Department of Electrical Engineering and Automation

Economic Impacts of Electric Power Outages and Evaluation of Customer Interruption Costs

Sinan Küfeoğlu

Aalto University

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Economic Impacts of Electric Power Outages and Evaluation of Customer Interruption Costs

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Abstract

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Abstract

Electricity has become a vital part of the modern societies. Thanks to using electrical equipment in almost every aspect of the life, in case of an interruption the daily routine is paralyzed. Whether the electricity is a social right or not is still debatable. No matter it is a social right or commodity, improving the electric power reliability so that more people (or customers) will have the opportunity to make use of this service is in favor of everyone in the market.

Europe has been known to have robust, well developed and well planned electric power systems. This meant considerably high level of reliability for the European societies until the beginning of 2000's. Nevertheless, during the last decade there has been an increase in the number of extreme weather related disasters throughout the world. Natural disasters have become the primary threats for the continuity of electricity service in Europe and in the rest of the world.

Studying customer interruption costs and proposing credible and practical estimation methods is a challenging task. The necessity of this research arose from the lack of widely accepted and easy to adopt approaches in the field. Each customer segment has its own distinct electric power consumption and dependence characteristics. This fact indicates the necessity of analyzing each customer group separately and proposing unique customer interruption costs estimation techniques. Having a developed power system and easiness to reach credible data for analysis, Finland is a proper country to study the economic impacts of the electric power interruptions. The ultimate goal of this research is to provide outage cost estimations which will be; customer specific, utilizing publicly declared and objective data, demanding less time, less money and less effort, easy to duplicate in any part of the world and providing credible and sound results.

In order to achieve these goals, in this research, the customers are divided into three main segments; industry customers, service customers and residential customers. Different and unique customer interruption costs estimation methodology has been proposed for each customer segment.

Keywords electric, power, reliability, customer, interruption, costs

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First of all, I would like to be modest and thank myself for achieving such a great research work in such a short time period. Without my unprecedented intellectual skills it would be impossible to complete this thesis. I am so grateful to my rich genetic inheritance which made me remarkably smart, handsome and cool. After having a little smile on our faces now we can get back to seriousness.

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Finally I would like to express my deepest love for my family for their unconditional and endless love and caring. I am the luckiest person on earth to have such a great family.

Espoo, 6 May 2015
Sinan Küfeoğlu

Contents

List of Abbreviations and Symbols

Abbreviations

CDF	Customer Damage Function
CIC	Customer Interruption Cost
CICae	Customer Interruption Cost annual energy
CIC_{DW}	Customer Interruption Cost Direct Worth
CICme	Customer Interruption Cost macroeconomic
CICp	Customer Interruption Cost planned, industrial sector
CICpe	Customer Interruption Cost price elasticity
CICpo	Customer Interruption Cost planned outage, service sector
CICpp	Customer Interruption Cost peak power
CICt	Customer Interruption Cost turnover
CICu	Customer Interruption Cost unexpected, industrial sector
CICuo	Customer Interruption Cost unexpected outage, service sector
CICva	Customer Interruption Cost value added
DSO	Distribution System Operator
DW	Direct Worth
GDP	Gross Domestic Product
LV	Low Voltage
MV	Medium Voltage
RW	Relative Worth
SAIDI	System Average Interruption Duration Index
SCDF	Sector Customer Damage Function

SRF	Strategic Response Factor
SSCDF	Subsector Customer Damage Function
WTA	Willingness to Accept
WTP	Willingness to Pay

Symbols

Kp	Coefficient for planned outages
Ku	Coefficient for unexpected outages

List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals

I Küfeoğlu, Sinan; Lehtonen, Matti. Evaluation of power outage costs for industrial sectors in Finland. In *22nd International Conference and Exhibition on Electricity Distribution, CIRED*, volume 2013, issue 615, pp. 1-4, Stockholm, Sweden, 10-13 June 2013.

II Küfeoğlu, Sinan; Lehtonen, Matti. A Novel Hybrid Approach to Estimate Customer Interruption Costs for Industry Sectors. In *Engineering*, volume 5, issue 10A, pp. 34-40, 2013.

III Küfeoğlu, Sinan; Lehtonen, Matti. Customer Interruption Costs Estima Tions for Service Sectors via Customer Survey Method: a Case Study, In *International Review of Electrical Engineering*, volume 8, issue 5, pp. 1532-1538, 2013.

IV Küfeoğlu, Sinan; Prittinen, Samuel; Lehtonen, Matti. A Summary of the Recent Extreme Weather Events and Their Impacts on Electricity. In *International Review of Electrical Engineering*, volume 9, issue 4, pp. 821-828, 2014.

V Küfeoğlu, Sinan; Lehtonen, Matti. Cyclone Dagmar of 2011 and its impacts in Finland. *In IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, pp. 1-6, Istanbul, Turkey, 10-12 Oct. 2014.

VI Küfeoğlu, Sinan; Lehtonen, Matti. Interruption costs of service sector electricity customers, a hybrid approach. In *International Journal of Electrical Power & Energy Systems*, volume 64, pp. 588-595, 2015.

VII Küfeoğlu, Sinan; Lehtonen, Matti. Comparison of different models for estimating the residential sector customer interruption costs. In *Electric Power Systems Research*, volume 122, pp. 50-55, 2015.

VIII Küfeoğlu, Sinan; Prittinen, Samuel; Lehtonen, Matti. Customer Inter ruption Costs Calculation of Finnish Electricity Customers. In *12th Inter national Conference on the European Energy Market*, Lisbon, Portugal, pp. 1-5, 19-22 May 2015.

Author’s Contribution

The author was responsible for all publications presented in this thesis as the main author. All data analysis and interpretations have been carried out by the author. All novel customer cost estimation models have been introduced by the author.

1. Introduction

Electric power business has changed dramatically over the past 30 years. There is a considerable change in the structure and electric power system operation throughout the world. As it is the case in Finland, in many countries, vertically integrated traditional system consisting of generation, transmission, distribution and retail at one hand, as a monopoly, has gone through unbundling. By this way, the system has been decomposed into separate and distinct bodies which perform just a single function of the whole power system. The main objective of a modern and developed electric power system is to provide more affordable, more sustainable and more reliable electricity to the customers. For the customers, reliability simply means continuous and high quality electric power.

Electricity has become a vital part of the modern societies. Thanks to using electrical equipment in almost every aspect of the life, in case of an interruption the daily routine is paralyzed. Whether the electricity is a social right or not is still debatable. However, in many parts of the world the perception by the people is in the way that reaching the electric power whenever and wherever needed is a social right rather than considering electricity as a commodity. No matter it is a social right or commodity, improving the electric power reliability so that more people (or customers) will have the opportunity to use it is in favor of everyone in the market. The customers, the authorities, the utilities and the retailers wish for securer electricity system. At this point two questions arise: "What is the optimum level for the reliability?" and "What is the economic worth of it?" The answer of the first question is not in the scope of this research. On the other hand, many researchers have been proposing solutions to answer the second question [1] – [21]. The question is related to the electric power interruptions. Understanding the economic impacts of the electric power interruptions is more crucial than it was in the past. Under the light of this fact, there have been numerous studies to come up with an estimation of the power outage costs for the last 30 years. Nonetheless, there is no widely accepted methodology that proposes a credible and acknowledged estimation to the economic impacts of the electric power interruptions yet. This makes studying the customer interruption costs (CIC) an attractive area of interest for the members of the electric power society.

Europe has been known to have robust, well developed and well planned electric power systems. This meant considerably high level of reliability for the European societies until the beginning of 2000s. Nevertheless, during the last decade there has been an increase in the number of extreme weather related disasters throughout the world. Natural disasters have become the primary threats for the continuity of electricity service in Europe. The impact of global warming have reflected itself as increased frequency of severe floods, hurricanes, storms and snow storms. European floods of 2002, 2010 and 2013, European winter storms and heavy snow fall of 2012, cyclone Dagmar of 2011 are some examples showing the catastrophic consequences of natural disasters for electric power infrastructure. Every extreme weather event means long lasting and extensive blackout thus it creates unrest among the people and the authorities. These undesired events resulted in questioning the real power reliability level of Europe. Extreme weather related interruptions have been pushing the member states of the European Union introduce new policies and regulations. The aim is to boost investments to strengthen the infrastructure and to improve the security of the system.

1.1 Aim of the Research

Studying customer interruption costs and proposing credible and practical estimation methods is a challenging task. The necessity of this research arose from the lack of widely accepted and easy to adopt approaches in the field. Each customer segment has its own distinct electric power consumption and dependence characteristics. This fact indicates the necessity of analyzing each customer group separately and proposing unique CIC estimation techniques. Having a developed power system and easiness to reach useful data for analysis, Finland is a proper country to study the economic impacts of the electric power interruptions. The ultimate goal of this research is to provide CIC estimations which will be:

- Customer specific
- Utilizing publicly declared and objective data
- Demanding less time, less money and less effort
- Easy to duplicate in any part of the world
- Providing credible and sound results

To achieve these goals the customers are divided into three main segments; industry customers, service customers and residential customers. Different and unique CIC estimation methodology has been proposed for each customer segment.

1.2 State of the Art

Understanding the nature of the electric power interruptions is a must before going into detailed analysis of the economic impacts of those. The interruptions could be studied under three titles: momentary interruptions, sporadic interruptions and chronic interruptions [22]. Momentary interruptions last for a very short time typically some seconds, or even less than one second. Sporadic interruptions are resulted from harsh weather conditions such as storms, floods or thunder storms. This type of interruptions pose a great threat to the power system since they cause long lasting blackouts which mean significantly high economic losses for the members of the electric power system. Chronic interruptions, on the other hand, might be triggered by many factors. Poor power system planning and operation, insufficient power generation, the faults caused by the power system operation or overloading of the system and faults in the power system due to aging or lack of maintenance are of some of the main sources of the chronic interruptions [22]. The main danger of this concern about this type of interruption is the duration of the cuts in the service. The outage might last from minutes to hours depending on the source of the problem. The frequency of the chronic interruptions is much higher. Therefore this research focuses on the economic outcomes of the chronic outages. The impacts of momentary interruptions are dealt with under the title of economic worth of power quality events [23]-[33]. The consequences of sporadic events are summarized in the Publications IV, V and the Section of 2.5 of this thesis provides a brief information based on a Finnish storm experience [V, 34].

To fully understand the consequences of the power outages, the impacts caused by these events must be analyzed and classified carefully. In the impact assessment report prepared by the US Department of Energy after the 1977 New York City blackout the impacts of power disruptions were grouped into two main categories: direct and indirect impacts [35]. The direct impacts cover loss of manufacturing and production, interruption of services such as transportation, telecommunication and so on, loss of sales, damages on the equipment, spoiled goods, damages on the electronic data, accidents and injuries. To measure the monetary worth of these events is a relatively easy task when they are compared to the indirect impacts of the power disruptions. The nature of the indirect consequences of the outages is quite complicated. Some of them reveal the true costs in a longer time period. These include public disorder, looting, arsons, other crimes seen upon blackouts, overtime payments to the personnel, cancellation of social activities, property losses, increasing insurance rates, lost tax revenues and so on. Many of these events mean severe economic losses. It is a rather complicated and challenging task to measure these losses since they are seen in a longer time period than the direct impacts. As it can be guessed, the report [35] and the study [36] show that the cost of the indirect impacts are much higher than the direct ones. Calculating the indirect economic losses of the outages demands large scale and tedious case studies. This necessity is not in line with the main purpose of this research, which is to avoid such heavy works. Therefore, this thesis has only focused on the estimation of the economic worth of the direct impacts of the electric power outages.

Assessment of the CICs has two major parts. The first question is "How will the necessary data be collected?" and the second part is "How will the existing data be interpreted?" The first point is the way of collecting necessary data for the analysis process to make estimations and suggestions about the CICs. When the suitable means for the data collection is selected, the second main challenge arises; How the raw data should be interpreted to reach as bias free as possible results for the sake of a reliable CIC analysis.

The data collection can be done either by customer surveys or by making use of readily available analytical data. The references [37]-[53] are based on customer surveys. The papers [54]-[60] are based on objective data such as electricity tariffs, value added or turnover, gross national product, the annual energy consumption or the peak power reached during a year of a customer group, region or a country. On the other hand, the studies [61]-[71] focus on comparison of the existing techniques, critical overviews, data elimination techniques and etc. The worth of power reliability has a broad meaning and it covers the quality events as well. And it is known that the abnormalities in the power quality result in economic losses especially for some of the sub-sectors in the industrial sector customers. However, in order to be more focused on the assessment of the CIC, the worth of power quality events have been excluded from this research.

Each customer group has its own unique power consumption characteristics. Therefore each customer segment has distinct electricity dependency yielding different economic losses. These groups can mainly be identified as industry, service (or commercial), residential and agriculture. Since the share of the electric energy consumption of the agriculture sector is much less than others, the majority of the references listed above focus only on industry, service or residential customers.

2. Customer Interruption Cost Analysis Approaches and Impacts of Extreme Weather Conditions on Electricity

There have been quite many approaches suggested to estimate the CICs. However three major methodologies have been extensively preferred by the researchers. These are compiled and presented in detail in CIGRE Task Force report of 2001 [72]. These widely adopted methods are: indirect analytical methods, customer surveys and case studies.

2.1 Indirect Analytical Methods

In indirect analytical methods, the main point is to use publicly available, easy to analyze and, most importantly, objective data such as the electricity prices or tariffs, value added of a related company, gross national product of a country and the annual electricity consumption of that company, country or region. To assess the interruption cost, the value of the lost leisure time is considered in the case of residential customers. For instance, to find out the interruption cost of a given region or country, the annual gross national product is divided by the total electrical consumption. The resulting ratio ($/kWh or €/kWh) gives a rough idea about the cost of the outage. Customer Damage Function (CDF) is defined as to show the economic loss incurred by the customers due to power outages. It is defined as monetary amount of damage against per outage, per kWh of unsupplied energy or per kWh annual consumption of energy. In indirect analytical analysis CDF is generally used to give an idea about the loss of the economic value.

Indirect analytical method is advantageous since it contains publicly declared, easy to reach and most importantly objective data like electricity prices and turnovers. In addition, it is quite straightforward to apply and it is a cheap method to find out the outage costs. Therefore this approach yields highly objective estimations in a shorter time and with less effort when compared to the other methods [72]. On the other hand, however, despite its advantages there are severe disadvantages as well. This methodology presents too broad and average results while the utilities seek for more specific and customer based results. Furthermore, having neither value added nor gross domestic product data, calculating residential outage costs is difficult and subjective. Hence, the results obtained by the indirect analytical methods are not completely useful to the utilities for their planning purposes [72]. The regulatory authorities and the utilities demand for customer specific results with as low error margin as possible. This fact makes the indirect analytical methods less attractive and less preferable by the researchers and professionals.

2.2 Customer Surveys

The customer surveys have been the most preferred methodology for calculating the outage costs. In the survey, there are questions about estimating the outage costs due to interruptions at several time durations at different times of the day (during working hours and outside working hours) and different times of the year (summer and winter). What makes this method superior to the other two is that it provides more accurate and sufficient outage cost data for planning purposes [72]. However, there are major disadvantages of this method. The most important one is its cost. Since the number of responses at the customer side to such surveys is low, in order to get more accurate data, the questionnaire must be done to as many customers as possible. The other drawback is its requirement of high effort to collect the necessary data. These surveys are conducted by one-to-one interviews, telephone calls, and sending and receiving e-mails. To collect the necessary data there are three major research methods used in customer surveys, namely; preparatory action method, direct worth approach and the price proportional method [72].

Preparatory action method (PAM) is a direct method that evaluates the costs in terms of avoiding the harm of interruption. Direct worth approach (DW) or direct costing is a method that presents different outage scenarios and asks the customers to estimate a rough cost in case of the scenarios. By directly asking the economic losses that arise from the interruptions, this method reduces the biases that are resulted from the customers. Thus, for data collection purposes this technique is considered as the most reliable tool. However, there are significant concerns about the credibility of this method as well. The problem of zero responses and strategic responses is a critical challenge for the surveyors during the analysis process. A more detailed analysis of the strategic and zero responses is presented at Section 2.6.2. The price proportional method, on the other hand, is a direct method as well. It contains willingness to pay (WTP) and willingness to accept (WTA) approaches. In WTP the survey asks the customers that how much they are willing to pay for continuity of service or to avoid a predefined power outage. On the other hand, in WTA, the survey asks the customers how much they are willing to be compensated in monetary means in case of a worse reliability of electric distribution system or in case of a predefined outage [73]. Author experiences and a customer survey study [VII, 48], [74] show that there is a large gap between WTA and WTP figures. It is not surprising to acquire the WTA ten times larger than the WTP for the same outage scenario [VII, 48]. The respondents are demanding more compensation while they are ready to pay less money for the same outage incident. This is why the WTP and WTA results are not and should not be used alone in the outage cost evaluation studies. This observation makes the credibility of these methods quite low. However, by setting lower and higher boundaries to the expected outage costs, it is a valuable tool to make use of WTA and WTP studies [62].

2.3 Case Studies

The case studies are carried out after large and significant blackouts which affect large areas, typically millions of customers. This type of study covers both direct and indirect costs of interruption. Direct costs include loss of sales, loss of food, etc. and the collected data is quite accurate to be made use of in the study. On the other hand, indirect costs include emergency costs and losses due to civil disorder during the outage. In fact, these costs are really difficult to determine, but studies show that they can be higher than the direct costs [35], [36]. Being conducted after a real interruption, this method has the advantage of collecting more accurate data. Since the outage event is live in the minds, the customers are in best position to assess the economic losses linked to the interruption. However, there are certain concerns about this methodology as well. One of them is that the frequency of the extensive blackout events is quite low. This means carrying out such studies is rare. Some of the major blackouts were seen during the Northeast Blackouts of 1965 and 2003, New York City Blackout of 1977 and during the California Electricity Crisis of 2000-2001. In addition making an analogy between large blackouts and small scaled blackouts is quite difficult. Due to the specified reasons and high expenses of carrying out such studies, case studies are not favored by the majority of the researchers and by the professionals. However including quite useful and detailed information, case study findings are crucial for the other CIC assessments. One of the most significant case study was carried out by the Department of Energy, US after the infamous New York City blackout of 1977 [35]. Another detailed study conducted in Sweden after the severe storm Gudrun in 2005 can be found at [74].

2.4 Extreme Weather Events

Providing secure and reliable electricity is already a challenging task for the utilities and for the authorities even under normal conditions. In case of abnormal conditions which will result in unexpected disruptions in the power systems this challenge increases by many folds. Extreme weather conditions are likely to trigger natural disasters like floods, hurricanes, winter storms, thunder storms and so on. These events pose great threat to the electric supply security hence they cause long lasting blackouts. These blackouts create excessive amount of economic losses for the societies.

The authorities are quite careful in planning the electric power system. The supply demand balance is the key concern for the planners. However there are many intangibles affecting the planners and the concepts of supply security and power system reliability is a complicated field. The security of power transmission and distribution is the core part of providing undisrupted electric power. The developed countries have robust, well – planned and well – operated power systems. This meant high level of supply security for the customers in these countries. However, the experiences during the last decade clearly showed that the electric power system in Europe and North America is not as reliable as it was thought to be. The extreme weather conditions threaten the supply security. The increasing number of natural disasters, and their tremendous impacts on the societies and on the economies arouse questions about the true level of security of the power system infrastructure in these regions. As it was seen in many occasions, the authorities start to take action only after a severe disaster to harden the infrastructure. This is done via policy changes and introducing more and more regulations which aim to push the utilities to take action and invest more on the transmission and distribution system infrastructure.

The summary of the recent extreme weather events and their impacts on electric power system is given at the studies [VIII, 75], [IV, 76]. Cyclone Dagmar and its impacts in Finland is a fine example to show the consequences of natural disasters on electricity and to present the following policy changes which were introduced after the event.

2.5 Cyclone Dagmar of 2011 and its impacts in Finland

Finland has been known to have a secure electric power system. Nevertheless, after the Cyclone Dagmar of 2011, locally known as Tapani storm, there has been a discussion among the Finnish people on the true level of supply security in Finland. Both the impacts of the storm on the society and the radical regulatory actions taken after the storm make this unpleasant experience an appealing topic to study.

2.5.1 The Storm

Before the Tapani storm, in the summer of 2010, Finland underwent another serious natural event that affected the continuity of electricity supply vastly. During the summer storm of 2010 481,000 customers (almost 15% of total customers in the country) suffered from outages [77]. After one year, the Tapani experience showed that neither the Finnish Distribution Systems Operators (DSOs) nor the authorities learnt necessary lessons from previous examples. During the winter storm of 2011 the power cuts were seen throughout the country. The duration of the blackouts changed from minutes to several days. In some rural places, the outages lasted up to three weeks [78]. Out of 3.2 million, almost 570,000 customers experienced power cuts [1]. The consequences of the interruptions were not surprising. Large areas went into darkness, there were widespread loss of lighting, heating, hot water, and there was a shortage of fresh water. Almost all social activities were cancelled, services including transportation and telecommunication disrupted and the daily life almost came to a halt. The Figure 2.1 shows the sharp increase in the outage durations experienced due to the storms of 2010 and 2011 with respect to the distribution areas.

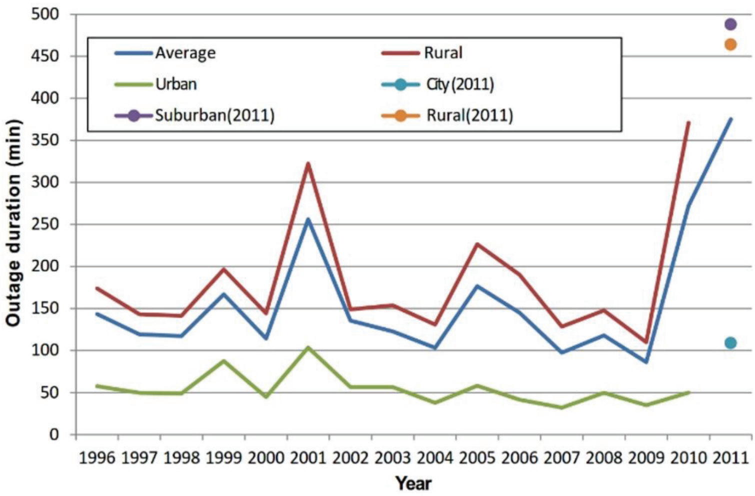

Figure 2.1. Distribution system average outage duration per secondary substation area in Finland [79].

The duration of power interruptions seen in Finland between the years 1996 and 2011 are summarized in the Figure 2.1. The only relief about the storm experience was that there were no public disorder, looting or arsons seen during the blackouts.

2.5.2 Actions taken after the storm

As it can be seen in the Figure 2.1, before 2011, the Finnish electricity distribution system was grouped as urban and rural area distributions. After the 2010 storm the Finnish authorities decided to regroup the distribution areas in order to address the new regulations better. In 2011 the distribution system areas were divided into three: city area (urban), suburban and rural area. Maximum allowed outage times that will not require any penalties and targeted degree of cabling were decided accordingly. To further harden the distribution system infrastructure, in 2013 the distribution areas were divided into four. These are: city, urban, suburban and rural areas [80]. When the Figure 2.1 is checked, it is seen that the number of outages in city region is much lower than that of suburban and rural regions.

To understand this dissimilarity of outage characteristics among the areas of the distribution it will be sufficient to examine the characteristics of the Finnish electric power network. The medium voltage (MV) network in Finland is 130,000 km long. Overhead lines comprise about 88% of the total network. Over 70% of these lines pass through forests. This means obstacles with fault detection and repair efforts in case of power interruptions. The major fault source is the falling trees over the distribution lines. On the other hand, in the urban regions the degree of cabling increases in the low voltage (LV) networks. The degree of cabling in all LV network is 38% where it is below 30% in the rural region [81]. 58% of Finnish electricity customers live in rural distribution area. The DSOs and the authorities are aware that if the level of reliability is to be increased, the degree of cabling has to be increased substantially especially in the rural distribution network.

In 2003 in order to protect the consumers and push the DSOs for a service with higher quality, Finland introduced maximum allowable time limits for a single interruption event and set various penalties which change with the duration of the interruption event. According to the Energy Market Act of Finland in 2003, if the maximum time limit is exceeded, the DSO is obliged to pay a compensation to the customer [79]. The time caps and the corresponding customer compensations are summarized in the Table 2.1.

Table 2.1. The customer outage compensation scheme according to the legislation accepted in Finland in 2003 [79].

Outage time (h)	Compensation (%)
12 - 24	10
24 - 72	25
72 - 120	50
>120	100

In case of exceeding the limit, the DSO is supposed to pay a compensation to the customer that will be equal to the corresponding percentage of the annual electricity fee that the customer paid to the DSO over the last year. The maximum amount of money that one consumer can receive in a year was decided to be 700 €. Table 2.2 summarizes the standard customer compensations paid from 2005 to 2011 [79]. It is obvious that after 2010 there is a considerable increase in the penalties. These are the natural effects of the 2010 and 2011 storms.

Table 2.2. The yearly change of compensation amounts and the share of the customers that received these compensations [79].

Year	Sum of compensation paid (€ M)	The customer share that received compensation (%)
2005	2.62	1.56
2006	2.75	1.37
2007	0.36	0.24
2008	0.83	0.58
2009	1.42	0.71
2010	10.12	3.39
2011	46.79	11.1

2010 and 2011 examples indicated that the compensation scheme of 2003 was not adequate to prevent long lasting blackouts. Therefore in 2013 the Finnish government went through an update in the Energy Market Act and brought in new time caps and new penalties for the outage events. Table 2.3 summarizes the update in the standard customer compensations in Finland.

Table 2.3. The customer outage compensation scheme in 2013 [82].

Outage time (h)	Compensation (%)
12 - 24	10
24 - 72	25
72 - 120	50
120 - 192	100
192 - 288	150
>288	200

According to the new market act, the maximum percentage of compensation is raised from 100% to 200%. The maximum annual penalty was raised from 700€ to 2,000€ per year [82]. In addition new penalties for longer outage times of a single event were defined. In the Figure 2.2 and Figure 2.3 the variation of the number of customers who received compensation and the amount of compensation paid to the customers due to the interruptions between the years 2005 and 2011 are presented correspondingly. When the Figure 2.2 is observed, it is seen that about half of the fine paid by the DSOs to the consumers were due to the outages longer than 72 hours. It is evident that in case of severe natural disasters such as storms, long lasting blackouts pose a danger to both the well-being of the society and to the financial position of the DSOs.

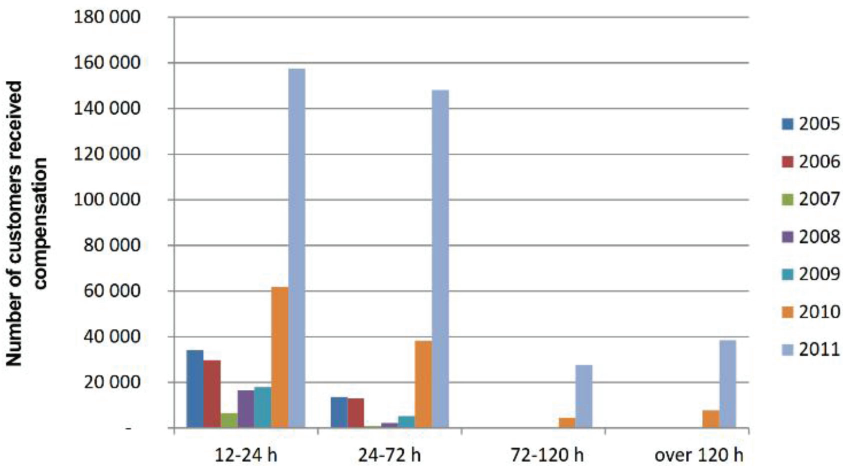

Figure 2.2. The share of the number of customers who received compensation with different outage time spans in 2005 – 2011 [79].

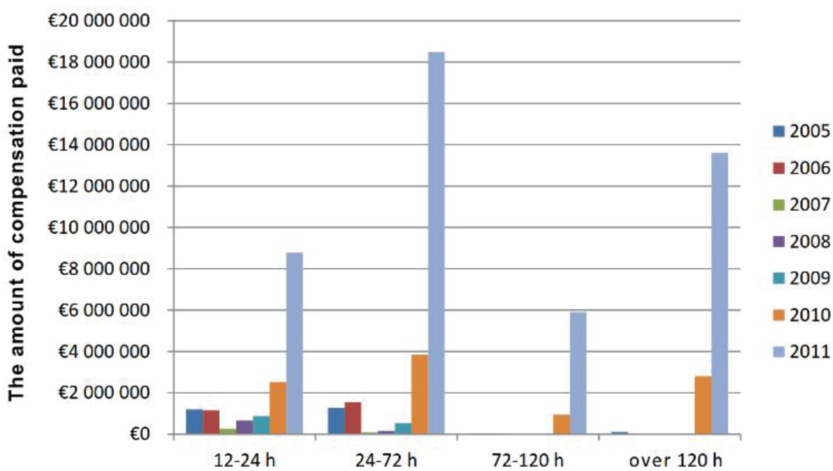

Figure 2.3. The amount of the compensation paid to the customers with different outage time spans in 2005 – 2011 [79].

2.5.3 Summary

The nature events have become the primary threats to the electric power reliability. Figure 2.4 illustrates the causes of the outage times in Finland between 2007 and 2012. It is seen that nature is the main reason of power cuts among technical, planned and other causes. Figure 2.5 shows the distribution of the different nature events that ended up disruptions in the electricity service.

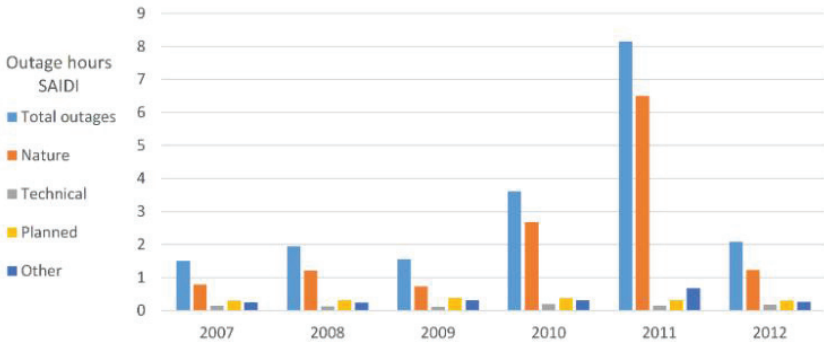

Figure 2.4. SAIDI outage hours in Finland between 2007 – 2012 [83].

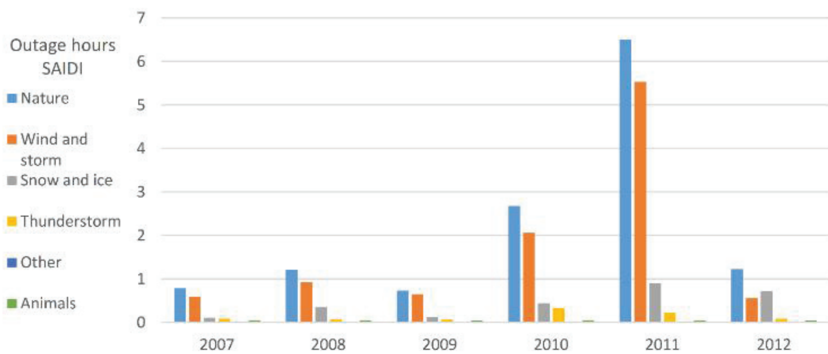

Figure 2.5. Nature events SAIDI outage hours in Finland between 2007 – 2012 [83].

The DSOs and the authorities are aware that both the number of interruptions and the duration of interruptions increase noticeably in case of extreme weather events. The impacts of global warming are still controversial, statistics show that the frequency of extreme weather events have increased for the last decade. As the essential precaution to prevent extensive blackouts, the Finnish government plans to increase the degree of cabling in the distribution network. Currently, the degree of cabling in LV network is 38% and it is 12% in the MV network [81]. Another solution is to enlarge the distribution line corridors that pass through forests by devegetation. Furthermore, in coordination with the Finnish Ministry of Transport and Communication, it is aimed to move the overhead distribution lines from inner forests to the road sides [79]. These are all long term plans and they will incur high costs to the country. Naturally this vast transformation will reflect itself as higher electricity tariffs. The authorities came to a consensus with the DSOs and there is widespread public support for hardening the countries power infrastructure. A public survey including 25,000 people conducted by YouGov reveals the public opinion about the power reliability in Finland [84]. Half of the surveyors say that the security level of the electricity distribution is already good, or very good. And about 65% of the participants are ready to pay for better security. 5% accepts significant raises in the tariffs while 57% is ready to accept moderate increases in the electricity prices.

The amount of economic losses of the Tapani storm is unknown. The repair costs of the power infrastructure exceeded 30 million euros [77]. When the standard customer compensations are added the figure hits to 80 million euros. The total economic loss will increase substantially when other damages such as loss of services, loss of manufacturing, cancellation of leisure activities, cost of spoiled materials and etc. are taken into account.

2.6 The Material and Data Elimination

2.6.1 The Material

There are many factors affecting the customer interruption costs. The duration of the interruption, the character of interruption (whether it is unexpected or planned), the time that the interruption happens (whether it is during working hours or outside working hours) and the season (summer or winter). On the other hand the type of the customer (industrial, service, residential or agricultural) come forth as the most crucial factor when unique estimation techniques are proposed. The material that constitutes as a basis for this research contains three distinct customer groups. These are; industry sector, service sector and residential sector customers. In the customer surveys questions were arranged by emphasizing changing outage factors. Firstly, as the duration of the interruption increases, naturally the cost of that interruption will rise as well. According to the study conducted by the Berkeley National Laboratory [85], customer interruption costs increase almost linearly for the first eight hours [85]. Secondly, the character of the power interruption plays a key role in evaluation as well. The consequences of an unexpected outage and a planned one are not the same for the customers. Naturally a customer will take measures if he/she is informed about the exact time when the outage will happen and how long that outage will last. As a result, the cost of a planned outage will be much lower than that of an unexpected one. Thirdly, for industrial and service sector loads, the time that the interruption occurs is vital in terms of electricity consumption. It is obvious that these facilities use most of their electric power during their working hours. The consumption is expected to be minimum outside working hours, which is clearly seen at the survey results. However, this situation is not valid for the domestic loads since there is no such thing as working or outside working hours with these consumers. Fourthly, the season plays a crucial role in power interruptions as well. Customers' electric energy consumption vary seasonally mainly due to heating and cooling.

The most significant parameter of all is the customer type. There is an increasing dependency of large industrial and commercial facilities on electrical and electronic equipment, which makes these facilities be more dependent on the reliability and the quality of the power supplied by electric utilities. When the amount of the power being used by these facilities is considered, the dependency on the reliability is understood better. That is why, the cost of an outage and power quality problems for the industrial and commercial facilities are far higher than those of smaller customers. The rate could be expected to be in orders of magnitude [86]. The method of estimating the outage costs of these customers should be more sophisticated. There are a few numbers of such large customers connected to the transmission lines or to the primary distribution feeder. The power consumption definitely changes in considerable amounts among these customers regarding the size, the production amount, the field that the company works in and the equipment that are being used by those facilities. Therefore, while estimating outage costs for the large industrial and commercial facilities for utility planning purposes, using average cost estimation techniques is not advised. Instead of using average values, each individual industrial and commercial sector must be analyzed separately [87]. During our survey the customers are divided into two main categories, namely, industrial and service sector categories. And then, due to the reasons explained above, by aiming to reach more customer specific results, the customers are divided into subcategories. The details of the customer survey which constitutes a basis for the industry and service sector analyses of this research is given at the Appendix. In this study the outcomes of a comprehensive customer survey designed to investigate the economic worth of power interruptions for the industrial service sectors in Finland has been used [88]. In the survey, the Direct Worth (DW) approach has been followed by asking the respondents their expected economic losses in case of different power interruption scenarios.

On the other hand, the electric power consumption behavior and thus the economic impacts of the power cuts are totally different with the domestic customers. Therefore, a separate and target oriented customer survey has been conducted.

2.6.2 Data Elimination Procedure

There are certain concerns about the customer surveys. The first one is the quality of the respondents. Large industry customers employ professionals who know about the costs of the power interruptions. Even though predicting the true costs of the outage events is not possible, these personnel are able to give as credible as possible answers to the questions of the surveys. However, this opportunity is almost non-existent with the service sector and residential sector customers. Unqualified regular personnel might respond the surveys in a very short time and without paying too much attention. This creates doubts about the reliability of the customer surveys. Moreover, many respondents specify the economic losses of short outages as zero loss. The main motivation behind this could be to finish the survey as quickly as possible. However, it is a fact that, even in the case of short interruptions, there are economic losses incurred. On the other hand, some surveyors come up with unreasonably high cost figures for the predefined outage scenarios. These extreme monetary figures are called as extreme responses. The final threat to the credibility of the surveys is the strategic responses [40]. In order to alter the results of the survey, some respondents might intentionally give misleading figures to the outage cost estimations. All these concerns bring criticism for the customer survey approach to be highly subjective.

Data elimination process is a must to censor the zero and extreme responses. To do it there are several statistical tools available. Being extensively used and easy to apply, the z-score test has been chosen to eliminate unwanted data points from the data sets.

A z-score, or a standard score is the number of standard deviations an individual data point deviates from the mean. It is calculated as:

$$z = (x - \mu) / \sigma \qquad (2.1)$$

Where; z is the z-score, x is the value of the data point, μ is the mean of the data set and σ is the standard deviation of the data set.

In a standard normal distribution 99.7% of the elements fall within 3 standard deviation of the mean in either direction (where z-score is 3.0). When the z-score is chosen as 2.0, the percentage of the uncensored data drops to 95%. The score of 3.0 was chosen for the censoring of the industry sector data. However, as the reasoning explained above, for the service sector a more strict data elimination was needed. For this reason, in the service sector analysis, the z-score was chosen to be 2.0. However the distribution of the data is not suitable for going through elimination process. When the Figure 2.6 is checked, it is seen that the histogram of the responses of the customer survey is highly right skewed.

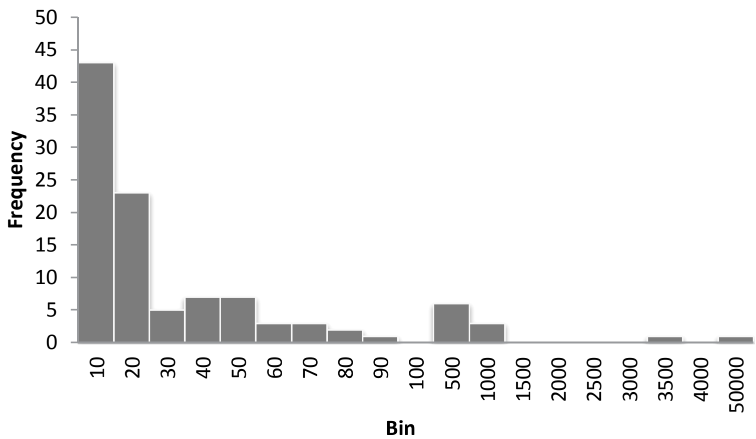

Figure 2.6. Uncensored distribution of the industry sector unexpected outage costs for 1hour in €/kW.

To apply an elimination method to censor the outliers of a response distribution which is highly right skewed will result in the loss of too many relevant data points in the analysis process To cope with this problem, converting the distribution into lognormal distribution has been suggested [40], [67]. The log normal distribution of the customer responses is given in the Figure 2.7.

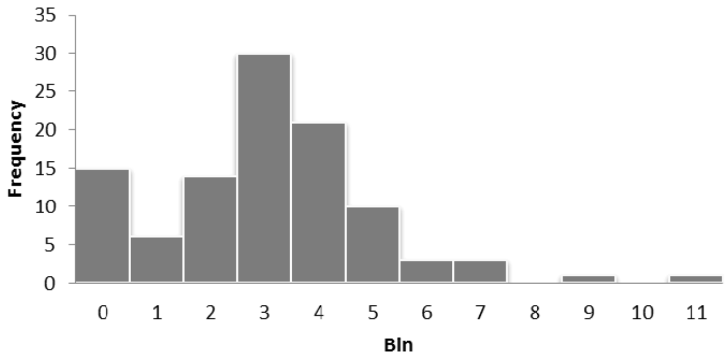

Figure 2.7. Uncensored lognormal distribution of the industry sector unexpected outage costs for 1hour in €/kW.

After censoring the raw data the lognormal distribution in Figure 2.8 was reached.

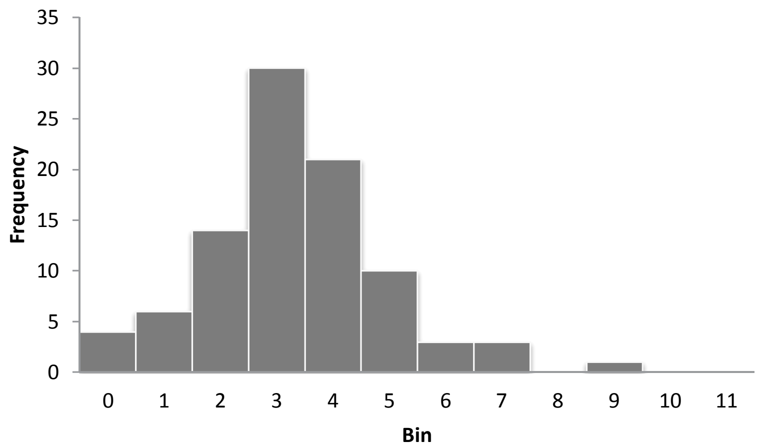

Figure 2.8. Censored lognormal distribution of the industry sector unexpected outage costs for 1hour in €/kW.

After censoring the outliers, the remaining data points have been transformed back to the normal values. Figure 2.9 shows the histogram of the remaining data points.

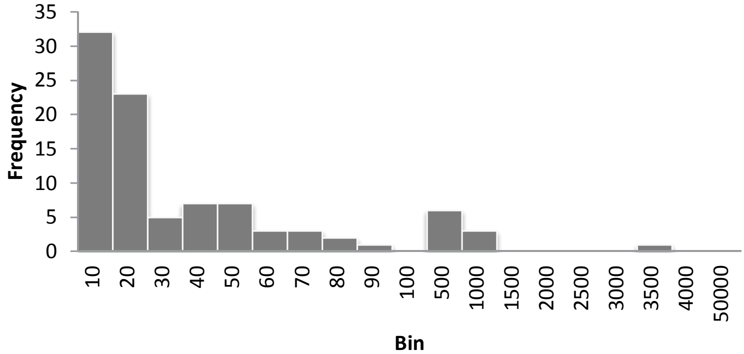

Figure 2.9. Censored distribution of the industry sector unexpected outage costs for 1hour in €/kW.

During the data elimination procedure of the service sector customers the z-score was taken as 2.0. The histogram of the censored and uncensored response distributions and the histogram of the logarithms of censored and the uncensored response distributions are presented in Figure 2.10 and Figure 2.11 correspondingly.

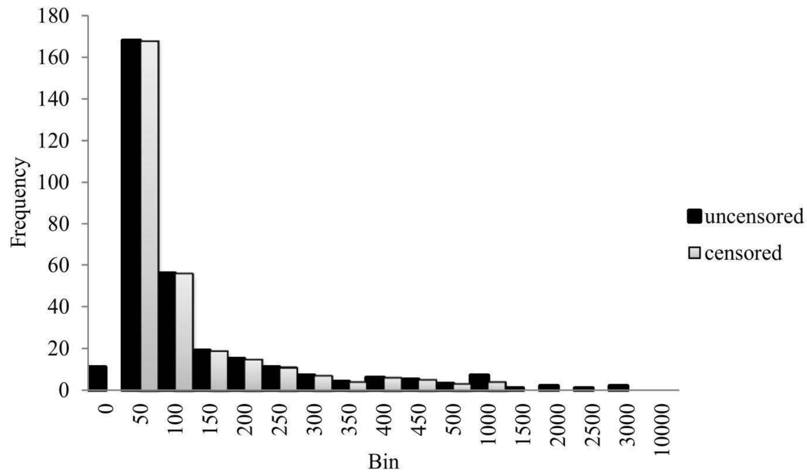

Figure 2.10. Uncensored and censored distributions of the service sector customers' unexpected outage costs for 1hour in €/kWh.

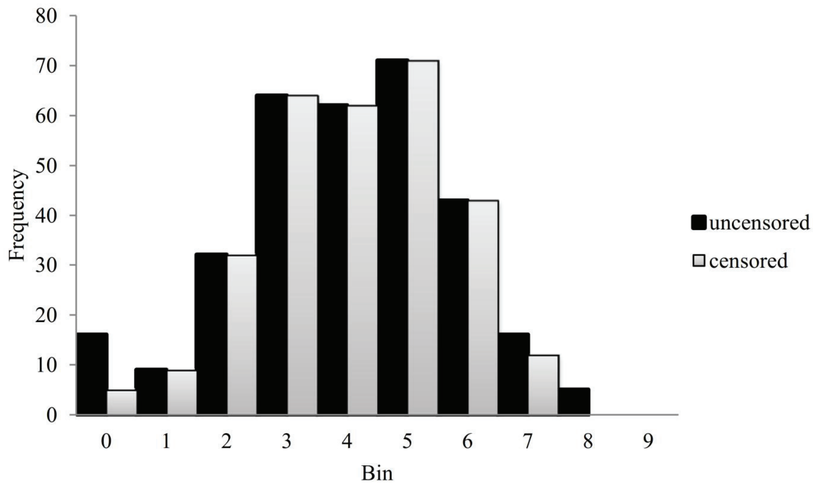

Figure 2.11. Uncensored and censored distributions of the logarithms of the service sector customers' unexpected outage costs for 1hour in €/kWh.

As it can be observed in the Figure 2.11, after the data elimination process, the remaining data set fits better to the normal distribution, which means that the remaining data is more appropriate to carry out further analysis.

Since characteristics of CIC of the residential customers are totally different from the industry and service sector ones, a data elimination process was not carried out for the domestic customers.

3. Industry Sector

Sector customer damage functions (SCDF) are used to evaluate the CICs [40], [68], [89]. These sectors include industrial, commercial (service), residential and agricultural ones. One of the main motivations that lead this research was the criticism on the SCDF approach. Through this approach all industry sector customers are assessed together in terms of the monetary losses of the power interruptions. It is clear that the customers' dependency on electricity and hence related CICs vary noticeably among the sub-sectors. For instance evaluating the food sector and construction sector customers together will only yield highly broad and average results. In order to reach more customer specific CIC estimations and to get more precise results, instead of dividing the customers into sectors, a more detailed approach has been adopted. In the customer survey the industry sector has been divided into subsectors. These are metal, food, chemical, glass, paper, timber, construction and electrical sectors. As a result, a new customer damage function (CDF), subsector customer damage function (SSCDF), has been introduced. There are two common practices for normalizing the outage costs. The first method is to use peak power reached by the customer during the previous year and the other one is to utilize annual energy consumption of the customer. By following the direct worth (DW) approach, the following CDF has been defined:

$$\boldsymbol{CICae} = \frac{Reported\ cost\ for\ an\ outage\ of\ t\ hours}{Annual\ energy\ consumption\ \ of\ the\ customer}\ in\ €/kWh \quad (3.1)$$

3.1 Research Method

One of the purposes of this research is to provide CIC estimations by using the analytical data as much as possible. Annual energy consumption, turnover and value added data of the industry sector customers are readily available and easy to reach. By making use of these data, a CDF of $CICva$ has been defined. It is the ratio of the value added for a certain time of period to the energy consumption during that time span. The load duration time for one year has been estimated to be 3000h per year [90]. By knowing each subsector customers' value added per year (€), the annual energy consumption (kWh) and the load duration time (3000 h), the $CICva$ per hour can be calculated easily.

$$\boldsymbol{CICva}\ for\ t\ hour\ per\ kWh = \frac{value\ added\ for\ one\ year}{annual\ energy * 3000\ h} * t \qquad (3.2)$$

In an industrial facility, the continuous production is present when there is continuous electric power. In addition industrial production leads sales and that creates value added. This means all three parameters are linearly related to each other. To illustrate the idea:

Continuous electric power ~ Production ~ Value added

To enable further and deeper analysis, in the customer survey the respondents were asked to express their losses in percentages by changing parameters. These are; production losses, restart losses, spoiled material losses, third party costs, damages and other costs for 1h, 4h and 8h time spans. The uncensored results of the customer survey are summarized in the Table 3.1.

Table 3.1. Average values of loss types in percentages for each industry sector.

Sectors	production	restart	spoiled materials	damages	third party costs	other
Food	50	3	36	1	0	10
Metal	60	6	5	8	9	12
Paper	58	15	2	4	0	21
Chemical	43	25	6	0	0	26
Glass	50	9	4	5	0	32
Timber	67	12	2	3	12	4
Construction	74	12	1	1	5	7
Electrical	63	7	5	1	3	21

3.1.1 Unexpected outages

The customers are caught unprepared if an unexpected outage takes place. This means the customer will suffer from all forms of losses specified in the Table 3.1. In order to relate the CIC to the analytical data of value added of each customer segment, a weighing factor Ku has been defined:

$$Ku = \frac{100\%\ (Total\ losses)}{percentage\ of\ production\ losses} \qquad (3.3)$$

Where;

Total losses (100%) = production losses + restart losses + losses of spoiled materials + damages + third party costs + other costs (3.4)

As a result a novel SSCDF for the unexpected outages has been defined as:

$$CICu = Ku * CICva \qquad (3.5)$$

3.1.2 Planned outages

The characteristics of the outcomes of the planned outages differ from the unexpected ones. For the planned outage case, another weighing factor is needed to convert the value added information into *CICp*. If the customers are informed about a planned interruption beforehand, they will take measures to minimize the losses. These measures include preventing the losses of damages, spoiled materials, third party costs and other costs. Production losses and restart losses will be the only ones that the industrial customer will suffer from. Thus, the weighing factor for planned outages is defined:

$$Kp = \frac{perc.of\ production\ losses + perc.of\ restart\ losses}{percentage\ of\ \ production\ losses} \tag{3.6}$$

As a result another novel SSCDF for the planned outages has been defined as:

$$CICp = Kp * CICva \tag{3.7}$$

The main idea is to accept the production losses as the basis and then reaching a CIC estimation by using its respective ratio to the other parameters. This approach is named as the Relative Worth approach. The typical values of *CICae, CICva, CICu, CICp*, and weighing factors *Ku* and *Kp* have been calculated for each sub-sectors for the analysis process.

3.1.3 Results

The censored average typical values of *Ku* and *Kp* coefficients for each sub-sector have been calculated and presented in the Table 3.2 and 3.3.

Table 3.2. Typical values of Ku weighing factors for different industry sectors.

Sectors	1h	4h	8h	average
Food	1.96	2.01	2	1.99
Metal	1.87	1.61	1.56	1.68
Paper	1.86	1.72	1.58	1.72
Chemical	3.48	2.17	1.88	2.51
Glass	2.37	1.91	1.79	2.03
Timber	1.71	1.52	1.32	1.52
Construction	1.43	1.31	1.31	1.35
Electrical	1.71	1.61	1.47	1.6

Table 3.3. Typical values of Kp weighing factors for different industry sectors.

Sectors	1h	4h	8h	average
Food	1.1	1.05	1.05	1.06
Metal	1.23	1.06	1.05	1.12
Paper	1.3	1.26	1.23	1.26
Chemical	1.96	1.44	1.53	1.64
Glass	1.45	1.11	1.07	1.21
Timber	1.3	1.18	1.08	1.19
Construction	1.16	1.15	1.15	1.16
Electrical	1.21	1.08	1.05	1.11

To see the relation between each SSCDF, the ratio of *CICae vs. CICu* and *CICae vs. CICp* have been plotted for each sub-sector for different time spans in the Figures 3.1 and 3.2 correspondingly.

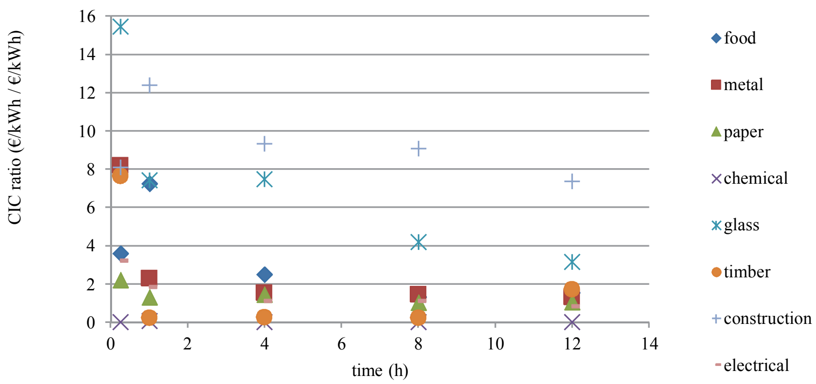

Figure 3.1. CICae/CICu ratios of industry sectors for the unexpected outage scenario.

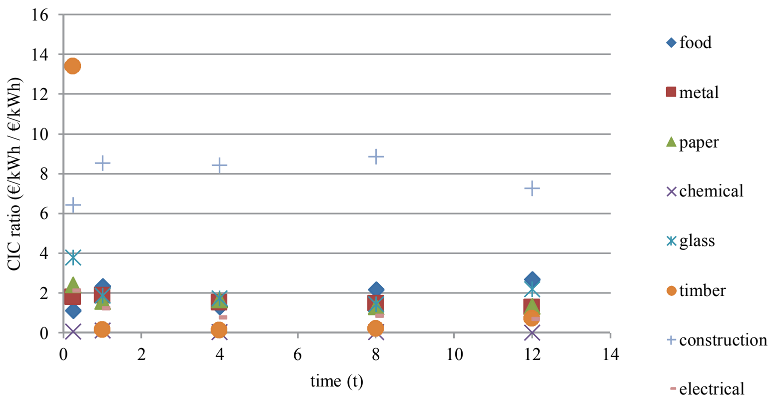

Figure 3.2. CICae/CICp ratios of industry sectors for the planned outage scenario.

It can be observed that as interruption time increases, the difference between the direct worth (DW) method and the econometric method, the Relative Worth (RW) approach, decreases and the ratio approaches to unity. More information and the details about the RW approach is given at [II, 45].

To illustrate the econometric model a rough example can be given. In case of an 1-hour interruption in a glass sector customer, the economic loss will approximately be;

- If it is an unexpected outage: CIC will be 2 times of the value added for one hour.
- If it is a planned outage: CIC will be 1.2 times of the value added for one hour.

One crucial conclusion is that the novel methodology fails to come up with credible estimations for momentary interruptions. The economic impacts of short outages and the voltage sags are investigated under the topic of economic worth of the power quality events. This topic is not in the scope of this research.

These results are encouraging to claim that the proposed econometric model is as credible as the direct costing one and it can be preferred as an alternative tool of handling the customer interruption cost estimation challenge in a faster, easier, cheaper and in a more objective way.

4. Service Sector

Many of the existing CIC studies adopt sector customer damage functions (SCDF) by categorizing the customers in the titles of industrial, service (or commercial), residential and agricultural customers [7], [19], [40], [68], [89]. This brings the criticisms of reaching highly average results which are not customer specific. By following the same logic that is presented in the industry sector CIC analysis procedure, the following sub-sector customer damage functions (SSCDF) have been defined and used throughout the analysis process.

$$\boldsymbol{CICt} = \frac{Annual\ Turnover\ of\ the\ customer\ for\ t\ hours}{Annual\ energy\ consumption\ of\ the\ customer}\ in\ €/kWh \qquad (4.1)$$

$$\boldsymbol{CICva} = \frac{Annual\ Value\ Added\ of\ the\ customer\ for\ t\ hours}{Annual\ energy\ consumption\ of\ the\ customer}\ in\ €/kWh \qquad (4.2)$$

$$\boldsymbol{CICpo} = \frac{Reported\ cost\ of\ the\ customer\ for\ a\ Planned\ Outage\ for\ t\ hours}{Annual\ energy\ consumption\ of\ the\ customer}\ in\ €/kWh \qquad (4.3)$$

$$\boldsymbol{CICuo} = \frac{Reported\ cost\ of\ the\ customer\ for\ an\ Unexpected\ Outage\ for\ t\ hour}{Annual\ energy\ consumption\ of\ the\ customer}\ in\ €/kWh \qquad (4.4)$$

By using analytical data only, annual energy consumption, annual turnover and annual value added, *CICt* and *CICva* are called as econometric model damage functions. In the normalization process of the outage costs, the annual working hours for the service sector customers has been chosen as 3000 hours and the calculations have been done accordingly [91]. For each sub-sector of the customers, the CIC assessment analyses have been carried out.

During the research only one scenario yielding the highest outage cost results is being processed and analyzed. In many countries the peak power consumption coincides the summer days due to excessive use of air conditioning systems. However Finland has mild summers and harsh winters. That is why the preferred outage scenario is the reported/planned outages in winter during working times which corresponds to the summer afternoon interruptions for the majority of the other countries.

Since Finland has a cold climate due to its geographical position, the country has mild summers. This results in the usage of air conditioning relatively less than other parts of the world. The cost analysis of the other scenarios have been done and presented in detail in the reference [III, 44].

4.1 The Hybrid Model

Thanks to the data elimination process, the problem of zero and extreme responses has been solved substantially. However, the challenge with the strategic responses still persists. The strategic responses that lie in the uncensored region of the data distribution cannot be removed with the aid of statistical tools. Another study conducted in Finland proposes three different models (strongest effect in average method, smallest and largest monetary values method and smallest and largest CIC/L-value method) to handle the strategic response issue [69]. A comprehensive study from the US utilizes Tobit regression to obtain more reliable estimations [67]. However, it is evident that if a response lies in the uncensored region of the data distribution, it is impossible to tell if that data point is healthy or unwanted (strategic) one. This observation creates doubts for the reliability and the objectivity of the outcomes of the customer survey studies. Therefore, it is imperative to bring in more analytical data and to reduce the weight of customer surveys in the CIC of service sector customers. By this way the ultimate goal is to propose new methodology that will make use of the customer surveys and the analytical data to reach a more objective hybrid model. To establish a relation between the analytical data and the CIC estimations, the following statistical data have been collected from the service sector customers.

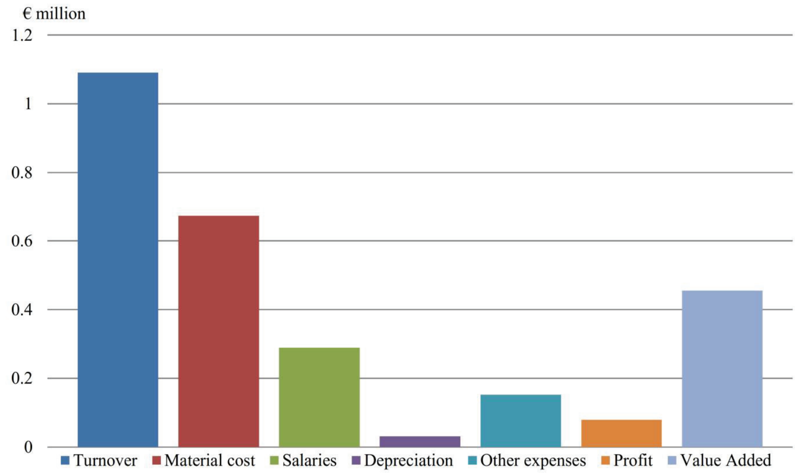

Figure 4.1. Income and expense distribution of the service sector customers.

The incomes and expenses of the service sector customers have been grouped and summarized in the Figure 4.1. When the reflections of power outages on the service sector entities are considered, it is easy relate the expenses and losses to the CICs with the following straightforward logic:

In case of a power outage, even though the business is not running properly, the personnel still receive their working time wages which can be accepted as an unnecessary expense. This means salary payments are directly related to the economic impacts of the power outages. Moreover, by assuming that there is no sales during a blackout, since the materials are not used and sold, the material costs can be excluded from the CICs. On the other hand, it is reasonable to focus on profit instead of sales costs by underlying that the materials stay in the business during an interruption but the profit is nonexistent since there is no sales present. When the income and cost parameters that are indicated in the Figure 4.1 are normalized by the annual energy consumptions of the customers, the CIC (in €/kWh) could be interpreted as:

CIC = Salaries (Salary costs) + Profit + Perishables (Spoiled materials and damages) (4.5)

Where all costs are calculated during the interruption time. Moreover, it is known that:

$$Turnover = Value\ Added + Material\ costs + other\ expenses \tag{4.6}$$

And,

$$Value\ Added = Salaries + Profit + Depreciation \tag{4.7}$$

At this point it can be assumed that the depreciation amount is negligible. Thus, in case of an unexpected outage, one can deduce:

$$CIC = Value\ Added + Perishables \tag{4.8}$$

In case of a reported outage (a planned outage), the customers have the opportunity take precautions to minimize the adverse effects of the interruption. By that way the amount of the perishables will be negligibly small. Thus, the CIC estimation for the planned outages will approximately be:

$$CIC = Value\ Added \tag{4.9}$$

This means the interruption costs will be equal to the lost value added due to the interrupted services in the time span of the outage.

The hybrid model makes use of analytical data to calculate the loss of *Value Added* and it requires a small scale customer survey to find out the cost of *Perishables* that will be seen during a predefined interruption scenario. Theoretically the CIC estimations reached via an extensive customer survey should be equal, or quite close to the ones acquired by the hybrid model. However, in practice, due to the responses from ineligible customers and the human nature of overstating of the losses (the strategic response problem), it is expected to have an amount of error between the hybrid model CICs and the customer survey CICs. This observation can be modeled as:

$$Customer\ Survey\ Model = Hybrid\ Model + Strategic\ Response\ Factor \tag{4.10}$$

Where, the Strategic Response Factor (SRF) (in €/kWh) is the difference between the CIC estimations of customer surveys and the estimations reached by the hybrid econometric approach.

To show the variation of different approaches, the CICs of the Customer Survey Model (*CICuo* and *CICpo*) and CICs of the econometric model, (*CICt* and *CICva*) have been calculated for each customer segment. The results of the

Whole Sale and Department Store customers are shown in Figure 4.2 and in Figure 4.3 respectively.

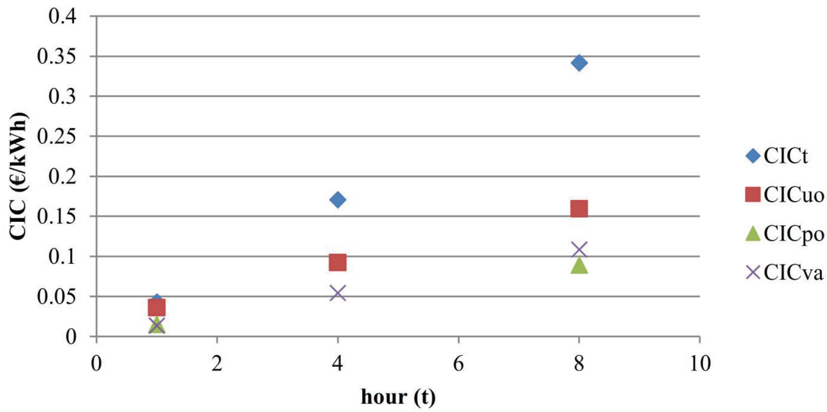

Figure 4.2. Results of SSCDFs for the whole sale sector customers in €/kWh.

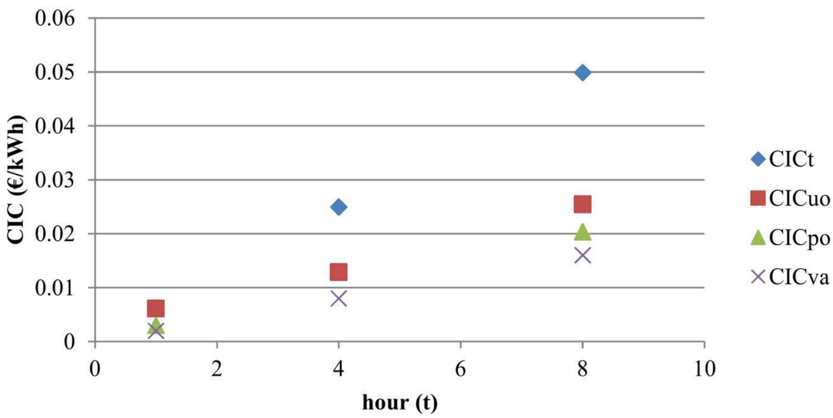

Figure 4.3. Results of SSCDFs for the department store sector customers in €/kWh.

*There is no data in the customer survey for the planned outages for the time span of 4 hours.

When the Figure 4.2 and Figure 4.3 are checked, it is obvious that assessing the outage costs via the econometric model by utilizing the turnover figures of the customers yields unreasonably high estimations. However, promising findings are seen when the variations of *CICva, CICuo* and *CICpo* are observed. In consistency with the relations (4.5), (4.6) and (4.7), the econometric model outcome of *CICva* is comparable to the customer survey outcomes of *CICuo* and *CICpo*. Consequently by referring the relations (4.8) and (4.9), the following deductions could be made and recommended;

For unexpected outages:

$$CICuo = CICva + Perishables + Strategic\ Response\ Factor \qquad (4.11)$$

For planned outages:

$$CICpo = CICva + Strategic\ Response\ Factor \qquad (4.12)$$

The hybrid model combines the indirect analytical method and the customer surveys and benefits from the findings of those. Within the hybrid model instead of carrying out extensive and complicated customer surveys, a limited survey which will focus only on the economic worth of the spoiled materials and the damages, i.e. the perishables, will be sufficient to calculate the economic losses incurred by the power interruptions. The novel approach yields sound estimations for both unexpected and planned electric power outages. A small scale survey responding to the fewer number of questions will be much easier for the respondent whether or not he/she is an eligible person to do it. In addition, since it is easy to tell the cost of a spoiled or damaged material, the level of subjectivity in the responses will be considerably low. This means the strategic response factor (SRF) will be minimal. Thus, in order to decrease the subjectivity of the analysis process and to provide objective CIC estimations, the SRF is recommended to be neglected by the ones who prefer to use the proposed novel model.

To sum up the hybrid model:

For the unexpected outages;

$$CICuo = CICva + Perishables \qquad (4.13)$$

For the planned outages;

$$CICpo = CICva \qquad (4.14)$$

Via the hybrid model, with less effort and less money spent on customer surveys, more objective and more customer specific CIC estimations will be reached faster than using the conventional approaches.

To verify the proposed theory a regression analysis has been applied to the findings of the department store sector customers. The report prepared by the Ernest Orlando Lawrence Berkeley National Laboratory [85] claim that the CIC characteristics is almost linear during the first 8 hours of outage. This finding is consistent with the results of this research. Thus linear regression technique is preferred for CIC estimations.

In order to reach more reliable results, the reported outage data for the 2 minutes and 15 minutes have been added to the regression. Let the regressed linear equations be in the format of $y = mx + n$. Then the coefficients of the equations and the coefficient of determinations are given in the Table 4.1.

Table 4.1. The CIC regression coefficients for the department store sector customers.

	m	n	R^2
CICuo	0.0031	0.001	0.98
CICpo	0.0025	0.0001	0.99
CICva	0.002	2.00E-18	1

The variation between the econometric model CIC and the customer survey CICs with respect to time has been illustrated in the Figure 4.4.

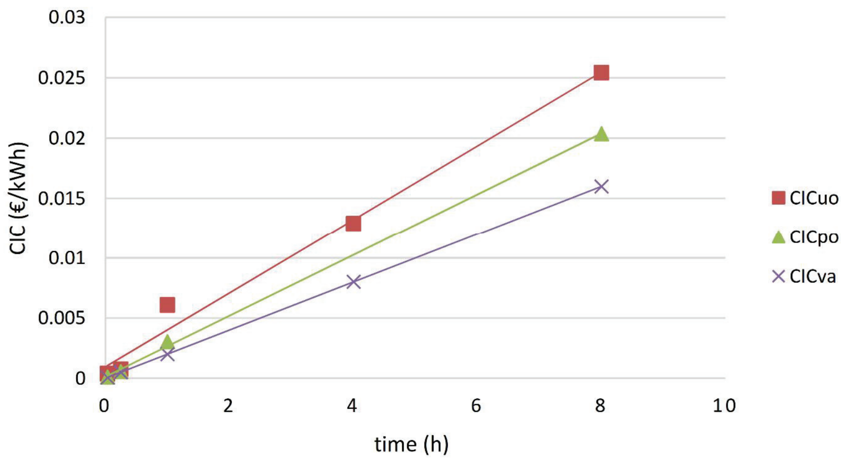

Figure 4.4. The CIC linear regression analysis for the department store sector customers.

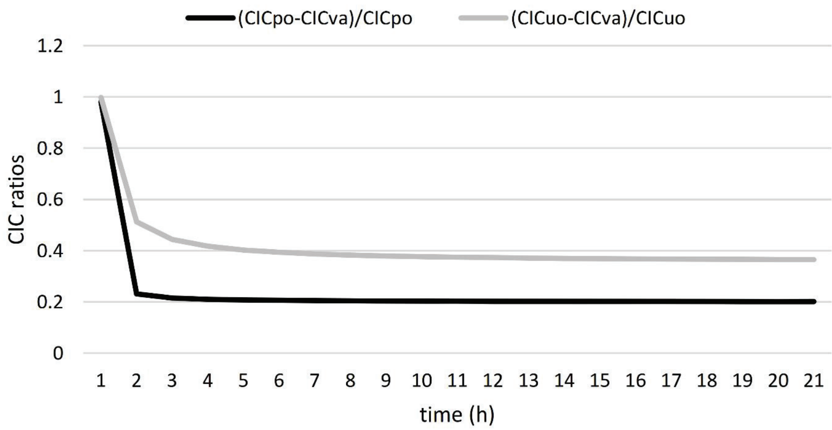

Figure 4.5. CIC ratios of different SSCDFs for the department store sector customers.

The Figure 4.5 shows that the hybrid model that attempts to link the customer survey findings to the indirect analytical approach fails at the short interruption times. One explanation for this conclusion might be that the economic losses get more apparent and clear upon longer interruption times. The customers might not be well aware of their economic losses in case of short interruptions, and therefore they report much higher outage costs than it should be for the interruptions shorter than 2 hours. On the other hand, however, it is obvious that as the outage time increases the variation ratio stabilizes around 20% for the planned outages and close to 40% for the unexpected outage scenarios. In accordance with the relation 4.12 the 20% difference could be claimed as the SRF which covers the strategic responses. In addition, by the relation (4.13), the gap between two lines stands for the cost of perishables. As it can be observed in the Figure 4.5, after a certain time, the relative cost of perishables slightly decreases. This is reasonable since it is known that if the blackout time gets longer, the customers start to take precautions to reduce the adverse effects of the event.

This means a reduction in the amount of damages and spoiled materials. Therefore, it ends up in a noticeable decrease in the costs of the total losses.

The CIC calculations of the other service sub-sectors have been summarized and tabulated for an outage time of one hour in the Table 4.2.

Table 4.2. Typical values for service sector customers for one hour in € Cents/kWh of annual energy demand.

Sub-sectors	CICuo	CICpo	CICva
Other retail	1.90	1.52	0.59
Whole sale	0.04	0.02	0.01
Hotel	0.60	0.15	0.12
Restaurant	0.31	0.25	0.21
Sports	4.86	3.89	2.26
Department store	0.006	0.003	0.002
Health	3.12	0.94	0.79
Other	3.65	2.47	2.17
Average	1.81	1.15	0.77

5. Residential Sector

The power consumption characteristics of the residential customers differ from the industrial and commercial ones. For the domestic customers one cannot speak of direct economic activity linked to the continuous and high quality electricity. This fact makes it difficult and challenging to evaluate the power outage costs of the residential customers. For this reason, there have been fewer studies focusing on the residential customers when compared to the number of industrial and service sector ones.

Customer surveys are the most appropriate means for estimating the customer interruption costs (CIC) of the domestic customers. In residential sector CIC studies the data collection process is done via the direct worth (DW) approach and the price proportional method (WTA and WTP). The study [49] estimates the power reliability worth of residential customers by the aid of a customer survey. The reference [92] deals with the same challenge by adopting the WTP approach. An extensive WTP study for the Swedish households is presented in [50]. Studies [51], [52] utilize WTP method for residential customers as well. The comparison of the findings of DW and WTP methodologies for domestic customers is given at [40]. The paper [53] introduces a study of WTA/WTP findings of Flemish households. Another comprehensive WTA/WTP study for German households can be found at [41]. In addition, even though the majority of the residential sector CICs are based on customer surveys, reference [70] follows a macro econometric approach to answer the challenge.

To further investigate the CICs of residential sector customers, this research makes use of a carefully prepared customer survey study conducted in Finland. Different consumer segments have distinct power consumption characteristics and thus the economic outcomes of the power interruptions differ considerably. To make more customer specific and precise estimations, the customers were divided into three sub-classes according to the location of the settlements. These segments are households, vacation houses and farm houses.

The customers who reside in urban areas were named as household customers. Secondly, the summer cottages/houses were categorized as vacation house customers. Thirdly, the ones living in rural agricultural areas were named as farmhouse customers. A total of 1009 customers were surveyed and about 30% of response rate was achieved.

The research includes the comparisons of DW, WTA and WTP models. Moreover, a price elasticity method and its results are given. Finally a novel macroeconomic model is introduced. What makes the residential sector CIC analysis different than the others is that instead of proposing a method that comes up with certain estimations, an estimation band with maximum and minimum levels is proposed. The DW, WTA, WTP and price elasticity method calculations are used for defining the boundaries to the cost estimations.

5.1 Interruption Costs Estimation Methods

5.1.1 The direct Worth Approach

The DW approach includes the responses to the outage scenario questions that change with the following parameters;

- duration of the interruption
- character of the interruption (unexpected or planned),
- time of the interruption (morning, noon, evening, night)
- the season when the interruption takes place (winter, spring, summer, autumn)

The reported costs were normalized by the average peak powers. As a result the customer damage function CIC_{DW} (in €/kW) was generated.

5.1.2 The Price Proportional Method

Finnish households experience the highest electricity consumption during winters. This means highest monetary loss in case of an interruption during winter times. Therefore, in the questionnaire the residential customers were asked to state an amount of compensation by which they are willing to accept (WTA) a scheduled one-hour outage during winter evening time and in addition, they were asked to report the amount of money they are willing to pay (WTP) in order to avoid the same outage scenario. Again the monetary figures were normalized with average peak powers.

5.1.3 The Price Elasticity Method

The customer receives a net value added if he/she feels that the value of a product is greater than or equal to the price of the same product. If the price increases, the customer customizes the amount of the product that he/she purchases accordingly. This logic can also be used when the electric energy is considered as the product. The real value of the electric power is the highest price that the customer is ready to pay. The difference between the real value of the electric power and the price of the power gives the value added that the customer enjoys. In case of a power outage the customer will lose his/her value in some extent. Figure 5.1 shows the use of electricity as a function of the price of the electrical energy.

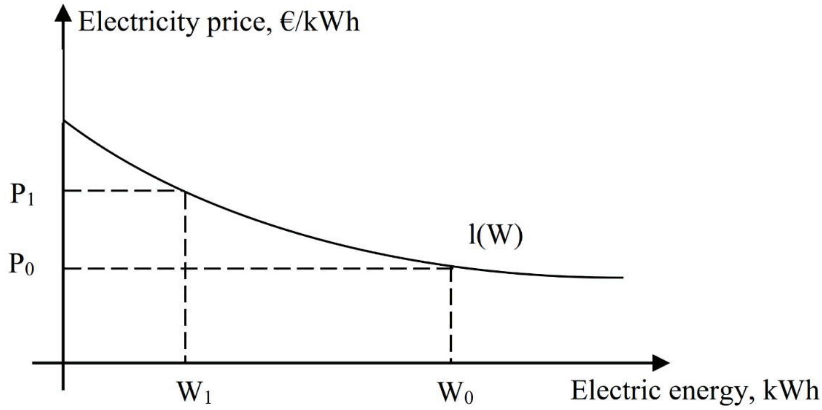

Figure 5.1. The Price Elasticity.

In a normal case the customer's electricity consumption is equal to W0 where the price of the electricity is P0. At this point the marginal value of the product is equal to the price of the product. If the electricity price rises to P1, the customer reduces the use of electricity. Then the customer's electricity consumption is set to the point (W1, P1). The electricity consumption is decreased by the amount of (W0 – W1) when the price of the electricity rises by the amount of (P1 – P0). The lost value of the undelivered energy can be calculated from equation (5.1).

$$loss = \int_{\Delta W} (l(W) - P_0)\, dW \tag{5.1}$$

In the customer survey, the domestic consumers were asked to report which electrical appliances they would not use for three hours if 5% of the annual energy cost is provided as a compensation. According to the survey responses the points W0, W1 and P1 were calculated. In addition, P0 was assumed to be as 0.10 €/ kWh. The calculated monetary losses were normalized by the average peak power and the CDF of CIC_{pe} in €/kW was generated.

5.2 A Novel Macroeconomic Model

A new macroeconomic approach, which is introduced in [70], was proposed. The theory that one outage-hour during the leisure time corresponds to one hour of less work during working hours provided the basis for the model. That means the value of this lost non-working hour is equal to the wage of one hour of work. By adopting the same reasoning a new macroeconomic model for CDF was derived. At this CDF, instead of annual energy consumption, average peak power was chosen as the normalization factor. The novel macroeconomic CDF, *CICme*, is defined as:

$$CICme = \mathrm{d}\frac{tw}{PP} \tag{5.2}$$

Where, pp is the average peak power consumption in kW, t is the interruption duration in hours and w is the hourly wage in euros (€). These variables are easy to find and use. However it is a challenge to calculate the parameter d. d is the continuous electric power dependency factor with $d \in [0, 1]$. The only way to find out d is to carry out a simple and target oriented customer survey. In the Finnish residential sector customer survey the respondents are asked to state which electrical appliances they are willing not to use in return for a certain compensation. The resulting reduction in power consumption will yield an approximate idea about the minimum requirements of a customer to carry out his/her basic daily requirements.

Then factor d can be calculated as;

$$d = \frac{100\% - \%\ of\ the\ reduction\ in\ power\ consumption}{100\%} \tag{5.3}$$

The Finnish average monthly earnings of wage and salary earners is 18.69 € per hour when inflated to the year 2013 [93]. As a result a CIC_{me} in €/kW has been calculated for each customer sub-class.

5.2.1 Households

The household customers constitutes the majority of the residential customers in Finland. 744 household customers participated in the survey. The average annual energy consumption for household customers is 11 214.4 kWh and the average peak power consumption is 3.7 kW. The CIC_{DW} results are summarized in Table 5.1.

Table 5.1. Summary of the CIC_{DW} of households' customers for unexpected and planned outages.

	unexpected outage					planned outage	
duration	1 s	2 min	1 h	12 h	36 h	1 h	12 h
CIC_{DW} in €/kW	0.12	0.84	7.8	65.88	196.44	3.72	48

In addition,

CIC_{pe} = 6.4 €/kW for 3 hours of outage where the accepted power reduction is 38%.

WTP = 1.2 €/kW and WTA = 12.12 €/kW for 1 hour of outage.

The last CDF to be calculated is the one by the macroeconomic model. For residential customers a 100% dependency on continuous electric power is possible. Naturally this will be the maximum value of d (d=1.0). However, telling the minimum power dependency is a difficult task. To cope with this challenge the customer survey was used. The data from the questionnaire which state the willingness to reduce the power consumption in case of a certain compensation provide meaningful information about the minimum value of d. An average of 38% of reduction was acquired from the respondents. When this figure is inserted to the formula (5.3), d_{min} is calculated as 0.62. Under the light of this figure, it could be assumed that 0.62 is the minimum electricity dependency that a customer is ready to experience. The customer damage functions (CDFs) of $CIC_{me,max}$ and $CIC_{me,min}$ are calculated according to the formula (5.2).

$CIC_{me,min}$ = 3.15 €/kW for 1 hour

$CIC_{me,max}$ = 5.08 €/kW for 1 hour

$CIC_{me,min}$ = 9.45 €/kW for 3 hours

$CIC_{me,max}$ = 15.24 €/kW for 3 hours

All CDF findings are summarized in the Table 5.2.

Table 5.2. Different CDFs in €/kW for household customers.

duration	CIC_{DW}	WTA	WTP	CIC_{pe}	$CIC_{me,max}$	$CIC_{me,min}$
1 h	7.8	12.12	1.2	-	5.08	3.15
3 h	23.4*	36.36*	3.6*	7.68	15.24	9.45

* The values have been linearly extrapolated

5.2.2 Vacation houses

102 vacation house customers attended to the survey. Since the power consumption characteristics of these customers are different, the macroeconomic model was not applied. The CIC_{DW} results of the unexpected and planned interruptions during winter time are summarized in Table 5.3.

Table 5.3. Summary of the CIC_{DW} of vacation house customers for unexpected and planned outages.

	unexpected outage					planned outage	
duration	1 s	2 min	1 h	12 h	36 h	1 h	12 h
CIC_{DW} in €/kW	0.12	0.24	29.16	90.36	206.76	10.32	95.76

Where the average annual energy consumption is 4 378.4 kWh and the average peak power consumption is 2.9 kW. The variation of the CIC_{DW} with respect to the season, time of the week and with time of the day are summarized in Table 5.4.

Table 5.4. Summary of the CIC_{DW} with respect to varying time parameters for vacation house customers.

	winter weekday	winter weekend	summer weekday	summer weekend
morning (5am-10pm)	5.52	4.56	12.12	10.56
noon (10am-4pm)	6.36	4.92	12.72	16.56
evening (4pm-11pm)	7.56	5.76	13.32	12.36
night (11pm-5am)	4.68	2.16	1.2	1.08

Furthermore,

CIC_{pe} = 5.64 €/kW for 3 hours of outage where the accepted power reduction is 30.3%.

WTP = 2.64 €/kW and WTA = 18.36 €/kW for 1 hour of outage.

All CDF findings are summarized in Table 5.5.

Table 5.5. Different CDFs in €/kW for vacation house customers.

duration	CIC_{DW}	WTA	WTP	CIC_{pe}
1 h	29.16	18.36	2.64	0
3 h	87.48*	55.08*	7.8*	2.88

* The values have been linearly extrapolated

5.2.3 Farm houses

163 farm house customers attended to the survey. Since the power consumption characteristics of these customers are different, the macroeconomic model was not applied. The CIC_{DW} results of the unexpected and planned interruptions during winter time are summarized in Table 5.6.

Table 5.6. The unexpected and planned CIC_{DW} with respect to varying season and time parameters for farm house customers.

	unexpected						planned
season	1 s	2 min	1 h	4 h	12 h	36 h	1 h
winter	0	0.72	12.48	47.04	140.88	383.4	8.88
spring	0	0.12	7.44	14.52	71.4	199.8	2.52
summer	0	0.24	3.6	11.64	69	186.12	2.28
autumn	0.24	1.08	15.84	33.12	178.08	428.76	3.24

Where the average annual energy consumption is 39 563.1 kWh and the average peak power consumption is 12.8 kW.

A price elasticity study was not carried out for farm house customers. The WTP and WTA findings are calculated as:

WTP = 1.2 €/kW and WTA = 11.4 €/kW for 1 hour of outage.

All CDF calculations are given in Table 5.7 and the seasonal change of CIC_{DW} values is depicted in the Figure 5.8.

Table 5.7. Different CDFs in €/kW for farm house customers.

duration	CIC_{DW}	WTA	WTP
1 h	12.48	11.4	1.2
3 h	37.44*	34.2*	3.6*

* The values have been linearly extrapolated

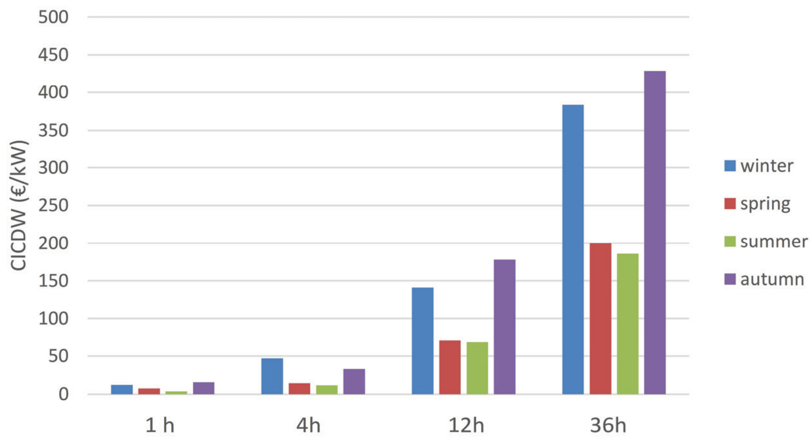

Figure 5.2. The variation of CIC_{DW} of the farm house customers with respect to seasons.

Figure 5.2 shows the noticeable fluctuation of farm house CICs with respect to season. As expected the season plays a crucial role for these customers. The costs are highest during autumns while they are the lowest during summers.

The findings of the household customer research can be summarized as follows:

$$WTA > CIC_{DW} > CIC_{me,max} > CIC_{me,min} > CIC_{pe} > WTP \tag{5.4}$$

On the other hand, for the scheduled outages of household customers, the CIC calculations are more promising:

$$CIC_{me,max} > CIC_{DW} > CIC_{me,min} \tag{5.5}$$

Under the light of these calculations, it could be claimed that $CIC_{me,max}$ and $CIC_{me,min}$ state credible boundaries for the domestic customer outage costs.

6. Conclusions

Electric power transmission and distribution planning cannot be done without a clear idea of the economic worth of the continuous electric power. Even though the smart grid technologies are being installed in the electric power infrastructure, the power reliability has been in an alarming state. The climate change brought and increased frequency of the extreme weather events and natural disasters. This poses a great threat to the electric power system. Publications IV, V and VIII summarize the adverse effects of the climate change on the electric power reliability.

The evaluation of the customer interruption costs has been a popular area of study for the last a couple of decades. The comprehensive report prepared by the Council of European Energy Regulators (CEER) compiles thorough guidelines for the existing methods for the estimation of costs due to electricity interruptions [94]. The existing evaluation techniques have been criticized in terms of many points. The most significant one is to propose one single methodology for all customer segments. This ends up with highly average estimations of the power outage costs. The other point that constitutes a motivation for this research is to avoid extensive customer surveys. These surveys demand so much time, money and effort. On the other hand making use of analytical data such as annual energy consumption, GDP, value added or the peak power promises faster and more objective interruption cost calculations. The main motivation behind this research was to combine the customer survey and the indirect analytical approaches to come up with unique techniques for each customer classes. By this way the following achievements are targeted:

- Reaching more customer specific estimations
- Making use of target oriented and small-scale customer surveys which demands less effort, less time and less money
- Utilizing publicly declared and readily available analytical data
- The proposed models are to be duplicated in any part of the world

The first customer segment is the industry sector. Publication I shows an example how to evaluate the costs via conventional customer survey methodology. However Publication II introduces the Relative Worth method which aims to find out the outage coefficient factors (*Ku* and *Kp*) via a limited customer survey and then combines the results with analytical data. On the other hand, for the service sector customers Publication III is a typical study of customer survey method. The novel hybrid approach introduced by the Publication VI eliminates the major disadvantages of the classic customer surveys. The hybrid econometric method makes use of only analytical data for planned outages. For unexpected outages a highly small-scale customer survey is needed to calculate the worth of the spoiled materials. For the residential customers, the econometric model presented by the Publication VII can be adopted by any country. The interruption duration t, the peak power consumption PP and the hourly wage w are easy to reach and publicly declared data. The only challenge is to calculate the continuous electric power dependency factor *d*. The maximum value is assumed to be 1.0 (100% dependency). However, to find out the minimum value a limited customer survey is needed. Table 6.1. presents the brief summary of the novel contributions of the publications that are included in this dissertation.

Table 6.1. Brief Summaries of the Publication Contributions

Publication No.	Brief Summaries of the Publication Contributions
I	A typical case study for the industry sector customers via customer survey, DW methodology
II	A typical case study for the industry sector customers via customer survey, DW methodology
III	Introduction of novel Relative Worth approach for the industry sector customers
IV	A typical case study for the service sector customers via customer survey, DW methodology
V	A comprehensive summary indicating the impacts of climate change on the electric power reliability
VI	Intoduction of a novel econometric approach for the service sector customers
VII	Introduction of novel econometric model for the residental sector customers and comparison with the other existing models
VIII	A case study showing the calculation of customer interruption costs by a regulatory office (Finland)

All proposed models meet the goals of this research. However as it is pointed out, the economic worth of electric power reliability covers a wider range of outage impacts while the calculation of the customer interruption costs focuses only on the direct impacts of the interruption events. A future research work which is based on the above mentioned goals is imperative. It is known that the indirect impacts of the blackouts can be much larger than the direct ones. Moreover the industrial sector customers are susceptible to the power quality events. A further study should analyze the economic costs of the voltage sags and momentary outages for industry customers.

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Appendix

A carefully designed customer survey questionnaire is the first condition for a reliable CIC study. There are many factors determining the economic losses dues to interruptions. These include the duration and the frequency of the power outage, the season that the interruption is seen in (summer or winter), the time of occurrence (during or outside working hours) and the character of the outage (whether or not a notification is given beforehand, unexpected or planned outage. In the customer survey, the respondents were asked to predict their losses via e-mails in case of different outage scenarios that differ with the factors explained above. A total of 236 commercial sector customers and 126 industry sector customers joined to the survey and 54% and 73%of response rates were reached. The questionnaire for the service sector includes the following for each customer:

- Annual energy consumption
- Turnover per year
- Value Added created per year
- The income and expenses per year (profit, salaries, material costs, depreciation and other expenses)
- Cost estimations for 15 minutes, 1, 4, 8 and 12 hours of unexpected outages during working hours
- Cost estimations for 15 minutes, 1, 4, 8 and 12 hours of unexpected outages outside working hours
- Cost estimations for 1and 8 hours of planned outages during working hours
- Cost estimations for 1and 8 hours of planned outages outside working hours
- Cost estimations for 15 minutes, 1, 4, 8 and 12 hours of unexpected outages in summer
- Cost estimations for 15 minutes, 1, 4, 8 and 12 hours of unexpected outages in winter
- Cost estimations for 1and 8 hours of planned outages in summer
- Cost estimations for 1and 8 hours of planned outages in winter

The questionnaire for the industrial sector includes the following data:

- Annual energy consumption.
- Value added per year.
- Cost estimation for 15 minutes, 1, 4, 8 and 12 hours unexpected outages.

- Cost estimation for 15 minutes, 1, 4, 8 and 12 hours planned outages.
- The percentage of production losses for 1 hour, 4 hours and 8 hours outages.
- The percentage of restart losses for 1 hour, 4 hours and 8 hours outages.
- The percentage of spoiled material losses for 1 hour, 4 hours and 8 hours outages.
- The percentage of third party losses for 1 hour, 4 hours and 8 hours outages.
- The percentage of other costs for 1 hour, 4 hours and 8 hours outages.
- The percentage of damages for 1 hour, 4 hours and 8 hours outages.

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Electricity has become a vital part of the modern societies. Thanks to using electrical equipment in almost every aspect of the life, in case of an interruption the daily routine is paralyzed. Whether the electricity is a social right or not is still debatable. However, in many parts of the world the perception by the people is in the way that reaching the electric power whenever and wherever needed is a social right rather than considering electricity as a commodity. No matter it is a social right or commodity, improving the electric power reliability so that more people will have the opportunity to use it is in favor of everyone in the market. The customers, the authorities, the utilities and the retailers wish for securer electricity system. This research focuses on the question of "What is the economic worth of power interruptions?"

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