Electric Power Distribution System Reliability and Outage Costs: An Undergraduate Industry Collaboration

Abstract:

This paper describes an undergraduate, cross-disciplinary research into the economic effects of power system outages, with a focus on the Pacific Northwest region. The results of this research are useful for utilities in their planning and assessment of electric grid reliability. The Pacific Northwest region of the United States experiences a temperate climate with brief summers and long-lasting winters. Generally, the highest electricity demand for the region occurs during the winter months, when heating is turned on. Therefore, an outage that occurs during winter months results in additional non-financial costs for customers (e.g., loss of comfort such as heating). Outages attributed to natural disasters such as hurricanes are not prevalent in this region, unlike the East Coast of the United States. However, the region's abundant vegetation (e.g., trees) do impact the distribution system, especially during storm seasons in the fall and winter, where they can cause faults on the distribution lines. This report examines the causes and consequences of electricity outages using a variety of metrics such as the Consumer Damage Function (CDF), Value of Lost Load (VOLL), Loss of Load Probability (LOLP), and other commonly used metrics for research and utility resource planning.

The methods for estimating and analyzing the economic impact of power outages include post-event analysis, economic output to energy consumption ratios, and customer surveys. Regression analysis (i.e., Tobit model) was performed on the data collected from a survey of the Pacific Northwest electric customers to estimate the Customer Damage Function (CDF). Major factors affecting the CDF include duration, timing of the outage, and customer type. The Department of Energy's (DOE) Interruption Cost Estimator (ICE) Calculator was used to assess the impacts of outages based on reliability data provided by the region's largest investor-owned utility, Puget Sound Energy (PSE). The reliability metrics included System Average Interruption Duration Index (SAIDI), which describes the average length of an outage in minutes, the System Average Interruption Frequency Index (SAIFI), which describes the average number of outages a customer experiences, and the Customer Average Interruption Duration Index (CAIDI), which is the ratio of SAIDI to SAIFI, and measures the average restoration time. These three metrics from Puget Sound Energy were used in the regression analysis for both residential and non-residential customers.

This project was conducted in collaboration between two undergraduate students, an electrical engineering faculty specializing in power systems, and engineers from a local utility. The nature of the research was interdisciplinary as it required both economics and power engineering knowledge, which was challenging but also very rewarding for the students. The students reached out to the local utility and worked with their engineering team to conduct this research that is both beneficial for the students and the utility. This partnership not only stimulated the students' interest in research but also helped them develop skills in communication, project management, and soft

skills that will serve them well into their professional careers. The opportunities and challenges from this collaboration are also presented in this paper.

1.0 Introduction

Modern society is dependent on a consistent and reliable supply of electricity for its economic development. As such, creating a resilient and reliable power grid is essential as additional loads are connected online. Power outages can have massive economic impacts, even if they are very short in duration. Previous studies have investigated the reduction in economic output due to power outages of varying duration, scale, time, and location.

In the Pacific Northwest, the time of year that an outage occurs can have a significant impact on the customers. For example, residents that lose power during a mild spring day may not be as inconvenienced as those experiencing an outage that occurs during a cold winter day. The Pacific Northwest typically does not experience outages resulting from severe weather events such as hurricanes. However, during storm seasons, outages can occur from various vegetation coming into contact with power lines [1].

The economic impact of power outages vary across different customer classes. Commercial and industrial customers suffer from loss of productivity, sales, and output, which results in direct financial losses. Residential customers also suffer from economic losses due to food spoilage or lost productivity; however, these customers are usually impacted to a greater extent by indirect costs such as inconvenience, anxiety, and discomfort. There exist a variety of metrics to capture these costs associated with electricity outages:

- Customer Damage Function (CDF) measures the costs resulting from a power disruption, measured in terms of the value of lost output in dollars, normalized by the magnitude of the power outage [2].
- Loss of Load Probability (LOLP) measures the likelihood of a load curtailment event occurring [3].
- Expected Unserved Energy (EUE) measures the magnitude of potential load curtailments (i.e., how much load and how many customers are impacted) [3].
- Value of Lost Load (VOLL) measures the economic cost that customers incur when they experience an interruption in electricity service [4].

Across different utility structures, there are various average values for frequency and duration of distribution system outages. An Energy Information Administration (EIA) study from 2015 showed that on average, municipal electric utilities had the lowest occurrences of outages in both frequency and duration. This was followed by investor-owned utilities (IOUs) and then cooperative utilities, which reported the most frequent and lengthy outages of the three broad utility structures [5]. Figures 1 and 2 show the average frequency and duration of power service interruptions per customer for the different utility structures.

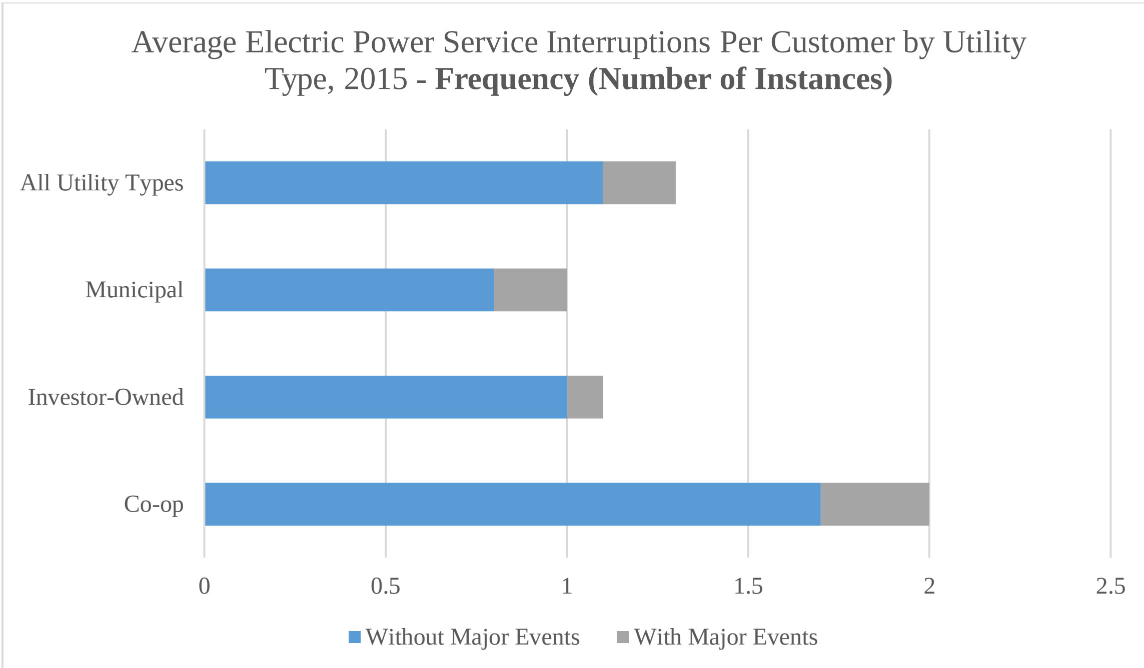

Figure 1: Average Electric Power Service Interruptions by Utility Type – Frequency [5]

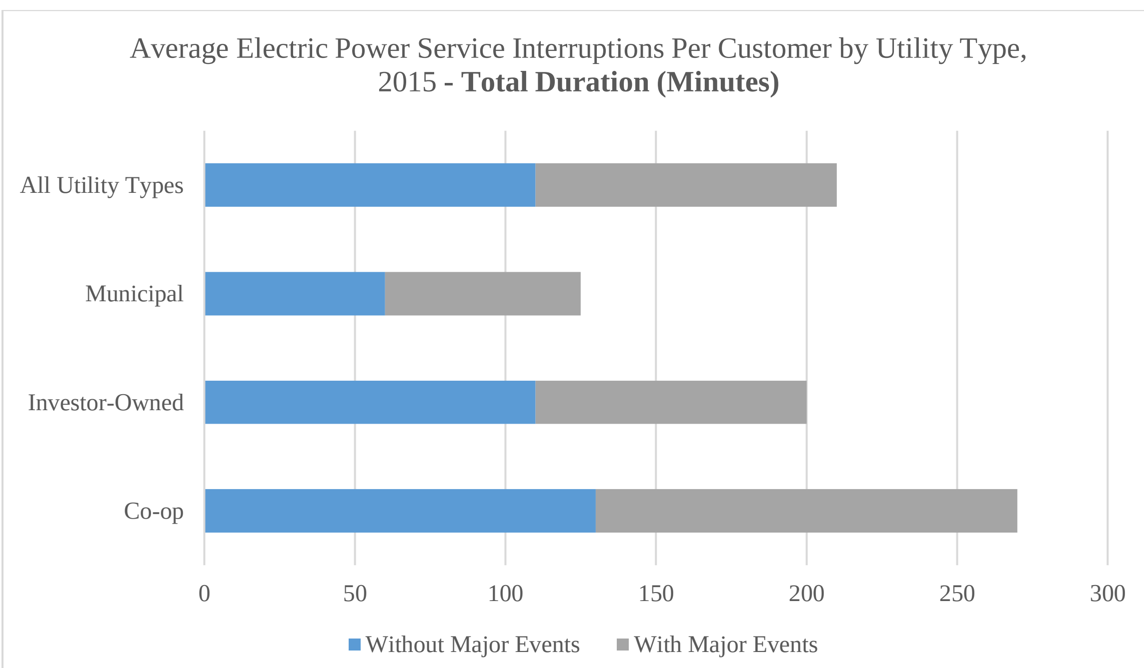

Figure 2: Average Electric Power Service Interruptions by Utility Type – Duration [5]

The average frequency and duration of service interruptions can be attributed to factors such as the density of vegetation, weather patterns, and customer populations. For example, cooperative utilities often service rural areas, where it is more likely to have vegetation that can short out distribution lines during storms. This explains the higher average service interruption frequency for this utility structure. Additionally, the longer outage durations are a result of the difficulty in accessing outage areas and the lack of personnel.

The Pacific Northwest has all three utility structures, with the most prominent utility being Puget Sound Energy (PSE), an investor-owned utility. PSE has over 1,000,000 electric customers and serves ten counties. The company's service area covers 6,000 square miles, which is shown in Figure 3. PSE owns 3,597 MW of generating capacity [6].

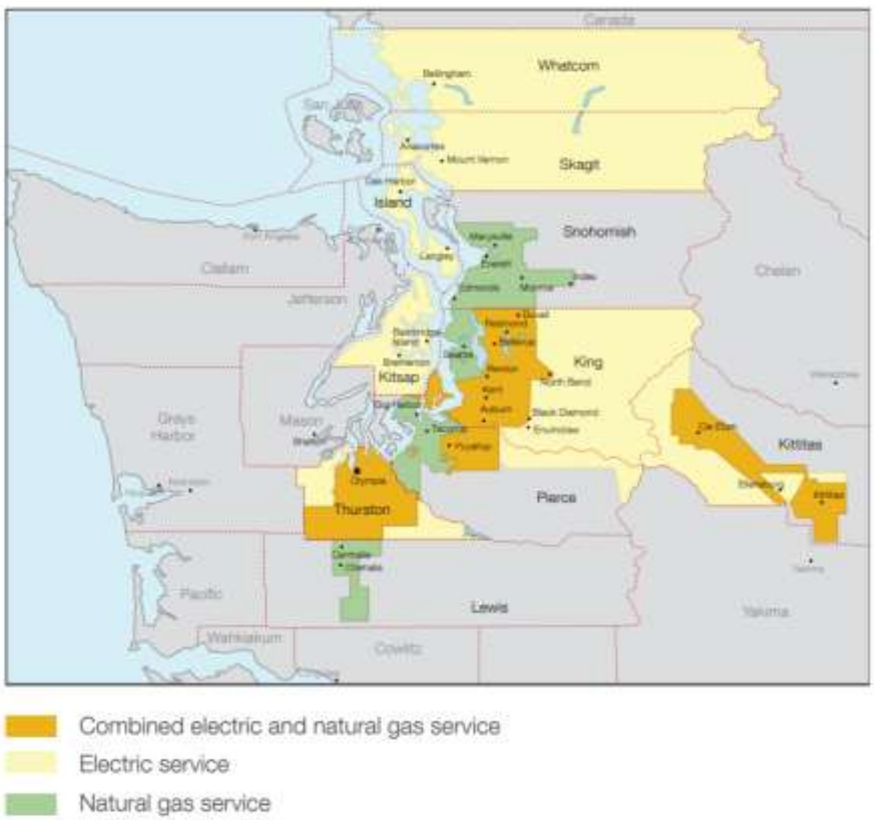

Figure 3: Puget Sound Energy Electric and Natural Gas Service Territory [6]

Based on EIA's outage data, a broad assumption can be made about PSE's distribution system reliability. Since Puget Sound Energy spans a large geographic area, which includes densely populated cities and rural areas with extensive forests, fallen trees account for approximately 2,000 outages on PSE's distribution system annually. In order to mitigate this hazard, the utility spends about $12 million annually on vegetation control [7].

2.0 Losses from Power Outages

When analyzing the economic consequences of an electricity outage, there are a variety of metrics used to measure the impact. A value can be assigned to a customer for an increased amount of reliability. This marginal value of reliability is equal to that of the lost electricity service. The lost value of the electricity from an outage can be estimated by the lost customer output (i.e., loss of business a company experiences due to an outage). The Value of Lost Load (VOLL) is a standard metric used for estimating losses. It is defined as the cost that a customer would incur from a service disruption as a function of its duration [8]. Data collected through surveys from customers estimate this value based on their response to a hypothetical outage of a certain duration. The VOLL is typically expressed in terms of the Customer Damage Function (CDF), which estimates the costs that arise from a power outage. Some of the factors that affect costs are the result of reduced or halted productivity, which is measured in dollars of lost output. This value is then normalized by the magnitude of the interruption in kW or kWh [8].

There are two types of losses resulting from outages: direct and indirect. Direct losses include lost business production while indirect costs are related to the impacts from the outage, such as increased crime. Macro-econometric models are used to estimate the reduction in economic output. These models mostly highlight the effects of a disruption using input variables such as income and employment [8].

2.1 Measuring Outage Impacts

Analyzing the cost of power outages is often challenging due to the lack of available data. Surveys are often used for initial data collection. Customers are surveyed from each sector or class, including residential, commercial, and industrial. These customer surveys help provide an understanding of the cost to consumers of reliable electricity supply from their perspective. Customers are asked to estimate costs arising from power outages for different time durations. Although this method is time-consuming and costly to implement, well-designed surveys yield reliable data that are directly from the end users. Once the surveys are collected, the data is aggregated and normalized to obtain estimates of the costs for each sector of customers [9].

Another method used to analyze outage costs is to conduct case studies after an outage event has occurred. The case studies are often limited to areas with large population centers. The results of these studies are rather limited in that they only focus on specific geographic areas and specific events with fixed durations. On the other hand, this kind of analysis can yield more detailed estimates of indirect costs compared to other methods.

As an example, consider the 1977 New York City Blackout, where more than 9 million people lost power for over 25 hours [10]. This event was instigated by a lightning strike on a substation that caused the Consolidated Edison system to fail. System protective devices failed to contain the propagating faults. Table 1 shows the costs associated with this particular event, broken down by impact areas.

Table 1: Cost of the 1977 New York City Blackout [10]

Impact Areas	**Direct Costs (in millions of $)**	**Indirect Costs (in millions of $)**
Business	Food Spoilage: 1.0 Wages Lost: 5.0 Securities Industry: 15.0 Banking Industry: 13.0	Small Businesses: 155.4 Private Emergency Aid: 5.0
Government		Federal Assistance Programs: 11.5 New York Assistance Programs: 1.0
Consolidated Edison	Restoration Costs: 10.0 Overtime Payments: 2.0	New Capital Equipment: 65.0
Insurance		Federal Crime Insurance: 3.5 Fire Insurance: 19.5 Private Property Insurance: 10.5
Public Health Services		Public Hospitals- Overtime, Emergency Room Charges: 1.5
Other Public Service	Metropolitan Transportation Authority (MTA): Revenue Losses: 2.6 Overtime and Labor: 6.5	MTA Vandalism: 0.2 MTA Capital Equipment: 11.0 Red Cross: 0.01 Fire Department: 0.5 Police Department: 4.4 State Courts: 0.5 Prosecution and Correction: 1.1
Westchester County	Food Spoilage: 0.25 Public Services: 0.19	
Total	**55.54**	**290.16**

The indirect costs resulting from the blackout are over five-times the direct costs. Much of these indirect costs are due to the various civil disruptions that occurred following the outage, including arson and looting.

The ratio of economic output to energy consumption is another method to estimate industry-specific costs of power disruption. This method uses a gross economic output unit (i.e., GDP) and a measure of electricity consumption (i.e., peak load) to estimate outage costs [9]. For example, if an industrial customer uses 1 MWh of electricity to produce $100,000 worth of product, then each kWh is associated with $100 worth of output. In this case, the cost of the outage for this customer is $100/kWh. This method is straightforward in that an analysis can be performed for any commercial or industrial customer that uses electricity to produce a commodity or service. However, this method is limited in its efficacy in computing indirect costs associated with an outage. This method also cannot yield cost estimates for residential customers as they do not produce any commodities.

2.2 Outage Modeling in Integrated Resource Planning

Puget Sound Energy's 2015 Integrated Resource Plan (IRP) describes the model used to assess the risks and impacts of outages. Monte Carlo simulations of outages were first performed on a selection of thermal plant generators using the Frequency Duration method in the AURORAxmp forecasting and modeling software [3]. AURORAxmp analyzes the Western power market to produce hourly price forecasts for electricity based on potential future resource dispatch and market conditions. The stochastic outputs from these simulations serve as the input to the PSM III model to compute the costs associated with outages.

PSE's IRP defines a resource adequacy model that includes the Loss of Load Probability (LOLP), Expected Unserved Energy (EUE), and Loss of Load Hours (LOLH). After a planning standard has been established, capacity planning margins and incremental capacity equivalents for different resources are defined using various risk metrics [3].

The VOLL is often derived from customer surveys. Implementing a well-designed survey can be challenging since the value placed on an outage by a customer could be biased. These values could also change over time depending on the season. Additionally, different types of customers have various values for avoiding a service interruption. The VOLL is a critical consideration for electric utilities in determining the appropriate EUE-based target for long-term peak load planning. A lower EUE target corresponds to a lower expected number of load curtailments, which results in a higher level of reliability. However, a lower EUE can only be achieved if additional capacity resources are invested [3]. The benefits of increasing service reliability must be weighed against the increase in electricity rates to recover the project costs. The point where the marginal benefits of increasing reliability equals the associated marginal costs of adding more firm capacity determines the optimal EUE level. Table 2 shows the VOLL for an average PSE customer for a one-hour duration [3].

The US Department of Energy's (DOE) Interruption Cost Estimator (ICE), which is described in depth by the Lawrence Berkeley Laboratory study titled "Updated Value of Service Reliability for Electric Utility Customers in the United States", models interruption costs per customer per event based on the length of outage duration and customer class (e.g., residential, small commercial and industrial, medium and large commercial and industrial) for each U.S. State. A per-customer peak load contribution is calculated and averaged across all customer classes. This value was used to estimate the expected number of PSE customers affected by a particular outage event [3].

Table 2: Interruption Cost of PSE Customer per Event of One-hour Duration

Customer Type	Number of Customers	Per Customer Interruption Cost per Event	Per Customer Interruption Cost per kW per Hour	Implied Average kW per Year	PSE Load Factors	Peak kW per Year	PSE Peak Shares	Average Peak per Year per Customer (kW)
Medium and Large Commercial and Industrial	10,889	$4,122.40	$27.80	148.3	1.47	218	0.2	43.6
Small Commercial and Industrial	126,531	$758.90	$179.70	4.2	1.42	6	0.1	0.6
Residential	1,060,975	$2.80	$1.90	1.5	2.05	3	0.7	2.1
All Customers	1,198,395	**$120.06**	$38.76	3.1	1.71	5.3		46.3
Interruption Cost Average per Customer per Hour		**$149.94**						

The customer VOLL is summed across all curtailment events in the year and then averaged over 6,160 simulations to obtain the expected annual value of lost load for any given level of EUE. As more gas-fired peaking plants are added in increments of 100 MW, the service reliability for PSE increases, which results in lower levels of EUE and VOLL. The reduction in the VOLL for the PSE system as new capacity is added to the portfolio is the marginal benefit of reliability.

3.0 Pacific Northwest Outage Analysis

When analyzing outage cost estimates within the Pacific Northwest region, there are a variety of factors to consider: weather patterns, seasonal changes, and vegetation hazards. Statistical regression can be used to determine the weights of these factors and the relative influence they have on outage costs. This information is useful for distribution and transmission planning. For example, utilities need to balance the cost of reducing tree hazards with the cost of power disruption to customers.

In order to capture the value of outage avoidance to various electric customers, a survey can be performed. The survey needs to be designed to capture the impact of an outage based on a variety of durations, in addition to the times of day, week, and year. Including time as a variable helps determine the indirect costs that customers experience, especially within the residential sector. For example, indirect costs to customers may be greater if an outage of significant duration were to occur in the winter, whereas, the indirect costs may be lower during the summer.

The Department of Energy's Interruption Cost Estimator (ICE) can also be utilized to derive an estimate of interruption costs for Puget Sound Energy and other Pacific Northwest utilities. The first input for this calculator is a breakdown of all electric customers' category, residential and non-residential. Based on PSE's 2018 base demand forecasts, it is estimated that there are 1,011,079 residential customers and 139,875 non-residential electric customers [1]. The next set of inputs for the calculation are the following reliability values:

- The System Average Interruption Duration Index (SAIDI), which describes the average length of an outage in minutes [11].
- The System Average Interruption Frequency Index (SAIFI), which describes the average number of outages a customer experiences [11].
- The Customer Average Interruption Duration Index (CAIDI), which is a measure of the outage duration, and is the ratio of SAIDI and SAIFI.

Utilities are required to report these reliability figures to the Washington Utilities and Transportation Commission (UTC). PSE's figures for 2017 were 175 for SAIDI and 1.12 for SAIFI [11], which results in a CAIDI value of 156.2. Given that SAIDI and CAIDI are time metrics (measured in minutes), the average time of restoration can also be computed from PSE's CAIDI value of 156.2 as 2.6 hours. The results of the ICE are summarized in Table 3 and Figure 4.

Table 3: ICE Detailed Results

Sector	Number of Customers	Cost Per Event	Cost Per Average kW	Cost Per Unserved kWh	Total Cost
Residential	1,011,079	$8.26	$5.57	$2.14	$9,358,885.02
Small Commercial and Industrial	128,791	$1,471.76	$348.45	$133.85	$212,294,949.41
Medium and Large Commercial and Industrial	11,084	$12,625.62	$85.06	$32.68	$156,735,464.45
All Customers	**1,150,954**	**$293.54**	**$91.57**	**$35.17**	**$378,389,298.89**

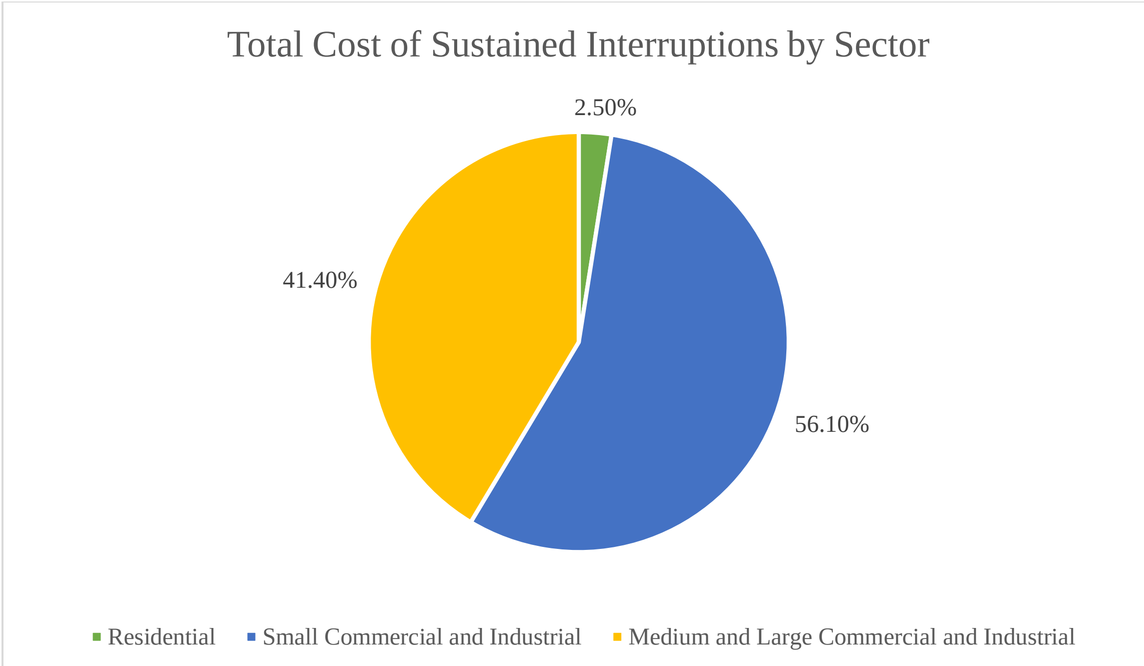

Figure 4: ICE Sector Results

4.0 Student Experience

This project was supported by a grant from the Snohomish Public Utility District. Two students were paid a stipend to conduct this research over the summer. They were advised by an electrical engineering faculty and engineers from a local utility. The interdisciplinary nature of this project made the project more challenging, as no one member of the team had all the knowledge needed to answer all the problems posed. The students learned to formulate a research problem, manage a project, and to communicate with professional engineers. As the students working on this project were not engineering majors, learning to communicate in the engineering parlance was part of the learning process.

"This work helped to better my education and professional experience in ways that are not traditionally available through academic coursework. I was able to bolster both my research skills and learn from my peers. Through this project I was able to improve my ability to communicate about my research." – WWU student

The students also noted challenges of such a project, especially the tight summer schedule. There was little time for background research, making the learning curve steep. It was also difficult at times reaching the industry engineers since they were prioritizing other projects or obligations. In the future, it would be helpful to ask for a clear commitment from industry so that their engineers are allocated time dedicated to helping the students on their projects. A regularly weekly meeting would have been very beneficial. The students did see merit in collaborating with industry, despite these issues.

"Reaching out to professionals working in the field allowed me to develop my network and advance my ability to connect with others. Overall this research opportunity gave me the chance to establish a working relationship with engineers from industry, faculties, and WWU students from other majors." – WWU student

The results of the research were presented to other engineering students staying on campus over the summer on a periodic basis. This allowed the students to build confidence in presenting their work. It was also an opportunity for them to develop communications skills with students outside of their major. Finally, the cross-collaboration amongst the students provided a rich environment for discussions that further shaped this research in beneficial ways.

5.0 Conclusion

The importance of reliable electricity supply could not be overstated. When outages occur, economic productivity grinds to a halt, and losses accumulate. This project investigated the costs associated with power outages with a focus on the Pacific Northwest region. There are many factors that contribute to outage costs, including geographical, temporal, and duration. In addition, residential, commercial, and industrial customers are affected differently by the power outages. This project investigating outage costs was conducted by two students working over the summer under the guidance of a faculty adviser and with input from professional engineers from a local utility. The students' experience working on this research and the challenges they faced are discussed.

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