EPRG WORKING PAPER

UNIVERSITY OF CAMBRIDGE | Energy Policy Research Group

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

EPRG Working Paper 1825

Cambridge Working Paper in Economics 1845

Sinan Küfeoğlu, Niyazi Gündüz, Hao Chen and Matti Lehtonen

Abstract Increasing distributed generation and intermittency, along with the increasing frequency of extreme weather events, pose a serious challenge supply security in the electric power sector. Understanding the costs of interruption is vital for enhancing power system infrastructure and planning the distribution grid. Customer rights and demand response are additional reasons to study the value of power reliability. We make use of the directional distance function and shadow pricing method for a case study from Finland with the aim of calculating 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 based on cost and network information between 2013 and 2015..

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

JEL Classification L42

Contact s.kufeoglu@jbs.cam.ac.uk
Publication August 2018
Financial Support Fortum Foundation

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

Sinan Küfeoğlu[a,1], Niyazi Gündüz[b], Hao Chen[c] and Matti Lehtonen[b]

[a] Energy Policy Research Group, Judge Business School, University of Cambridge, Cambridge, United Kingdom; e-mail: s.kufeoglu@jbs.cam.ac.uk

[b] Department of Electrical Engineering and Automation, Aalto University, Espoo, Finland; e-mail: niyazi.gunduz@aalto.fi, matti.lehtonen@aalto.fi

[c] Center for Energy and Environmental Policy, Beijing Institute of Technology, Beijing, China; e-mail: chenhao9133@126.com

Abstract: *Increasing distributed generation and intermittency, along with the increasing frequency of extreme weather events, pose a serious challenge supply security in the electric power sector. Understanding the costs of interruption is vital for enhancing power system infrastructure and planning the distribution grid. Customer rights and demand response are additional reasons to study the value of power reliability. We make use of the directional distance function and shadow pricing method for a case study from Finland with the aim of calculating 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 based on 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 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" (White House, 2013), while (Securing the US Electrical Grid, 2014) emphasizes the significance of the electric power grid as "the most critical of critical infrastructure". As rapidly increasing intermittent renewable energy sources create a challenge for the power system planners, the increasing frequency and the duration of the extreme weather events have become a major threat for the electric power security (Küfeoğlu et al., 2014). Consequently, estimation of the costs of power interruptions or the value of lost load has become an attractive field for researchers. Customer surveys, indirect analytical methods and case studies are the three major methodologies which are commonly used to assess customer interruption costs (CIC). Each method has certain advantages and disadvantages. Customer Surveys are the preferred and most extensively used approach. A customer survey is prepared and distributed to the electricity customers through various means such as one-to-one interviews, telephone calls, e-mails or by mail and will ask questions about various interruption scenarios. This method is the most popular one for obtaining customer-specific results (Küfeoğlu and Lehtonen, 2015). However, extensive surveys requires time, effort and money. 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. The main advantage of this method is that it is relatively a 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

[1] Corresponding author: S. Küfeoğlu. email: s.kufeoglu@jbs.cam.ac.uk

since it uses general and average data, naturally it provides broad and average results. Finally, the Case Studies approach is another method for CIC analysis. Case studies are conducted after major or significant blackouts. It is the best way of evaluating both direct and indirect economic costs incurred as a result of 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 from New York City blackout of 1977 (Corwin and Miles, 1978) and Storm Gudrun of 2005 in Sweden (Carlsson et al., 2008) are good examples for this. The comprehensive review paper (Küfeoğlu and Lehtonen, 2016) compiles the academic studies in the field of worth of electric power reliability until 2015. More recent studies can be found based on country-specific data. Studies (London Economics, 2013; Growitsch et al., 2015; Sullivan et al., 2015) adopt customer surveys. The report by Sullivan et al. (2015) summarizes the value of service reliability for the electricity customers in the United States. Another detailed report (London Economics, 2013) investigates the value of lost load (VoLL) for electricity customers in Great Britain. Study (Growitsch et al., 2015) uses a customer survey in Germany. In addition to these survey-based studies, indirect analytical methods are commonly used as well. Some examples can be found at (Poudineh and Jamasb, 2017; Shivakumar et al., 2017; Minnaar et al., 2017; Kim and Cho, 2017; Abrate et al., 2016). The paper (Poudineh and Jamasb, 2017) presents the worth of energy not supplied (ENS) in Scotland. The studies by Shivakumar et al. (2017) and Abrate et al. (2016) 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 (Kim and Cho, 2017). One generic power interruption assessment paper has been published for customers from South Africa (Minnaar et al., 2017). Most of the sources follow indirect analytical methods, customer surveys or case studies methodologies (Küfeoğlu and Lehtonen, 2016). However, in this paper, rather than conventional methods, we would like to adopt 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 (Färe et al., 1993). The directional distance function is introduced in detail at (Chambers et al., 1998). Shadow pricing of a product has been calculated for many areas such as; pollution costs in agriculture production in US (Färe et al., 2006) and in China (Tang et al., 2016), costs of water cuts in Chile (Molinos-Senante et al., 2016), price licenses in salmon farming in Norway (Färe et al., 2009), banking inefficiency in Japan (Fukuyamaa and Weber, 2008) and price of CO2, SO2 and NOx in the United States coal power industry (Lee and Zhouc, 2015). On the other hand, (Coelli et al., 2013) 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 technique assess customer interruption costs from the DSO perspective. We should note that VoLL or worth of ENS are not in the scope of this paper. The following of the 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. Section 4 provides a conclusion and discussion.

2. Shadow Pricing of Electric Power Interruptions

We may assume that the electricity supply has two main states: the continuity of supply (supplied energy), and the interruptions (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 (Färe et al., 2006). 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 at (Färe et al., 2006). 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 (Shephard, 1970; Färe et al., 1993). 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 paper, 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. 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:

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

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

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

Let P(x) denote the production technology (Hang et al., 2015), 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 Do (Chung et al., 1997). 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 *Do* is defined as:

$$\overrightarrow{D_0}(x, y, b; g_y, gb) = max\{\, \beta : (y + \beta g_y, b - \ \beta g_b) \in P(x)\} \tag{5}$$

$$\overrightarrow{D_0}(x, y + \alpha g_y, b - \alpha g_y; g) = \overrightarrow{D_0}(x, y, b; g) - \alpha \tag{6}$$

Our aim is to increase the amount of energy supplied to the customers, while decreasing the amount of energy not supplied 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 (Färe et al., 2006). Let *p* indicate the good output prices and *q* indicate the bad output prices. These are represented as:

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

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

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 Do as:

$$R(x,p,q) \geq (py - qb) + p.\overrightarrow{D_0}(x,y,b;g).g_y + q.\overrightarrow{D_0}(x,y,b;g).g_b \tag{10}$$

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: 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 (10), the directional output distance function and the maximal revenue function are related as:

$$\overrightarrow{D_0}(x,y,b;g) \leq \frac{R(x,p,q) - ((py - qb))}{pg_y + qg_b} \tag{11}$$

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

$$\overrightarrow{D_0}(x,y,b;g) = min_{p,q}\left\{\frac{R(x,p,q) - ((py - qb))}{pg_y + qg_b}\right\} \tag{12}$$

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

$$\nabla_y\overrightarrow{D_0}(x,y,b;g) = \frac{-p}{pg_y + qg_b} \tag{13}$$

$$\nabla_b\overrightarrow{D_0}(x,y,b;g) = \frac{q}{pg_y + qg_b} \tag{14}$$

The details of the physical meaning of the shadow pricing technique is explained in (Färe et al., 2006) 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 (Luenberger, 1992):

$$q_j = -p_m\left(\frac{\frac{\partial\overrightarrow{D_0}(x,y,b;g)}{\partial b_j}}{\frac{\partial\overrightarrow{D_0}(x,y,b;g)}{\partial y_m}}\right), j = 1, \ldots, J. \tag{15}$$

The references (Chambers et al., 1998) and (Wei et al., 2013) 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 expanding the desirable outputs, while keeping the undesirable outputs the same. Since our aim is to increase the good outputs and decrease the bad outputs simultaneously, 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 (16) are calculated via solving (17) with Python by adopting the directional vector as g = (1, 1). Equation (18) requires the output–input vector to be feasible. Equation (19) and (20) impose the monotonicity conditions of (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, $\bar{x}$, an increase in input usage holding good and bad outputs constant, causes the directional output distance function to increase, implying greater inefficiency. Equation (22) is due to the translation property of (6).

$$\overrightarrow{D_0} = (x_k, y_k, b_k; 1, 1) = l + \sum_{n=1}^{N} \alpha_n x_{nk} + \sum_{m=1}^{M} \beta_m y_{mk} + \sum_{j=1}^{J} \gamma_j b_{jk} + \frac{1}{2}\sum_{n=1}^{N}\sum_{n'=1}^{N} \alpha_{mn'} x_{nk} x_{n'k} + \frac{1}{2}\sum_{m=1}^{M}\sum_{m'=1}^{M} \beta_{mm'} y_{mk} y_{m'k} + \frac{1}{2}\sum_{j=1}^{J}\sum_{j'=1}^{J} \gamma_{jj'} b_{jk} b_{j'k} + \sum_{n=1}^{N}\sum_{m=1}^{M} \delta_{nm} x_{nk} y_{mk} + \sum_{n=1}^{N}\sum_{j=1}^{J} \eta_{nj} x_{nk} b_{jk} + \sum_{m=1}^{M}\sum_{j=1}^{J} \mu_{mj} y_{mk} b_{jk} \quad (16)$$

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 (17) to (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 they are solved with Python.

$$Minimize \sum_{k=1}^{K} \left[\overrightarrow{D_0}(x_k, y_k, b_k; 1, 1) - 0\right] \quad (17)$$

Subject to,

$$\overrightarrow{D_0}(x_k, y_k, b_k; 1, 1) \geq 0, \qquad k = 1, \dots, K \quad (18)$$

$$\frac{\partial \overrightarrow{D_0}(x_k, y_k, b_k; 1, 1)}{\partial b_j} \geq 0, j = 1, \dots, J; k = 1, \dots, K \quad (19)$$

$$\frac{\partial \overrightarrow{D_0}(x_k, y_k, b_k; 1, 1)}{\partial y_m} \leq 0, m = 1, \dots, M; k = 1, \dots, K \quad (20)$$

$$\frac{\partial \overrightarrow{D_0}(\bar{x}, y_k, b_k; 1, 1)}{\partial x_n} \geq 0, n = 1, \dots, N \quad (21)$$

$$\sum_{m=1}^{M} \beta_m - \sum_{j=1}^{J} \gamma_j = -1; \quad \sum_{m'=1}^{M} \beta_{mm'} - \sum_{j=1}^{J} \mu_{mj} = 0, m = 1, \dots, M; \quad (22)$$

$$\sum_{j'=1}^{J} \gamma_{jj'} - \sum_{m=1}^{M} \mu_{mj} = 0, \qquad j = 1, \dots, J; \quad \sum_{m=1}^{M} \delta_{nm} - \sum_{j=1}^{J} \eta_{nj} = 0, \qquad n = 1, \dots, N$$

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

3. Empirical Study and Results

3.1. Empirical Study

This paper targets Finland for the empirical study. In our study, we made use of 78 Finnish DSOs and their data for 2013, 2014 and 2015. Since some of the DSOs have not announced their interruption statistics yet for 2016 (The Energy Market Authority, 2017), it is not included in this paper. As useful data for the directional distance function, from the Finnish Energy Market Authority (Energiavirasto), we selected 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:

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

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:

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

Even though Finland has a robust electric power infrastructure, the security of supply is being threatened by extreme weather events (Küfeoğlu et al., 2014). Natural events, especially storms, are the leading causes of the power interruptions in Finland (Küfeoğlu et al., 2014). These events might cause long lasting outages which eventually drive Finnish DSOs to invest and spend more money on operational and maintenance expenses. Overhead lines are obviously more prone to these harsh weather-related accidents than underground cables. Therefore, 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 for 2013, 2014 and 2015 for the 78 Finnish DSOs. A total of 936 sample observations have been used in the analysis. OPEX and CML are represented in thousand euros and thousands of minutes respectively. In addition, energy supplied is tabulated in GWh.

3.2. Results

Within this optimization model, the objective function (17) has been solved using constraints (18-23) by Python programming language 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. 1176 constraints equations have been created with the script using (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 minutes with a laptop which has 8gb Ram, and 4 core processor. 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, (15) is solved where p is taken as 5.5 € cents as the average electricity distribution price in Finland (Energy Market Authority, 2017) and the results are summarized in Table A in the Appendix. Table B in the Appendix provide the summary of the SAIDI for the Finnish DSOs. SAIDI figures include all planned and unplanned interruptions which last longer than 1 minute.

Table 1. Descriptive Statistics for Pooled Sample Observations, 2013–2015

	Inputs		**Desirable output**	**Undesirable output**
	SC (%)	OPEX (k €)	ES (GWh)	CML (k mins)
2013				
Mean	47.27	3,015.51	619.92	14,299.67
Stdev.	25.60	5,674.63	1,200.07	45,908.75
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

Table 2. Coefficients Of (16) Per Year

	2013	**2014**	**2015**
l	16.3252	0.007764978	0.017882857
α_1	0	0	0
α_2	-7E-10	0.24284221	0.27902876
β_1	-1	-0.99987881	-1
γ_1	0	0.000121188	0
α_{11}	0	0	0
α_{22}	-1E-10	0.050119522	0.020527845
β_{11}	0	-1.977E-07	0
γ_{11}	0	-1.977E-07	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	-1.977E-07	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 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 1. As it 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 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 for 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 since 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 whether the outputs will expand, contract or remain the same.

In Finland, by law, DSOs are obligated to pay certain customer compensations varying by annual customer interruption times (Electricity Market Act, 2017). 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 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 (26).

$$R = q\text{b} \tag{26}$$

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 each minutes-lost as an interruption. The result for 2015 is 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 that results better, the comparison between the shadow prices and the compensation prices for Finnish DSOs in 2015 is presented in Figure 3. Figure 2 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.

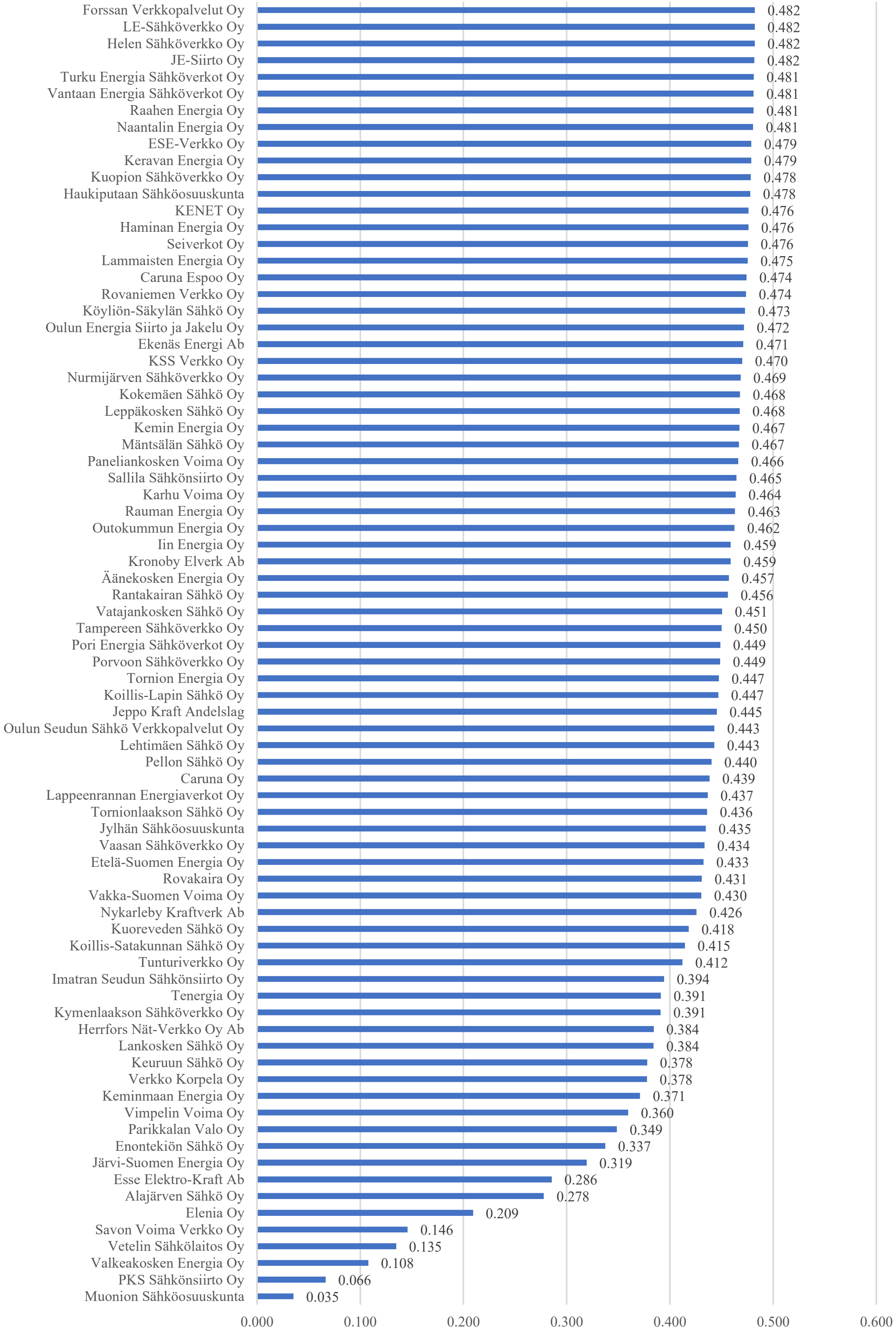

Figure 1. Shadow Price (€ in cents) of One Minute of Interruption for 2015

Table 3 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

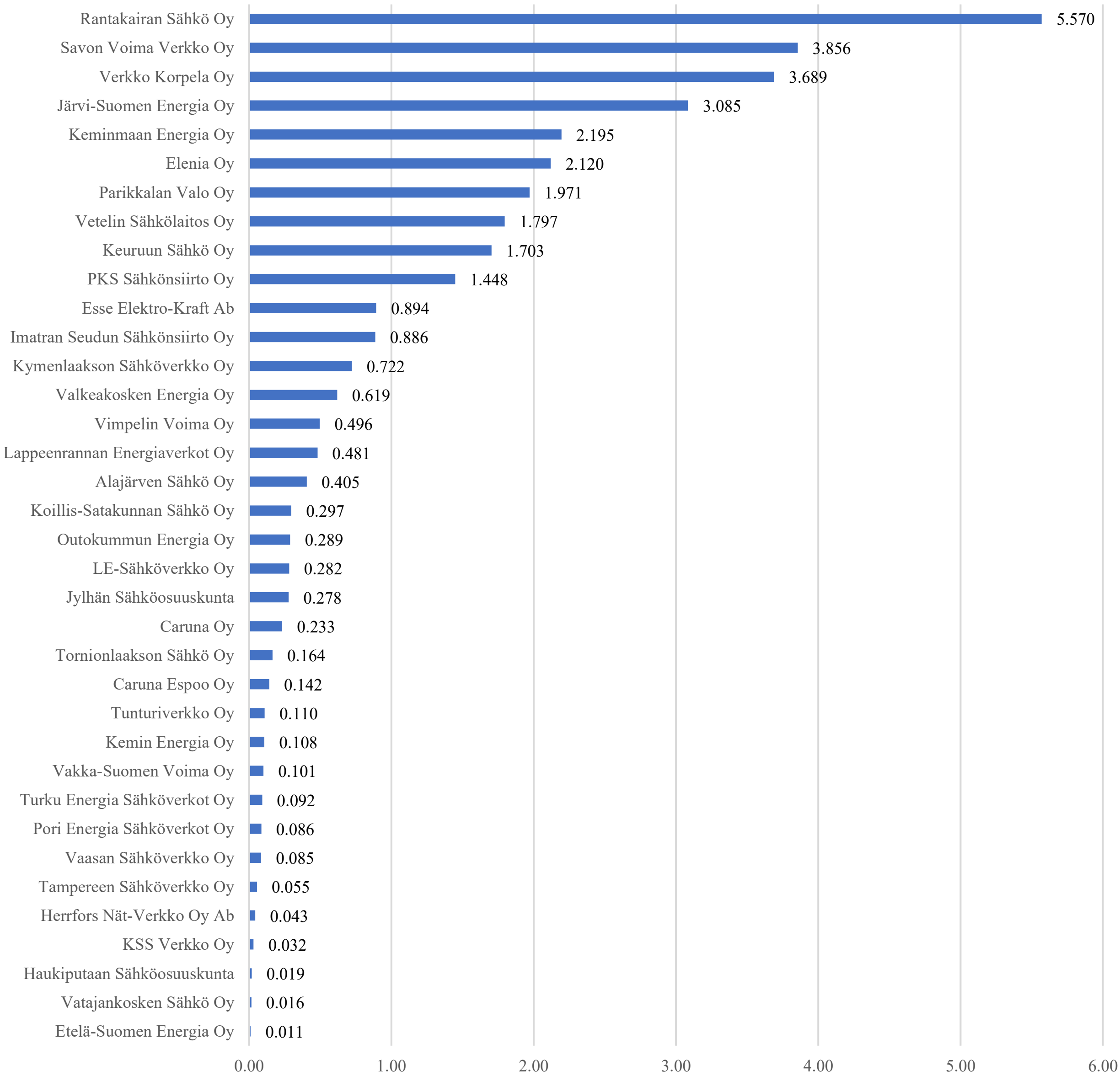

Figure 2. Compensation Price of One Minute of Interruption for 2015 (€ cents)

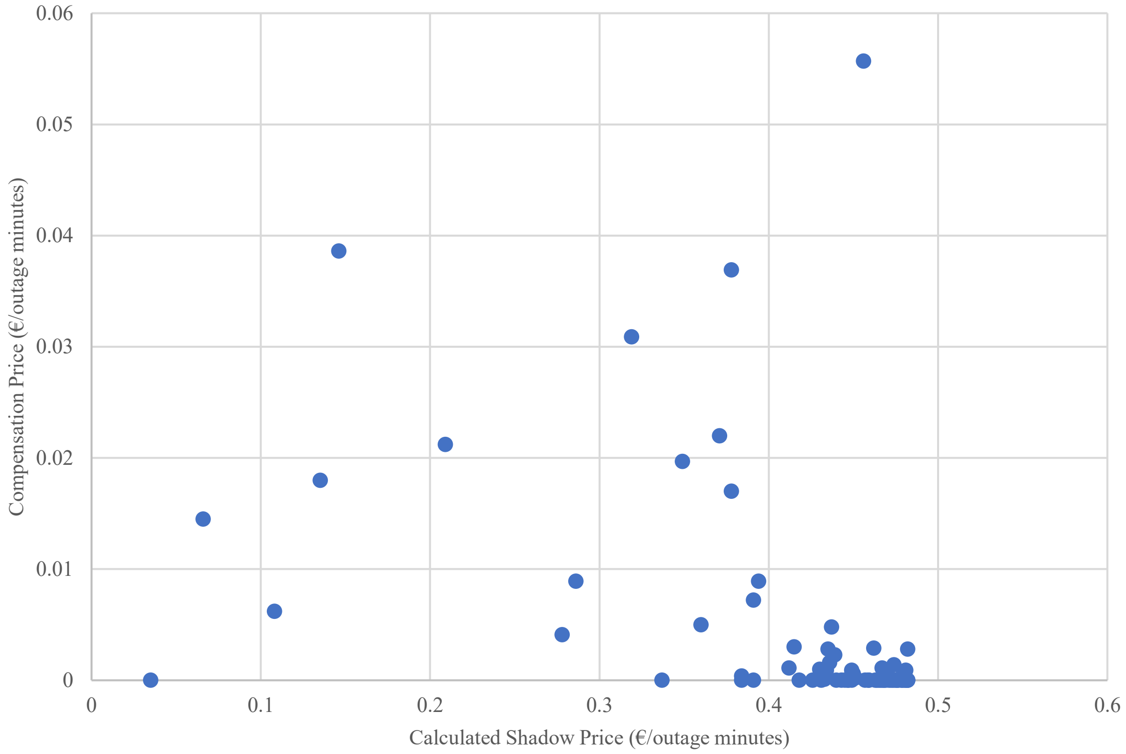

Figure 3. Comparison of Compensation price vs. Shadow price

4. Discussion & Conclusions

The continuity of electric power supply is a necessity to run critical infrastructures such as transportation, telecommunications, health, finance as well as 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 in many folds. At this point, understanding the economic impacts of power interruptions from a macro perspective becomes crucial. Estimating value of lost load (VoLL) and the worth of energy not supplied (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, being time consuming, requiring extensive labour to prepare and carry out questionnaires and high costs are the main disadvantages of the customer surveys. Moreover, the problem of zero responses and strategic responses is a critical challenge for the ones carrying out these studies. Human behaviour becomes a major issue for the researchers to consider when they adopt customer survey methodology (Küfeoğlu and Lehtonen, 2015. Shadow pricing technique could be assessed as one of the indirect analytical methods. To introduce a different perspective to the phenomenon from a DSO point of view, in this paper, the authors present the method of shadow pricing of power outages which solely relies on publicly available analytical data rather than survey questionnaires. By this way, cost estimation can be done by only using publicly available and objective analytical data such as 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 vary considerably among sub-sectors of the same sector such as textile, construction, chemical, pharmaceuticals etc. within the industry sector. To reach customer specific outage cost estimations, the network operators should share sector and customer specific energy consumption data.

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 evaluates the problem from the DSO perspective, so that each DSO will be able to have an idea about their interruption losses in a fast and straightforward manner. This information is needed for future planning of power system, enhancing the existing infrastructure and paying the standard compensations purposes. In some countries such as United Kingdom, and Finland, to protect the customers, the DSOs are obliged 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 hours, then the DSO pays 10% of the annual electricity delivery fee back to the customer. Let's assume that a typical Finnish household's annual delivery fee be around 94 euros per year (Helen, 2018). In case of a 20-hour interruption, the value of one minute of interruption will be 0.78 € cents / minute. We should note that the customers experiencing single time interruption events less than 12 hours receive no compensation at all. 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 will be around 0.5 € cents.

Another study of shadow pricing of power reliability, which targeted 92 DSOs in France (Coelli et al., 2013), follows a similar approach, but used a distance function but not a directional distance function. We use the number of interruption events rather than customer minutes lost as the bad output and suggests that one customer interruption (>3 minutes) has a shadow price of 4.9 € of OPEX costs for rural regions, while it costs 7.5 € for urban areas. We should remind 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 much 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 certain amount of losses, some DSOs did not pay any compensation at all because of the standard compensation calculation method summarized in Table 3. If a single-time outage event does not exceed 12 hours, 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 much more 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 introduce them higher quality of services. However, it should be noted that another major principle is fairness and Finnish DSOs should be treated fairly by designing a better standard compensation scheme which will be more cost reflective. Price signals are crucial in terms of providing continuous service quality and affecting future investments. The authors will continue doing further analysis in relation to the customer interruption costs and standard customer compensations.

Acknowledgement

The authors would like to acknowledge Fortum Foundation, Espoo, Finland for their funding support through B3 201700083 research grant.

Appendix A

Table A. 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 B. 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
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

References

Abrate, G., Bruno, C., Erbetta, F., Fraquelli G. and Lorite-Espejo, A., 2016. "A choice experiment on the willingness of households to accept power outages," Utilities Policy, vol. 43, pp. 151-164.

Carlsson, F., Martinsson, P. and Akay, A., 2008. 'The Effect of Power Outages and Cheap Talk on Willingness to Pay to Reduce Outages," Energy Economics, vol. 30, no. 3, pp. 1232-1245.

Chambers, R., Chung, Y. and Färe, R., 1998. "Profit, Directional Distance Functions, and Nerlovian Efficiency," Journal of Optimization Theory and Applications, vol. 98, no. 2, p. 351–364.

Chung, Y. H., Färe, R. and Grosskopf, S., 1997. "Productivity and undesirable outputs: a directional distance function approach," Journal of Environmental Management, vol. 51, no. 3, p. 229–240.
Coelli, T. J., Gautier, A., Perelman, S. and Saplacan-Pop, R., 2013. "Estimating the cost of improving quality in electricity distribution: A parametric distance function approach," Energy Policy, vol. 53, pp. 287-297.
Corwin, J. L. and Miles, W.T., 1978. "Impact Assessment of the 1977 New York City Blackout," U.S. Department of Energy, Washington D.C.
Electricity Market Act, 2017. (Sähkömarkkinalaki, in Finnish), Ministry of Trade and Industry, Finland. Available: http://www.finlex.fi. [Accessed 11 November 2017].
Färe, R., Grosskopf, S. and Weber, W., 2006. "Shadow prices and pollution costs in U.S. agriculture," Ecolological Economics, vol. 56, no. 1, p. 89–103.
Färe, R., Grosskopf, S., Lovell. C. and Yaisawarng, S., 1993. "Derivation of Shadow Prices for Undesirable Outputs: A Distance Function Approach," The Review of Economics and Statistics, vol. 75, no. 2, pp. 374-380.
Färe, R., Grosskopf, S., Roland, B. and Weber, W. L., 2009. "License fees: the case of norwegian salmon farming," Aquaculture Economics & Management, vol. 1, no. 13, pp. 1-21.
Fukuyamaa, H. and Weber, W. L., 2008. "Japanese banking inefficiency and shadow pricing," Mathematical and Computer Modelling, vol. 48, p. 1854–1867.
Growitsch, C., Malischek, R., Nick, S. and Wetzel, H., 2015. "The Costs of Power Interruptions in Germany: A Regional and Sectoral Analysis," German Economic Review, vol. 16, no. 3, pp. 307-323.
Hang, Y., Sun, J., Wang, Q., Zhao, Z. and Wang, Y., 2015. "Measuring energy inefficiency with undesirable outputs and technology heterogeneity in Chinese cities," Economic Modelling, vol. 49, p. 46–52.
Helen, 2018. Helen newsletter, Electricity distribution prices to rise in Helsinki. Available: https://www.helen.fi/en/news/2016/electricity-distribution-prices-to-rise-in-helsinki. [Accessed 2 March 2018].
Kim, K. and Cho, Y., 2017. "Estimation of power outage costs in the industrial sector of South Korea," Energy Policy, vol. 101, no. 1, pp. 236-245.
Küfeoğlu, S. and Lehtonen, M., 2015. "Interruption costs of service sector electricity customers, a hybrid approach," International Journal of Electrical Power & Energy Systems, vol. 64, pp. 588 – 595.
Küfeoğlu, S. and Lehtonen, M., 2016. "A Review on the Theory of Electric Power Reliability Worth and Customer Interruption Costs Assessment Techniques," in 13th International Conference on the European Energy Market (EEM), Porto, Portugal.
Küfeoğlu, S., Prittinen, S. and Lehtonen, M., 2014. "A summary of the recent extreme weather events and their impacts on electricity," International Review of Electrical Engineering (IREE), vol. 9, no. 4, pp. 821-828.
Lee, C. and Zhouc, P., 2015. "Directional shadow price estimation of CO2, SO2 and NOx in the United States coal power industry 1990–2010," Energy Economics, vol. 51, p. 493–502.
London Economics, 2013. Final report for OFGEM and DECC, "The Value of Lost Load (VoLL) for Electricity in Great Britain," London, UK.
Luenberger, D. G., 1992. "Benefit functions and duality," Journal of Mathematical Economics, vol. 21, p. 461– 486.
Minnaar, U., Visser, W. and Crafford, J., 2017. "An economic model for the cost of electricity service interruption in South Africa," Utilities Policy, vol. 48, pp. 41-50.
Molinos-Senante, M., Mocholí-Arce, M. and Sala-Garrido, R., 2016. "Estimating the environmental and resource costs of leakage in water distribution systems: A shadow price approach," Science of the Total Environment, vol. 568, p. 180–188.
Poudineh, R. and Jamasb, T., 2017. "Electricity supply interruptions: Sectoral interdependencies and the cost of energy not served for the Scottish economy," Energy Journal, vol. 38, no. 1, pp. 51-76.
Securing the U.S. Electrical Grid, 2014. "Understanding the threats to the most critical of critical infrastructure, while securing a changing grid," Center for the Study of the Presidency & Congress.
Shephard, R. W., 1970. Theory of cost and production functions, Princeton: Princeton University Press.
Shivakumar, A., Welsch, M., Taliotis, C., Jakšić, D., Baričević, T., Howells, M., Gupta S. and Rogner, H., 2017. "Valuing blackouts and lost leisure: Estimating electricity interruption costs for households across the European Union," Energy Research and Social Science, vol. 34, pp. 39-48.
Sullivan, M. J., Schellenberg, J. and Blundell, M., 2015. "Updated Value of Service Reliability Estimates for Electric Utility Customers in the United States," Ernest Orlando Lawrence Berkeley National Laboratory.
Tang, K., Gong, C. and Wang, D., 2016. "Reduction potential, shadow prices, and pollution costs of agricultural pollutants in China," Science of the Total Environment, vol. 541, p. 42–50.

The Energy Market Authority, 2017. (Energiavirasto, in Finnish), "Energy Authority, Muut tilastot ja tunnusluvut,". Available: https://www.energiavirasto.fi/muut-tilastot. [Accessed 11 November 2017].
The White House, 2013. Office of the Press Secretary, "Presidential Policy Directive/Ppd-21, Critical Infrastructure Security and Resilience," Washington D.C.
Wei, C., Löschel, A. and Liu, B., 2013. "Energy-saving and emission-abatement potential of Chinese coal-fired power enterprise: a non-parametric analysis," Energy Economics, vol. 49, p. 33–43.