Center, 2013) and (HornBrook, 2013). Figures 1.8 and 1.9 break down the total existing and potential CHP capacity by state. Washington D.C. was excluded because of a lack of data on installed and potential CHP capacity.

**Figure 1.8: Total CHP Capacity by State in Megawatts**
New Jersey leads the states in installed generation. It is no surprise then that New Jersey also generates 20.5% of its total energy from CHP (Mid-Atlantic Clean Energy Application Center, 2013.) However, Pennsylvania has the most potential for growth with an estimated future capacity of 36,627 MW (Mid-Atlantic Clean Energy Application Center, 2013.) The majority of installed capacity in this region is due to a few large facilities. However, the installation of smaller, more distributed CHP units is becoming more common, and may make up a large amount of total capacity in the future.
1.5: The Objective of This Thesis

Combined Heat and Power is a commercially available and reliable technology that is beginning to see increased support and investment. CHP provides environmental, economic, and efficiency benefits to energy users. However, there are certain costs associated with the installation and operation of CHP generators. Although operating costs are generally lower for CHP as opposed to heating and powering a building separately, the initial investment can be significant enough to discourage its use.

Yet, there are additional benefits that CHP can provide to a business or organization through the reliable power that it provides as a distributed generation technology. Power interruptions cost U.S. businesses and organizations billions of dollars overall every year. There is evidence that a strained power grid and increasingly unpredictable climate will increase the frequency and duration of these blackouts. It is possible to monetize the value of reliability under expectation. This thesis will analyze data concerning electricity blackouts in the PJM zone over a period from 1990-2010. The study attempts to model a distribution of annual economic harm inflicted by a blackout in the PJM zone. Only harm to small and large C/I will be considered. Once this model has been developed, the costs associated with a 1 MW CHP unit will be compared to the value of economic harm produced by a blackout.

After completing this analysis, it is expected that the installation of CHP will have significant monetary benefits to small and large C/I customers. These benefits will take form in the money saved from avoiding a loss of power. At its most basic objective, this thesis aims to put a monetary value on the total reliability benefits that CHP can provide to the PJM electricity market.
Chapter 2: Literature Review

There has been a great deal of research into the areas of power reliability, outage costs, and reliability benefits over the last few decades. Generally, this research indicates that electricity blackouts have been, currently are, and will continue to be a hindrance to electricity reliability within the United States. Furthermore, research suggests that power interruptions can have significantly negative and costly impacts to businesses within the United States. Distributed generation technology and, more specifically, combined heat and power have long been of interest to both policy makers and researchers. DG represents a growing industry within power generation and offers several benefits to those who invest in the technology. Specifically, CHP is attractive because it is a proven technology, and relies on traditional and dependable fuel sources for operation. In the scope of this paper, DG and CHP are valuable in the reliability benefits that they provide to the grid and the end-user of the technology. Although the literature on reliability benefits of CHP is scarce, there is adequate research in the area of DG benefits to grid reliability. There is also extensive research on the cost of power outages to various customer bases throughout the United States. This research is valuable in determining the overall cost of a blackout.

The supply of scientific and economic analyses of the reliability benefits of CHP are lacking. This absence of adequate information is one of the driving reasons for the necessity of this thesis. There is, however, literature that documents anecdotal evidence on certain situations in which CHP provided benefits to select businesses, hospitals, etc. during and after significant power interruptions or weather events. These accounts range from basic news articles to published reports, and provide a good primary example of the reliability benefits of CHP.
This literature review will present the research that has already been published on electricity blackouts and distributed generation. It will use this discussion to argue that electricity blackouts remain an issue in the United States, and that an analysis of the reliability benefits of CHP to a business is necessary. First, the author examines recent trends in electricity reliability and the costs of power interruptions to consumers. Secondly, research involving calculations of the value of lost load (VOLL) of a blackout is summarized. Thirdly, the reliability benefits of DG and CHP to the power grid are presented. Finally, a brief account of anecdotal evidence of the benefits of CHP as a power source are discussed to provide a more first-hand perspective on the topic.

This report uses historical evidence of electricity blackouts to formulate the model by which it performs its analysis. It is therefore important to analyze general trends in power reliability and power interruption reporting over time. There are three major indexes used by researchers to determine the length and significance of an electricity blackout. These indices are the System Average Interruption Duration Index (SAIDI), the System Average Interruption Frequency Index (SAIFI), and the Momentary Average Interruption Frequency Index (MAIFI). The SAIDI measures the average duration of a customer’s interruption that lasts for more than 5 minutes. The SAIFI measures the frequency of these interruptions per customer per year. Lastly, the MAIFI measures the frequency of blackouts that last less than 5 minutes (LaCommare and Eto, 2005). Furthermore, many reports reference the North American Electric Reliability Corporation (NERC) database. This database contains information relating to blackout duration, frequency, and size (Hines, Apt and Talukdar, 2009).

There have been changes in electricity reliability and reliability reporting in recent years. Eto, Fisher, LaCommare, Larsen, and Todd performed a study which collected information from 155
U.S. utilities from the years 2000-2009. The report concluded that blackout reporting increased from 2000-2006, and then began to decline. Additionally, the authors found that both SAIDI and SAIFI were larger when major blackouts were included. Most importantly, the analysis concluded that there has been about a 2% annual increase in blackout frequency and duration over 2000-2009 (La Commare, Eto, and Larson, 2012). This conclusion indicates that the reported reliability of the electricity grid is getting worse with time, and that blackouts are becoming more frequent.

The reliability benefits of CHP can be realized for any type of power interruption. However, the generators are truly beneficial to society in large blackout situations that last for significant amounts of time and are large in respect to number of customers affected. Hines, Apt, and Talukar analyzed the largest blackouts in North America from 1984-2006. The majority of the raw data in this study was also used throughout the analysis of this thesis. The blackouts analyzed in the report were events that lasted for more than 5 minutes and were either larger than 300 MW in magnitude or effected more than 50,000 customers. After filtering out non-essential events, the authors analyzed 547 total events that were categorized into subdivisions: earthquakes, tornados, hurricanes, ice storms, lightening, wind or rain storms, extremely cold weather, fire, intentional attack, supply shortage, other external events, equipment failure, or operating errors. The report reached several conclusions two of which are particularly relevant to the subject of this thesis. The authors were able to determine that there has been no decline in blackout frequency over time, however, they were not able to collect sufficient information to prove that there has been an increase in blackout frequency over time. The writers also found that blackouts tend to be more frequent in the summer and winter months (Hines, Apt and Talukdar, 2009)
Power interruptions can have many negative consequences to consumers. There is some research that seeks to put a monetary value on the disruption that a blackout causes. LaCommare and Eto derived a formula for this value in a 2005 study. The formula relies on four parameters: the number of electricity customers, reliability event data, cost per outage data, and vulnerability. Upon the culmination of this study, LaCommare and Eto estimate a total annual interruption cost of $79 billion dollars (LaCommare and Eto, 2005). The commercial and industrial sectors are responsible for 72% and 26% of this number, respectively, with the residential sector contributing only 2% to the total cost per consumer (LaCommare and Eto, 2005). Furthermore, momentary power outages (less than 5 minutes in duration) accounted for two-thirds of overall outage cost (LaCommare and Eto, 2005). The authors also conducted a sensitivity analysis that suggests average total interruption cost could be as low as $22 billion or as high as $119 billion (LaCommare and Eto, 2005).

A report published by Arthur D. Little consulting group titled “Distributed Generation and Reliability” also touches on some more specific details of the effects of power outages on businesses. The report concludes that key areas of economic loss for businesses during power outages stem from the following: lost productivity, process disruptions and restarts, losses in finished products and raw materials, equipment damage, canceled contracts, penalties for failing to meet obligations, and lost customers (Arthur D. Little, 2000). Impacts on individual businesses can be severe. The report cites an example of a statement by Hewlett-Packard that a 20-minute power outage in one of their factories would result in a loss of $30 million to the business (Arthur D. Little, 2000).

A metric that is most relevant to this thesis is what is commonly referred to as the value of lost load (VOLL). VOLL is a representation of the monetary value of lost electricity, and is usually
presented in units of $/MWh of lost load. Several studies have been done calculating the VOLL for certain areas of the United States and the world. VOLL is usually calculated either through macroeconomic analysis or by customer surveys that quantify a customer’s willingness to pay for electricity (London Economics International, 2013). London Economics International prepared a paper for the Electric Reliability Council of Texas. The literature review of this study provides an excellent summary of past studies done on VOLLs in the United States. One study done by Sullivan, Mercurio, Schellenberg and the Berkeley National Laboratory analyzed data from 28 surveys conducted by 10 utilities over the period 1989-2005. The report concluded that the average VOLL for a large C/I customer in the U.S. was $8,239/MWh, and $17,013/MWh for a small C/I customer (London Economics Internationl, 2013). These values are the best are used in the analysis of this study.

CHP can provide significant benefits to commercial and industrial businesses. There are anecdotal accounts of businesses, hospitals, etc. that were able to keep running during severe power outages caused by cascading power failures or extreme weather events. One report prepared for the Oak Ridge National Laboratories documents the experiences of several businesses that had CHP as a backup source during the August 14, 2003 electricity blackout. The blackout on August 14, 2003 affected around 50 million people in Ohio, Michigan, Pennsylvania, New York, New Jersey, and Connecticut; and was around 61,800 MW in magnitude (Carlson and Hedman, 2004). The outage affected large portions of the Midwestern and Northeast United States as well as parts of Canada. Power was out in some parts of the country for more than 4 days, and estimates of costs to the U.S. economy vary between $4 billion and $10 billion (Carlson and Hedman, 2004). Despite these losses there are several businesses that were able to keep running due to CHP.
The study contacted facilities that remained in operation to find out how CHP units performed and what benefit the system provided to the business and the local community. The initial scan of the report indicated that the amount of CHP systems in areas affected by the outage numbered 446 accounting for 9280 MW of capacity. The study focused primarily on hospitals, nursing homes, multifamily housing units, food processing facilities, and chemical/pharmaceutical facilities. The authors interview 12 businesses in total, 9 of which had CHP systems that remained in operation during the blackout. The other three were either undergoing maintenance or not designed to provide backup power. According to the interviews, most customers cited operating savings and power reliability as the primary reasons for investing in CHP. Overall, the study concluded that all CHP systems in operation performed as designed during the blackout. The overall impression from the users was positive, and in several cases the continued power provided excess benefits to the surrounding community (Carlson and Hedman, 2004).

As extreme and unpredictable weather events begin to increase due to climate change, the reliability benefits of CHP will become more important. Several victims of Hurricane Sandy experienced the benefits of CHP while 8.5 million of their neighbors lost power following the storm. Residential buildings, hospitals, universities, and public service facilities were able to keep producing electricity and heat until the grid was restored (Chittum, 2012). Notable locations that were able to remain online were the College of New Jersey, Princeton University, South Oaks Hospital, and Danbury hospital (Chittum, 2012). During this time of chaos, these institutions were able to not only keep running, but also provide shelter and other services to refugees of the storm. Examples such as these show the further benefits to society that CHP generators can provide outside of just private gains.
There is a good deal of research that examines trends in U.S. power reliability, costs of power interruptions, and the reliability benefits of DG and CHP. Upon analysis of this research it is clear that the reliability of the power grid is decreasing by some predictions at 2% per year. Additionally, there has been no decrease in the instances of large blackouts (over 300MW) in the last ten years. These power outages have been estimated to cost U.S. customers around $79 billion annually. There are real-life examples of DG and CHP providing more reliable electricity to consumers during power outages. Facilities are able to keep running and provide services to the outside community. However, there is need for more analysis on the monetary value of this added reliability. It is the objective of this thesis to perform this needed analysis, and to try to quantify the benefits of CHP to the PJM market as a hedge against power interruptions.
Chapter 3: Data Review

The majority of the data analyzed for this report stems from the North American Electric Reliability Corporation’s Disturbance Analysis Working Group (NERC DAWG) database. NERC requires electricity supplying entities to report all power outages that they experience. Therefore, the NERC DAWG database contains information on the date and time of the outage, the duration, the size, the amount of customers affected, the cause of the failure, and the geographic location. The comprehensive analysis of the NERC DAWG data is critical to developing a model that can assess the economic harm inflicted by a blackout in the PJM zone.

In his paper “Large Blackouts in North America: Historical Trends and Policy Implications”, Paul Hines collected NERC DAWG data from 1984-2006 and filtered it into a comprehensive table.

This thesis uses the same raw data collected by Paul Hines and filters out all events that took place outside of the PJM zone. The data used in this thesis is based on recorded electricity blackouts in the PJM zone from 1990-2010. However, the Paul Hines data only goes up to the year 2004. Data from the NERC online database was retrieved to obtain blackout data for the years 2005-2010. Appendix A contains the raw data that was used for this study. Events before 1990 and after 2010 were ignored due to incomplete data on electricity demand for other years. Many events had incomplete data on size, duration, and number of customers effected by the blackout. Only events that had information on both the blackout size (MW) and duration (hours) were considered. By the end of this process there were 81 total events from 1990-2010 that were able to be studied. The year of occurrence, blackout size (MW), duration (hrs.), adjusted load lost (MWh), and the cause of the event were record for all 81 events. The adjusted load lost was
calculated by adjusting each value of load lost to electricity demand for the PJM zone in year 2010. The season in which the blackout occurred was also taken into account.

There are several important distinctions that can be made from the data set. Table 3.1 provides a the mean and a 5 number summary for blackout size (MW), duration (hrs), and adjusted load lost (MWh).

**Table 3.1: Descriptive Statistics of Outage Data**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Sample Mean</th>
<th>Min</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blackout Size (MW)</td>
<td>430.89</td>
<td>15</td>
<td>110</td>
<td>300</td>
<td>500</td>
<td>2,800</td>
</tr>
<tr>
<td>Blackout Duration (hrs.)</td>
<td>35.41</td>
<td>0.07</td>
<td>3.92</td>
<td>10.75</td>
<td>51</td>
<td>212.50</td>
</tr>
<tr>
<td>Adj. Load Lost (MWh)</td>
<td>14,350.43</td>
<td>10.91</td>
<td>670.97</td>
<td>3,528</td>
<td>16,298</td>
<td>159,761.90</td>
</tr>
</tbody>
</table>

The most important trend in this table is that the median is less than the mean for all measures. This pattern indicates that the data is right-skewed, and has more low values that high values. Because the data is right-skewed it is likely to have a long tail that extends outward as the values become larger. To depict the distribution of the values, the blackout data was import into the software MATLAB, where it was fitted into histograms. Figures 3.1, 3.2, and 3.3 represent histograms of blackout size, blackout duration, and adj. load lost respectively.
Figure 3.1: Distribution of Blackout Size (MW)

Figure 3.2: Distribution of Blackout Duration (hrs.)
Each histogram shows that its respective data set is largely right skewed. It is also important to note that each event has a low probability of occurring. These histograms represent the likelihood of a blackout being a certain size, duration, or loss given that the blackout has already occurred. They do not, however, indicate the probability of a blackout occurring in the PJM zone. They are also not detailed enough to fully depict the true mean or shape of the distribution, and therefore a distribution curve must be fit over the data to accomplish this. The details of the curve fitting are covered in Chapter 4 of this paper.

It is beneficial to analyze the different causes of each blackout to determine any similarities or differences in the distribution of data. The author analyzed all 81 events and categorized each outage based on its cause. First, each cause was categorized into whether or not it was caused by a weather event or not. Figure 3.4 represents the breakdown of weather and non-weather related outages for the 81 events.
The overwhelming majority of blackouts were caused by some sort of weather event. Those that were not caused by weather were usually a result of equipment failure or a human error. This trend is of critical importance for future studies attempting to analyze blackout data and its effect on reliability. As climate change begins to produce more unpredictable and extreme weather events, blackouts are sure to become more significant and common.

The blackouts caused by weather events could be further characterized into the types of weather event that caused the outage. After analyzing the weather-related data, four main categories were defined: thunder storms, ice storms, extreme events, and severe wind/rain. Thunder storms are instances that involve high wind and rain, but the data also indicated the presence of lightening. Severe wind/rain involves wind and rain without the indication that there was lightening. Ice storms were indicated as such in most of the data, except certain situations that were described as “severe cold weather”. The two were grouped together. Lastly, extreme events were any...
descriptions that involved tornadoes, hurricanes, or tropical storms. Figure 3.5 indicates the percentage breakdown of each weather-related cause.

**Figure 3.5: Breakdown of Weather-Related Causes**

As the chart indicates, the majority of blackouts in the data set were caused by thunderstorms (46%). Ice storms and severe wind/rain caused about the same amount of outages, with extreme weather events causing the least. The histograms of weather related events are similar in nature to the shape of all blackout events. The figures were all still right-skewed for blackout size, duration, and load lost.
Chapter 4: Data Analysis and Discussion

4.1 Modeling the Cost of an Electricity Outage

In order to determine the value CHP provides to a business in the commercial and industrial sector it is first necessary to find a way to value the cost of a power outage to a consumer. Transforming the initial NERC DAWG data into a distribution that represents the probability of a power outage having a certain annual cost involves several steps. First, the study determines the ideal probability distribution to fit over the histograms provided in the data review. This accomplishes the task of determining an expected value for blackout size, duration, and load lost. The next step involved determining which measure of blackout impact (size, duration, or load lost) was most important in modeling the cost of a blackout. Thirdly, VOLLs from the literature were used to transform the appropriate distribution into one that represents the economic losses of a blackout given that one has occurred. After this transformation, the distribution was altered to represent distribution of annual economic harm inflicted by a power outage in the PJM zone. Final steps involve the integration of the costs and benefits of CHP into the distribution.

For each event of the 81 events recorded, there were three main measures of impact that were analyzed. The data included the size in mega-watts and the duration in hours. Additionally, there was the load lost in mega-watt hours. This was calculated by multiplying the size of the blackout by the amount of hours it lasted. As mentioned, the shape of each measure within the data set was highly right-skewed with a long tail. MATLAB was used to attempt to fit a probability distribution over the data sets for size, duration, and load lost. It was decided that a Generalized Pareto Distribution would best capture the right-skewed nature of the sets while still being able to provide values for the long tail.
A Generalized Pareto Distribution is usually used to model the tail of another distribution. The blackout data used in this study is complex and contains many extreme values. The Generalized Pareto Distribution is the optimal fit for the data sets. The Generalized Pareto Distribution contains parameters for shape, scale, and threshold which are represented by $k$, $\sigma$, and $\Theta$ respectively. The distribution is a continuous probability distribution and defines a value $f(x)$ for each $x$ entered into its probability density function (PDF). The distribution’s pdf is defined as:

$$y = f(x|k, \sigma, \theta) = \left(\frac{1}{\sigma}\right) \cdot \left(1 + k \cdot \left(\frac{x - \theta}{\sigma}\right)\right)^{-1-\left(\frac{1}{k}\right)}$$

MATLAB’s distribution fitting software takes a data set and can fit a number of distributions over it. The values for size, duration, and load lost were imported into MATLAB, and were then fitted into a Generalized Pareto Distribution. The software analyzes the data set, determines $k$ and $\sigma$ ($\Theta$ must be given. It was always a number 0.1 less than the minimum value of the data set), and then determines $f(x)$ for each value of $x$. A Generalized Pareto Distribution was fit over each measure for all events.

This study seeks to determine the private sector benefits that CHP can provide as a backup source of power. It had to be determined which measure of blackout impact was most relevant to the main concerns of a business in terms of receiving reliable power. The author determined that although the size and load lost are important metrics to a business, the amount of time that the business cannot function is the most critical. Therefore, blackout duration was the measure used in modeling the annual economic loss of a blackout and is presented in this analysis. The remaining distributions can be found in Appendices B and C.
A Generalized Pareto Distribution was fit over the duration data for all 81 outages recorded from 1990-2010. For the purpose of quantifying this measure, the duration of a blackout will be referred to as \( f(D) \). Figure 4.1 is a Generalized Pareto Distribution of the blackout durations with \( \Theta = 0.06 \).

**Figure 4.1: Generalized Pareto Distribution of Blackout Duration (hrs.)**

This distribution represents the expected amount of time that a power outage will last given that the blackout has already occurred. The next step was to determine a means of placing a monetary value on the distribution of blackout duration. This involved deciding on the appropriate metric that described the overall cost of an outage to a consumer.

There are a good amount of studies that seek to calculate the value of lost load (VOLL) in several areas of the country. VOLLs for residential customers are negligible as this study focuses on the benefits of CHP in the private sector. It seemed most appropriate for the context of this
study to utilize the VOLL values for large and small commercial and industrial customers estimated by Sullivan, Mercurio, Schellenberg, and the Berkeley National Laboratory. The study calculates that the average VOLL is $8,239/MWh for large C/I customers and $17,013/MWh for small C/I customers. These two values are critical for the estimation of the economic harm of a blackout in the PJM zone.

These VOLLs are essential to the results of this study, and must be discussed in more detail to understand the outcome of the analysis. There is a large difference between the estimated VOLL for a small C/I customer and a large C/I customer. The VOLL for a small C/I customer is more than double that of a large C/I customer. Therefore, the overall value of economic harm to a small C/I customer due to a blackout will also be larger than a large C/I business. Many of the VOLLs presented in the research follow this same trend. There are several reasons why the VOLL for a small C/I might be larger than for a large C/I. Firstly, a small C/I business is less likely to have a designed plan for a power outage. For example, a large C/I will likely already have a backup generator of some sort to prepare for a power outage. Additionally, contracts between business partners of a large C/I will likely have clauses hedging against power outages in the contract. This is not as likely for a small business that may have less business partners or not as detailed contracts (London Economics International, 2013). Furthermore, insurance policies that contain protection against economic loss from power outages are often too expensive for a small C/I customer to afford. Additionally, many financial and business records are kept on computers that can be damaged during a power outage. Small businesses are less likely to have backup files or computers that have the information at another office (Zerilli, 2013). Overall, small C/I customers are less prepared than large C/I customers to handle the
effects of a blackout. Therefore, when an outage does occur, small businesses can be affected the most on a monetary basis.

The next step was creating a distribution of the economic losses per MW of demand given there had been a blackout. From this part of the analysis forward values were calculated separately for small and large C/I customers. An equation was necessary to transform the duration of the blackouts (hrs.) into a value that included monetary value. The following equation was created to cause this transformation:

\[ f(D) = \text{Duration (hrs.)}, \ V = \text{Value of Load Load ($/MWh)} \]

\[ f(D\times V) = F(H) = \text{Economic Loss Given Blackout ($/MW-Demand)} \]

Economic loss per MW-demand can be determined by multiplying the duration values by the appropriate VOLLs. Essentially the original distribution curve for blackout duration is simply being shifted outward by the value of the VOLL that is used. Figure 4.2 is the distribution of economic loss per MW-demand given there has been a blackout for a small C/I customer. The values are determined from multiplying each duration data point from the NERC DAWG data by a VOLL of $17,013/MWh.
Figure 4.2: Distribution of Economic Loss/MW Demand Given Blackout: Small C/I

Figure 4.3 is the distribution of economic loss per MW of demand given there has been a blackout for a large C/I customer. The values are determined by multiplying each duration data point from the NERC DAWG data by a VOLL of $8,239/MWh.

Figure 4.3: Distribution of Economic Loss/MW Demand Given a Blackout: Large C/I
These two distributions model the likelihood of a blackout causing a certain amount of harm given that the blackout had already occurred. The true value of interest is the average amount of economic harm a blackout causes per year. This process involved transforming f(H) into the desired value. This calculation was made using the following formulae:

\[ f(H) = \text{Economic Loss per MW of Demand given a Blackout} \]

\[ B = \text{Average # of blackouts per season} = \frac{\text{total # of blackouts in each season}}{\text{total number of seasons}} \]

\[ f(BxH) = f(BH) = \text{Distribution of Economic Harm ($)} \text{ per season per MW} \]

F(H) is multiplied by the average number of blackouts per season to achieve four different distributions. A distribution of the economic harm/season/MW is calculated for each of the four seasons. Appendices B and C contain the distributions of f(BH) for each of the four seasons.

The final step is calculating the average annual economic harm of a blackout in the PJM interconnection zone for each customer base. For the purpose of this study the assumption is made that the seasonality of blackouts are independent. Therefore, it is possible to add each seasonal value together and then form an aggregate Generalized Pareto Distribution of the annual average economic harm. Figure 4.4 is a distribution of the annual average economic harm in the PJM zone per MW- demand for a small commercial and industrial customer with a VOLL of $17,013/MWh.
Figure 4.4: Distribution of Small C/I Annual Economic Harm per MW demand ($/MW)

The mean value is $13,300,400/MW-demand, and is the expected value of the annual harm caused by a blackout in the PJM zone. Figure 4.5 represents the distribution of economic harm on average to a large commercial and industrial consumer using a VOLL of $8,239/MWh.
The two distributions represent the overall costs associated with a blackout occurring in the PJM zone in a given year. The mean of each distribution can be interpreted as the expected annual economic loss of a blackout for both small and large industrial and commercial customers. Table 4.1 summarizes important values of each distribution.

### Table 4.1: Summary of Statistical Values for Annual Economic Harm

<table>
<thead>
<tr>
<th>Customer Base</th>
<th>Mean</th>
<th>Variance</th>
<th>S.D</th>
<th>k</th>
<th>Sigma</th>
<th>Theta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small C/I</td>
<td>13,300,400.00</td>
<td>$1.01 \times 10^{13}$</td>
<td>3,177,415.67</td>
<td>0.95</td>
<td>741,767.00</td>
<td>4,820.34</td>
</tr>
<tr>
<td>Large C/I</td>
<td>1,647,360.00</td>
<td>$2.37 \times 10^{12}$</td>
<td>1,538,748.47</td>
<td>0.72</td>
<td>524,783.00</td>
<td>2,334.37</td>
</tr>
</tbody>
</table>

(Units for non-parameter values are Annual $/MW-Demand)

Obtaining the distributions of annual average economic harm and acquiring the expected values shown in the table above complete the task of modeling the annual economic harm produced by a blackout in the PJM zone. Conversely, one can also view the value of annual economic harm
inflicted by a blackout as the annual reliability value of 1 MW of CHP capacity. The economic harm experienced by a blackout is the same as the benefit a business could experience by being able to maintain operations during the blackout. CHP provides the ability to continue these critical operations. The final steps of the analysis involve integrating the costs of CHP into the model of economic harm.

4.2: Integrating Combined Heat and Power into the Model of Economic Harm

It has been determined that there are significant losses that can be experienced by a business due to an interruption in electricity service. However, there are also significant costs that are associated with installing, operating, and maintaining a CHP unit. If the costs of owning a CHP unit are larger than the expected costs associated with a blackout it is not economical for a business to install a unit. If the costs are less than the harm of a blackout, then the business would then do well to consider CHP as an option for backup generation. It is therefore necessary to determine a method of evaluating the cost of CHP against the expected value of the annual economic harm of a blackout.

There are two main questions of critical importance to the outcome of this thesis. The values of economic harm are measured in $/MW-demand. Therefore, the study seeks to determine what annual reliability value would pay for the capital cost of 1 MW of CHP over the units 15 year life. Additionally, what is the average annual value of economic harm endured because of blackouts and how does the cost of CHP measure against this cost over its lifetime? Each analysis was performed separately, and values were calculated for both small and large C/I. The cost values that were assigned to the CHP unit were taken from the EPA’s information on the costs of a typical CHP unit.
To measure how much harm would be compensated for by 1 MW of CHP, a breakeven analysis was performed. The annual value of economic harm was viewed as a constant stream of benefits that the customer would receive if they installed CHP. Therefore, it can be assumed that the value of benefits equates to an annuity payment received over the life of the CHP system. The study sought to calculate the annuity payment that would offset the capital cost of the CHP unit using three discount rates: 15%, 20%, and 25%. The cost of the system was estimated to be $1,200,000, and the life of the system is assumed to be the standard 15 years (DOE and EPA, 2012). The value of A is the annual stream of payments that would offset the capital cost of 1 MW of CHP. This value was determined by solving for A in the following equation:

\[-1,200,000 + A \times \left( \frac{1 - (1 + i)^{-n}}{i} \right) = 0\]

The capital cost and lifetime of a CHP unit is assumed to be the same for both a large and small business, and therefore the following values of A hold true for both customer bases. Table 4.2 shows the different breakeven values of A that would offset the capital cost of 1 MW of CHP over 15 years. Values of A are calculated for three separate discount rates (r).

<table>
<thead>
<tr>
<th>Value of r</th>
<th>A Units</th>
<th>A Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>15%</td>
<td>$205,220.46</td>
<td>$/MW</td>
</tr>
<tr>
<td>20%</td>
<td>$256,658.54</td>
<td>$/MW</td>
</tr>
<tr>
<td>25%</td>
<td>$310,940.24</td>
<td>$/MW</td>
</tr>
</tbody>
</table>

Table 4.2: Value of A to Offset CHP Capital Cost
Each value of A was then integrated into the model for economic harm for both small and large business. Figure 4.6 shows each value of A against the distribution of annual economic harm for a small C/I customer.

**Figure 4.6: Small C/I Breakeven Reliability Value for 1 MW CHP Capacity**

A, A1, and A2 represent annual reliability values of $205,220/MW-Demand, $256,659/MW-Demand, and $310,940/MW-Demand respectively. The x-axis was cut off at $1,000,000/MW-Demand to better portray the values of A. The graph is meant to be read off to the right. In other words, the part of the distribution that is to the right of each value of A is the portion of annual economic loss that could be negated by installing 1 MW of CHP. The part of the distribution to the left of each A value represents the annual value of economic loss that would make an investment in CHP uneconomical. For example, the value of A at a 15% discount rate is $205,220/MW Demand. If a business perceives the potential value of annual economic loss due to a blackout to be higher than this number, then it would be economic to invest in 1 MW of
CHP. However, if the perceived expected value of annual blackout costs is less than this number, then it is not beneficial to install a 1 MW CHP generator.

Similarly, Figure 4.7 shows the same values against the distribution of economic harm for a large C/I customer. Again, the x-axis was cut off at $1,000,000/MW-Demand to better portray the values of A.

Figure 4.7: Large C/I Breakeven Reliability Value for 1 MW CHP Capacity

The only difference between figure 4.7 and figure 4.6 is that figure 4.7 uses the VOLL for a large C/I as opposed to that of a small C/I.

Lastly, the major objective of this study is to calculate the overall net present value of the reliability benefits of CHP. This involved taking the annual expected value of economic harm, and comparing it to the total cost of CHP. A net present value analysis for both small and large
C/I customers was performed at discount rates of 15%, 20%, and 25%. The average life of a CHP generator is assumed to be 15 years. Therefore, the PV of economic harm is the NPV of the expected value of economic harm over 15 years. The NPV of the cost of CHP was also determined. This is the NPV of the capital cost and operating costs of CHP over 15 years. In this analysis the capital cost of a MW of CHP is $1,200,000 and the operating cost is assumed to be $0.0505/kWh (EPA, 2013). The annual assumed kWh usage of a small and large C/I is assumed to be 19,214 kWh and 7,140,501 kWh respectively (Sullivan, Mercurio and Schellenberg, 2009). The NPV of outage costs and CHP costs were calculated for both small and large C/I. Then, the NPV of CHP was subtracted from the NPV of outage cost to arrive at the total reliability benefits of 1 MW of CHP over the unit’s lifetime. Tables 4.3 and 4.4 represent the reliability values calculated for small and large C/I.

**Table 4.3: Total Reliability Benefits of 1 MW CHP to Small C/I**

<table>
<thead>
<tr>
<th>Discount Rate</th>
<th>NPV Cost of Outage</th>
<th>CHP Total Cost</th>
<th>Total Reliability Benefit CHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>r=15%</td>
<td>$79,193,705.44</td>
<td>$1,048,411.95</td>
<td>$78,145,293.49</td>
</tr>
<tr>
<td>r=20%</td>
<td>$62,905,046.94</td>
<td>$1,003,780.54</td>
<td>$61,901,266.41</td>
</tr>
<tr>
<td>r=25%</td>
<td>$51,704,108.09</td>
<td>$962,995.74</td>
<td>$50,741,112.35</td>
</tr>
</tbody>
</table>

**Table 4.4: Total Reliability Benefits of 1 MW CHP to Large C/I**

<table>
<thead>
<tr>
<th>Discount Rate</th>
<th>NPV Cost of Outage</th>
<th>CHP Total Cost</th>
<th>Total Reliability Benefit CHP</th>
</tr>
</thead>
<tbody>
<tr>
<td>r=15%</td>
<td>$9,808,768.35</td>
<td>$2,876,986.24</td>
<td>$6,931,782.11</td>
</tr>
<tr>
<td>r=20%</td>
<td>$7,791,288.84</td>
<td>$2,404,961.22</td>
<td>$5,386,327.62</td>
</tr>
<tr>
<td>r=25%</td>
<td>$6,403,963.75</td>
<td>$2,073,305.54</td>
<td>$4,330,658.21</td>
</tr>
</tbody>
</table>
4.3: Discussion of Results

The results of this study present several important conclusions that can be used for future research in the area of electrical grid reliability improvements. Additionally, there are several assumptions that were made that could potentially effect the accuracy of the estimations presented in this analysis. All conclusions reached in this thesis are simply an estimate determined based upon the data that was available. The nature of the data may also have provided inconsistencies and inaccuracies in the results.

The results of this study indicate that there is a significant monetary benefit to installing CHP as a hedge against blackout costs. Commercial and industrial businesses stand to be the customers that benefit the most from avoided blackout costs. Coincidentally, the facilities used by these types of businesses are ideal for the installation of a CHP unit. The results indicate that small C/I could experience significantly more benefit from the installation of a CHP unit than a large C/I. The average VOLL of a small C/I customer is a little more than double the VOLL for a large C/I. A small C/I customer in the PJM zone could experience up to $78,145,293.49/MW-demand in expected reliability benefits from 1 MW of CHP capacity over the lifetime of the unit. At an interest rate of 15%, the total CHP cost represents only 1% of the potential economic harm that could be inflicted by a blackout. This value is significant, and cannot be ignored by future policy makers in regards to incentivizing the implementation of CHP.

Although smaller than for a small C/I, the benefits that could be experienced by large C/I customers are also very large. Large C/I customers in the PJM could potentially experience up to $6,931,782.11/MW-demand in reliability benefits by installing 1 MW of CHP. At a 15% discount rate, the cost of CHP represents only 29% of the total expected cost of a power blackout. Although the values for a large C/I customers are smaller than for small C/I customers,
they may be more accurate. A large commercial or industrial facility that uses an average of over 7,000,000 kWh a year is much more likely to have a CHP unit the size of 1 MW or greater. For the purpose of this study it was easiest to evaluate CHP costs on a MW scale, however in reality it is unlikely that a small C/I facility would have a CHP unit of this size. Therefore the costs of CHP used in the analysis of large C/I can be assumed to be more accurate.

The final results for small and large C/I rely heavily on the VOLL that was assigned to each customer class. There are several reasons why the VOLL for a small C/I could be significantly larger than for a large C/I. Firstly, large C/I businesses are more likely to have more than one operating facility that may be outside the area where the blackout has occurred. In this case, the business can continue to run at another facility until the power is back online. Secondly, a large business is more likely to have a more rigid plan as to how to run operations in the event of an electricity blackout than a smaller business. Lastly, large C/I customers are also more likely to already have a system of backup generation in place, whether it be traditional diesel or a newer more efficient technology. The VOLLs used in this study were calculated by surveying several different customers throughout the country. Therefore it is likely that the customers may have already had backup generation capabilities.

Several assumptions were made throughout the course of this study. These assumptions were used for the purpose of streamlining the analysis process. However, the assumptions made may or may not be true, and can affect the outcome of this study. A major estimate was on the VOLL for small and large C/I customers. There is a large amount of studies that seek to determine the VOLL values for different areas of the country. The values they estimate range from very low to very high. The values used in this study were derived from a meta-study that combined the results of several surveys. It is the most applicable value that could be found for small and large
C/I customers. However, the nation-wide VOLLs estimated in the study are not necessarily the values that are specific to the PJM zone. Depending on the true VOLL for the PJM zone, the estimates in this study could be more or less than what is presented.

For reasons of simplicity, the costs associated with a 1 MW CHP unit were assumed to be a fixed value for both small and large C/I. The CHP unit was assumed to be a 1 MW natural gas powered generator that was installed onsite at the facility. The unit was predicted to have a useful life of 15 years. The costs were obtained from the section of the EPA’s website that covers combined heat and power generation. Capital costs were assumed to be $1,200,000/MW and operating costs were held at $0.0505/kwh. The annual kilowatt-hour usage of each customer base was also derived from the same study that provided their respective VOLLs. These values are an average, and may not hold true for many businesses within the PJM zone. Therefore, the operating costs may be more or less than what is shown. The capital costs of a CHP unit can also vary drastically. For example, the capital cost of a CHP unit for a small C/I customer will likely be far below $1,200,000 because a smaller system would be the most economic. Capital costs also rely heavily on the type of turbine installed, the logistics of installation, and other advanced add-ons to the system. Again, the value of the capital cost could vary up or down, which would have an effect on the total reliability value of CHP presented in this study.

Lastly, the nature of the data evaluated in this study could impact the accuracy of this analysis. The blackout data relies on events reported to the NERC DAWG committee from 1990-2010. The data was largely incomplete in some areas. For example, there were many events that did not indicate one or more of the following: size, duration, and number of customers affected. Therefore all events that did not have both size and duration were not included. Furthermore, the event data from 1990-2004 was taken from the data compiled by Paul Hines. The remainder of
the events (2005-2010) were taken from an online database provided by the NERC website. There may be some inconsistencies in how the data was recorded between these two sources. Lastly, the best effort was made to ensure that all events recorded took place within the PJM operating zone. However, there may be some events that occurred in this zone that were not taken into account due to a lack of information on the geography of the blackout. Conversely, there may be some events that were analyzed that did not actually occur in the PJM zone. These gaps effect the duration values that were used to model the economic harm of a blackout and therefore could alter the final values determined.
CHAPTER 5: Conclusion

Power outages in the United States have been estimated to cost $79 billion annually to electricity customers. As the U.S. electricity grid becomes increasingly strained and unreliable, the frequency of blackouts are expected to increase at a rate of 1.4% through 2020. Additionally, as climate change becomes more and more of a factor in future weather patterns, the United States may see more unpredictable large storms. This will lead to an increase in the amount of very large blackouts that can disrupt the economy for up to weeks at a time. Trends in power outages and the economic costs that these incidents have on the economy have long been of interest to researchers and policy makers. Within the last decade, there has been significant interest in determining a way to increase the reliability of the electrical grid and lower the costs of blackouts.

The electricity transmission system in the United States relies heavily on centralized power plants that produce electricity for a large geographic area. These power plants are usually run off of fossil fuels and transfer power through transmission and distribution cables to end-customers. The nature of this system lends itself to outages due to human errors or weather related harm. Distributed generation is one solution that many believe is the answer to reliable power. A DG technology is any technology that can generate power on or near the point of consumption, and that is not reliant on the centralized power grid. Combined heat and power is a technology that can simultaneously power and heat a facility. CHP generators typically run off of natural gas and can be installed on-site at many facilities. CHP is more efficient than the separate production of heat and power, and is often cheaper to run and better for the environment. Although there is
some research on the benefits DG can provide to a power grid, there is little analysis done on the value that CHP in particular can provide. This thesis seeks to determine the reliability value that CHP can provide to small and large C/I businesses that are located in the PJM Interconnection zone.

This report uses NERC DAWG blackout data from 1990-2010 to model the annual economic harm that is inflicted on the PJM zone by electricity blackouts. There are two values of annual economic harm that are calculated: the value experienced by small C/I businesses, and the value experienced by large C/I businesses. A value of lost load of $17,013/MWh was used for small C/I businesses, and $8,239/MWh was used for large C/I businesses. These values of lost load were extracted from previous research done in the topic of costs of power outages. These values are essential to the results of this study, and any change, up or down, in the numbers would have a significant impact on the end values determined for the reliability benefits of CHP.

After modelling the annual economic costs of a power blackout, the overall reliability benefits of CHP were determined. This was done by comparing the net present values of the costs associated with CHP and power blackouts over the 15 year assumed useful life of a 1 MW CHP generator. This study finds that a 1 MW CHP generator could provide $50,741,112/MW - $78,145,293.49/MW demand in reliability benefits to a small C/I business over the course of its lifetime. The same 1 MW generator could provide $4,330,658/MW - $6,931,782/MW demand in reliability benefits to a large C/I customer. These values pertain solely to the PJM Interconnection zone. The value of these numbers are significantly large and demonstrates the promising potential of combined heat and power as a hedge against the costs of blackouts.

The results of this report should be taken into consideration when researching the reliability value of combined heat and power to a business in the PJM Interconnection zone. However,
several reasons were discussed as to why the results may not represent the true reliability value of CHP in the PJM zone. Given these inconsistencies, this report concludes that there are recommendations for improvements in the quality of data on blackouts and the costs associated with them. The NERC DAWG data used in this report was inconsistent and incomplete at times, allowing only 81 total events to be studied in the analysis. If there were more complete reporting on the characteristics of each blackout event, then more accurate distributions of annual economic harm could be created. Going forward, this report recommends that reporting or power outages by utilities be more heavily enforced and specific. Additionally, there is little data on the true VOLL for the actual PJM zone. Each utility going forward should make an effort to publish annual VOLLs experienced by their customers.

Despite these inconsistencies, the results of this report conclude that there is significant value in installing a CHP generator for the purpose of reducing blackout cost. In addition to these benefits CHP also has efficiency, cost, and environmental advantages. As the nation’s energy strategy begins to transform, hopefully policy makers and businesses will realize the benefit that CHP can provide to the electrical grid.
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Appendix B: Additional Generalized Pareto Distributions: Small C/I

Small C/I Spring Distribution of Economic Harm ($/MW Demand):

Small C/I Summer Distribution of Economic Harm ($/MW Demand):
Small C/I Fall Distribution of Economic Harm ($/MW Demand):

Small C/I Winter Distribution of Economic Harm ($/MW Demand):
Appendix C: Additional Generalized Pareto Distributions: Large C/I

Large C/I Spring Distribution of Economic Harm ($/MW Demand):

Large C/I Summer Distribution of Economic Harm ($/MW Demand):
Large C/I Fall Distribution of Economic Harm ($/MW Demand):

Large C/I Winter distribution of Economic Harm ($/MW Demand):
Bibliography


ACADEMIC VITA

Drew Miller
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Education:
- The Pennsylvania State University – Schreyer Honors College, University Park, PA
  - Major: Energy, Business and Finance (Bachelor of Science)
  - Minor: Chinese Language
- East China Normal University – Shanghai, China
  - Business, Language and Culture Study Abroad Program
- The Haverford School – K-12, Haverford, PA

Honors and Awards:
- Dancer – Penn State Dance Marathon – Acacia and Gamma Phi Beta
- GK Nelson Scholarship – Acacia Fraternity
- Dean’s List (Fall 2009 – Fall 2011, Fall 2012 – Fall 2013)
- The Hess Scholarship

Association Memberships:
- Acacia Fraternity – Brother
- Vice President (2011-2012)
- Former THON Chairman (2011)
- Former Greek Sing Chairman (2011)
- Former Homecoming Chairman (2010)
- Former Alumni Relations Chairman (2010-2011)

Professional Experience:
- Management Consultant – Pricewaterhouse Coopers (Fall 2014 - )
- Product Management Intern – First Solar, Inc. (Summer 2013)
- Financial Analyst Intern – Dynamic Solar, LLC. (Summer 2012)