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Shadow Pricing of Electric Power Interruptions for Distribution System Operators in Finland

Sinan Küfeoğlu [1,*], Niyazi Gündüz [2], Hao Chen [3] and Matti Lehtonen [2]

1 Energy Policy Research Group, Judge Business School, University of Cambridge, Cambridge CB2 1AG, UK
2 Department of Electrical Engineering and Automation, Aalto University, Espoo 02150, Finland; niyazi.gunduz@aalto.fi (N.G.); matti.lehtonen@aalto.fi (M.L.)
3 Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China; chenhao9133@126.com
* Correspondence: s.kufeoglu@jbs.cam.ac.uk

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Abstract: Increasing distributed generation and intermittencies, along with the increasing frequency of extreme weather events, impose a serious challenge for electric power supply security. Understanding the costs of interruption is vital in terms of enhancing the power system infrastructure and planning the distribution grid. Furthermore, customer rights and demand response techniques are further reasons to study the worth of power reliability. In this paper, the authors make use of directional distance function and shadow pricing methods in a case study of Finland. The aim is to calculate the cost of one minute of power interruption from the perspective of the distribution network operator. The sample consists of 78 distribution network operators from Finland, and uses cost and network information between 2013 and 2015.

Keywords: power interruption; distribution system operator; interruption cost; shadow price

1. Introduction

Continuity of electric power supply is a key concern for authorities, Distribution System Operators (DSOs) and consumers. As each sector, such as finance, telecommunications, health, entertainment, transportation, etc., become increasingly dependent on electricity, the results of power interruptions become more devastating. There is no surprise that the United States Homeland Security defines the energy sector as "uniquely critical because it provides an "enabling function" across all critical infrastructure sectors" [1]. They also emphasize the significance of the electric power grid as "the most critical of critical infrastructure" [2]. The increasing frequency and duration of extreme weather events have become a major threat for electric power security [3]. Consequently, estimation of the costs occurred due to power interruptions, or the value of lost load, has become an attractive field for researchers. The three major methodologies which are commonly used by the research society to assess the customer interruption costs (CIC) are: customer surveys, indirect analytical methods and case studies. Each method has particular advantages and disadvantages. Customer surveys are the most preferred, and extensively used, approach. This method involves the preparation of a customer survey, which is then distributed to the electricity customers through various means (such as one-to-one interviews, telephone calls, e-mails or by mail). The survey includes questions about various interruption scenarios. This method is the most popular one in the literature, as it attains customer-specific results [4]. However, doing extensive surveys can be costly in regard to the time, effort and money spent. Furthermore, challenges of this methodology include analyzing the raw responses, and censoring outliers from the data sets. The second approach is Indirect Analytical Methods (IAM). The main advantage of this method is that it is relatively straightforward and easy to apply, compared to customer surveys. The input data for this approach can include data on:

Electricity prices or tariffs, value added or turnover of a customer, gross domestic product of a country, and annual energy consumption or the peak power reached during a year of a customer group, region or a country. These data are publicly available, objective and easy to attain. The major shortcoming of this methodology is that since it uses general and average data, it provides broad and average results. Finally, the case studies approach is another method that can used in CIC analysis. 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. Case studies, such as the New York City blackout of 1977 [5], and power issues during 2005's Cyclone Gudrun in Sweden [6], are good examples of this method. The comprehensive review paper [7] compiles useful academic studies regarding the field of electric power reliability up to the year 2015. More recent studies can be found based on country specific data. Studies [8–10] adopt customer surveys, whereas [11–15] follow indirect analytical methods. The report [8] summarizes the value of service reliability for the electricity customers in the United States. Another detailed report [9] investigates the value of lost load (VoLL) for electricity customers in Great Britain. Study [10] uses a customer survey in Germany. The paper [11] presents the worth of energy not supplied (ENS) in Scotland. The studies [12] and [13] 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 [14]. One generic power interruption assessment paper has been published for customers from South Africa [15]. Most of the sources follow indirect analytical methods, customer surveys or case studies methodologies [7]. However, in this paper, we would like to adopt the directional distance function approach to calculate the shadow pricing of electricity outages rather than conventional methods. The shadow pricing of a production technology through distance function is presented at [16]. The directional distance function is introduced in detail at [17]. Shadow pricing of a product has been calculated for many areas such as: pollution costs in agriculture production in US [18] and China [19], costs of water cuts in Chile [20], price licenses in salmon farming in Norway [21], banking inefficiency in Japan [22] and price of CO_2, SO_2 and NO_x in the United States coal power industry [23]. On the other hand, ref. [24] adopts parametric distance function approach to calculate the value of power outages for French DSOs. The purpose of this paper is to use shadow pricing techniques to assess customer interruption costs from the DSO perspective. This paper aims to provide a reliable CIC estimation method for the DSOs, so that they can make careful arrangements in operational and capital costs. Another crucial contribution of this paper is to show the weaknesses of the customer compensation scheme in Finland. We propose that a fairer compensation scheme should be designed to reflect the true costs of the power interruptions incurred from the DSO point of view. We should note that VoLL or the worth of ENS are not in the scope of this paper. The following paper is organized as follows: Section 2 introduces the methodology of the directional distance function and shadow pricing of a production technology. Section 3 presents the empirical study and the results of the shadow pricing of power interruption analysis for 78 DSOs from Finland. Sections 4 and 5 include our discussion remarks and conclusion.

2. Directional Distance Function and the Shadow Pricing of Electric Power Interruptions

We may assume that an electricity supply has two main states: a continuous supply (supplied energy), and an interrupted supply (energy not supplied). To estimate the worth of the energy not supplied, one can establish an analogy with the directional distance function. The directional distance function has desirable (or good) and undesirable (or bad) outputs [18]. In this study, the desirable output will be energy supplied to the customers, 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, we will utilize the shadow price technique to evaluate the costs of power interruptions. The shadow price of bad outputs is presented in Reference [18]. The methodology assumes that the production of good outputs includes 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. The shadow price can be obtained via the distance function as well [16,25]. The main advantage of the directional distance function over the distance function is that it simultaneously enables the expansion of the good outputs and the contraction of the bad outputs. 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 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 paper, the value of one minute of interruption. Therefore, 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. The main features of the directional distance function are 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:

$$x = (x_1, \ldots, x_N) \in R_+^N \tag{1}$$

$$y = (y_1, \ldots, y_M) \in R_+^M \tag{2}$$

$$b = (b_1, \ldots, b_J) \in R_+^J \tag{3}$$

Let $P(x)$ denote the production technology [26], where:

$$P(x) = \{(y, b) : x \; can \; produce \; (y, b)\} \tag{4}$$

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 [27]. 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:

$$\vec{D}_0(x, y, b; g_y, gb) = max\{\, \beta : (y + \beta g_y,\; b - \; \beta g_b) \in P(x)\} \tag{5}$$

$$\vec{D}_0(x, y + \alpha g_y, b - \alpha g_y; g) = \vec{D}_0(x, y, b; g) - \alpha \tag{6}$$

Our aim is to increase the amount of energy supplied to the customers, while decreasing the amount of energy not supplied by 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 [18]. Let p indicate the good output prices and q indicate the bad output prices. These are represented as:

$$p = (p_1, \ldots, p_M) \in R_+^M \tag{7}$$

$$q = (q_1, \ldots, q_J) \in R_+^J \tag{8}$$

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:

$$R(x, p, q) = max_{yb}\{py - qb \; : (y, b) \in P(x)\} \tag{9}$$

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:

$$R(x, p, q) \geq (py - qb) + p\vec{D}_0(x, y, b; g) \cdot g_y + q\vec{D}_0(x, y, b; g) g_b \tag{10}$$

The left-hand side of the equation stands for the maximum revenue, while the right-hand side is equal to the actual revenue ($py - qb$) plus the revenue gain from the elimination of technical inefficiency. The gain in revenue from the elimination of technical inefficiency has two components: (1) the gain due to an increase in good outputs $(p\vec{D}_0(x, y, b; g) \cdot g_y)$, and (2) the gain due to a decrease in bad outputs $(q\vec{D}_0(x, y, b; g) \cdot g_b)$—since the cost of bad outputs is subtracted from good revenues. Rearranging (10), the directional output distance function and the maximal revenue function are related as:

$$\vec{D}_0(x, y, b; g) \leq \frac{R(x, p, q) - ((py - qb))}{pg_y + qg_b} \tag{11}$$

The directional output distance function given in Equation (5) can also be recovered from the revenue function as:

$$\vec{D}_0(x, y, b; g) = min_{p,q}\left\{\frac{R(x, p, q) - ((py - qb))}{pg_y + qg_b}\right\} \tag{12}$$

Applying the envelope theorem twice to (12) yields our shadow price model:

$$\nabla_y \vec{D}_0(x, y, b; g) = \frac{-p}{pg_y + qg_b} \tag{13}$$

$$\nabla_b \vec{D}_0(x, y, b; g) = \frac{q}{pg_y + qg_b} \tag{14}$$

The details of the physical meaning of the shadow pricing technique is explained in Reference [18] in detail. By assuming that we know the m-th price of the good output (in our case the operational expenses of the DSOs), then the j-th nominal bad output price (the price of one minute of interruption) can be calculated as [28]:

$$q_j = -p_m \left(\frac{\frac{\partial \vec{D}_0(x,y,b;g)}{\partial b_j}}{\frac{\partial \vec{D}_0(x,y,b;g)}{\partial y_m}} \right), \; j = 1, \ldots, J. \tag{15}$$

References [17,29] parameterize the directional distance function through a quadratic function. At this point we are supposed to choose our directional vector g, so that we can 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 to expand the desirable outputs, while keeping the undesirable outputs the same. Since our aim is to simultaneously increase the good outputs and decrease the bad outputs, the directional vector g = (1, 1) is set. We assume that there are k = 1, . . . , K DSOs, then the quadratic distance function for the k-th DSO is shown in Equation (16):
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 (16), 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 Equation (16) are calculated via solving Equation (17) with Python, by adopting the directional vector as g = (1, 1). Equation (18) requires the output–input vector to be feasible. Equations (19) and (20) impose the monotonicity conditions of Equations (13) and (14). Equation (21) imposes positive monotonicity on the inputs for the mean level of input usage. That is, at the mean level of inputs, x^{-}, an increase in input usage holding good and bad outputs constant, causes the directional output distance function to increase, implying greater inefficiency. Equation (22) is due to the translation property of Equation (6).

$$\begin{aligned}\vec{D}_0 &= (x_k, y_k, b_k; 1, 1) \\ &= l + \sum_{n=1}^{N} a_n x_{nk} + \sum_{m=1}^{M} \beta_m y_{mk} + \sum_{j=1}^{J} \gamma_j b_{jk} + \frac{1}{2}\sum_{n=1}^{N}\sum_{n'=1}^{N} \alpha_{mn'} x_{nk} x_{n'k} \\ &+ \frac{1}{2}\sum_{m=1}^{M}\sum_{m'=1}^{M} \beta_{mm'} y_{mk} y_{m'k} + \frac{1}{2}\sum_{j=1}^{J}\sum_{j'=1}^{J} \gamma_{jj'} b_{jk} b_{j'k} \\ &+ \sum_{n=1}^{N}\sum_{m=1}^{M} \delta_{nm} x_{nk} y_{mk} + \sum_{n=1}^{N}\sum_{j=1}^{J} \eta_{nj} x_{nk} b_{jk} + \sum_{m=1}^{M}\sum_{j=1}^{J} \mu_{mj} y_{mk} b_{jk}\end{aligned} \tag{16}$$

Then, an optimization model is established which will 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 Equations (17)–(23). Moreover, the decision variables in the optimization model are l, α_n, $\alpha_{mn'}$, β_m, $\beta_{mm'}$, γ_j, $\gamma_{jj'}$, δ_{nm}, η_{nj}, μ_{mj} and are solved with Python.

$$Minimize \sum_{k=1}^{K} [\vec{D}_0(x_k, y_k, b_k; 1,\ 1) - 0] \tag{17}$$

Subject to,

$$\vec{D}_0(x_k, y_k, b_k; 1, 1) \geq 0, \;\; k = 1, \ldots, K \tag{18}$$

$$\frac{\partial \vec{D}_0(x_k, y_k, b_k; 1, 1)}{\partial b_j} \geq 0, \; j = 1, \ldots, J; k = 1, \ldots, K \tag{19}$$

$$\frac{\partial \vec{D}_0(x_k, y_k, b_k; 1, 1)}{\partial y_m} \leq 0, \; m = 1, \ldots, M; k = 1, \ldots, K \tag{20}$$

$$\frac{\partial \vec{D}_0(\overline{x}, y_k, b_k; 1, 1)}{\partial x_n} \geq 0, \; n = 1, \ldots, N \tag{21}$$

$$\begin{aligned}&\sum_{m=1}^{M} \beta_m - \sum_{j=1}^{J} \gamma_j = -1; \quad \sum_{m'=1}^{M} \beta_{mm'} - \sum_{j=1}^{J} \mu_{mj} = 0, \; m = 1, \ldots, M; \\ &\sum_{j'=1}^{J} \gamma_{jj'} - \sum_{m=1}^{M} \mu_{mj} = 0, \;\; j = 1, \ldots, J; \quad \sum_{m=1}^{M} \delta_{nm} - \sum_{j=1}^{J} \eta_{nj} = 0, \;\; n = 1, \ldots, N\end{aligned} \tag{22}$$

$$\alpha_{mn'} = \alpha_{n'n}, \quad n \neq n'\,; \quad \beta_{mm'} = \beta_{m'm}, \quad m \neq m'\,; \quad \gamma_{jj'} = \gamma_{j'j}, \quad j \neq j' \tag{23}$$

3. Empirical Study and Results

3.1. Empirical Study

This paper's empirical study investigates Finland. Even though Finland has a robust electric power infrastructure, the security of supply is threatened by extreme weather events [3]. These events could cause long lasting outages, which may eventually drive Finnish DSOs to invest and spend more money on operational and maintenance expenses. In our study, we used data from 78 Finnish DSOs from 2013, 2014 and 2015. Since some of the DSOs had not announced their interruption statistics yet [30], the year 2016 is not included in this paper. To investigate the directional distance function, from the Finnish Energy Market Authority (Energiavirasto), we selected data on energy supplied, number of customers, share of underground cabling, operational expenses, and System Average Interruption Duration Index (SAIDI) for each DSO. SAIDI is calculated as:

$$SAIDI = \frac{sum\ of\ all\ customer\ interruptions\ in\ a\ year}{total\ number\ of\ customers\ served}\ (h) \tag{24}$$

The 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:

$$CML = SAIDI\ \times\ 60\ \times\ number\ of\ customers\ \ (min) \tag{25}$$

The 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 1 by specifying the mean, standard deviation, minimum and maximum values of each data set from 2013, 2014 and 2015 for the 78 Finnish DSOs. A total of 936 sample observations were used in the analysis process. OPEX and CML are represented in thousand euros and thousand minutes, respectively. In addition, energy supplied is tabulated in GWh.

Table 1. Descriptive statistics for the pooled sample observations, 2013–2015.

	Inputs		Desirable Output	Undesirable Output
	SC (%)	**OPEX (k €)**	**ES (GWh)**	**CML (k mins)**
2013				
Mean	47.27	3015.51	619.92	14,299.67
Stdev.	25.60	5674.63	1200.07	45,908.75
Minimum	3.04	35.35	16.67	0.81
Maximum	100.00	32,156.33	7492.00	300,711.21
2014				
Mean	48.65	2891.61	616.07	5367.14
Stdev.	25.46	5021.57	1189.88	14,184.51
Minimum	3.23	55.30	16.38	1.90
Maximum	100.00	25,616.35	7425.00	85,712.50
2015				
Mean	50.34	3134.97	613.64	14,575.97
Stdev.	25.27	5857.64	1177.45	56,013.63
Minimum	3.30	71.00	15.84	6.18
Maximum	100.00	29,906.08	7283.00	448,823.76

3.2. Results

Within this optimization model, the objective function of Equation (17) has been solved using constraints of Equations (18)–(23) by Python programming language in order to optimize the problem, and the following coefficients have been calculated and presented in Table 2. When Linear Programming variables are assigned, free "Continuous" form has been selected to get relaxed solution. A number of 1176 constraints equations have been created with the script using Equations (18)–(23), and they were added to problem to find the optimal solution. Even though this depends on the computer's hardware, it takes around 1–2 min with a laptop which is a Quad-Core, 8 GB RAM device. Thus, it is quite fast for solving the problem. We used "pandas" and "PuLP" packages for Python script. Basically, the algorithm is as follows: script reads the stored data from excel, creates the optimization problem, and constraints then solves it using "CBC" solver. After calculating the coefficients, Equation (15) is solved where p is taken as 5.5 € cents as the average electricity distribution price in Finland [30] and the results are summarized in Table A1 in Appendix A.

Table 2. Coefficients of Equation (16) per year.

Variables	2013	2014	2015
l	16.3252	0.007764978	0.017882857
α_1	0	0	0
α_2	-7×10^{-10}	0.24284221	0.27902876
β_1	-1	-0.99987881	-1
γ_1	0	0.000121188	0
α_{11}	0	0	0
α_{22}	-1×10^{-10}	0.050119522	0.020527845
β_{11}	0	-1.977×10^{-7}	0
γ_{11}	0	-1.977×10^{-7}	0
α_{12}	0	0	0
δ_{11}	0	0	0
δ_{21}	0	0.000204027	0
η_{11}	0	0	0
η_{21}	0	0.000204027	0
μ_{11}	0	-1.977×10^{-7}	0

The shadow price for each DSO stands for the price of one minute of interruption in terms of operational expenses. At this point, the main objective 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 1. As can be seen from Figure 1, 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 the 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, we see that shadow prices of one minute of outage for the majority of the DSOs change between 0.4–0.5 € cents during 2013–2015. 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 as it provides the lowest boundary for the cost estimations for the network operators. In addition, as we mentioned in the methodology, the shadow prices are determined according to the directional vector g. The vector shows the incremental expansion or contraction of the outputs. Shadow prices will be affected by changing directional vectors. In this analysis, we only used $g\,(1, 1)$. However, the directional vectors $g\,(1, 0)$ and $g\,(0, -1)$ could also be used. Depending on the purpose, the outputs will expand, contract or remain the same.

In Finland, DSOs are obligated by law to pay certain customer compensations varying by annual customer interruption times [31]. According to this legislation, in the case of a single outage event that 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 1200 €/year. Table 3 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 Equation (26).

$$R = qb \tag{26}$$

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

$$comp = \frac{Standard\ compensation\ paid\ by\ the\ DSO}{CML} \tag{27}$$

The compensation cost is calculated in euros, per minute lost, as an interruption. The results for 2015 are summarized in Figure 2. We can see that majority of the Finnish DSOs did not pay any compensations at all during 2015, in accordance with the legislation in Table 3. 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 for 2015 is presented in Figure 3. Figure 2 shows us that among 78 Finnish DSOs, only 35 paid compensations during 2015. This observation is directly related to the fairness concerns of the customer compensation scheme in Finland.

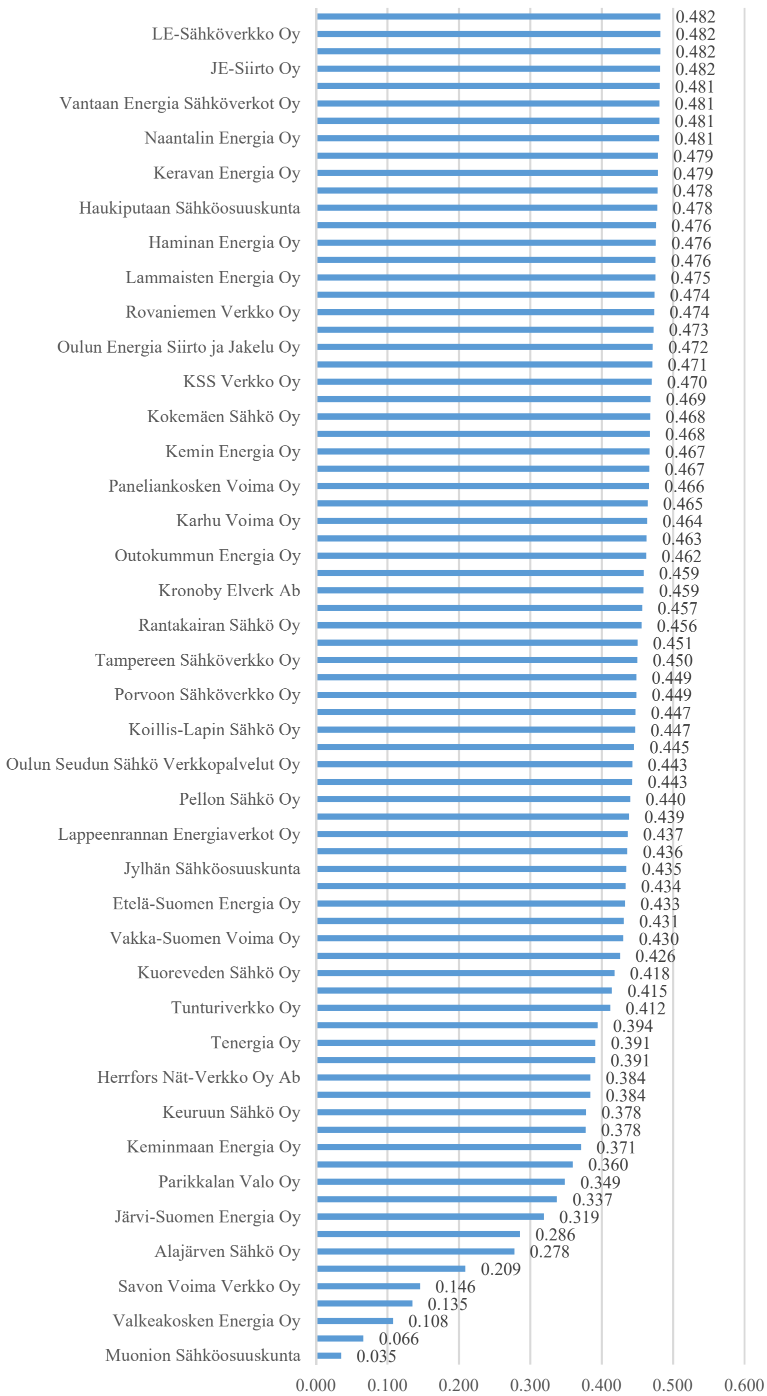

Figure 1. Shadow price (€ in cents) of one minute of interruption during 2015.

Table 3. The standard customer compensations according to legislation accepted during 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

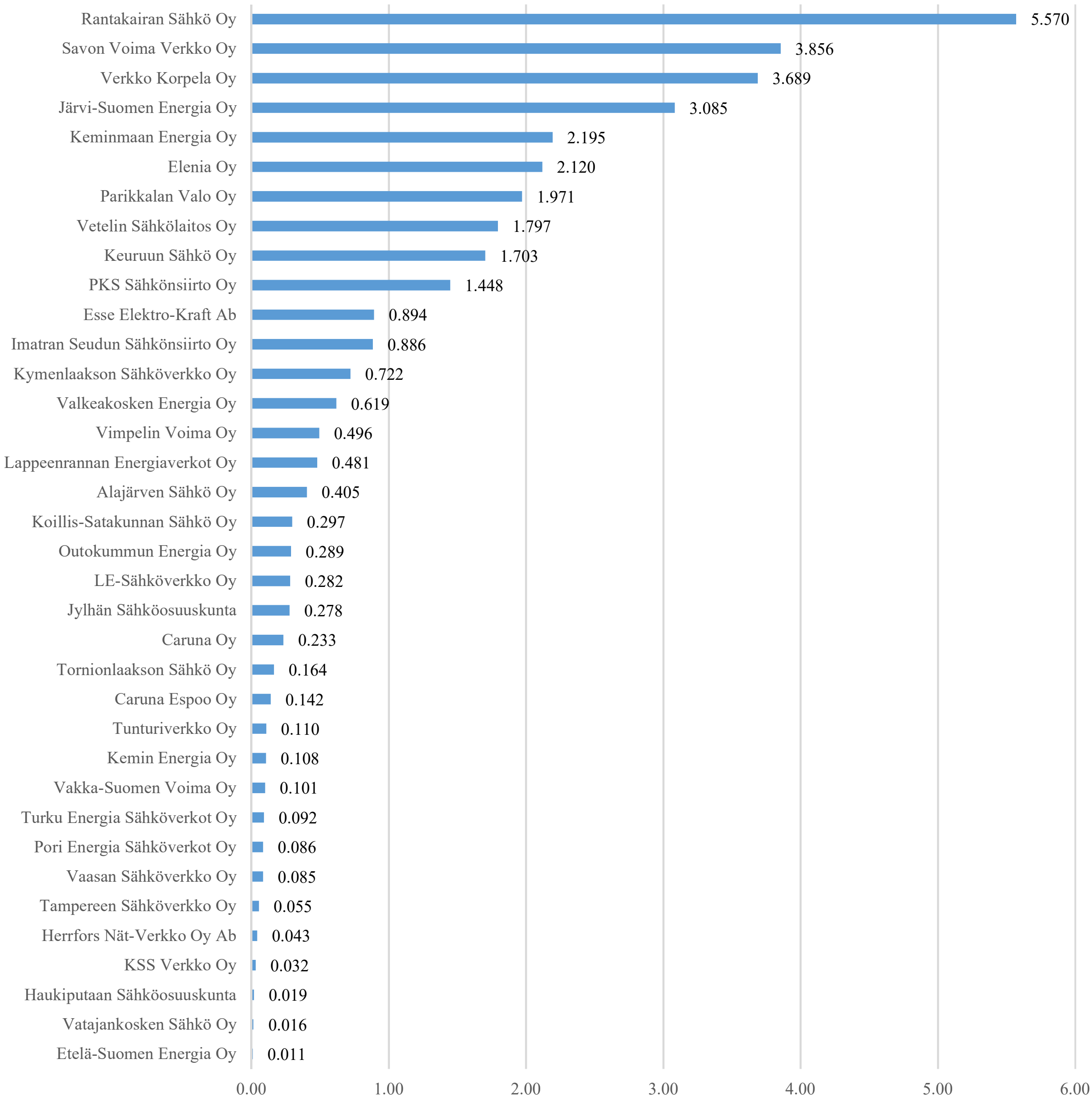

Figure 2. Compensation price of one minute of interruption during 2015 (€ cents).

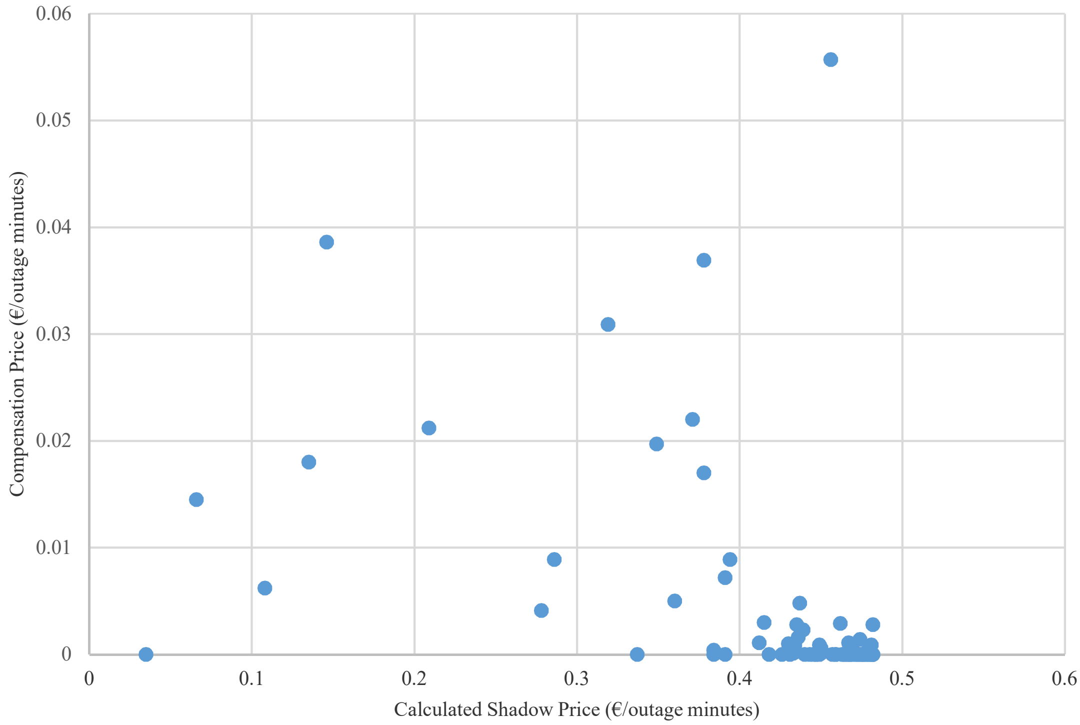

Figure 3. Comparison of compensation price vs. shadow price.

Customers' activities are directly related to the cost of one minute of interruption. There are numerous types of costs, both direct and indirect, that incur after a fault event. To reflect these in the analysis, a customer-centric study is necessary. Nonetheless, this paper approaches the same problem from the DSO's point of view, and therefore reflects the cost of CML in terms of OPEX of these DSOs. For a better understanding and critique of the compensation scheme, this study should be supported by supplementary studies, mainly customer surveys.

4. Discussion

A continuous electric power supply is a necessity for critical infrastructures, such as transportation, telecommunications, health, and finance. Furthermore, it is required to keep industry production, public services and daily activities running. As electrification of energy systems continue, and more intermittent sources are connected to the power grid, the significance of supply security increases. Therefore, understanding the economic impacts of power interruptions from a macro perspective is crucial. Estimating VoLL and the worth of ENS is a must, both for the authorities and for the network operators. Customer surveys are the most commonly used approach to assess these phenomena. However, the main disadvantages of the customer surveys are that they are time consuming, require extensive labor to prepare and carry out, and are expensive. Moreover, the problem of zero responses and strategic responses is a critical challenge for researchers carrying out these studies. Human behavior becomes a major issue for the researchers to consider when they adopt customer survey methodology [4]. Instead, indirect analytical methods can be employed, where shadow pricing technique can be adopted as a useful assessment tool. This paper investigates the phenomenon from a DSO point of view. The authors present the method of shadow pricing of power outages which solely relies on publicly available analytical data, rather than survey questionnaires. This cost estimation can be done by only using publicly available and objective analytical data, such as the number of customers, share of cabling in the distribution system, energy supplied to the low voltage customers and SAIDI. Nevertheless, the major advantage of reaching customer specific results via the customer survey methodology is not applicable here. The shadow pricing technique yields average results, which omits sectoral differences in power consumption and customer interruption costs. One should remember that the cost of one minute of interruption for a residential customer and the same cost for an industry customer will be different. In addition, this cost will considerably vary amongst sub-sectors with the same sector, such as within the textile, construction, chemical, and pharmaceuticals industries. In order to reach customer specific outage cost estimations, the network operators should share sector and customer specific energy consumption data.

5. Conclusions

This study makes use of analytical data shared by 78 Finnish DSOs which provide 99% of the energy to the low voltage customers in Finland. There are numerous studies in the literature that evaluate the interruption costs phenomenon from the customer point of view. However, this paper is not assessing the customer's VoLL. Instead, this paper evaluates the problem from the DSO perspective, so that each DSO has more information regarding interruption losses in a fast and straightforward manner. This information is needed for the future planning of power systems, enhancing the existing infrastructure, and for the purposes of paying standard compensations. In some countries, such as the United Kingdom and Finland, customers are protected by laws that obligate DSOs to pay certain compensations in case of interruptions. In Finland, the electricity law states that if a single time interruption event is between 12–24 h, then the DSO must pay 10% of the annual electricity delivery fee back to the customer. If we assume that a typical Finnish household's annual delivery fee is approximately 94 euros per year [32], then during a 20-h interruption, the value of each minute of interruption will be 0.78 € cents. We should note that the customers experiencing single time interruption events that are less than 12 h receive no compensation. When we have a look at the actual compensations paid, from Figure 2, we see that only 11 DSOs pay more than 1 cent/minute. In this paper, we propose that to reduce one minute of interruption, in terms of OPEX, the cost would be approximately 0.5 € cents.

Another shadow pricing of power reliability study targeting 92 DSOs in France [24] followed a similar approach; a distance function but not a directional distance function. The paper used number of interruption events, rather than customer minutes lost, as the bad output, and suggests that one customer interruption (>3 min) has a shadow price of 4.9 € of OPEX costs for rural regions, while it costs 7.5 € for urban areas. We should note that one interruption event might last days or weeks, depending on the fault type and repair efforts. Therefore, we believe targeting the cost of CML is more useful than targeting the cost of number of interruption events. From the results we can see that even though the outage minutes correspond to a certain amount of losses, some DSOs did not pay any compensation at all, due to the standard compensation calculation method, as summarized in Table 3. If a single-time outage event does not exceed 12 h, the operator is not forced to pay a fine to the consumers. On the other hand, when we look at the Figure 3, the DSOs which exceed the allowed outage durations pay a higher amount of compensation than the calculated amount through shadow pricing method. Based on these observations, we can conclude that in Finland, while some of the DSOs did not offer enough compensation for the power interruptions, some DSOs over-compensated the electricity outages. The main principle of the Finnish authorities is to protect consumer rights and ensure a high quality of service. However, another major principle is fairness, and Finnish DSOs should be treated fairly by designing a better standard compensation scheme which would be more cost-reflective. Price signals are crucial in terms of providing continuous service quality and effecting future investments. The authors will continue to do further analysis in relation to the customer interruption costs and standard customer compensations.

Author Contributions: S.K. carried out the reliability and customer interruption costs analysis. N.G. was responsible of data analysis and programming. H.C. contributed theoretical knowledge in directional distance function and shadow pricing. Finally, M.L. provided general guidance on the methodology and results of the paper.

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Appendix A

Table A1. Shadow prices of one minute of interruption (€ cents), 2013–2015.

DSO	2013	2014	2015	DSO	2013	2014	2015
Äänekosken Energia Oy	0.454	0.449	0.457	Lehtimäen Sähkö Oy	0.457	0.461	0.443
Alajärven Sähkö Oy	0.447	0.466	0.278	Leppäkosken Sähkö Oy	0.457	0.470	0.468
Caruna Espoo Oy	0.462	0.472	0.474	LE-Sähköverkko Oy	0.477	0.481	0.482
Caruna Oy	0.348	0.447	0.439	Mäntsälän Sähkö Oy	0.458	0.474	0.467
Ekenäs Energi Ab	0.477	0.470	0.471	Muonion Sähköosuuskunta	0.426	0.343	0.035
Elenia Oy	0.295	0.445	0.209	Naantalin Energia Oy	0.479	0.479	0.481
Enontekiön Sähkö Oy	0.000	0.357	0.337	Nurmijärven Sähköverkko Oy	0.463	0.474	0.469
ESE-Verkko Oy	0.480	0.482	0.479	Nykarleby Kraftverk Ab	0.429	0.422	0.426
Esse Elektro-Kraft Ab	0.416	0.452	0.286	Oulun Energia Siirto ja Jakelu Oy	0.468	0.470	0.472
Etelä-Suomen Energia Oy	0.364	0.399	0.433	Oulun Seudun S. Verkkopalvelut Oy	0.452	0.467	0.443
Forssan Verkkopalvelut Oy	0.481	0.482	0.482	Outokummun Energia Oy	0.457	0.432	0.462
Haminan Energia Oy	0.478	0.480	0.476	Paneliankosken Voima Oy	0.414	0.472	0.466
Haukiputaan Sähköosuuskunta	0.471	0.474	0.478	Parikkalan Valo Oy	0.179	0.444	0.349
Helen Sähköverkko Oy	0.483	0.483	0.482	Pellon Sähkö Oy	0.465	0.449	0.440
Herrfors Nät-Verkko Oy Ab	0.347	0.433	0.384	PKS Sähkönsiirto Oy	0.376	0.376	0.066
Iin Energia Oy	0.477	0.478	0.459	Pori Energia Sähköverkot Oy	0.386	0.440	0.449
Imatran Seudun Sähkönsiirto Oy	0.268	0.448	0.394	Porvoon Sähköverkko Oy	0.399	0.439	0.449
Järvi-Suomen Energia Oy	0.242	0.438	0.319	Raahen Energia Oy	0.482	0.480	0.481
Jeppo Kraft Andelslag	0.454	0.453	0.445	Rantakairan Sähkö Oy	0.465	0.466	0.456
JE-Siirto Oy	0.481	0.480	0.482	Rauman Energia Oy	0.445	0.475	0.463
Jylhän Sähköosuuskunta	0.457	0.474	0.435	Rovakaira Oy	0.413	0.452	0.431
Karhu Voima Oy	0.481	0.477	0.464	Rovaniemen Verkko Oy	0.480	0.480	0.474
Kemin Energia Oy	0.478	0.479	0.467	Sallila Sähkönsiirto Oy	0.434	0.466	0.465
Keminmaan Energia Oy	0.446	0.478	0.371	Savon Voima Verkko Oy	0.175	0.287	0.146
KENET Oy	0.469	0.473	0.476	Seiverkot Oy	0.470	0.475	0.476
Keravan Energia Oy	0.472	0.468	0.479	Tampereen Sähköverkko Oy	0.449	0.478	0.450
Keuruun Sähkö Oy	0.355	0.414	0.378	Tenergia Oy	0.405	0.427	0.391
Koillis-Lapin Sähkö Oy	0.371	0.445	0.447	Tornion Energia Oy	0.469	0.473	0.447
Koillis-Satakunnan Sähkö Oy	0.441	0.443	0.415	Tornionlaakson Sähkö Oy	0.418	0.463	0.436
Kokemäen Sähkö Oy	0.425	0.466	0.468	Tunturiverkko Oy	0.443	0.451	0.412
Köyliön-Säkylän Sähkö Oy	0.452	0.469	0.473	Turku Energia Sähköverkot Oy	0.469	0.481	0.481
Kronoby Elverk Ab	0.440	0.410	0.459	Vaasan Sähköverkko Oy	0.417	0.430	0.434
KSS Verkko Oy	0.454	0.455	0.470	Vakka-Suomen Voima Oy	0.352	0.458	0.430
Kuopion Sähköverkko Oy	0.481	0.481	0.478	Valkeakosken Energia Oy	0.476	0.476	0.108
Kuoreveden Sähkö Oy	0.445	0.468	0.418	Vantaan Energia Sähköverkot Oy	0.479	0.480	0.481
Kymenlaakson Sähköverkko Oy	0.375	0.426	0.391	Vatajankosken Sähkö Oy	0.419	0.455	0.451
Lammaisten Energia Oy	0.457	0.473	0.475	Verkko Korpela Oy	0.323	0.253	0.378
Lankosken Sähkö Oy	0.274	0.410	0.384	Vetelin Sähkölaitos Oy	0.431	0.474	0.135
Lappeenrannan Energiaverkot Oy	0.401	0.455	0.437	Vimpelin Voima Oy	0.359	0.446	0.360

Table A2. SAIDI figures of DSOs (hours), 2013–2015.

DSO	2013	2014	2015	DSO	2013	2014	2015
Äänekosken Energia Oy	1.87	2.20	1.68	Lehtimäen Sähkö Oy	1.66	1.44	2.57
Alajärven Sähkö Oy	2.29	1.10	13.29	Leppäkosken Sähkö Oy	1.67	0.87	1.02
Caruna Espoo Oy	1.37	0.74	0.60	LE-Sähköverkko Oy	0.42	0.17	0.11
Caruna Oy	8.69	2.30	2.85	Mäntsälän Sähkö Oy	1.62	0.65	1.07
Ekenäs Energi Ab	0.41	0.85	0.80	Muonion Sähköosuuskunta	3.35	9.00	30.21
Elenia Oy	12.16	2.41	17.93	Naantalin Energia Oy	0.32	0.29	0.20
Enontekiön Sähkö Oy	32.80	8.10	9.35	Nurmijärven Sähköverkko Oy	1.32	0.60	0.96
ESE-Verkko Oy	0.22	0.09	0.31	Nykarleby Kraftverk Ab	3.46	3.91	3.65
Esse Elektro-Kraft Ab	4.31	2.01	12.78	Oulun Energia Siirto ja Jakelu Oy	0.98	0.84	0.76
Etelä-Suomen Energia Oy	7.62	5.39	3.22	Oulun Seudun S. Verkkopalvelut Oy	1.99	1.05	2.56
Forssan Verkkopalvelut Oy	0.19	0.09	0.10	Outokummun Energia Oy	1.69	3.25	1.34
Haminan Energia Oy	0.35	0.27	0.49	Paneliankosken Voima Oy	4.38	0.73	1.10
Haukiputaan Sähköosuuskunta	0.82	0.59	0.38	Parikkalan Valo Oy	19.99	2.49	8.62
Helen Sähköverkko Oy	0.08	0.06	0.11	Pellon Sähkö Oy	1.18	2.18	2.74
Herrfors Nät-Verkko Oy Ab	8.71	3.22	6.31	PKS Sähkönsiirto Oy	6.86	6.85	27.96
Iin Energia Oy	0.44	0.40	1.56	Pori Energia Sähköverkot Oy	6.22	2.76	2.20
Imatran Seudun Sähkönsiirto Oy	13.98	2.26	5.67	Porvoon Sähköverkko Oy	5.38	2.80	2.21
Järvi-Suomen Energia Oy	15.73	2.87	10.54	Raahen Energia Oy	0.12	0.27	0.18
Jeppo Kraft Andelslag	1.90	1.95	2.41	Rantakairan Sähkö Oy	1.16	1.11	1.74
JE-Siirto Oy	0.20	0.26	0.13	Rauman Energia Oy	2.44	0.55	1.30

Table A2. *Cont.*

DSO	2013	2014	2015	DSO	2013	2014	2015
Jylhän Sähköosuuskunta	1.67	0.59	3.09	Rovakaira Oy	4.44	2.00	3.33
Karhu Voima Oy	0.19	0.40	1.24	Rovaniemen Verkko Oy	0.22	0.24	0.63
Kemin Energia Oy	0.39	0.33	1.03	Sallila Sähkönsiirto Oy	3.12	1.13	1.21
Keminmaan Energia Oy	2.36	0.37	7.16	Savon Voima Verkko Oy	20.28	12.66	22.32
KENET Oy	0.92	0.69	0.49	Seiverkot Oy	0.86	0.57	0.52
Keravan Energia Oy	0.73	0.97	0.32	Tampereen Sähköverkko Oy	2.17	0.37	2.12
Keuruun Sähkö Oy	8.20	4.38	6.71	Tenergia Oy	5.00	3.60	5.86
Koillis-Lapin Sähkö Oy	7.20	2.42	2.32	Tornion Energia Oy	0.95	0.68	2.29
Koillis-Satakunnan Sähkö Oy	2.71	2.59	4.37	Tornionlaakson Sähkö Oy	4.17	1.28	3.01
Kokemäen Sähkö Oy	3.68	1.15	1.00	Tunturiverkko Oy	2.57	2.08	4.52
Köyliön-Säkylän Sähkö Oy	1.99	0.91	0.69	Turku Energia Sähköverkot Oy	0.96	0.17	0.16
Kronoby Elverk Ab	2.77	4.69	1.57	Vaasan Sähköverkko Oy	4.24	3.40	3.17
KSS Verkko Oy	1.86	1.81	0.86	Vakka-Suomen Voima Oy	8.41	1.64	3.36
Kuopion Sähköverkko Oy	0.19	0.19	0.35	Valkeakosken Energia Oy	0.48	0.47	25.00
Kuoreveden Sähkö Oy	2.45	0.98	4.14	Vantaan Energia Sähköverkot Oy	0.31	0.27	0.17
Kymenlaakson Sähköverkko Oy	6.88	3.63	5.87	Vatajankosken Sähkö Oy	4.08	1.78	2.09
Lammaisten Energia Oy	1.67	0.67	0.53	Verkko Korpela Oy	10.33	14.93	6.73
Lankosken Sähkö Oy	13.56	4.67	6.31	Vetelin Sähkölaitos Oy	3.33	0.65	23.08
Lappeenrannan Energiaverkot Oy	5.27	1.78	2.96	Vimpelin Voima Oy	7.95	2.36	7.91

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