Department of Electrical Engineering and Automation

Value of Continuity of Electricity Supply from the Distribution System Operators' Perspective

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Niyazi Gündüz

Aalto University

DOCTORAL
DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 108/2019

Value of Continuity of Electricity Supply from the Distribution System Operators' Perspective

Niyazi Gündüz

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held at the lecture hall AS1 of the school on 18 June 2019 at 12.

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Aalto University publication series
DOCTORAL DISSERTATIONS 108/2019

ISBN 978-952-60-8589-0 (printed)
ISBN 978-952-60-8590-6 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-8590-6

Unigrafia Oy
Helsinki 2019

Finland

NORDIC SWAN ECOLABEL
Printed matter
4041-0619

Aalto University

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

Author
Niyazi Gündüz

Name of the doctoral dissertation
Value of Continuity of Electricity Supply from the Distribution System Operators’ Perspective

Publisher School of Electrical Engineering

Unit Department of Electrical Engineering and Automation

Series Aalto University publication series DOCTORAL DISSERTATIONS 108/2019

Field of research Power Systems and High Voltage Engineering

Manuscript submitted 7 March 2019 **Date of the defence** 18 June 2019

Permission for public defence granted (date) 9 May 2019 **Language** English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

Abstract

Continuous electric power service is vital for the users, companies and the public authorities. Due to extreme weather events, this continuity of supply is under threat in Nordic countries such as Finland and Sweden. Therefore, improving reliability and hence decreasing annual interruption hours is a must for the public authorities and for the distribution system operators (DSOs). Understanding the costs of interruption is crucial in terms of improving the power system infrastructure and planning the distribution grid.

Value of continuity of electricity supply and customer interruption costs have been a popular area of study since the liberalization of the electric power markets. However, majority of these studies approach the problem from customers' point of view. To bring a novel insight, this dissertation aims to assess the economic losses from distribution system operators' perspective. There are numerous methods to calculate the Customer Interruption Costs (CICs). Each method has its advantages and disadvantages. In addition to a number of previously introduced methods, this dissertation adopts directional distance function approach to estimate the value of the continuity of supply from the distribution network operator perspective via calculating shadow pricing of one minute of power interruption. This dissertation uses reliability and financial data of Finnish DSOs between 2013-2017. Finland is an attractive country for the researchers to carry out such a study due to availability of open access, publicly available, transparent and reliable data.

Main goal of this study is to use indirect analytical methods to calculate customer interruption costs while providing a credible method which is straight forward, easy to apply, less time, money and labour demanding. In order to succeed this goal, shadow prices of 78 DSOs' data have been analyzed. It was seen that shadow price of one minute of interruption for the majority of the DSOs vary between 0.4 and 0.5 € cents for the years 2013 – 2015. This is valuable information for both DSOs and for the public authorities in Finland, since the DSOs are supposed to pay standard customer compensations due to interruptions.

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

ISBN (printed) 978-952-60-8589-0 **ISBN (pdf)** 978-952-60-8590-6

ISSN (printed) 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2019

Pages 132 **urn** http://urn.fi/URN:ISBN:978-952-60-8590-6

Acknowledgements

When I started my Master of Science study in Istanbul Technical University, I spent the Autumn semester of 2011 in Aalto University as an Erasmus student. The education system, research and academic environment in Finland had a big impact in my career plans. That is why, in August 2014 I came back to Aalto University and started my Doctoral study at the Department of Electrical Engineering and Automation. After 4.5 years of hard work and strong resilience of achieving a meaningful contribution to science, I came to the last step which is writing of this dissertation.

First of all, I should express my gratitude and thank Professor Matti Lehtonen for trusting and supporting me for the whole period of my research and course work. Without his valuable supervision, it would be impossible to complete this study. Secondly, I would like to thank my advisor Dr. Sinan Küfeoğlu for his help and contribution. This work is a continuation of his previous work and I should say that he did a marvelous job in his doctoral thesis.

I should also thank all of my friends and especially mention Süleyman Yılmaz and Can Cengiz for their great friendship. Finnish climate is harsh to survive without true and warm friendship. Finally, I would like to thank my family for believing in me and loving me from my birth until today. I know my father Ali Gündüz and my mother Semra Gündüz are so proud of their son, and I should say that I am the proud one to have you as my parents.

Helsinki, 10 May 2019
Niyazi Gündüz

Contents

List of Abbreviations

CIC	customer interruption cost
CML	customer minutes lost (in minutes)
DDF	directional distance function
DSO	distribution system operator
DW	direct worth
ENS	energy not supplied
ES	energy supplied to the low voltage customers (in GWh)
IAM	indirect analytical methods
LP	linear programming
OPEX	operational expenses (in euros)
PV	photovoltaics
SAIDI	system average interruption duration index
SAIFI	system average interruption frequency index
SC	share of underground cabling in distribution lines (in %)
TSO	finnish transmission system operator
VoLL	value of lost load
WTA	willingness to accept
WTP	willingness to pay
a	number of average income earners per household
AN	annual energy consumption
b	bad outputs
CIC_{me}	interruption cost estimation via the macroeconomic approach
d	factor for continuous electric power dependency
$\overrightarrow{D_0}$	directional output distance function

g	directional vector
GW	gigawatt
GWh	gigawatt hour
h	hour
kW	kilowatt
kWh	kilowatt hour
l	constant of the quadratic directional distance function
p	desirable output prices
$P(x)$	production technology
PP	peak power consumption
q	undesirable output prices
$R(x, p, q)$	revenue function
t	outage duration
w	average hourly earnings
x	inputs
y	good outputs

α_n	input coefficients
$\alpha_{mn'}$	quadratic of input coefficients
β_m	desirable output coefficients
$\beta_{mm'}$	quadratic of desirable output coefficients
δ_{nm}	product of the inputs and desirable outputs coefficients
γ_j	undesirable output coefficients
$\gamma_{jj'}$	quadratic of undesirable output coefficients
μ_{mj}	coefficients of the product of the desirable & undesirable outputs
η_{nj}	product of the inputs and undesirable outputs coefficients

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.

1. Küfeoğlu, Sinan; Gündüz, Niyazi; Lehtonen, Matti. Climate Change Concerns and Finnish Electric Power Supply Security Performance. IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Ljubljana, Slovenia, 9-12 October 2016.

2. Gündüz, Niyazi; Küfeoğlu, Sinan; Lehtonen, Matti. Impacts of Natural Disasters on Swedish Electric Power Policy; a Case Study. MDPI Sustainability. Sustainable Energy Policy and Policy Implications - Good Examples and Critical Reflections, Vol 9, No. 2, page 230, published on 8 February 2017.

3. Gündüz, Niyazi; Küfeoğlu, Sinan; Winser, Christian; Lehtonen, Matti. Regional Differences in Economic Impacts of Power Outages in Finland. University of Cambridge, EPRG Working Paper 1822, Cambridge Working Paper in Economics, published on June 2018.

4. Küfeoğlu, Sinan; Gündüz, Niyazi; Chen, Hao; Lehtonen, Matti. Shadow Pricing of Electric Power Interruptions for Distribution System Operators in Finland. MDPI Energies, Vol 11, No. 7, Page 1831, published on 12 July 2018.

5. Gündüz, Niyazi; Küfeoğlu, Sinan; Lehtonen, Matti. Customer Interruption Cost Estimations for Distribution System Operators in Finland. IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Sarajevo, Bosnia and Herzegovina, 21-25 October 2018.

6. Lehtonen, Matti; Gündüz, Niyazi; Küfeoğlu, Sinan. On the Evaluation of Customers Interruption Costs due to Unexpected Power Outages. 2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 12-14 November 2018.

Author's Contribution

Publication 1: Climate Change Concerns and Finnish Electric Power Supply Security Performance.

The author was responsible for data collection, data analysis and articulation of the results.

Publication 2: Impacts of Natural Disasters on Swedish Electric Power Policy; a Case Study.

The author developed the idea for the study and conducted data collection, data analysis and economic calculations. He was the main author of the publication.

Publication 3: Regional Differences in Economic Impacts of Power Outages in Finland.

The author presented the problem statement and introduced the underlying idea behind this publication. He carried out data collection, data analysis and interpretation of these inputs. He was the main author of the publication.

Publication 4: Shadow Pricing of Electric Power Interruptions for Distribution System Operators in Finland.

The author derived and adopted the directional distance function methodology and then applied this for calculating the shadow pricing of one minute of electric power interruption. He also carried out data collection, data analysis and required linear programming.

Publication 5: Customer Interruption Cost Estimations for Distribution System Operators in Finland.

The author was responsible for data collection, data analysis and articulation of the results. He was the main author of the publication.

Publication 6: On the Evaluation of Customers Interruption Costs due to Unexpected Power Outages.

The author contributed to the main author of the publication via providing a generic assessment and critique of the results presented in this paper.

1. Introduction

Continuity of electric power supply is a key concern for authorities, Distribution System Operators (DSOs) and for the consumers. As each sector, such as finance, telecommunications, health, entertainment, transportation etc. become more and more dependent on electricity, the results of power interruptions become more devastating. There is no surprise that the United States Homeland Security defines energy sector as “uniquely critical because it provides an “enabling function” across all critical infrastructure sectors” [1] while [2] emphasizing the significance of the electric power grid as “the most critical of critical infrastructure”. The increasing frequency and the duration of the extreme weather events have become a major threat for the electric power security [3]. Consequently, estimation of the costs of power interruptions or the value of lost load has become an attractive field for the researchers. Customer surveys, indirect analytical methods and case studies are the three major methodologies which are commonly used by the research society to assess the customer interruption costs (CIC). Each method has certain advantages and disadvantages. Customer surveys are the most preferred and extensively used approach. In the customer surveys, a questionnaire is prepared and distributed to the electricity customers through various means such as one-to-one interviews, telephone calls, e-mails or by mail. The questionnaire includes questions about various interruption scenarios. For reaching customer specific results, this method is the most popular one in the literature [4]. However, doing extensive surveys means too much time, effort and money to be spent. Furthermore, dealing with the raw responses and censoring outliers from the data sets are other challenges of this methodology. The second approach is Indirect Analytical Methods (IAM). The main advantage of this method is that it is relatively straightforward and easy to apply when compared to customer surveys. Electricity prices or tariffs, value added or turnover of a customer, gross domestic product of a country, annual energy consumption or the peak power reached during a year of a customer group, region or a country are some of the input data for this approach. These data are publicly available, objective and easy to reach. The major shortcoming of this methodology is that since it uses general and average data, naturally it provides broad and average results. Finally, case studies approach is another method for the CIC analysis purposes. The case studies are done after major and significant blackouts. It is the best way of evaluating both direct and indirect economic costs incurred by the power outages. Even though this method provides the most accurate and reliable results, since they are done after actual events, they are not commonly used.

Finland is one of the developed countries that heavily depend on services which are provided by electricity. By being aware of the crucial impacts of power outages, the Finnish network operators have designed and constructed a robust electric power transmission and distribution infrastructure despite the harsh winter conditions the country is accustomed to experience. Nevertheless, what the country has not been used to is the increasing numbers of extreme weather conditions such as severe storms and thunderstorms. Nature has been proven to be the number one enemy against the supply security of the electricity [3], [5], [6]. The Finnish electric power security has been under heavy criticism after the summer storms of 2010, as well as winter storms of 2011, 2013 and 2015. Sweden is another developed Nordic country, which is struggling with extreme weather events and their impacts on the supply security. Therefore, to fully understand the consequences of power interruptions, it is imperative to study the nature events and their impacts on the electric power security.

1.1 Aim of the Research

Value of continuity of electricity supply and customer interruption costs have been a popular area of study since 1980s. Nonetheless, majority of the studies reviewed in this dissertation approach the problem from customers' point of view. The main motivation behind this dissertation was the impending necessity for an approach that will be utility or Distribution System Operator (DSO) centric since in case of an interruption event, there are losses incurred by both network operators and the customers. This dissertation aims to achieve;

- Highlighting how nature events are crucial for the supply security by illustrating the reliability performance of Finland and Sweden with actual case studies,
- Proposing shadow pricing technique as a DSO centric, analytical, objective and easy to apply method for the DSOs to assess their economic losses due to interruptions,
- Using actual DSO historic data from Finland, so that the outcomes could be meaningful for the DSOs,
- Presenting two previously used methods; customer survey and indirect analytical method.

The dissertation is structured by closely following the main motivation and aim of the research. Section 1.2 includes state of the art with an extensive literature review. Section 2 introduces extreme weather events and their impacts of the supply security with two case studies from Finland and Sweden. Section 3 is the main body of this dissertation and it includes the methodology on estimating the value of continuity of electricity supply for the DSOs via shadow pricing approach. Section 4 makes a conclusion with discussion about the results of this dissertation. Finally, Appendix A includes the original data set, whereas

Appendix B summarizes the detailed results as tables for the 78 DSOs in Finland. Appendix C introduces the Linear Programming script which was used at section 3.3 with shadow pricing approach.

1.2 State of the Art

Customer Interruption Cost (CIC) estimation methods can mainly be classified as: customer surveys, indirect analytical methods and case studies. Each approach has its own advantages and drawbacks. Customer Surveys are preferred most frequently in literature [7]. They follow Direct Worth (DW), Willingness to Pay (WTP) or Willingness to Accept (WTA) approaches. A customer survey is prepared and sent to the customers by one-to-one interviews, telephone calls, e-mails or by mails. The questionnaires include questions about different power interruption scenarios. In DW method, the customers are usually given different outage scenarios and they are asked to directly estimate the value of harm and losses they would face. In WTP method, the customers are asked how much they would be prepared to pay in order to avoid certain predefined outages, whereas in WTA they are asked about how much compensation they would require in order to accept such outages correspondingly. Getting customer specific results is the most significant advantage of customer surveys, since the questionnaires can be tailored, and they can target industry, service, commercial, residential and agriculture sectors. However, customer surveys demand too much time, labor and money. Moreover, dealing with the subjective responses is another concern. Researchers may end up with high amount of extreme and zero responses at analysis process [4]. Numerous examples for customer surveys can be found in [8], [9], [10], [11]. Indirect analytical methods are the second most preferred CIC estimation approach. Relying on objective data such as electricity prices, value added or turnover of a customer or sector, gross domestic product of a country or annual energy consumption makes indirect analytical methods more favourable if reaching objective results is aimed. They are straightforward, easy to apply, less time, money and labor demanding. However, they tend to yield broad and average results. The studies [12], [13], [14], [15] are examples for indirect analytical methods. Thirdly, case studies can be used to assess CICs. These are done after major blackout events. It is regarded as the most reliable CIC estimation method since both direct and indirect economic costs incurred by the power outages are covered through case studies. Nevertheless, large scale blackout events are not seen frequently and carrying out case studies is highly costly, hence these methods are not common in the literature. Case studies from New York City blackout of 1977 [16] and Storm Gudrun of 2005 in Sweden [17] can be named as successful examples for these. A more comprehensive literature review about the existing studies and a more in-depth assessment of merits and weaknesses of each methodology can be found at [18]. More recent studies can be found based on country specific data. The report [19] summarizes the value of service reliability for the electricity customers in the United States. Another detailed report [20] investigates the value of lost load (VoLL) for electricity customers in Great Britain. The paper [21] presents the worth of energy not supplied (ENS) in Scotland. The studies [22] and [23] target the costs of power interruptions at residential sector in the European Union and Italy respectively. Another paper introduces outage cost estimations for industry sector customers from South Korea [24]. Various other generic power interruption assessment papers have been published for customers from Germany [25], Lebanon [26] and South Africa [27]. These studies make use of customer surveys and indirect analytical methods to make the estimations. However, they approach the problem from customer's point of view. This dissertation aims to assess the economic losses from DSOs' perspective.

Rather than adopting the conventional methods, this dissertation uses the directional distance function approach to calculate the shadow pricing of electricity outages. The shadow pricing of a production technology through distance function is presented at [28]. The directional distance function is introduced in detail at [29]. Shadow pricing of a product has been calculated for many areas such as; pollution costs in agriculture production in US [30] and China [31], costs of water cuts in Chile [32], price licenses in salmon farming in Norway [33], banking inefficiency in Japan [34] and price of CO2, SO2 and NOx in the United States coal power industry [35]. On the other hand, [36] adopts parametric distance function approach to calculate the value of power outages for French DSOs.

2. Nature Events and Supply Security in Finland and Sweden

The future of climate and energy are bound together. Speaking of one without mentioning the other is quite difficult. The increasing number of natural disasters such as hurricanes, snow storms, ice storms, thunderstorms, floods and etc. pose a significant threat to the electric power supply security [3]. Finland and Sweden are developed countries sharing publicly available, accurate and transparent data for research purposes. These facts make these countries proper places to study the impacts of natural disasters on electric power reliability.

To assess the reliability performances, there are two common indices which are used by the industry and research society. System Average Interruption Duration Index (SAIDI) is defined as the total duration of sustained interruptions in a year divided by the total number of consumers. SAIDI is calculated as:

$$SAIDI = \frac{sum\ of\ duration\ of\ all\ customer\ interruptions\ in\ a\ year}{total\ number\ of\ customers\ served}\ (h)\ . \tag{1}$$

On the other hand, SAIFI is defined as the total number of sustained interruptions in a year divided by the total number of consumers and it is calculated as:

$$SAIFI = \frac{sum\ of\ number\ of\ all\ customer\ interruptions\ in\ a\ year}{total\ number\ of\ customers\ served}\ (h)\ . \tag{2}$$

2.1 Extreme Weather Events and Supply Security in Finland

Finland has adapted its electric power system according to the tough winter conditions. Thanks to its robust infrastructure the country had been enjoying a high level of reliability until the recent years. However, starting from the year 2010, the Finnish authorities have begun to realize that the electric power system is highly vulnerable against the extreme weather-related natural disasters.

During late July 2010, the country was hit by severe storms accompanied by thunders [37]. The storms caused excessive damage on forests. In addition, the thunderstorm activity reached a record high by 170.000 registered ground flashes, which was 20% higher than the long-term average. The falling trees on the aerial distribution lines and excessive number of the thunders caused extensive blackouts throughout the country. From a total of 3.2 million electricity customers, about 481.000 had to experience power interruptions [38].

One year after the unusual storms' activity of 2010, the country was shocked by another extreme weather event. During the Christmas time of 2011, the whole Baltic region was hit by Cyclone Dagmar. The storm caused devastating impacts around the region. In addition to the hazardous outcomes of the storm such as accidents, lack of fresh water and heating, interruptions in communication and transportation services, Finland experienced unusual long-lasting blackouts [5]. About 18% of the whole customers suffered from interruptions which varied from minutes to several weeks [5]. The detailed information on the impacts of Cyclone Dagmar in Finland can be found at [5].

The year 2013 was another difficult year for the distribution system operators (DSO). The Storm Eino of October 2013 caused some 110 kV lines to trip and resulted in about 250.000 customer-outages [39]. According to Finnish transmission system operator (TSO) Fingrid, some transmission lines were disconnected due to the falling trees from the storm and the situation could be fixed within 40 minutes [40]. Major damage was seen at the distribution level. The DSO Elenia was the most affected company with 92.000 customer-outages [41]. The year 2015 was another unlucky year for Finland. By autumn, the storm Valio hit the country resulting in massive blackouts which left almost 170.000 households without electricity [42]. The extreme weather continued during winter and the snow storm caused long lasting blackouts especially around central-Finland [43]. Figure 1 illustrates the yearly change of SAIDI hours in Finland between 2007 and 2014 [44]. It also presents the main causes of the outages.

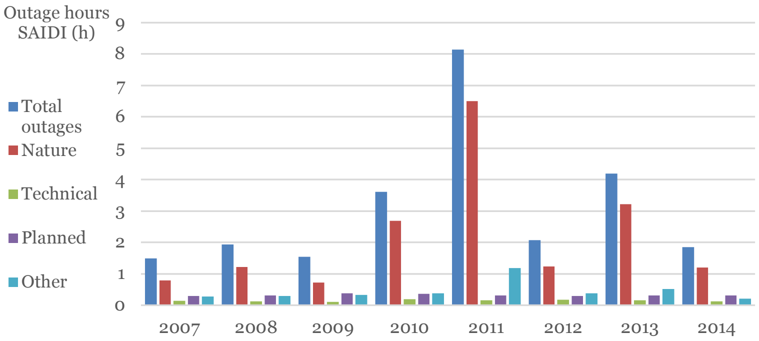

Figure 1. SAIDI outage hours in Finland, 2007 – 2014

The power interruptions are mainly caused by natural effects such as storms, hurricanes, heavy snowfall, thunderstorms etc. The other parameters are technical reasons, planned outages due to repair and maintenance and other causes. The impacts of the 2010, 2011 and 2013 storms on electric power security can easily be observed on the Figure 1. When these years are excluded, it is seen that the SAIDI outage hours are below 2 hours per year. This figure clearly shows that the main threat against the Finnish electric power security is the natural disasters. Figure 2 indicates the distribution of the nature events in the outage hours [44].

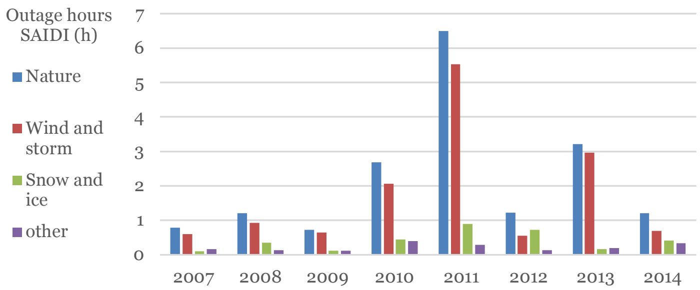

Figure 2. Nature SAIDI outage hours in Finland, 2007 – 2014

Thanks to the increasing number of the natural disasters the time that the Finnish electricity customers enjoyed high level of supply security seems to be over. An annual average of 2 hours of interruption is regarded to be acceptable for the Finnish authorities. However, statistics show that this figure is easily exceeded in case of severe storms, heavy snowfalls and large thunderstorms.

2.2 Extreme Weather Events and Supply Security in Sweden

Sweden had been enjoying a high level of electric power security until the year 2005. In January 2005, the storm Gudrun hit northern Europe causing substantial amount of destruction in Sweden, Denmark, Latvia, Lithuania and Estonia. Sweden was the place that experienced the most severe losses. Around 730,000 customers experienced long lasting power interruptions [45]. The electricity was restored within 24 hours for almost half of the customers who lost power. Throughout the country, the interruption durations varied by the different usage of underground cables. The city areas were the least affected thanks to the high degree of underground cabling. The outages in these places lasted up to several hours. On the other hand, since the power distribution heavily relies on aerial lines, the outages in rural areas persisted up to 20 days [45]. The lines passing through forests were the main places where the damages occurred. The falling trees over power lines caused considerable number of interruptions for the Swedish customers. Almost 30,000 km of distribution lines were harmed by falling trees on the lines and by collapsing poles [46]. Fortunately, the storm did not create excessive damages to the transmission lines. The power generation capacity of Sweden was also not affected to a large extent by the storm [46]. Only 20% of the power capacity was lost due to the shutdown of 4 nuclear reactors and to the downregulating of one reactor [46].

Figure 3 shows the changes in SAIDI outage hours in Sweden between 2005 and 2014. The interruptions which were taken account are the whole planned and unplanned interruptions lasting more than 3 minutes [47].

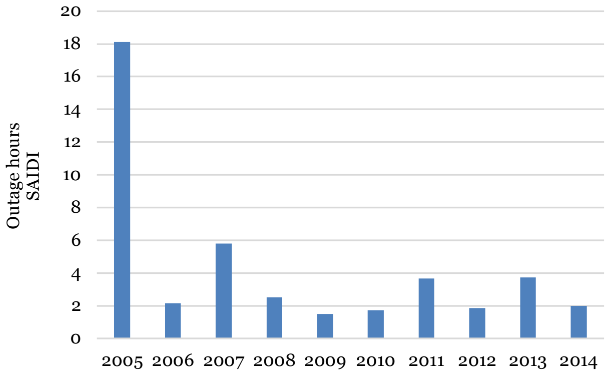

Figure 3. SAIDI outage hours in Sweden, 2005 – 2014.

When the characteristics of the outages is investigated, it is seen that the majority of the events were unexpected (or unplanned) events. Figure 4 illustrates the characteristics of the power interruptions in Sweden from 2007 to 2014.

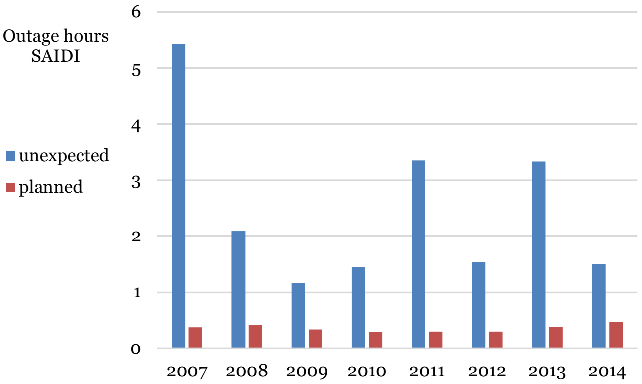

Figure 4. Distribution of the unexpected and planned outages in Sweden, 2007 – 2014.

When a closer look is given at the causes for the interruptions at Figure 5, it will be seen that during 2005 almost 50% of all outages in Sweden resulted from nature events. The parameters for the distribution of causes are chosen as follows:

- nature: thunders and other weather conditions
- human: personnel and vandalism
- operation: material, overload, reconnection and fuse malfunctioning
- unknown

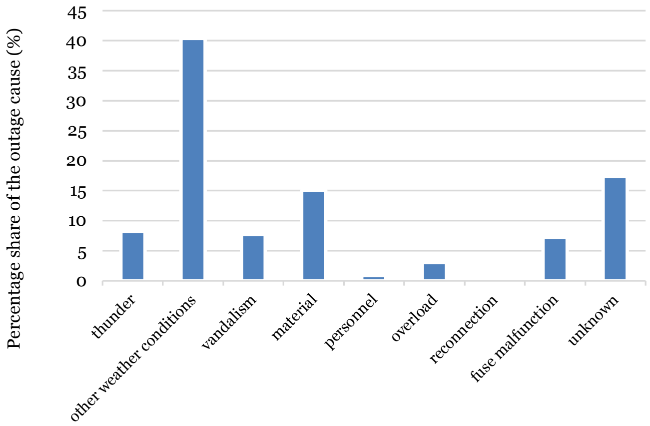

Figure 5. Causes for the power interruptions in Sweden during 2005.

When the causes for the interruptions are investigated, it is seen that the Swedish DSOs have overcome the shock of Gudrun and strengthened their supply security after the year 2005 [47]. The summary of the distribution of the outage causes during 2007 – 2014 is depicted in Figure 6.

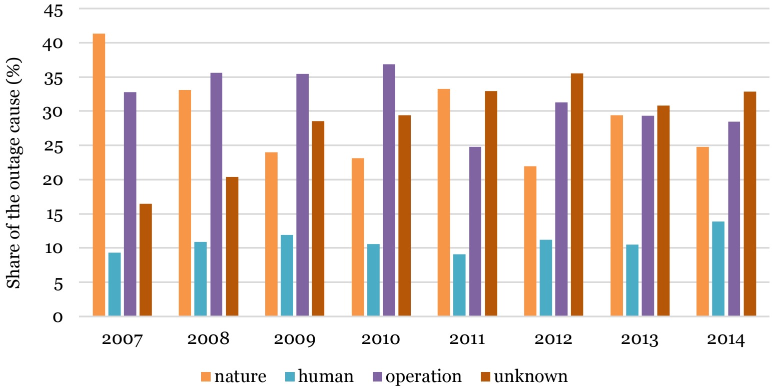

Figure 6. Share of the causes for the power interruptions in Sweden, 2007 – 2014.

One alarming observation is that while the share of nature related events is decreasing almost gradually, there is a considerable increase in the outages with unknown causes. When the same reliability performance of Finland is checked during the same time span in Figure 7, it is seen that the Finnish power system has mainly been suffering from nature events. Whilst the unknown interruption reasons are negligible [44].

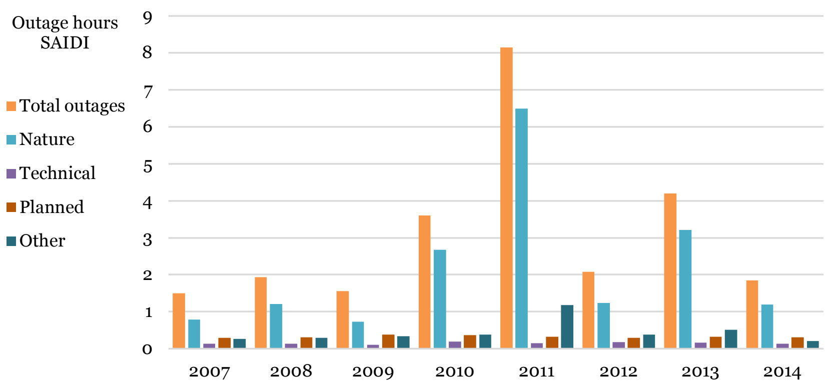

Figure 7. Outage hours and the causes for the power interruptions in Finland, 2007 – 2014.

3. Value of Continuity of Electricity Supply

This dissertation makes use of three different methodologies for CIC analysis and cost estimations. Section 3.1 introduces the first method. This is a typical customer survey study conducted in Finland which adopts Direct Worth approach. This study only highlights the sectoral differences in Customer Interruption Costs (CICs) in Finland. Section 3.2 presents two indirect analytical methods. These are the formula used by the Finnish Energy Market authority [48] and the macroeconomic model suggested by Kufeoglu [18]. Finally, Section 3.3 gives the Shadow Pricing of electric power interruptions for the Finnish DSOs. To make solid conclusions, this study targeted 78 Finnish Distribution System Operators and used reliability data and financial reports of these companies from the years 2013, 2014, and 2015.

3.1 Customer Survey and Customer Segments

Direct Worth (DW) estimates of CIC in Finland are based on the large national survey conducted in 2005 [49] and the results are updated to the present day by using January 2018 Customer Price Index in Finland. Industry, commercial and public sector customers are asked to assess their economic losses in case of an unexpected interruption that will last 1, 4 or 8 hours. Table 1 summarizes direct costing estimates of CIC of small and medium size industrial customers in Finland. Table 2 and 3 present a summary of outage costs in commercial sector and public sector obtained by the direct costing method respectively. It can be seen from Table 1, 2, and 3 that there can be big differences between mean and median values inside the same sector. This can be explained with the strategic response problems of the customer survey methodologies. These responses often include extreme high and zero responses [4].

Table 1. DW CIC Values of Industrial Customers €/kW

SECTOR	value	1 h	4 h	8 h
All in average	mean	25.9	91.4	226
	median	15.7	52.7	131
Food	mean	25.3	1230	1200
	median	13.8	37.6	69.0
Textile and apparel	mean	23.1	46.3	69.6
	median	23.1	46.3	69.6
Timber	mean	18.5	81.5	158
	median	14.5	35.5	53.6
Mass, paper, graphical	mean	33.7	149	212

SECTOR	value	1 h	4 h	8 h
	median	25.8	103	65.6
Construction	mean median	56.8 53.6	169 168	328 316
Metal industry	mean median	21.8 12.1	91.3 48.5	177 97.0
Chemical industry	mean median	132 19.9	299 55.8	527 179
Clay, glass, concrete	mean median	132 20.4	237 242	266 283
Electrical and electronics	mean median	24.1 18.1	50.6 49.4	99.1 95.4
Telecommunication	mean median	476 476	952 952	1040 1040

Table 2. DW CIC Values of Commercial Customers €/kW

SECTOR	value	1 h	4 h	8 h
All in average	mean median	57.7 23.5	166 83.6	255 130
Whole sale	mean median	129 105	332 216	394 314
Department store	mean median	17.9 8.52	42.4 32.2	82.8 82.3
Other retail	mean median	68.5 38.5	225 184	351 291
Car service and sales	mean median	37.3 23.0	165 97.3	285 177
Hotels	mean median	21.5 8.3	53.8 47.9	92.9 85.2
Restaurant	mean median	11.3 5.52	21.9 11.0	37.0 22.2
Banks, Insurance	mean median	565.3 565.3	1885 1885	1885 1885
Culture, sports	mean median	200 83.0	415 83.0	746 194
Computer services	mean median	75.2 17.4	145 56.7	267 178
Health	mean median	144 64.2	298 176	468 301

Table 3. DW CIC Values of Public Customers €/kW

SECTOR	value	1 h	4 h	8 h
All in average	mean median	41.2 6.6	149 26.3	417 62.2
Administration, public order	mean median	48.8 12.7	145 30.2	535 68.2
Schools, education and research	mean median	45.7 3.6	162 7.3	682 20.0
Health and social care	mean median	59.2 47.2	330 158	693 215
Organizations, churches	mean median	21.8 2.9	175 43.8	313 111
Culture, sports	mean median	24.6 7.6	35.6 7.6	35.6 7.6
Public infra (water, gas, heat)	mean median	236 1.6	580 5.2	1590 37.4

DW method has been previously used for the Finnish customers before [50], [51], [52] and the critical assessment was done in [53], [54], DW is considered as a reliable method, although there is always a number of zero and strategic answers which need to be filtered away prior to final analysis. The drawback of this method is the large number of customer responses required, which makes the method rather costly and labor intensive [18]. Indirect analytical methods are less precise, but they are simple to use and easy to apply on large groups of customers thus providing area and network specific information about CIC.

3.2 Application of Two Indirect Analytical Methods

In order to calculate the customer interruption costs experienced in each DSO region, two different methodologies can be used. The first one is the formula which is used by the Energy Market Authority of Finland (Energiavirasto). It aims to estimate the total monetary disadvantages caused by outages according to the formula (3) [48].

$$CIC_{t,k} = \begin{pmatrix} OD_{unexp,t} * h_{E,unexp} + OF_{unexp,t} * h_{W,unexp,t} + \\ OD_{plan,t} * h_{E,plan} + OF_{plan,t} * h_{W,plan} \end{pmatrix} * \frac{W_t}{T_t} * \frac{CPI_{k-1}}{CPI_{2004}} \qquad (3)$$

Where;

$CIC_{t,\,k}$: monetary worth of the power interruptions to the DSO's customers in year t in the value of money in year k, (euros)

$OD_{unexp,\,t}$: customer's average annual unexpected outage time weighted by annual energies in the year t, (hours)

$h_{E,\,unexp}$: value of the unexpected outages to the customer in the 2005 value of money, (€/kWh)

$OF_{unexp,\,t}$: customer's average annual unexpected outage number weighted by annual energies in the year t, (numbers)

$h_{W,\,unexp,\,t}$: value of the unexpected outages to the customer in the 2005 value of money, (€/kW).

$OD_{plan,\,t}$: customer's average annual planned outage time weighted by annual energies in the year t, (hours)

$h_{E,\,plan}$: value of the planned outages to the customer in the 2005 value of money, (€/kWh)

$OF_{plan,\,t}$: customer's average annual planned outage number weighted by annual energies in the year t, (numbers)

$h_{W,\,plan}$: value of the planned outages to the customer in the 2005 value of money, (€/kW)

W_t: the customer's amount of energy consumption in the year t, (kWh)

T_t: the number of hours in a year (hours)

CPI: Customer Price Index

The h values are given by the Energy Market Authority and they are shown in Table 4.

Furthermore, by assuming the CPI of 2004 and 2005 as 100 in Finland, CPI in 2016 was 120.7 [55].

Table 4. Prices in 2005 Values for Calculation of the Customer Interruption Costs [48]

coefficient	**$h_{E,unexp}$ (€/kWh)**	**$h_{W,unexp}$ (€/kW)**	**$h_{E,plan}$ (€/kWh)**	**$h_{W,plan}$ (€/kW)**
value	11.0	1.1	6.8	0.5

It can be also noted that formula 3 does not include prosumers who produce and consume energy. If the number of Finnish prosumers and the amount of energy they produce increase in the future, the Energy Market Authority needs to consider this fact and update the formula accordingly.

The second methodology to assess these costs is the macroeconomic approach suggested for the residential customers only [56]. To see the applicability of that approach to the whole customer classes which include industry, service (commercial) and residential ones, it was adopted and then the results were compared with the CIC results obtained from formula (3). The theory behind the macroeconomic approach is that one outage-hour during the leisure time corresponds to one hour of less work during working hours and therefore the value of this lost non-working hour is equal to the wage of one hour of work. This theory is based on Nobel Prize Winner Becker's conclusion that one hour of non-working time is financially equal to the compensation of an individual's hourly wage for work [57]. The details of the macroeconomic approach are as follow:

$$CIC_{me} = \mathrm{d}\frac{\mathrm{tw}}{\mathrm{PP}} \quad . \tag{4}$$

Where;
CIC_{me}: the interruption cost estimation via the macroeconomic approach (€/kW)
t: outage duration (hours)
w: average hourly earnings (€)
PP: peak power consumption (kW)
d: factor for continuous electric power dependency with $d \in [0,1]$.

Factor d is calculated as:

$$\mathrm{d} = \frac{100\% - \%\ of\ reduction\ in\ power\ consumption}{100\%} . \tag{5}$$

It defines the % of critical load, which the customers are not willing to postpone without sacrificing their comfort. In formula (4) peak power is used as a normalization factor. In this dissertation, another widely accepted normalization factor, which is the annual energy consumption, has been adopted. By this way, it is possible to compare the results obtained from (3) with the ones from (4). In 2016, the gross average of total hourly earnings of wage and salary earners was 19.76 € in Finland [58]. Moreover, [56] assumes d_{max} as 1.0 and d_{min} as 0.62. d_{max} is assumed as 1.0 by implying that the theoretical limit of a customer's dependency to electric power would be 100%, which means the customer would like to use all the electrical appliances without giving consent to a power cut. d_{min} is calculated according to the customer survey conducted in Finland. Details regarding to this study could be found at [56]. On the other hand, the factor that there might be more than one income earner in one electricity customer should be also included. According to the Finnish statistical institution, in average there are 1.79 income earners per household in Finland [58]. While using the income data, prosumers are neglected due to lack of data shared by the Statistics Finland. Therefore, it should be modified (4) as:

$$CIC_{me} = \mathrm{a} * \mathrm{d}\frac{\mathrm{tw}}{\mathrm{AE}} \quad . \tag{6}$$

Where,
a is the number of average income earners per household (€),
AE is the annual energy consumption (kWh).

According to the formula (3), CIC and to formula (6), $\mathrm{CIC}_{\mathrm{me,max}}$ and $\mathrm{CIC}_{\mathrm{me,min}}$ have been calculated. The necessary statistical data to calculate the CIC for each DSO, which include the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI), as well as the data such as number of customers and energy supplied can be found in [59]. The CIC results are normalized by the annual energy supply per each DSO and then summarized in € cents/kWh in Appendix B. Figure 8 is presented for better understanding the comparison of the outcomes of (3) and (4).

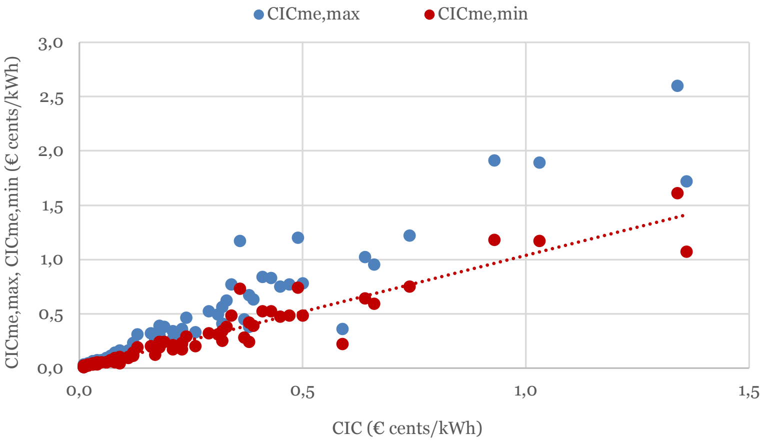

Figure 8. Comparison of CIC vs. $\mathrm{CIC}_{\mathrm{me,max}}$ and $\mathrm{CIC}_{\mathrm{me,min}}$ in 2016 (€ cents / kWh)

From Figure 8 it can be seen that for 78 different DSOs, majority of the results of CIC are closer to $\mathrm{CIC}_{\mathrm{me,min}}$ than those of $\mathrm{CIC}_{\mathrm{me,max}}$. From this observation and the deeper analysis regarding this method which has been carried out by Küfeoğlu and Lehtonen in 2015 [56], it can be said that instead of following (3) which requires extensive data, the novel macroeconomic approach (4) could be used to estimate the total costs of direct and indirect impacts of electric power outages. As it can be seen that (4) is simpler and more straightforward when compared to the methodology used by the Energy Market Authority of Finland.

3.2.1 Drawbacks and Regional Differences

Both (3) and (4) could be assessed as indirect analytical methods. By these methods the customer interruption costs are calculated through publicly available and objective analytical data such as number of customers, annual energy consumption, gross domestic product, average wages, SAIDI and SAIFI. Nonetheless, to be able to reach customer specific results via these methods is not possible. Extensive customer surveys targeting specific customer groups are necessary for that purpose. The macroeconomic model, CIC_{me} (4) makes use of national averages of wages, rather than regional averages that each DSO is active in. Figure 9 shows the income distribution in each Finnish region. According to the income figure from 2016, blue regions are above the national average whereas grey ones are below [58].

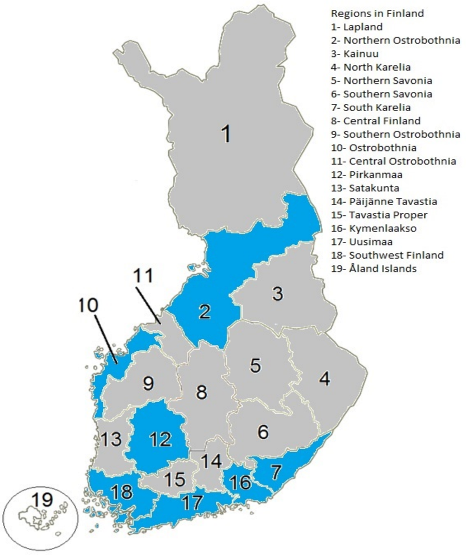

Figure 9. Regional income distribution in Finland in 2016. Blue: above national average, Grey: below national average

One may conclude that since the income level is higher in southern and western Finland, the customer interruption costs per kWh of annual energy will be higher as well. In fact, this is not the case. According to the calculations, CIC is higher in northern and eastern parts of Finland and it is the lowest at the southern regions, especially in the Uusimaa region where Helsinki metropolitan area is located. Figure 10 illustrates the lowest and highest CIC regions in Finland in 2016. The share of underground cabling in the distribution network system is crucially important in power reliability. Overhead lines are more prone to external threats than the underground cables. Storms cause substantial damage to the distribution system in Nordic countries. Extreme weather events are the primary causes of power interruptions in countries like Finland and Sweden [5] [60]. When the reliability figures of Finnish DSOs are checked, it can be seen that there are more frequent and longer lasting outages in rural regions where the distribution distances are longer [59].

Figure 9 and Figure 10 tell us that there is an inverse proportion between regional level of income and regional CIC in Finland. Therefore, instead of using national average of wages at the macroeconomic model (4), it is imperative to use average wages per each DSO region.

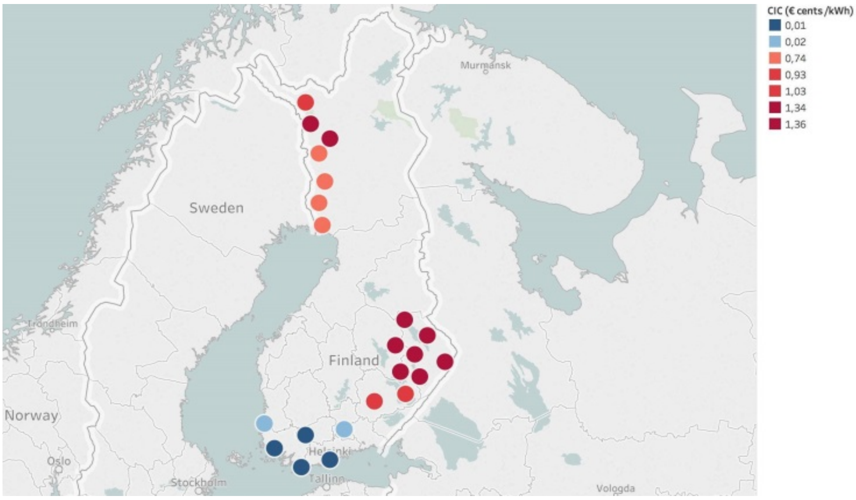

Figure 10. Regional CIC distribution in Finland (€ cents / kWh)

Major regional differences are an alarming factor for the researchers when they use these two customer-centric indirect analytical models. In Section 3.3, Shadow Pricing technique is given as a DSO centric, objective and easy to apply method for the DSOs.

3.3 Shadow Pricing of Electric Power Interruptions

It can be assumed that the electricity supply has two main states: the continuity of supply (supplied energy), and the interruptions (energy not supplied). With increasing distributed PV generation and increasing number of prosumers, these two states could be questionable. However, the prosumers were neglected in this dissertation due to lack of data and having too little share on the grid in Finland. For instance, as of 2016, the share of prosumers in Helsinki area was about 0.1% of all the DSO's customers connected to the power grid [61]. To estimate the worth of the energy not supplied, one can establish an analogy with the directional distance function. The directional distance function (DDF) has desirable (or good) and undesirable (or bad) outputs [30]. In this study, the desirable output will be energy supplied to the customers (ES), while the undesirable output will be the total minutes lost in a year, or customer minutes lost (CML). By the aid of the directional distance function, the shadow price technique to evaluate the costs of power interruptions will be utilized. The shadow price of bad outputs is presented at [30]. The methodology assumes that the production of good outputs brings along the production of bad outputs. It should be noted that, to talk about power interruptions in a region, naturally there must be electricity service provided in that region in the first place. On the other hand, the shadow price can be obtained via the distance function as well [28], [62]. However, the main advantage of the directional distance function over the distance function is that it enables the expansion of the good outputs and the contraction of the bad outputs simultaneously. For the electricity service, both the DSOs and the authorities wish to reduce the frequency and the durations of interruptions and increase the total amount of energy supplied to the consumers. As a result, it is more convenient to adopt the directional distance function to estimate the shadow prices of the value of lost load, or as it will be presented in this dissertation, the value of one minute of interruption. So, the result of the shadow pricing will yield the cost of contraction of one unit of bad output (customer minutes lost) and the expansion of one unit of good output (energy supplied) simultaneously in terms of operational expenses (OPEX). The main features of the directional distance function can be briefed as follows:

Let us assume that there are N inputs, M good outputs and J bad outputs, then inputs (x), good outputs (y) and bad outputs (b) are denoted respectively by:

$$x = (x_1, \dots, x_N) \in R_+^N \,, \tag{7}$$

$$y = (y_1, \dots, y_M) \in R_+^M, \tag{8}$$

$$b = \left(b_1, \dots, b_J\right) \in R_+^J \,. \tag{9}$$

Let P(x) denote the production technology [63], where:

$$P(x) = \{(y, b): x\ can\ produce\ (y, b)\} \,. \tag{10}$$

The directional output distance function serves as the functional representation of the technology. The production technology *P(x)* is represented by the directional distance function D_o [64]. Let $g = (g_y, g_b)$ be a directional vector and β be the maximum expansion of good outputs in the direction of g_y and the minimum contraction of the bad outputs in the direction of g_b, then D_o is defined as:

$$\overrightarrow{D_0}\left(x, y, b; g_y, gb\right) = max\{\, \beta: (y + \beta g_y, b - \ \beta g_b) \in P(x)\} \,, \tag{11}$$

$$\overrightarrow{D_0}\left(x, y + \alpha g_y, b - \alpha g_y; g\right) = \overrightarrow{D_0}(x, y, b; g) - \alpha \,. \tag{12}$$

Our aim is to increase the amount of energy supplied to the customers, while decreasing the amount of energy not supplied via reducing the CML. The directional vectors of $g_y > 0$ mean the expansion of desirable output, while $g_b > 0$ mean the contraction of the undesirable output. The relationship between the directional distance function and the revenue function reveals the shadow price for the undesirable outputs [30]. Let p indicate the good output prices and q indicate the bad output prices. These are represented as:

$$p = (p_1, \dots, p_M) \in R_+^M \,, \tag{13}$$

$$q = (q_1, \dots, q_J) \in R_+^J \,. \tag{14}$$

The revenue function is then introduced to account for the negative revenue generated by the bad outputs. The negative revenue due to the undesirable output (CML) is defined by the revenue function as follows:

$$R(x, p, q) = max_{yb}\{py - qb : (y, b) \in P(x)\}\,. \tag{15}$$

The revenue function, *R(x, p, q)*, gives the largest feasible revenue that can be obtained from inputs, *x*, when the production technology, electricity in our case, has good output prices, *p*, and bad output prices, *q*. The desirable output prices (*p*) and the undesirable output prices (*q*) can be used to calculate the largest feasible revenue in terms of the directional distance function D_o as:

$$R(x, p, q) \geq (py - qb) + p.\overrightarrow{D_0}(x, y, b; g).g_y + q.\overrightarrow{D_0}(x, y, b; g).g_b\,. \tag{16}$$

The left-hand side of the equation stands for the maximum revenue, while the right-hand side is equal to the actual revenue ($p_y - q_b$) plus the revenue gain from the elimination of technical inefficiency. The gain in revenue from the elimination of technical inefficiency has two components: the gain due to an increase in good outputs ($p.\overrightarrow{D_0}(x, y, b; g).g_y$) and the gain due to a decrease in bad outputs ($q.\overrightarrow{D_0}(x, y, b; g).g_b$), since the cost of bad outputs is subtracted from good revenues. Rearranging (16), the directional output distance function and the maximal revenue function are related as:

$$\overrightarrow{D_0}(x, y, b; g) \leq \frac{R(x, p, q) - ((py - qb))}{pg_y + qg_b}\,. \tag{17}$$

The directional output distance function given in (11) can also be recovered from the revenue function as:

$$\overrightarrow{D_0}(x, y, b; g) = min_{p,q}\left\{\frac{R(x, p, q) - ((py - qb))}{pg_y + qg_b}\right\}. \tag{18}$$

Applying the envelope theorem twice to (18) yields our shadow price model:

$$\nabla_y\overrightarrow{D_0}(x, y, b; g) = \frac{-p}{pg_y + qg_b}\,, \tag{19}$$

$$\nabla_b\overrightarrow{D_0}(x, y, b; g) = \frac{q}{pg_y + qg_b}\,. \tag{20}$$

The details of the physical meaning of the shadow pricing technique is explained in [30] in detail. By assuming that the *m-th* price of the good output (in our case the operational expenses of the DSOs) is known, then the *j-th* nominal bad output price (the price of one minute of interruption) can be calculated as [65]:

$$q_j = -p_m \left(\frac{\dfrac{\partial \overrightarrow{D_0}(x, y, b; g)}{\partial b_j}}{\dfrac{\partial \overrightarrow{D_0}(x, y, b; g)}{\partial y_m}} \right), j = 1, \ldots, J. \qquad (21)$$

The references [29] and [66] parameterize the directional distance function through a quadratic function. At this point directional vector g has been chosen in order to increase the amount of energy provided to the customers and decrease the customer interruptions in a year. 1, 0 and -1 within the vector g means increase, no change and decrease in the outputs respectively. For example, g=(1,0) means expanding the desirable outputs, while keeping the undesirable outputs the same. Since the aim is to increase the good outputs and decrease the bad outputs simultaneously, the directional vector g = (1, 1) is set. It is assumed that there is k = 1, ..., K DSOs, then the quadratic distance function for the *k-th* DSO is shown in equation (22):

Where,
l: the constant of the quadratic directional distance function,
α_n: the input coefficients,
β_m: the desirable output coefficients,
γ_j: the undesirable output coefficients,
$\alpha_{mn'}$: the quadratic of input coefficients,
$\beta_{mm'}$: the quadratic of desirable output coefficients,
$\gamma_{jj'}$: the quadratic of undesirable output coefficients,
δ_{nm}: the product of the inputs and desirable outputs coefficients,
η_{nj}: the product of the inputs and undesirable outputs coefficients,
μ_{mj}: the coefficients of the product of the desirable and undesirable outputs.

The parameters of (22), l, α_n, $\alpha_{mn'}$, β_m, $\beta_{mm'}$, γ_j, $\gamma_{jj'}$, δ_{nm}, η_{nj}, μ_{mj}, are chosen to minimize the sum of the deviations of the directional distance function value from the frontier technology (in our case the electric power supply). The coefficients of (22) are calculated via solving (23) with linear programming (LP) by adopting the directional vector as g = (1, 1). Equation (24) requires the output–input vector to be feasible. Equation (25) and (26) impose the monotonicity conditions of (19) and (20). Equation (27) imposes positive monotonicity on the inputs for the mean level of input usage. That is, at the mean level of inputs, $\bar{x}$, an increase in input usage holding good and bad outputs constant, causes the directional output distance function to increase, implying greater inefficiency. Equation (28) is due to the translation property of (12).

$$
\begin{aligned}
\overrightarrow{D_0} = (x_k, y_k, b_k; 1, 1) \\
&= l + \sum_{n=1}^{N} \alpha_n x_{nk} + \sum_{m=1}^{M} \beta_m y_{mk} + \sum_{j=1}^{J} \gamma_j b_{jk} \\
&+ \frac{1}{2} \sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{nn'} x_{nk} x_{n'k} \\
+ \frac{1}{2} \sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} y_{mk} y_{m'k} &+ \frac{1}{2} \sum_{j=1}^{J} \sum_{j'=1}^{J} \gamma_{jj'} b_{jk} b_{j'k} + \sum_{n=1}^{N} \sum_{m=1}^{M} \delta_{nm} x_{nk} y_{mk} \\
&+ \sum_{n=1}^{N} \sum_{j=1}^{J} \eta_{nj} x_{nk} b_{jk} + \sum_{m=1}^{M} \sum_{j=1}^{J} \mu_{mj} y_{mk} b_{jk}
\end{aligned}
\tag{22}
$$

Then, an optimization model is established which minimize the sum of the deviations of the directional distance function value from the frontier technology (in our case the electric power supply), see from (23) to (29). Moreover, the decision variables in the optimization model, which are l, α_n, $\alpha_{mn'}$, β_m, $\beta_{mm'}$, γ_j, $\gamma_{jj'}$, δ_{nm}, η_{nj}, μ_{mj} , solved with LP and the code has been given in Appendix C.

$$
Minimize \sum_{k=1}^{K} \left[\overrightarrow{D_0}(x_k, y_k, b_k; 1, 1) - 0 \right] \tag{23}
$$

Subject to,

$$
\overrightarrow{D_0}(x_k, y_k, b_k; 1, 1) \geq 0, \qquad k = 1, \ldots, K \ , \tag{24}
$$

$$
\frac{\partial \overrightarrow{D_0}(x_k, y_k, b_k; 1, 1)}{\partial b_j} \geq 0, j = 1, \ldots, J; k = 1, \ldots, K \ , \tag{25}
$$

$$
\frac{\partial \overrightarrow{D_0}(x_k, y_k, b_k; 1, 1)}{\partial y_m} \leq 0, m = 1, \ldots, M; k = 1, \ldots, K \ , \tag{26}
$$

$$
\frac{\partial \overrightarrow{D_0}(\bar{x}, y_k, b_k; 1, 1)}{\partial x_n} \geq 0, n = 1, \ldots, N \ , \tag{27}
$$

$$
\begin{aligned}
\sum_{m=1}^{M} \beta_m - \sum_{j=1}^{J} \gamma_j = -1 \, , \ \sum_{m'=1}^{M} \beta_{mm'} - \sum_{j=1}^{J} \mu_{mj} = 0, m = 1, \ldots, M \ , \\
\sum_{j'=1}^{J} \gamma_{jj'} - \sum_{m=1}^{M} \mu_{mj} = 0, \qquad j = 1, \ldots, J; \ \sum_{m=1}^{M} \delta_{nm} \\
- \sum_{j=1}^{J} \eta_{nj} = 0, \qquad n = 1, \ldots, N \ ,
\end{aligned}
\tag{28}
$$

$$
\alpha_{mn'} = \alpha_{n'n} \, , \ n \neq n' \ ; \ \ \beta_{mm'} = \beta_{m'm} \, , \ m \neq m' \ ; \ \ \gamma_{jj'} = \gamma_{j'j} \, , \ j \neq j' \ . \tag{29}
$$

3.3.1 Empirical Study

In this dissertation, 78 Finnish DSOs and their data for the years 2013, 2014, 2015 have been used. As useful data for the directional distance function, from the Finnish Energy Market Authority (Energiavirasto), energy supplied, number of customers, share of underground cabling, operational expenses and System Average Interruption Duration Index (SAIDI) for each DSO are selected. Sum of all customer interruptions in a year can also be defined in terms of customer minutes lost (CML) in a year. Therefore, CML is calculated as:

$$CML = SAIDI\ x\ 60\ x\ number\ of\ customers\ \ (min)\ . \tag{30}$$

Share of underground cabling in distribution lines (SC in %) and the operational expenses (OPEX in euros) have been chosen as inputs, while energy supplied to the low voltage customers (ES in GWh) and the customer minutes lost (CML in minutes) have been designated as desirable and undesirable outputs respectively. The descriptive statistics of the input and output variables are shown in Table 5 specifying the mean, standard deviation, minimum and maximum values of each data set for the years between 2013 and 2015 for the 78 Finnish DSOs. OPEX and CML are represented in thousand euros and thousand minutes respectively. In addition, energy supplied is tabulated in GWh.

Table 5. Descriptive Statistics for the Pooled Sample Observations, 2013–2015

	Inputs		**Desirable output**	**Undesirable output**
	SC (%)	OPEX (k €)	ES (GWh)	CML (k mins)
2013				
Mean	47.47	3,015.51	619.92	14,299.67
Stdev.	25.60	5,674.63	1,200.07	46,908.75
Minimum	3.04	35.35	16.67	0.81
Maximum	100.00	32,156.33	7,492.00	300,711.21
2014				
Mean	48.65	2,891.61	616.07	5,367.14
Stdev.	25.46	5,021.57	1,189.88	14,184.51
Minimum	3.23	55.30	16.38	1.90
Maximum	100.00	25,616.35	7,425.00	85,712.50
2015				
Mean	50.34	3,134.97	613.64	14,575.97
Stdev.	25.27	5,857.64	1,177.45	56,013.63
Minimum	3.30	71.00	15.84	6.18
Maximum	100.00	29,906.08	7,283.00	448,823.76

3.3.2 Empirical Study Results

Within this optimization model, the objective function (23) has been solved using constraints (24-29) and the following coefficients have been calculated and presented in Table 6. When Linear Programming variables are assigned, free "Continuous" form has been selected to get relaxed solution. Number of 1176 constraints equations have been created for each year with the script using (24-29) and they were added to the problem to find the optimal solution. Even though this depends on the computer's hardware, it takes around 1-2 minutes with a laptop which is a Quad-Core, 8 GB RAM device. Thus, it is quite fast for solving the problem. "Pandas" and "PuLP" packages were used in the Python script. Basically, the algorithm is as follows: script reads the stored data from excel, creates the optimization problem and constraints, and then solves it using "CBC" solver. After calculating the coefficients of (22) which are presented in Table 6, (21) is solved where p is taken as 5.5 € cents as the average electricity distribution price in Finland [67] and the results are summarized in Appendix B.

Table 6. Coefficients Of (22) Per Each Year

	2013	2014	2015
l	0.022237	0.007765	0.017883
α_1	0	0	0
α_2	0.199567	0.242842	0.279029
β_1	-1	-0.999879	-1
γ_1	0	0.0001212	0
α_{11}	0	0	0
α_{22}	-0.031818	-0.05012	-0.0205281
β_{11}	0	-1.98E-07	0
γ_{11}	0	-1.98E-07	0
α_{12}	0	0	0
α_{21}	0	0	0
δ_{11}	0	0	0
δ_{21}	0	0.000204	0
η_{11}	0	0	0
η_{21}	0	0,000204	0
μ_{11}	0	-1,98E-07	0

The shadow price for each DSO stands for the price of one minute of interruption in terms of operational expenses. Since this dissertation only focuses on DSO-Customer interaction, interruptions from the transmission system operators' side needs to be evaluated with future studies. At this point, the main idea is to increase the desirable output by one unit while decreasing the undesirable output by one unit at the same time. The shadow price of electricity outages in 2015 is shown in Figure 11. As it can be seen from Figure 11, in 2015, Muonion Sähköosuuskunta (0.035 € cents), PKS Sähkönsiirto Oy (0.066 € cents), Valkeakosken Energia Oy (0.108 € cents), and Vetelin Sähkölaitos Oy (0.135 € cents) have least shadow prices, while Forssan Verkkopalvelut Oy, LE-Sähköverkko Oy, Helen Sähköverkko Oy and JE-Siirto Oy have the highest shadow prices with a figure of 0.482 € cents/minute each. As a result of the analysis, it can be seen that shadow prices of one minute of outage for the majority of the DSOs change between 0.4 – 0.5 € cents for the years 2013 – 2015. In order to evaluate these results per hour instead of minute, methodology and the data set need to be prepared accordingly. Due to directional distance function methodology, the value of the incremental increase of the frontier will increase by each increment. This means that we cannot assess the value of 1 hour of outage by simply multiplying the cost figure of 1 minute by 60 due to the fact that the cost of next one minute of interruption will be higher than the cost of previous one minute-interruption. It should be noted that as CML decreases incrementally, the shadow price will increase. Therefore, the findings of this analysis give the lowest costs incurred due to the interruptions. This is valuable information since it provides the lowest boundary for the cost estimations for the network operators.

At this point, a more up-to-date analysis is needed for the years 2016 and 2017. Therefore, we would like to use the same shadow pricing method and run the same code. Figures 12 and 13 present shadow pricing of 1 minute of interruption for Finnish DSOs for the years 2016 and 2017 respectively.

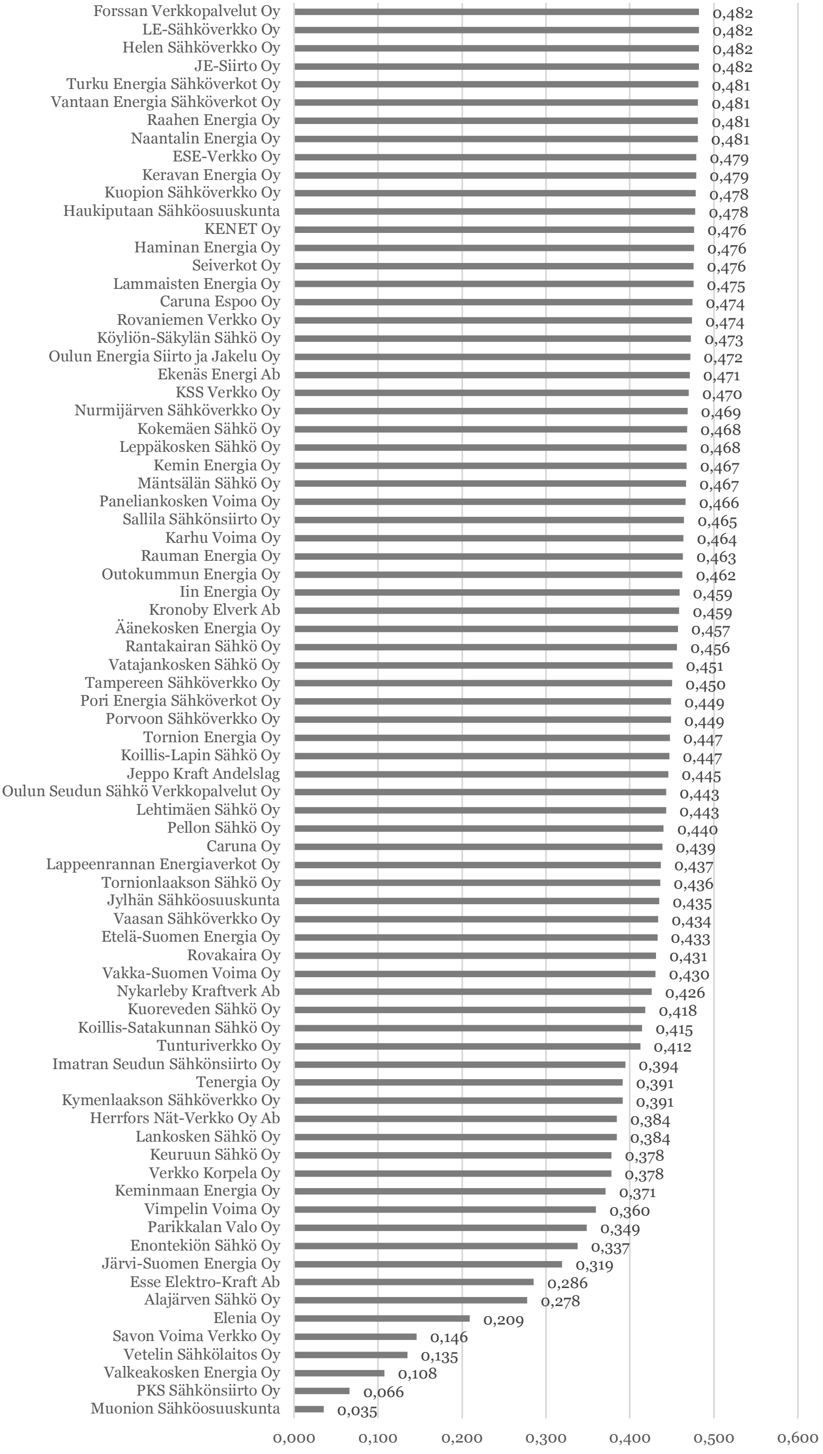

Figure 11. Shadow Price (€ in cents) of One Minute of Interruption for 2015

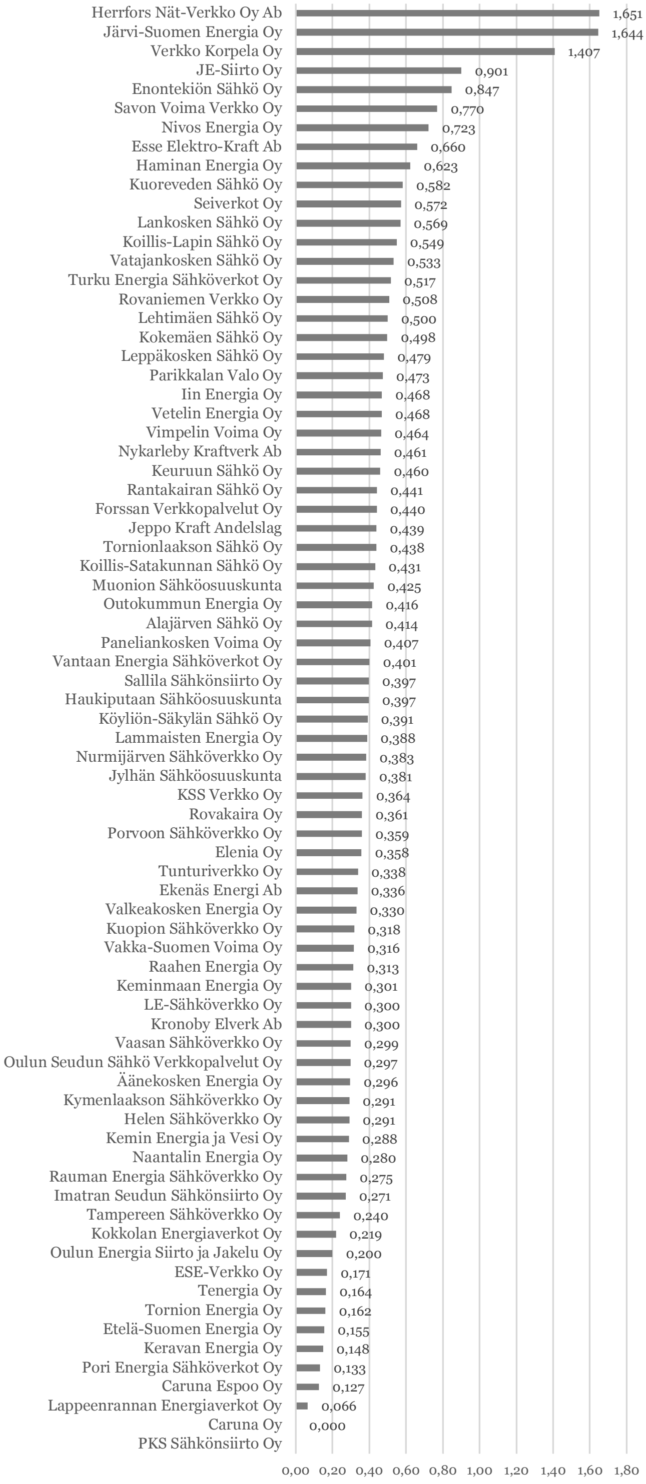

Figure 12. Shadow Price (€ in cents) of One Minute of Interruption for 2016

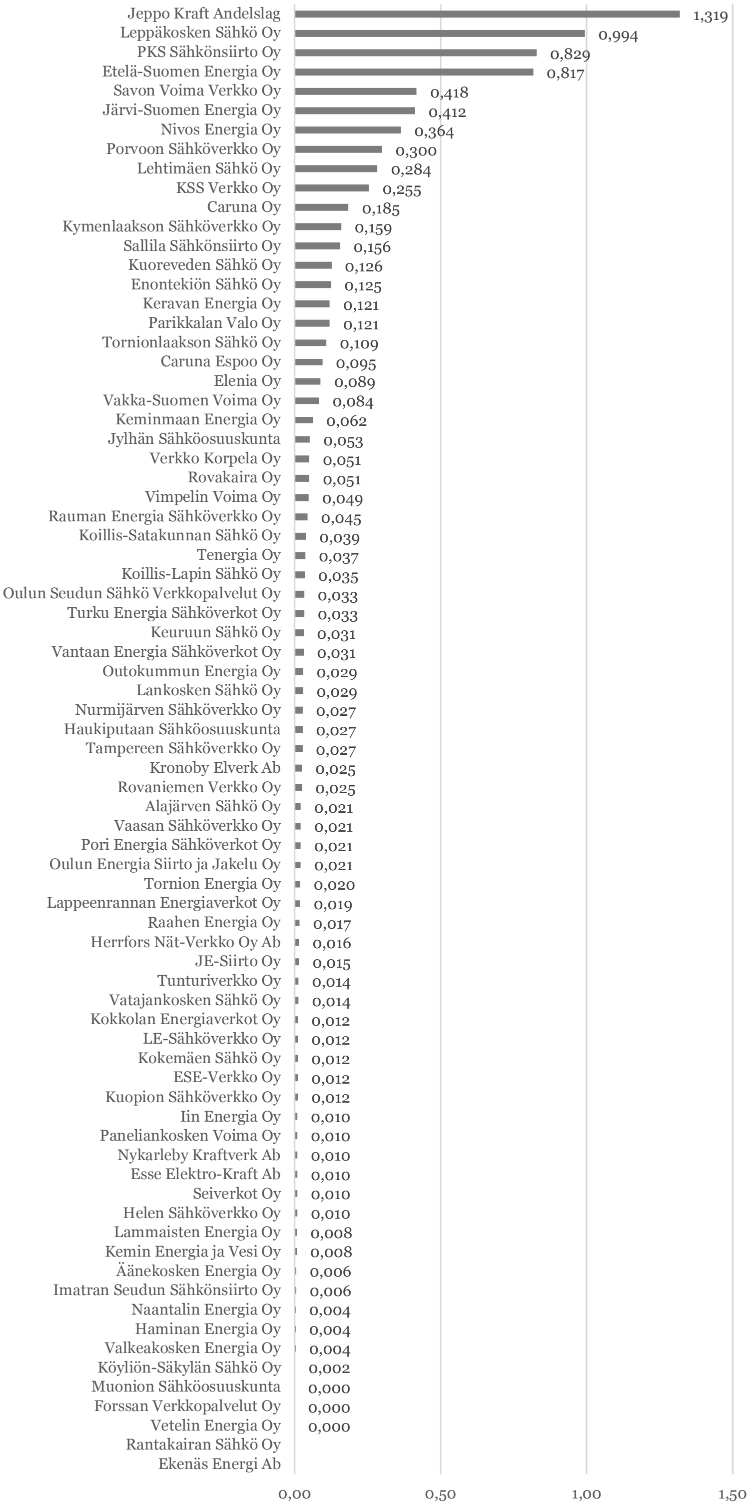

Figure 13. Shadow Price (€ in cents) of One Minute of Interruption for 2017

Figure 14 provides a visual representation of the values of the directional distance function $\vec{D}_o(x_k, y_k, b_k; 1, 1)$ (DDF) by year. The estimate of the directional distance function can be used to show inefficiency for each observation (year). The estimate of zero for DDF indicates that all DSOs have been operated on the frontier of P(x) in a given year.

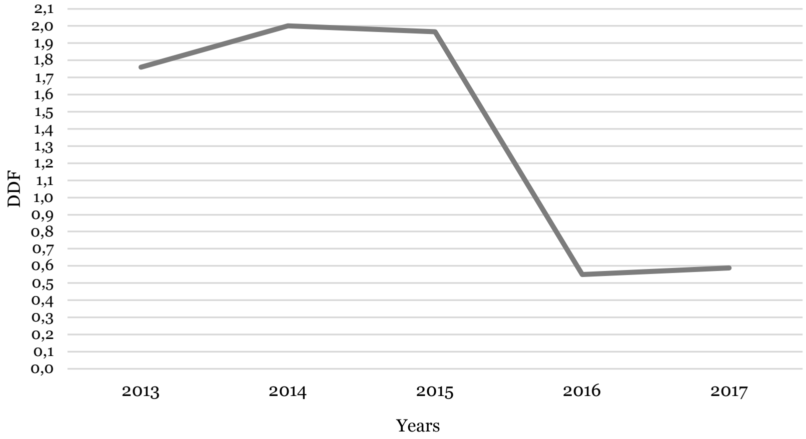

Figure 14. Optimal Directional Distance Function (DDF) estimates by year

The Figure 14 tells us that inefficiency which is designated by $\vec{D}_o$ is lower in 2016 and 2017 than 2013-2015. In other words, the DSOs performed more efficiently in power reliability during 2016 and 2017. As a result, in average the values of 1 CML are higher during these years than the ones in 2013-2015. Figures 11, 12 and 13 demonstrate the value of CML among Finnish DSOs.

3.3.3 Standard Customer Compensation Scheme in Finland

In Finland, by law, DSOs are obligated to pay certain customer compensations depending on annual customer interruption times [68]. According to this legislation, in case of a single outage event exceeds the allowable limit, the operator is supposed to pay the corresponding percentage of the annual electric power delivery fee back to the customer. The maximum amount of compensation to be paid to a single customer is limited to 1,200 €/year. Table 7 summarizes the standard customer compensation scheme applied in Finland. In theory, the amount of compensation should not be lower than the bad revenue (in our case the cost of power outage) which is calculated by shadow price of undesirable output times the undesirable output (CML) as in (31).

$$R = q\mathrm{b} \tag{31}$$

To suggest a simpler comparison between the shadow pricing of power interruptions and standard compensations, let us define compensation price as follows:

$$comp = \frac{Standard\ compensation\ paid\ by\ the\ DSO}{CML} \ . \tag{32}$$

The compensation cost is calculated in euros per each minute lost as an interruption. The result of the year 2015 is summarized in Figure 15. It can be seen that majority of the Finnish DSOs did not pay any compensations at all during 2015 in accordance with the legislation in Table 7. This table shows the percentages which penalize the DSOs in case of a single outage event lasting longer that the allowable limits. If this limit is exceeded, the DSO is supposed to pay a certain percentage of the annual electricity delivery fee back to the customer. Most of the compensation prices range from 0.1€ cent/outage minutes to 1 € cent/outage minutes, while for Rantakairan Sähkö Oy compensation price exceeds 5 € cents. Finally, to see the results better, the comparison between the shadow prices and the compensation prices for Finnish DSOs in year 2015 is presented in Figure 16. Figure 13 shows us that among 78 Finnish DSOs, only 35 of those paid compensations during 2015. This observation is directly related to the fairness concerns of the customer compensation scheme in Finland.

Table 7. The Standard Customer Compensations According to the Legislation Accepted In 2013

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

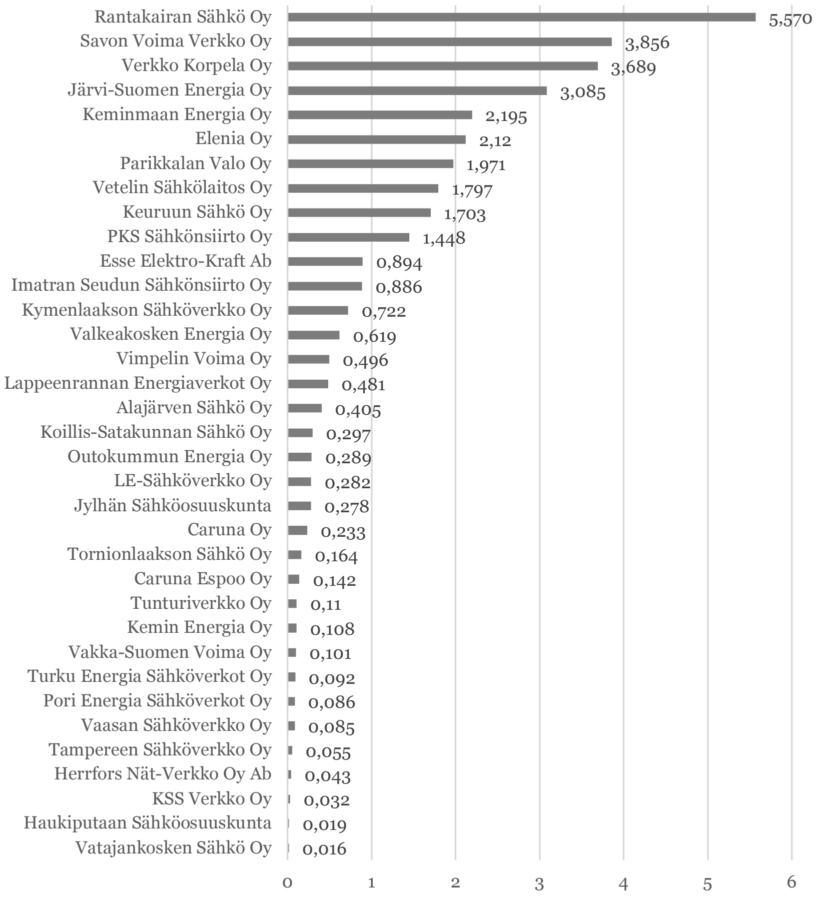

Figure 15. Compensation Price of One Minute of Interruption for 2015 (€ cents)

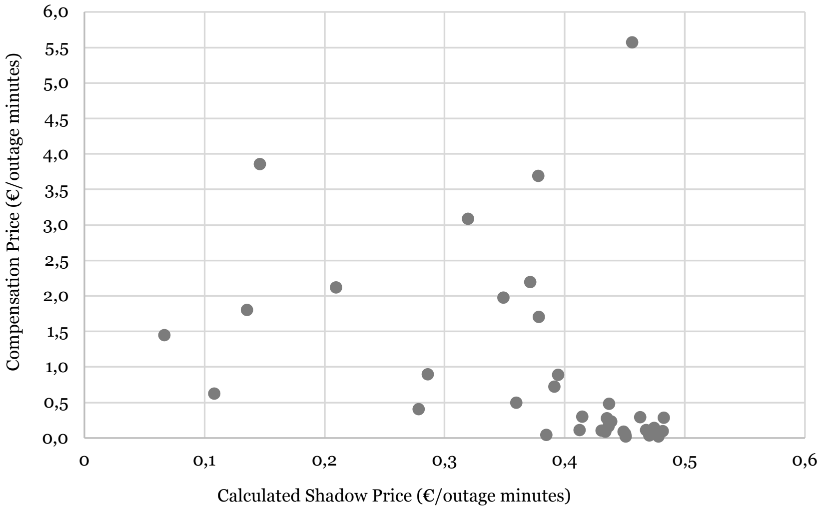

Figure 16. Comparison of Compensation price vs. Shadow price

According to the shadow pricing calculations, 17 Finnish DSOs paid more customer compensations than the value of the interruptions in 2015. Figure 16 shows the number and the distribution of DSOs which paid more and less compensations than the value of one minute of interruption.

Customers' activities are naturally directly related to the cost of one minute of interruption. There are numerous types of costs, both direct and indirect, incurred after a fault event. To reflect these in the analysis, a customer centric study is necessary. Nonetheless, this dissertation approaches the same problem from DSO point of view and therefore it reflects the cost of CML in terms of OPEX of these DSOs. For a better understanding and critique of the compensation scheme, this dissertation should be supported by supplementary studies, mainly customer surveys. Nevertheless, the supplementary customer surveys should pay utmost attention to the strategic responses, which mainly include extreme and zero responses. Effective and credible ways need to be devised to eliminate these responses [4].

4. Conclusions

Power system reliability is a generic terminology and continuity of supply is one of the subtitles of this. A 100% reliable power system ensures power without interruption. An availability of 99.9% may sound acceptable at the first instance, however it means 8.75 hours without electric service each year, a level of service that can be considered dissatisfactory by nearly all electric consumers in developed countries [69]. Therefore, improving reliability and hence decreasing annual interruption hours is a must for the public authorities and for the DSOs. To foster this struggle, it is imperative to understand the true costs of power interruptions. Different than the majority of the sources in the literature, this dissertation aims to evaluate the economic losses from DSOs' perspective instead of approaching the problem from customers' point of view. Finland has been chosen for the dissertation due to availability of open access, publicly available, transparent and reliable data.

Without doubt, increasing frequency and the duration of the extreme weather events have become a major threat for the electric power security, as it has been pointed out on Publications 1 and 2. Even though Finnish electric power system is designed for tough winter conditions, it had been experiencing extraordinary weather-related natural disasters during recent years. Finnish electric power system was affected tremendously especially from 2010, 2011 and 2013 storms. For instance, during Christmas time of 2011, all Baltic region was hit by Cyclone Dagmar. Finland experienced unusual long-lasting blackouts. Around 18% of the whole customers suffered from interruptions which varied from minutes to several weeks. Similar effect of natural events has also been observed in the neighboring Nordic country, Sweden. Almost 50% of all outages in Sweden resulted from nature events in 2005. Consequently, the integrity of future of climate and energy cannot be ignored. Since weather events are quite unpredictable, there is still imperative risk of long-lasting interruptions in the Nordic Countries. That's why, the public authorities, the companies and the society deserve to know the true monetary impacts of electric power interruptions.

Customer surveys, indirect analytical methods and case studies are the main methods to estimate Customer Interruption Costs. Each of them has its own advantages and disadvantages. While customer surveys are mostly preferred in the literature, case studies are considered as the most reliable CIC estimation method. Customer surveys require relatively more time, labor and money. Case studies are conducted after large scale blackout events which are infrequent. On the other hand, indirect analytical methods rely on objective data such as electricity prices, value added or turnover of a customer or sector, gross domestic product of a country or annual energy consumption. This makes these methods favourable if reaching objective results is aimed. They are straight forward, easy to apply, less time, money and labour demanding. Nevertheless, they tend to yield broad and average results. In addition to using a previously introduced customer survey and a macroeconomic model, this dissertation provides a novel contribution to the literature by using directional distance function in the power interruption phenomenon. It estimates the shadow pricing of one minute of interruption by using statistical data and financial statements of 78 DSOs in Finland.

As it is explained in Section 3.3 in this dissertation, as well as in Publication 4, shadow price for each DSO stands for the price of one minute of interruption in terms of operational expenses. Thus, increasing the energy supplied by one unit while decreasing the customer minute lost by one unit at the same time is the main idea behind the methodology. As a result of the shadow price approach, it was seen that shadow price of one minute of interruption for the majority of the DSOs vary between 0.4 and 0.5 € cents for the years 2013 – 2015. It was also observed that when CML decreases incrementally, the shadow price will increase. For this reason, the findings of this analysis give the lowest costs incurred due to the interruptions. This is valuable information for both DSOs and for the public authorities in Finland since the DSOs are supposed to pay standard customer compensations due to interruptions. In the analysis, Figure 16 shows that the customer compensation scheme, which is summarized in Table 7, is not properly designed and a fairer plan is needed to support the DSOs in their efforts to boost their service reliability.

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6. Appendices

6.1 Appendix A – Data Set for Linear Programming

TABLE A. Original Data set which is used in the directional distance function. Share of underground cabling in distribution lines (SC in %), operational expenses (OPEX in thousand euros), energy supplied to the customers (ES in GWh), total minutes lost in a year, or customer minutes lost (CML in minutes) respectively.

DSOs	SC (%)	OPEX (k€)	ES (GWh)	CML (min)	Year
Alajärven Sähkö Oy	24.73	381.00	68.30	2.10	2017
Caruna Espoo Oy	73.09	13183.00	2006.10	3.00	2017
Caruna Oy	44.95	5879.00	5433.69	6.42	2017
Ekenäs Energi Ab	94.66	339.23	64.42	1.80	2017
Elenia Oy	47.55	25023.86	4587.06	3.60	2017
Enontekiön Sähkö Oy	8.22	261.47	28.75	3.84	2017
ESE-Verkko Oy	82.96	503.33	233.39	0.60	2017
Esse Elektro-Kraft Ab	47.30	493.12	47.69	0.48	2017
Etelä-Suomen Energia Oy	27.96	285.49	165.80	26.88	2017
Forssan Verkkopalvelut Oy	87.04	747.04	138.74	0.00	2017
Haminan Energia Oy	61.61	633.30	88.32	0.84	2017
Haukiputaan Sähköosuuskunta	62.34	659.00	138.02	4.50	2017
Helen Sähköverkko Oy	97.98	15652.23	2438.80	3.24	2017
Herrfors Nät-Verkko Oy Ab	52.07	13515.57	410.00	0.84	2017
Iin Energia Oy	42.52	368.26	65.61	0.30	2017
Imatran Seudun Sähkönsiirto Oy	55.02	910.00	235.88	0.36	2017
JE-Siirto Oy	97.14	11126.79	403.37	1.38	2017
Jeppo Kraft Andelslag	30.90	98.29	18.11	193.68	2017
Jylhän Sähköosuuskunta	67.89	348.06	70.22	2.88	2017
Järvi-Suomen Energia Oy	25.67	35926.71	909.65	15.18	2017
Kemin Energia ja Vesi Oy	82.96	561.16	150.83	0.84	2017
Keminmaan Energia Oy	57.92	260.00	70.69	4.32	2017
Keravan Energia Oy	86.02	335.51	171.65	6.60	2017
Keuruun Sähkö Oy	37.70	687.00	86.88	1.20	2017
Koillis-Lapin Sähkö Oy	28.59	1133.24	147.56	2.76	2017
Koillis-Satakunnan Sähkö Oy	34.93	1306.09	164.11	2.16	2017
Kokemäen Sähkö Oy	34.93	532.73	55.52	0.42	2017
Kokkolan Energiaverkot Oy	70.83	599.68	268.95	0.48	2017
Kronoby Elverk Ab	45.05	137.24	46.84	3.54	2017
KSS Verkko Oy	48.49	3280.22	497.56	9.36	2017
Kuopion Sähköverkko Oy	79.95	2501.69	389.87	2.94	2017
Kuoreveden Sähkö Oy	48.94	146.12	17.58	9.96	2017
Kymenlaakson Sähköverkko Oy	24.78	5995.36	1125.20	4.98	2017
Köyliön-Säkylän Sähkö Oy	60.24	438.39	79.79	0.84	2017
Lammaisten Energia Oy	66.23	507.48	91.99	0.24	2017
Lankosken Sähkö Oy	18.71	262.39	22.91	5.76	2017
Lappeenrannan Energiaverkot Oy	54.08	752.53	505.55	1.14	2017

DSOs	SC (%)	OPEX (k€)	ES (GWh)	CML (min)	Year
LE-Sähköverkko Oy	75.92	3772.07	854.85	0.96	2017
Lehtimäen Sähkö Oy	9.17	166.99	16.87	12.60	2017
Leppäkosken Sähkö Oy	42.32	2690.31	323.72	31.14	2017
Muonion Sähköosuuskunta	5.56	159.00	42.74	0.00	2017
Naantalin Energia Oy	81.08	281.99	90.22	1.44	2017
Nivos Energia Oy	32.84	1967.25	192.82	11.28	2017
Nurmijärven Sähköverkko Oy	57.84	1471.29	356.00	4.74	2017
Nykarleby Kraftverk Ab	39.32	371.00	63.38	1.20	2017
Oulun Energia Siirto ja Jakelu Oy	87.72	2082.82	868.10	1.44	2017
Oulun Seudun Sähkö Verkkopalvelut Oy	36.37	1465.27	441.25	1.50	2017
Outokummun Energia Oy	41.67	377.65	69.56	0.96	2017
Paneliankosken Voima Oy	47.95	736.97	128.24	0.48	2017
Parikkalan Valo Oy	54.33	869.09	83.51	4.62	2017
PKS Sähkönsiirto Oy	18.95	20881.38	907.40	27.36	2017
Pori Energia Sähköverkot Oy	72.91	372.00	493.25	0.72	2017
Porvoon Sähköverkko Oy	42.74	2535.18	393.63	12.36	2017
Raahen Energia Oy	91.01	637.73	78.03	1.32	2017
Rantakairan Sähkö Oy	6.76	232.00	39.35	0.00	2017
Rauman Energia Sähköverkko Oy	75.39	1027.36	209.65	2.22	2017
Rovakaira Oy	45.38	1993.83	463.06	1.68	2017
Rovaniemen Verkko Oy	92.54	2098.54	233.08	2.76	2017
Sallila Sähkönsiirto Oy	67.10	1437.94	303.14	5.52	2017
Savon Voima Verkko Oy	34.43	16706.87	1436.08	13.14	2017
Seiverkot Oy	89.21	2267.61	238.98	3.78	2017
Tampereen Sähköverkko Oy	70.77	3992.32	1287.10	1.68	2017
Tenergia Oy	20.10	32.77	33.53	1.14	2017
Tornion Energia Oy	73.88	495.80	144.34	1.56	2017
Tornionlaakson Sähkö Oy	22.58	1291.69	218.13	4.32	2017
Tunturiverkko Oy	29.81	415.96	153.82	1.08	2017
Turku Energia Sähköverkot Oy	71.41	7314.19	975.23	4.32	2017
Vaasan Sähköverkko Oy	64.81	3263.35	712.84	1.20	2017
Vakka-Suomen Voima Oy	35.87	1205.69	286.88	3.72	2017
Valkeakosken Energia Oy	56.99	709.39	129.41	0.42	2017
Vantaan Energia Sähköverkot Oy	86.93	7016.08	1168.57	2.40	2017
Vatajankosken Sähkö Oy	42.82	1681.49	185.36	1.50	2017
Verkko Korpela Oy	45.49	6789.83	323.82	2.10	2017
Vetelin Energia Oy	27.82	185.47	28.32	0.00	2017
Vimpelin Voima Oy	76.31	168.08	27.83	5.58	2017
Äänekosken Energia Oy	78.45	402.77	89.85	3.12	2017
Alajärven Sähkö Oy	23.06	360.00	67.62	1.98	2016
Caruna Espoo Oy	71.49	11934.48	2005.16	51.12	2016
Caruna Oy	41.67	6513.00	5496.65	34.92	2016
Ekenäs Energi Ab	92.72	353.58	63.59	1.02	2016
Elenia Oy	44.52	25428.33	4606.98	6.66	2016
Enontekiön Sähkö Oy	7.89	293.46	26.79	0.00	2016
ESE-Verkko Oy	81.71	345.56	239.90	0.84	2016
Esse Elektro-Kraft Ab	43.43	478.17	48.72	3.06	2016
Etelä-Suomen Energia Oy	26.81	235.79	170.34	9.00	2016
Forssan Verkkopalvelut Oy	85.21	771.29	139.61	0.00	2016
Haminan Energia Oy	61.22	868.23	93.53	2.52	2016
Haukiputaan Sähköosuuskunta	59.94	620.00	139.06	4.92	2016
Helen Sähköverkko Oy	97.93	15538.52	2461.00	3.30	2016
Herrfors Nät-Verkko Oy Ab	50.99	10971.01	398.04	2.58	2016
Iin Energia Oy	22.61	386.84	62.68	0.00	2016
Imatran Seudun Sähkönsiirto Oy	53.69	926.00	241.51	1.26	2016
JE-Siirto Oy	96.40	9264.16	401.35	1.08	2016
Jeppo Kraft Andelslag	30.49	110.30	19.31	240.12	2016
Jylhän Sähköosuuskunta	65.87	330.43	71.32	0.00	2016
Järvi-Suomen Energia Oy	22.38	37440.20	919.55	29.10	2016
Kemin Energia ja Vesi Oy	81.98	588.49	148.87	0.42	2016
Keminmaan Energia Oy	56.31	239.00	70.94	4.02	2016

DSOs	SC (%)	OPEX (k€)	ES (GWh)	CML (min)	Year
Keravan Energia Oy	85.64	285.72	159.60	8.64	2016
Keuruun Sähkö Oy	38.02	750.00	89.62	12.48	2016
Koillis-Lapin Sähkö Oy	28.30	1125.10	144.38	4.44	2016
Koillis-Satakunnan Sähkö Oy	31.74	1168.86	166.74	2.46	2016
Kokemäen Sähkö Oy	36.41	499.18	56.94	0.60	2016
Kokkolan Energiaverkot Oy	69.29	560.16	285.65	0.36	2016
Kronoby Elverk Ab	43.65	135.59	47.59	0.00	2016
KSS Verkko Oy	46.80	2960.06	495.70	1.56	2016
Kuopion Sähköverkko Oy	78.39	2571.59	391.90	0.00	2016
Kuoreveden Sähkö Oy	47.27	248.34	17.96	4.80	2016
Kymenlaakson Sähköverkko Oy	24.18	4138.87	1146.01	0.00	2016
Köyliön-Säkylän Sähkö Oy	60.13	396.70	80.43	0.54	2016
Lammaisten Energia Oy	64.48	472.56	96.05	0.00	2016
Lankosken Sähkö Oy	16.16	259.99	23.76	8.16	2016
Lappeenrannan Energiaverkot Oy	53.10	740.31	514.90	20.70	2016
LE-Sähköverkko Oy	74.86	3658.52	864.55	1.08	2016
Lehtimäen Sähkö Oy	8.42	160.22	16.94	7.02	2016
Leppäkosken Sähkö Oy	40.49	2560.59	327.81	5.82	2016
Muonion Sähköosuuskunta	5.15	169.00	40.03	0.00	2016
Naantalin Energia Oy	80.26	234.92	89.84	3.42	2016
Nivos Energia Oy	31.27	1969.37	195.71	0.60	2016
Nurmijärven Sähköverkko Oy	56.07	1506.25	358.25	3.84	2016
Nykarleby Kraftverk Ab	36.79	381.00	62.53	0.84	2016
Oulun Energia Siirto ja Jakelu Oy	86.78	2116.57	831.12	1.56	2016
Oulun Seudun Sähkö Verkkopalvelut Oy	33.32	1268.85	433.83	0.96	2016
Outokummun Energia Oy	39.23	381.56	74.03	2.88	2016
Paneliankosken Voima Oy	46.94	635.79	130.47	0.78	2016
Parikkalan Valo Oy	52.38	863.65	88.53	8.16	2016
PKS Sähkönsiirto Oy	16.63	20272.22	927.80	253.38	2016
Pori Energia Sähköverkot Oy	71.34	370.00	504.21	2.22	2016
Porvoon Sähköverkko Oy	41.14	2229.75	407.36	10.26	2016
Raahen Energia Oy	90.76	642.77	78.45	90.60	2016
Rantakairan Sähkö Oy	5.12	283.00	39.22	0.00	2016
Rauman Energia Sähköverkko Oy	73.39	808.23	211.30	2.22	2016
Rovakaira Oy	43.81	1794.28	445.61	4.32	2016
Rovaniemen Verkko Oy	91.81	2234.91	230.98	1.80	2016
Sallila Sähkönsiirto Oy	64.48	1489.39	307.52	1.74	2016
Savon Voima Verkko Oy	30.57	17788.37	1453.92	7.26	2016
Seiverkot Oy	87.97	2506.13	237.75	1.50	2016
Tampereen Sähköverkko Oy	69.45	4337.48	1281.85	1.80	2016
Tenergia Oy	19.40	33.04	33.38	0.24	2016
Tornion Energia Oy	72.54	446.89	145.12	54.60	2016
Tornionlaakson Sähkö Oy	19.58	1209.09	211.64	1.14	2016
Tunturiverkko Oy	31.06	406.12	145.30	1.74	2016
Turku Energia Sähköverkot Oy	70.03	7250.47	975.82	3.12	2016
Vaasan Sähköverkko Oy	63.79	3054.21	717.90	1.38	2016
Vakka-Suomen Voima Oy	34.42	1195.24	286.47	5.16	2016
Valkeakosken Energia Oy	56.36	618.52	129.81	0.54	2016
Vantaan Energia Sähköverkot Oy	86.19	7526.17	1168.98	1.74	2016
Vatajankosken Sähkö Oy	41.02	1699.82	186.95	1.02	2016
Verkko Korpela Oy	42.65	5877.17	322.82	4.32	2016
Vetelin Energia Oy	26.45	172.94	28.88	0.00	2016
Vimpelin Voima Oy	74.56	166.22	28.38	8.40	2016
Äänekosken Energia Oy	76.47	391.72	88.90	0.00	2016
Alajärven Sähkö Oy	21.92	393.00	65.04	797.52	2015
Caruna Espoo Oy	69.94	10390.30	1929.00	36.18	2015
Caruna Oy	38.98	7733.00	5193.00	171.00	2015
Ekenäs Energi Ab	89.37	414.13	64.17	48.24	2015
Elenia Oy	41.43	22472.82	4310.13	1075.80	2015
Enontekiön Sähkö Oy	3.30	223.35	26.74	561.06	2015
ESE-Verkko Oy	80.65	435.51	228.70	18.66	2015

DSOs	SC (%)	OPEX (k€)	ES (GWh)	CML (min)	Year
Esse Elektro-Kraft Ab	37.23	527.89	45.16	766.98	2015
Etelä-Suomen Energia Oy	25.82	481.81	157.25	193.32	2015
Forssan Verkkopalvelut Oy	83.88	870.29	125.59	6.00	2015
Haminan Energia Oy	61.16	790.72	88.24	29.28	2015
Haukiputaan Sähköosuuskunta	58.10	520.00	131.52	22.56	2015
Helen Sähköverkko Oy	97.70	14235.78	2375.60	6.60	2015
Herrfors Nät-Verkko Oy Ab	49.85	10862.92	405.38	378.72	2015
Iin Energia Oy	19.72	345.22	61.39	93.60	2015
Imatran Seudun Sähkönsiirto Oy	56.02	5981.00	230.76	339.90	2015
JE-Siirto Oy	96.16	7375.10	384.35	7.68	2015
Jeppo Kraft Andelslag	26.00	75.49	17.37	144.60	2015
Jylhän Sähköosuuskunta	63.46	381.54	67.85	185.28	2015
Järvi-Suomen Energia Oy	22.70	29906.08	856.62	632.40	2015
Karhu Voima Oy	100.00	393.84	3.35	74.40	2015
Kemin Energia Oy	80.95	531.18	144.48	61.62	2015
Keminmaan Energia Oy	54.44	299.00	68.21	429.72	2015
KENET Oy	66.21	369.99	274.71	29.16	2015
Keravan Energia Oy	84.93	1211.45	161.04	18.90	2015
Keuruun Sähkö Oy	33.64	659.00	81.95	402.84	2015
Koillis-Lapin Sähkö Oy	27.88	1131.18	141.68	139.38	2015
Koillis-Satakunnan Sähkö Oy	28.75	1284.08	157.05	262.44	2015
Kokemäen Sähkö Oy	36.09	513.04	55.77	59.76	2015
Kronoby Elverk Ab	41.19	115.34	44.82	94.20	2015
KSS Verkko Oy	44.55	2927.41	475.00	51.48	2015
Kuopion Sähköverkko Oy	77.12	2791.34	377.22	20.70	2015
Kuoreveden Sähkö Oy	45.57	149.80	17.07	248.22	2015
Kymenlaakson Sähköverkko Oy	23.40	4290.45	1075.69	352.44	2015
Köyliön-Säkylän Sähkö Oy	55.79	389.05	84.54	41.46	2015
Lammaisten Energia Oy	62.18	513.35	90.29	31.56	2015
Lankosken Sähkö Oy	14.75	247.03	21.76	378.84	2015
Lappeenrannan Energiaverkot Oy	51.59	868.91	487.09	177.84	2015
LE-Sähköverkko Oy	73.68	3745.38	826.11	6.54	2015
Lehtimäen Sähkö Oy	7.73	185.02	15.84	154.20	2015
Leppäkosken Sähkö Oy	39.20	2371.30	310.73	61.26	2015
Muonion Sähköosuuskunta	5.16	186.00	39.00	1812.60	2015
Mäntsälän Sähkö Oy	28.96	1883.37	186.01	64.08	2015
Naantalin Energia Oy	79.76	246.93	83.88	12.18	2015
Nurmijärven Sähköverkko Oy	54.70	1538.71	332.01	57.66	2015
Nykarleby Kraftverk Ab	34.18	407.00	62.01	219.12	2015
Oulun Energia Siirto ja Jakelu Oy	85.25	2136.98	802.32	45.48	2015
Oulun Seudun Sähkö Verkkopalvelut Oy	30.64	1566.00	410.45	153.42	2015
Outokummun Energia Oy	36.72	424.96	72.06	80.40	2015
Paneliankosken Voima Oy	42.77	569.67	123.29	66.12	2015
Parikkalan Valo Oy	49.67	848.84	83.70	517.20	2015
Pellon Sähkö Oy	39.90	71.00	20.62	164.34	2015
PKS Sähkönsiirto Oy	14.64	21486.31	879.16	1677.72	2015
Pori Energia Sähköverkot Oy	69.92	528.00	606.18	131.76	2015
Porvoon Sähköverkko Oy	39.10	2054.79	377.99	132.42	2015
Raahen Energia Oy	88.38	639.61	76.24	10.62	2015
Rantakairan Sähkö Oy	4.01	221.00	38.39	104.46	2015
Rauman Energia Oy	71.08	785.15	196.80	77.94	2015
Rovakaira Oy	44.07	1972.60	432.87	199.56	2015
Rovaniemen Verkko Oy	90.94	1462.45	222.30	37.92	2015
Sallila Sähkönsiirto Oy	61.79	1476.61	290.98	72.72	2015
Savon Voima Verkko Oy	29.16	26629.32	1377.93	1338.90	2015
Seiverkot Oy	87.50	2520.91	227.91	30.96	2015
Tampereen Sähköverkko Oy	68.23	4471.67	1233.74	127.32	2015
Tenergia Oy	17.17	80.13	30.56	351.60	2015
Tornion Energia Oy	72.36	464.24	138.25	137.10	2015
Tornionlaakson Sähkö Oy	16.77	801.62	182.23	180.30	2015
Tunturiverkko Oy	22.10	351.28	140.77	271.20	2015

DSOs	SC (%)	OPEX (k€)	ES (GWh)	CML (min)	Year
Turku Energia Sähköverkot Oy	68.80	7660.31	933.58	9.84	2015
Vaasan Sähköverkko Oy	62.61	2902.29	676.35	190.02	2015
Vakka-Suomen Voima Oy	37.24	1158.00	267.16	201.66	2015
Valkeakosken Energia Oy	54.44	808.36	122.22	1500.12	2015
Vantaan Energia Sähköverkot Oy	85.51	7931.07	1106.50	10.32	2015
Vatajankosken Sähkö Oy	38.64	1491.21	176.54	125.16	2015
Verkko Korpela Oy	39.61	6269.79	308.08	404.04	2015
Vetelin Sähkölaitos Oy	18.40	162.82	27.45	1384.98	2015
Vimpelin Voima Oy	68.33	185.77	27.26	474.60	2015
Äänekosken Energia Oy	75.29	337.86	81.85	100.80	2015
Alajärven Sähkö Oy	20.75	332.00	63.96	66.00	2014
Caruna Espoo Oy	69.36	12256.00	1935.00	44.40	2014
Caruna Oy	37.82	6098.00	5337.00	138.00	2014
Ekenäs Energi Ab	85.21	294.50	60.68	51.00	2014
Elenia Oy	38.74	21875.27	4391.10	144.60	2014
Enontekiön Sähkö Oy	3.30	197.70	26.92	486.00	2014
ESE-Verkko Oy	79.98	525.91	235.20	5.40	2014
Esse Elektro-Kraft Ab	34.94	527.73	47.00	120.60	2014
Etelä-Suomen Energia Oy	24.84	575.38	163.03	323.40	2014
Forssan Verkkopalvelut Oy	81.55	837.47	142.89	5.40	2014
Haminan Energia Oy	61.25	662.05	92.19	16.20	2014
Haukiputaan Sähköosuuskunta	57.11	620.00	133.33	35.40	2014
Helen Sähköverkko Oy	97.57	12699.90	2408.40	3.60	2014
Herrfors Nät-Verkko Oy Ab	39.11	7875.25	252.70	193.20	2014
Iin Energia Oy	15.22	269.97	62.23	24.00	2014
Imatran Seudun Sähkönsiirto Oy	54.24	5679.00	242.04	135.60	2014
JE-Siirto Oy	95.82	8041.83	390.83	15.60	2014
Jeppo Kraft Andelslag	18.10	68.51	16.25	117.00	2014
Jylhän Sähköosuuskunta	57.36	383.12	68.98	35.40	2014
Järvi-Suomen Energia Oy	21.13	25616.35	880.75	172.20	2014
Karhu Voima Oy	100.00	390.70	3.39	24.00	2014
Kemin Energia Oy	79.76	536.42	147.83	19.80	2014
Keminmaan Energia Oy	53.85	315.00	67.53	22.20	2014
KENET Oy	63.86	3965.48	277.13	41.40	2014
Keravan Energia Oy	83.87	1240.03	166.42	58.20	2014
Keuruun Sähkö Oy	32.15	579.00	84.20	262.80	2014
Koillis-Lapin Sähkö Oy	27.63	658.72	143.83	145.20	2014
Koillis-Satakunnan Sähkö Oy	25.91	1247.72	161.65	155.40	2014
Kokemäen Sähkö Oy	36.02	507.36	57.07	69.00	2014
Kronoby Elverk Ab	39.50	56.33	45.94	281.40	2014
KSS Verkko Oy	43.16	2996.56	485.50	108.60	2014
Kuopion Sähköverkko Oy	76.62	2629.53	379.44	11.40	2014
Kuoreveden Sähkö Oy	42.79	124.15	17.23	58.80	2014
Kymenlaakson Sähköverkko Oy	22.76	4274.32	1108.58	217.80	2014
Köyliön-Säkylän Sähkö Oy	54.57	409.47	84.26	54.60	2014
Lammaisten Energia Oy	60.33	510.25	90.61	40.20	2014
Lankosken Sähkö Oy	13.86	292.80	22.42	280.20	2014
Lappeenrannan Energiaverkot Oy	51.02	941.75	507.71	106.80	2014
LE-Sähköverkko Oy	72.84	3550.05	841.23	10.20	2014
Lehtimäen Sähkö Oy	7.28	151.59	16.38	86.40	2014
Leppäkosken Sähkö Oy	37.17	2437.37	316.68	52.20	2014
Muonion Sähköosuuskunta	5.31	173.00	39.49	540.00	2014
Mäntsälän Sähkö Oy	27.06	1101.41	190.94	39.00	2014
Naantalin Energia Oy	78.46	302.29	85.98	17.40	2014
Nurmijärven Sähköverkko Oy	53.40	1505.21	341.72	36.00	2014
Nykarleby Kraftverk Ab	32.53	319.00	67.42	234.60	2014
Oulun Energia Siirto ja Jakelu Oy	83.80	2724.89	823.07	50.40	2014
Oulun Seudun Sähkö Verkkopalvelut Oy	28.92	1499.64	414.52	63.00	2014
Outokummun Energia Oy	35.13	352.87	70.22	195.00	2014
Paneliankosken Voima Oy	40.70	637.16	124.20	43.80	2014
Parikkalan Valo Oy	48.93	880.27	86.74	149.40	2014

DSOs	SC (%)	OPEX (k€)	ES (GWh)	CML (min)	Year
Pellon Sähkö Oy	38.92	73.52	20.70	130.80	2014
PKS Sähkönsiirto Oy	11.72	20526.80	904.09	411.00	2014
Pori Energia Sähköverkot Oy	68.89	361.00	628.89	165.60	2014
Porvoon Sähköverkko Oy	36.33	2085.59	388.93	168.00	2014
Raahen Energia Oy	87.91	658.58	76.98	16.20	2014
Rantakairan Sähkö Oy	3.23	247.00	38.91	66.60	2014
Rauman Energia Oy	68.59	825.50	201.00	33.00	2014
Rovakaira Oy	43.11	1037.12	436.24	120.00	2014
Rovaniemen Verkko Oy	89.24	1651.89	222.94	14.40	2014
Sallila Sähkönsiirto Oy	58.96	1559.18	297.01	67.80	2014
Savon Voima Verkko Oy	26.82	16042.86	1376.39	759.60	2014
Seiverkot Oy	86.79	3080.27	228.20	34.20	2014
Tampereen Sähköverkko Oy	67.11	4693.19	1255.24	22.20	2014
Tenergia Oy	16.87	55.30	31.34	216.00	2014
Tornion Energia Oy	70.42	583.54	140.40	40.80	2014
Tornionlaakson Sähkö Oy	14.00	945.18	193.99	76.80	2014
Tunturiverkko Oy	21.54	377.05	142.81	124.80	2014
Turku Energia Sähköverkot Oy	68.16	7469.67	962.74	10.20	2014
Vaasan Sähköverkko Oy	61.44	2838.36	698.31	204.00	2014
Vakka-Suomen Voima Oy	33.91	1219.00	267.80	98.40	2014
Valkeakosken Energia Oy	53.29	619.70	122.44	28.20	2014
Vantaan Energia Sähköverkot Oy	84.72	7916.33	1133.35	16.20	2014
Vatajankosken Sähkö Oy	36.81	1487.28	177.83	106.80	2014
Verkko Korpela Oy	37.09	5480.79	313.42	895.80	2014
Vetelin Sähkölaitos Oy	17.09	173.48	25.81	39.00	2014
Vimpelin Voima Oy	66.00	150.40	27.50	141.60	2014
Äänekosken Energia Oy	73.33	280.66	83.24	132.00	2014
Alajärven Sähkö Oy	20.17	298.00	65.90	137.40	2013
Caruna Espoo Oy	68.74	10295.00	1913.00	82.20	2013
Caruna Oy	36.16	11438.00	5432.00	521.40	2013
Ekenäs Energi Ab	85.19	91.23	66.10	24.60	2013
Elenia Oy	35.77	22967.59	4416.61	729.60	2013
Enontekiön Sähkö Oy	10.14	234.23	26.59	1968.00	2013
ESE-Verkko Oy	79.39	443.39	239.30	13.20	2013
Esse Elektro-Kraft Ab	32.06	404.68	46.69	258.60	2013
Etelä-Suomen Energia Oy	23.89	540.47	163.43	457.20	2013
Forssan Verkkopalvelut Oy	79.79	858.85	152.32	11.40	2013
Haminan Energia Oy	60.99	567.84	94.09	21.00	2013
Haukiputaan Sähköosuuskunta	55.96	774.00	136.81	49.20	2013
Helen Sähköverkko Oy	97.32	12727.31	2445.50	4.80	2013
Herrfors Nät-Verkko Oy Ab	35.21	7466.87	256.20	522.60	2013
Iin Energia Oy	14.63	283.23	65.78	26.40	2013
Imatran Seudun Sähkönsiirto Oy	52.54	5977.00	237.95	838.80	2013
JE-Siirto Oy	95.48	8276.97	393.25	12.00	2013
Jeppo Kraft Andelslag	16.12	68.81	14.39	114.00	2013
Jylhän Sähköosuuskunta	55.75	449.20	68.98	100.20	2013
Järvi-Suomen Energia Oy	19.75	32156.33	893.34	943.80	2013
Karhu Voima Oy	100.00	445.33	3.39	11.40	2013
Kemin Energia Oy	78.73	588.29	152.71	23.40	2013
Keminmaan Energia Oy	52.78	337.00	70.86	141.60	2013
KENET Oy	62.14	4235.37	284.75	55.20	2013
Keravan Energia Oy	83.07	1237.15	170.86	43.80	2013
Keuruun Sähkö Oy	30.37	591.00	88.89	492.00	2013
Koillis-Lapin Sähkö Oy	26.33	703.56	147.22	432.00	2013
Koillis-Satakunnan Sähkö Oy	23.17	1220.82	164.27	162.60	2013
Kokemäen Sähkö Oy	34.88	440.37	58.48	220.80	2013
Kronoby Elverk Ab	37.48	35.35	48.09	166.20	2013
KSS Verkko Oy	42.01	3007.30	493.70	111.60	2013

DSOs	SC (%)	OPEX (k€)	ES (GWh)	CML (min)	Year
Kuopion Sähköverkko Oy	75.29	2817.96	375.25	11.40	2013
Kuoreveden Sähkö Oy	41.33	122.85	15.76	147.00	2013
Kymenlaakson Sähköverkko Oy	21.81	5387.23	1124.88	412.80	2013
Köyliön-Säkylän Sähkö Oy	52.96	429.30	77.57	119.40	2013
Lammaisten Energia Oy	59.51	591.71	93.05	100.20	2013
Lankosken Sähkö Oy	10.08	256.87	23.06	813.60	2013
Lappeenrannan Energiaverkot Oy	46.80	1195.22	522.30	316.20	2013
LE-Sähköverkko Oy	72.24	3779.15	847.75	25.20	2013
Lehtimäen Sähkö Oy	6.56	153.53	16.67	99.60	2013
Leppäkosken Sähkö Oy	35.45	2352.87	308.70	100.20	2013
Muonion Sähköosuuskunta	5.36	154.00	38.87	201.00	2013
Mäntsälän Sähkö Oy	24.87	1084.02	189.57	97.20	2013
Naantalin Energia Oy	78.11	288.26	87.02	19.20	2013
Nurmijärven Sähköverkko Oy	52.19	1467.97	343.79	79.20	2013
Nykarleby Kraftverk Ab	30.90	314.00	68.40	207.60	2013
Oulun Energia Siirto ja Jakelu Oy	81.52	2674.53	839.10	58.80	2013
Oulun Seudun Sähkö Verkkopalvelut Oy	27.47	1465.00	414.34	119.40	2013
Outokummun Energia Oy	33.23	393.75	72.06	101.40	2013
Paneliankosken Voima Oy	38.15	598.88	127.41	262.80	2013
Parikkalan Valo Oy	46.62	829.58	88.56	1199.40	2013
Pellon Sähkö Oy	31.64	43.15	21.30	70.80	2013
PKS Sähkönsiirto Oy	11.41	22976.73	920.60	411.60	2013
Pori Energia Sähköverkot Oy	67.51	393.00	659.51	373.20	2013
Porvoon Sähköverkko Oy	33.55	1963.87	393.58	322.80	2013
Raahen Energia Oy	87.88	645.48	78.04	7.20	2013
Rantakairan Sähkö Oy	3.04	272.00	39.66	69.60	2013
Rauman Energia Oy	65.59	801.90	202.54	146.40	2013
Rovakaira Oy	42.84	1195.01	435.40	266.40	2013
Rovaniemen Verkko Oy	88.64	1713.28	226.28	13.20	2013
Sallila Sähkönsiirto Oy	56.84	1441.10	307.71	187.20	2013
Savon Voima Verkko Oy	23.89	17885.37	1403.08	1216.80	2013
Seiverkot Oy	86.33	3593.55	235.40	51.60	2013
Tampereen Sähköverkko Oy	66.00	4549.79	1268.26	130.20	2013
Tenergia Oy	16.58	46.06	32.66	300.00	2013
Tornion Energia Oy	70.09	539.24	145.70	57.00	2013
Tornionlaakson Sähkö Oy	13.51	804.30	189.59	250.20	2013
Tunturiverkko Oy	21.53	300.55	140.97	154.20	2013
Turku Energia Sähköverkot Oy	67.10	7557.65	959.24	57.60	2013
Vaasan Sähköverkko Oy	60.12	2865.93	683.69	254.40	2013
Vakka-Suomen Voima Oy	32.25	1256.00	274.03	504.60	2013
Valkeakosken Energia Oy	52.60	514.59	126.38	28.80	2013
Vantaan Energia Sähköverkot Oy	83.80	7587.11	1065.15	18.60	2013
Vatajankosken Sähkö Oy	34.63	1359.44	177.04	244.80	2013
Verkko Korpela Oy	35.15	5425.29	317.56	619.80	2013
Vetelin Sähkölaitos Oy	12.01	163.01	27.57	199.80	2013
Vimpelin Voima Oy	63.54	141.19	28.03	477.00	2013
Äänekosken Energia Oy	72.34	247.59	85.00	112.20	2013

6.2 Appendix B – Customer Interruption Costs

TABLE B1. *CIC*, $CIC_{me,max}$ and $CIC_{me,min}$ per each DSO in 2016 (€ cents / kWh)

DSO	**CIC**	**$CIC_{me,max}$**	**$CIC_{me,min}$**
Äänekosken Energia Oy	0.12	0.23	0.14
Alajärven Sähkö Oy	0.21	0.27	0.17
Caruna Espoo Oy	0.23	0.36	0.23
Caruna Oy	0.31	0.49	0.31
Ekenäs Energi Ab	0.01	0.01	0.01
Elenia Oy	0.47	0.77	0.48
Enontekiön Sähkö Oy	1.03	1.89	1.17
ESE-Verkko Oy	0.03	0.06	0.04
Esse Elektro-Kraft Ab	0.64	1.02	0.64
Etelä-Suomen Energia Oy	0.37	0.45	0.28
Forssan Verkkopalvelut Oy	0.01	0.01	0.01
Haminan Energia Oy	0.03	0.04	0.03
Haukiputaan Sähköosuuskunta	0.08	0.12	0.07
Helen Sähköverkko Oy	0.01	0.03	0.02
Herrfors Nät-Verkko Oy Ab	0.17	0.20	0.12
Iin Energia Oy	0.12	0.18	0.11
Imatran Seudun Sähkönsiirto Oy	0.19	0.38	0.24
Järvi-Suomen Energia Oy	0.93	1.91	1.18
Jeppo Kraft Andelslag	0.59	0.36	0.22
JE-Siirto Oy	0.03	0.04	0.03
Jylhän Sähköosuuskunta	0.23	0.35	0.22
Kemin Energia Oy	0.02	0.03	0.02
Keminmaan Energia Oy	0.45	0.75	0.47
KENET Oy	0.06	0.08	0.05
Keravan Energia Oy	0.09	0.16	0.10
Keuruun Sähkö Oy	0.38	0.67	0.42
Koillis-Lapin Sähkö Oy	0.49	1.20	0.74
Koillis-Satakunnan Sähkö Oy	0.41	0.84	0.52
Kokemäen Sähkö Oy	0.07	0.09	0.06
Köyliön-Säkylän Sähkö Oy	0.23	0.27	0.17
Kronoby Elverk Ab	0.09	0.14	0.09
KSS Verkko Oy	0.08	0.14	0.09
Kuopion Sähköverkko Oy	0.03	0.06	0.04
Kuoreveden Sähkö Oy	0.06	0.09	0.05
Kymenlaakson Sähköverkko Oy	0.33	0.62	0.38
Lammaisten Energia Oy	0.05	0.07	0.05
Lankosken Sähkö Oy	0.36	1.17	0.73
Lappeenrannan Energiaverkot Oy	0.24	0.46	0.29
Lehtimäen Sähkö Oy	0.34	0.77	0.48
Leppäkosken Sähkö Oy	0.32	0.56	0.34
LE-Sähköverkko Oy	0.02	0.04	0.02
Loiste Sähköverkko Oy	0.18	0.39	0.24
Muonion Sähköosuuskunta	1.36	1.72	1.07
Naantalin Energia Oy	0.01	0.01	0.01
Nivos Energia Oy	0.04	0.04	0.03
Nurmijärven Sähköverkko Oy	0.11	0.16	0.10
Nykarleby Kraftverk Ab	0.18	0.30	0.19
Oulun Energia Siirto ja Jakelu Oy	0.04	0.07	0.05
Oulun Seudun Sähkö Verkko. Oy	0.12	0.20	0.12
Outokummun Energia Oy	0.09	0.06	0.04
Paneliankosken Voima Oy	0.08	0.09	0.05
Parikkalan Valo Oy	0.39	0.63	0.39
PKS Sähkönsiirto Oy	1.34	2.60	1.61
Pori Energia Sähköverkot Oy	0.09	0.10	0.06
Porvoon Sähköverkko Oy	0.17	0.26	0.16
Raahen Energia Oy	0.29	0.52	0.32
Rantakairan Sähkö Oy	0.13	0.31	0.19
Rauman Energia Oy	0.02	0.04	0.03
Rovakaira Oy	0.38	0.38	0.24
Rovaniemen Verkko Oy	0.03	0.06	0.03
Sallila Sähkönsiirto Oy	0.07	0.11	0.07
Savon Voima Verkko Oy	0.66	0.95	0.59
Seiverkot Oy	0.03	0.04	0.03
Tampereen Sähköverkko Oy	0.03	0.06	0.03
Tenergia Oy	0.50	0.78	0.48
Tornion Energia Oy	0.21	0.34	0.21
Tornionlaakson Sähkö Oy	0.74	1.22	0.75

DSO	CIC	$CIC_{me,max}$	$CIC_{me,min}$
Tunturiverkko Oy	0.32	0.41	0.25
Turku Energia Sähköverkot Oy	0.02	0.03	0.02
Vaasan Sähköverkko Oy	0.08	0.12	0.08
Vakka-Suomen Voima Oy	0.11	0.15	0.09
Valkeakosken Energia Oy	0.06	0.08	0.05
Vantaan Energia Sähköverkot Oy	0.02	0.03	0.02
Vatajankosken Sähkö Oy	0.18	0.30	0.19
Verkko Korpela Oy	0.26	0.33	0.20
Vetelin Energia Oy	0.43	0.83	0.52
Vimpelin Voima Oy	0.16	0.32	0.20

TABLE B2. Shadow Prices of One Minute of Interruption (€ Cents), 2013 and 2014.

DSO	2013	2014	DSO	2013	2014
Äänekosken Energia Oy	0.454	0.449	Lehtimäen Sähkö Oy	0.457	0.461
Alajärven Sähkö Oy	0.447	0.466	Leppäkosken Sähkö Oy	0.457	0.470
Caruna Espoo Oy	0.462	0.472	LE-Sähköverkko Oy	0.477	0.481
Caruna Oy	0.348	0.447	Mäntsälän Sähkö Oy	0.458	0.474
Ekenäs Energi Ab	0.477	0.470	Muonion Sähköosuuskunta	0.426	0.343
Elenia Oy	0.295	0.445	Naantalin Energia Oy	0.479	0.479
Enontekiön Sähkö Oy	0.000	0.357	Nurmijärven Sähköverkko Oy	0.463	0.474
ESE-Verkko Oy	0.480	0.482	Nykarleby Kraftverk Ab	0.429	0.422
Esse Elektro-Kraft Ab	0.416	0.452	Oulun Energia Siirto ja Jakelu Oy	0.468	0.470
Etelä-Suomen Energia Oy	0.364	0.399	Oulun Seudun S. Verkkopalvelut Oy	0.452	0.467
Forssan Verkkopalvelut Oy	0.481	0.482	Outokummun Energia Oy	0.457	0.432
Haminan Energia Oy	0.478	0.480	Paneliankosken Voima Oy	0.414	0.472
Haukiputaan Sähköosuuskunta	0.471	0.474	Parikkalan Valo Oy	0.179	0.444
Helen Sähköverkko Oy	0.483	0.483	Pellon Sähkö Oy	0.465	0.449
Herrfors Nät-Verkko Oy Ab	0.347	0.433	PKS Sähkönsiirto Oy	0.376	0.376
Iin Energia Oy	0.477	0.478	Pori Energia Sähköverkot Oy	0.386	0.440
Imatran Seudun Sähkönsiirto Oy	0.268	0.448	Porvoon Sähköverkko Oy	0.399	0.439
Järvi-Suomen Energia Oy	0.242	0.438	Raahen Energia Oy	0.482	0.480
Jeppo Kraft Andelslag	0.454	0.453	Rantakairan Sähkö Oy	0.465	0.466
JE-Siirto Oy	0.481	0.480	Rauman Energia Oy	0.445	0.475
Jylhän Sähköosuuskunta	0.457	0.474	Rovakaira Oy	0.413	0.452
Karhu Voima Oy	0.481	0.477	Rovaniemen Verkko Oy	0.480	0.480
Kemin Energia Oy	0.478	0.479	Sallila Sähkönsiirto Oy	0.434	0.466
Keminmaan Energia Oy	0.446	0.478	Savon Voima Verkko Oy	0.175	0.287

DSO	2013	2014	DSO	2013	2014
KENET Oy	0.469	0.473	Seiverkot Oy	0.470	0.475
Keravan Energia Oy	0.472	0.468	Tampereen Sähköverkko Oy	0.449	0.478
Keuruun Sähkö Oy	0.355	0.414	Tenergia Oy	0.405	0.427
Koillis-Lapin Sähkö Oy	0.371	0.445	Tornion Energia Oy	0.469	0.473
Koillis-Satakunnan Sähkö Oy	0.441	0.443	Tornionlaakson Sähkö Oy	0.418	0.463
Kokemäen Sähkö Oy	0.425	0.466	Tunturiverkko Oy	0.443	0.451
Köyliön-Säkylän Sähkö Oy	0.452	0.469	Turku Energia Sähköverkot Oy	0.469	0.481
Kronoby Elverk Ab	0.440	0.410	Vaasan Sähköverkko Oy	0.417	0.430
KSS Verkko Oy	0.454	0.455	Vakka-Suomen Voima Oy	0.352	0.458
Kuopion Sähköverkko Oy	0.481	0.481	Valkeakosken Energia Oy	0.476	0.476
Kuoreveden Sähkö Oy	0.445	0.468	Vantaan Energia Sähköverkot Oy	0.479	0.480
Kymenlaakson Sähköverkko Oy	0.375	0.426	Vatajankosken Sähkö Oy	0.419	0.455
Lammaisten Energia Oy	0.457	0.473	Verkko Korpela Oy	0.323	0.253
Lankosken Sähkö Oy	0.274	0.410	Vetelin Sähkölaitos Oy	0.431	0.474
Lappeenrannan Energiaverkot Oy	0.401	0.455	Vimpelin Voima Oy	0.359	0.446

6.3 Appendix C – Linear Programming Script

```
#!/usr/bin/env python2
# -*- coding: utf-8 -*-
"""
Data File (in xlsx format) contains following columns:
    "Company": Defines the company name
    "SC" (x1): Share of underground cabling in distribution lines (In-
put 1),
    "OPEX" (x2): Operational Expenses (Input 2),
    "ES" (y1): Energy Supplied (Good Output),
    "CML" (b1): Energy NOT Supplied (Bad Output),
    "Year": Indicates the year of the data point for particular com-
pany.
"""
import sys

import pandas as pd
import pulp
import pprint

reload(sys)
sys.setdefaultencoding('utf8')

OPERATION_NAME = 'Shadow_Prices_of_DSOs_2013_14_15'
WRITER = pd.ExcelWriter('{}_results.xlsx'.format(OPERATION_NAME))

df = pd.read_excel("{}.xlsx".format(OPERATION_NAME))
df['SC_SQUARE'] = df['SC'] * df['SC']
df['OPEX_SQUARE'] = df['OPEX'] * df['OPEX']
df['ES_SQUARE'] = df['ES'] * df['ES']
df['CML_SQUARE'] = df['CML'] * df['CML']
df['SC_x_OPEX'] = df['SC'] * df['OPEX']
df['SC_x_ES'] = df['SC'] * df['ES']
df['OPEX_x_ES'] = df['OPEX'] * df['ES']
df['SC_x_CML'] = df['SC'] * df['CML']
df['OPEX_x_CML'] = df['OPEX'] * df['CML']
df['ES_x_CML'] = df['ES'] * df['CML']

data_points = {'number_of_data_points': len(df.index),
               'sum_of_sc': df['SC'].sum(),
               'sum_of_opex': df['OPEX'].sum(),
               'sum_of_es': df['ES'].sum(),
               'sum_of_cml': df['CML'].sum(),
               'sum_of_sc_square': df['SC_SQUARE'].sum(),
               'sum_of_opex_square': df['OPEX_SQUARE'].sum(),
               'sum_of_es_square': df['ES_SQUARE'].sum(),
               'sum_of_cml_square': df['CML_SQUARE'].sum(),
               'sum_of_sc_x_opex': df['SC_x_OPEX'].sum(),
               'sum_of_sc_x_es': df['SC_x_ES'].sum(),
               'sum_of_opex_x_es': df['OPEX_x_ES'].sum(),
               'sum_of_sc_x_cml': df['SC_x_CML'].sum(),
               'sum_of_opex_x_cml': df['OPEX_x_CML'].sum(),
               'sum_of_es_x_cml': df['ES_x_CML'].sum(),
               }
prob = pulp.LpProblem(OPERATION_NAME, pulp.LpMinimize)

LP_VARIABLES = ['K', 'alfa_1', 'alfa_2', 'beta_1', 'gama_1',
                'alfa_1_1', 'alfa_1_2', 'alfa_2_1', 'alfa_2_2',
                'beta_1_1', 'gama_1_1', 'delta_1_1', 'delta_2_1',
                'nu_1_1', 'nu_2_1', 'mu_1_1']

for lp_var in LP_VARIABLES:
    locals()[lp_var] = pulp.LpVariable(lp_var, cat='Continuous')

# Minimizing function
prob += data_points['number_of_data_points'] * K + \
        alfa_1 * data_points['sum_of_sc'] + \
```

```
        alfa_2 * data_points['sum_of_opex'] + \
        beta_1 * data_points['sum_of_es'] + \
        gama_1 * data_points['sum_of_cml'] + \
        0.5 * alfa_1_1 * data_points['sum_of_sc_square'] + \
        0.5 * alfa_1_2 * data_points['sum_of_sc_x_opex'] + \
        0.5 * alfa_2_1 * data_points['sum_of_sc_x_opex'] + \
        0.5 * alfa_2_2 * data_points['sum_of_opex_square'] + \
        0.5 * beta_1_1 * data_points['sum_of_es_square'] +\
        0.5 * gama_1_1 * data_points['sum_of_cml_square'] +\
        delta_1_1 * data_points['sum_of_sc_x_es'] + \
        delta_2_1 * data_points['sum_of_opex_x_es'] +\
        nu_1_1 * data_points['sum_of_sc_x_cml'] +\
        nu_2_1 * data_points['sum_of_opex_x_cml'] +\
        mu_1_1 * data_points['sum_of_es_x_cml'], 'Minimizing Func-
tion'

##### CONSTRAINTS: #####
# (1) DDF >= 0 for each company
# Each row represents one company in the df
for i, row in df.iterrows():
    prob += K + \
            alfa_1 * row['SC'] + \
            alfa_2 * row['OPEX'] + \
            beta_1 * row['ES'] + \
            gama_1 * row['CML'] + \
            0.5 * alfa_1_1 * row['SC_SQUARE'] + \
            0.5 * alfa_1_2 * row['SC_x_OPEX'] + \
            0.5 * alfa_2_1 * row['SC_x_OPEX'] + \
            0.5 * alfa_2_2 * row['OPEX_SQUARE'] + \
            0.5 * beta_1_1 * row['ES_SQUARE'] + \
            0.5 * gama_1_1 * row['CML_SQUARE'] + \
            delta_1_1 * row['SC_x_ES'] + \
            delta_2_1 * row['OPEX_x_ES'] + \
            nu_1_1 * row['SC_x_CML'] + \
            nu_2_1 * row['OPEX_x_CML'] + \
            mu_1_1 * row['ES_x_CML'] >= 0


# (2)
# gama_1 + gama_1_1*b_1_k + nu_1_1*x_1_k +
# nu_2_1*x_2_k + mu_1_1*y_1_k >= 0
for ind, row in df.iterrows():
    prob += gama_1 + \
            gama_1_1 * row['CML'] + \
            nu_1_1 * row['SC'] + \
            nu_2_1 * row['OPEX'] + \
            mu_1_1 * row['ES'] >= 0

# (3)
# beta_1 + beta_1_1*y_1_k + delta_1_1*x_1_k +
# delta_2_1*x_2_k + mu_1_1*b_1_k <= 0
for inde, row in df.iterrows():
    prob += beta_1 + \
            beta_1_1 * row['ES'] + \
            delta_1_1 * row['SC'] + \
            delta_2_1 * row['OPEX'] + \
            mu_1_1 * row['CML'] <= 0


# (4)
# alfa_1 + alfa_1_1*x_1_k + 0.5*alfa_1_2*x_2_k +
# 0.5*alfa_2_1*x_2_k + delta_1_1*y_1_k + nu_1_1*b_1_k >= 0
# alfa_2 + alfa_2_2*x_2_k + 0.5*alfa_1_2*x_1_k +
# 0.5*alfa_2_1*x_1_k + delta_2_1*y_1_k + nu_2_1*b_1_k >= 0
for index, row in df.iterrows():
    prob += alfa_1 + \
            alfa_1_1 * row['SC'] + \
            0.5 * alfa_1_2 * row['OPEX'] + \
```

```
            0.5 * alfa_2_1 * row['OPEX'] + \
            delta_1_1 * row['ES'] + \
            nu_1_1 * row['CML'] >= 0

    prob += alfa_2 + \
            alfa_2_2 * row['OPEX'] + \
            0.5 * alfa_1_2 * row['SC'] + \
            0.5 * alfa_2_1 * row['SC'] + \
            delta_2_1 * row['ES'] + \
            nu_2_1 * row['CML'] >= 0
# (5)
prob += beta_1 - gama_1 == -1
prob += beta_1_1 - mu_1_1 == 0
prob += gama_1_1 - mu_1_1 == 0
prob += delta_1_1 - nu_1_1 == 0
prob += delta_2_1 - nu_2_1 == 0
prob += alfa_2_1 - alfa_1_2 == 0


# print df
print prob
prob.writeLP("{}.lp".format(OPERATION_NAME))


ddf = {}
optimization_result = prob.solve()
print "Status:", pulp.LpStatus[prob.status]
ddf['Status'] = pulp.LpStatus[prob.status]


print "Optimal Solution to minimizing function: ", pulp.value(prob.objec-
tive)
ddf['Optimal DDF Value'] = pulp.value(prob.objective)
print "Individual decision_variables:"
for v in prob.variables():
    print v.name, "=", v.varValue
    locals()[v.name] = float(v.varValue)
    ddf[v.name] = v.varValue

pprint.pprint(ddf, indent=4)

ddf_frame = pd.DataFrame(ddf.items(), columns=['Variable or Descrip-
tion',
                                               'Value'])
ddf_frame.to_excel(WRITER, 'Coefficients', index=False)

# SHADOW_PRICES
# Shadow Price of j-th undesirable output
# q_j = -p_m * (derivative_of_ddf_to_b / derivative_of_ddf_to_y)
# derivative_of_ddf_to_b = "gama_1 + gama_1_1*b_1_k +
# nu_1_1*x_1_k + nu_2_1*x_2_k + mu_1_1*y_1_k"
# derivative_of_ddf_to_y = "beta_1 + beta_1_1*y_1_k +
# delta_1_1*x_1_k + delta_2_1*x_2_k + mu_1_1*b_1_k"
p_m = 5.5
shadow_prices = {}
for index_number, row in df.iterrows():
    derivative_of_ddf_to_b = gama_1 + \
                             gama_1_1 * row['CML'] + \
                             nu_1_1 * row['SC'] + \
                             nu_2_1 * row['OPEX'] + \
                             mu_1_1 * row['ES']

    derivative_of_ddf_to_y = beta_1 + \
                             beta_1_1 * row['ES'] + \
                             delta_1_1 * row['SC'] + \
                             delta_2_1 * row['OPEX'] + \
                             mu_1_1 * row['CML']
```

```
    q_j = -1 * p_m * (derivative_of_ddf_to_b / deriva-
tive_of_ddf_to_y)

    shadow_prices[index_number] = {'index_number': index_number,
                                   'company_name': row['Company'],
                                   'year': row['Year'],
                                   'shadow_price': "%.8f" % q_j,
                                   'input_file_name': OPERATION_NAME}

final_df = pd.DataFrame(shadow_prices.values())
final_df.sort_values(by='index_number', ascending=True)

print final_df

final_df.to_excel(WRITER, 'Shadow Prices', index=False)

WRITER.save()
```

Aalto-DD 108/2019

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ISBN 978-952-60-8589-0 (printed)
ISBN 978-952-60-8590-6 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

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