electricity

MDPI

Article

The Total Cost of Reliable Electricity Distribution

Joel Seppälä [1,*], Joonas Kari [2] and Pertti Järventausta [1]

[1] Unit of Electrical Engineering, Tampere University, Korkeakoulunkatu 7, FI-33720 Tampere, Finland; pertti.jarventausta@tuni.fi
[2] Energy Authority (Finland), Lintulahdenkuja 2 A, FI-00530 Helsinki, Finland; joonas.kari@energiavirasto.fi
* Correspondence: joel.seppala@tuni.fi

Abstract: Clean transition increases the demand for reliable electricity distribution, but while the capacity can be improved through investments, responding to the demand increases costs for the customers. This study presents a methodological improvement to the assessment of the reasonability of pricing, by comprehensively analyzing pricing regulation data to define the total cost of electricity distribution by clustering. A novel systematic view on the volume and distribution of economic steering shows that according to the regulation data in Finland, the total annual cost of distribution for the present level of reliability varies from EUR 490/a in an urban environment to EUR 1220/a per customer in sparsely populated areas. The majority of the total costs of distribution stem from actual utility expenses. The approach and results may be used for implementing TOTEX models for future pricing regulation.

Keywords: electricity distribution; security of supply; economic regulation; clustering

1. Introduction

Customers of the electricity distribution network initially pay the Distribution System Operator (DSO) for market connection, followed by ongoing payments for distribution services. DSOs invest in developing and maintaining the network to facilitate new customer connections and ensure continuous service. To sustain this process, an attractive investment environment must be established, allowing DSOs to earn a profit from assets that enable new connections and continuous service. However, excessive profits may lead DSOs to inefficiencies in producing the service (Averch-Johnson effect) [1,2]. Inefficiency may appear in the form of "gold-plating" the network, resulting in an exaggerated capacity or reliability. In such cases, the costs of the overbuilt network are ultimately borne by the customers. The ongoing challenge, then, is to assess whether investments efficiently provide the service and if the profits from these assets are reasonable.

In the 1980s, the initial approach to pricing focused on controlling the prices paid by customers. During the 1990s, actions were taken to account for increasing productivity. In the 2000s, the focus shifted from average prices optimizing short-term costs towards considerations of life-cycle costs and qualitative aspects [3,4]. Progress has since moved towards incentive-based regulation, such as that contained within the current RIIO-2 framework, though defining the results remains challenging. This study offers a methodological improvement in assessing electricity distribution pricing by clustering the formation of the total costs, including the actual utility costs, policy costs, and interruption costs. Given that extensive pricing decision data is publicly available from the national regulatory authority (NRA), the results are reproducible.

This empirical study consists of three parts. The first part provides a concise literature review of studies related to the economic regulation of supply reliability. The second part presents the formation of electricity distribution costs producing a certain level of reliability. The third part discusses the results in the context of policy implications.

check for updates

Citation: Seppälä, J.; Kari, J.; Järventausta, P. The Total Cost of Reliable Electricity Distribution. *Electricity* **2024**, *5*, 916–930. https://doi.org/10.3390/electricity5040046

Academic Editor: Andreas Sumper

Received: 24 September 2024
Revised: 14 November 2024
Accepted: 18 November 2024
Published: 21 November 2024

2. Literature Review

The rationale for regulating electricity distribution is twofold: protecting customers from the adverse effects of natural monopolies while simultaneously ensuring the reliable functionality of the energy system, which is essential for a functioning society. Consequently, "energy security" is recognized as a key dimension of the Energy Union in Europe [5]. Binding steering is given in article 18 of Regulation (EU) 2019/943, stating at the abstract level that the charges applied for accessing the network must be cost-reflective and take into account the need for network security and not include costs supporting unrelated policy objectives [6].

According to Rothwell's comprehensive handbook on electricity economics, the general objective of regulation is "to protect the short-run and long-run interests of consumers by promoting economic efficiency" [2]. Decker extends these general rationales, noting that "empirical evidence suggests that the practice of regulation is not always consistent with a goal of improving economic welfare." While the normative rationale focuses on enhancing the economic efficiency of regulated utilities, the extended rationale aims to provide tools for implementing desired policies related to security, the environment, or the continuity of regulated businesses [7].

Today's regulatory frameworks often rely on the reasonable rate of return (RoR) for assets or performance-based rating (PBR) to reduce utility costs [2]. As an evolutionary step, some frameworks, such as those in Finland, combine these approaches and introduce incentives to improve various aspects of regulated businesses. For instance, in the UK, a pioneer in regulation, traditional PBR has evolved to include output aspects of the electricity distribution process alongside economic efficiency enhancements. The second version of the Revenue–Incentive–Innovation–Output framework (RIIO-2) also includes an incentive for controlling the total expenses (TOTEX) [8].

Typically, the value of lost load (VoLL) during distribution interruptions has a negligible impact on a DSO's revenue. Therefore, a study by Jooshaki et al. on minimizing interruption costs highlights the importance of incorporating quality incentives into regulatory frameworks [9]. Service quality, or supply reliability, is included in the pricing regulation of many European countries [10]. Common methods involve implementing incentive schemes to reward or penalize for the difference between target and actual service quality levels or incorporating such elements into efficiency benchmarking [1]. It is also important to consider whether service levels are described using absolute indices or monetized values. Concrete measurements enhance the transparency of incentives, while advanced benchmarking with multiple input and output variables provides a more sophisticated method for comparing results across different operational environments (e.g., urban vs. rural areas) [11].

Sappington notes that pricing regulation can worsen, improve, or complicate service quality issues that would occur without regulation [12]. In some frameworks, quality incentives may, for example, reward improvements in supply reliability, even if overall reliability remains suboptimal [13]. Cooper et al. discuss how using average indices can lead to inconsistencies in user experience among different customers [14]. Implementing incentives requires careful consideration of their convergence points. Ultimately, the supply reliability depends on the entire energy system. Therefore, it is important to consider the impact on the overall supply reliability, as noted by Rey [15].

In general, the distribution reliability can be improved by investing in the network and increasing maintenance. Theoretically, the optimum level of distribution reliability is achieved when the additional reliability equals the companies' marginal cost of increasing reliability [1,12]. Since the net-total costs of actual investments are not known, macroeconomic assessments are typically unavailable. However, costs were evaluated when preparing changes to the electricity market law in Finland, prompted by major disturbances caused by a single winter storm in 2011 [16]. To approach the optimum costs of the distribution system, the total costs for improving reliability to avoid long interruptions due to weather conditions were assessed. Setting a maximum interruption length of 36 h would require investments of EUR 3500 million (EUR 1.2-c/kWh) and EUR 5100 million (EUR 1.7 -c/kWh) for a 24-h limit. The final quality standard limited interruption lengths to 6 h in urban areas and 36 h in non-urban areas, and was estimated to result in a 16–22% increase in network service fees and an 8–10% increase in overall electricity bills, including taxes and delivered energy [17]. Public discussion on the reasonableness of distribution prices, following changes to obligations and DSO regulations, led to an extended schedule for newly implemented quality standards to mitigate price increases. Concurrently, DSOs were given new obligations, such as public network development plans, to improve the transparency of cost-efficient network development [18].

Another element in assessing reasonableness is the cost of interruptions to society. Three commonly used methodologies are customer surveys, indirect analytical methods, and case studies; their properties are reviewed, for example, in [19]. Based on the advantages and disadvantages of these methods, advanced methods for assessing customer interruption costs, such as the shadow pricing of production technology, are proposed [20]. Shadow pricing is a concept used earlier to study duality in agriculture, which produces goods and generates pollution [21], and to estimate the costs of leakage in water distribution [22]. In electricity distribution, shadow prices are applied to estimate the cost of preventing interruptions in France [23] and to estimate the cost of one minute of power interruption from the perspective of the distribution network operator in Finland [20]. An incentive mechanism can be divided into measurement and application functions [13]. In this context, shadow prices effectively capture the measurement function but require additional elements to provide a gradient that indicates where the incentive should converge, i.e., to achieve the optimum level of quality.

According to the presented literature, the legal framework in the EU region sets general aims for qualitative regulation, leaving the detailed assessment to national regulators. While European energy regulators document reliability, they do not assess it from an economic perspective. Research on reliability often focuses on the technical and economic aspects of improvement, with shadow prices providing partial estimates of the marginal costs. However, there is a lack of information and methods for assessing reliability from a macroeconomic perspective. This study addresses this gap by offering a data-driven analysis of the total costs of electricity distribution to society and the regulatory impact on these costs.

This study has two essential aims. Firstly, it presents the formation of the total costs of electricity distribution based on publicly available information provided by the Finnish Regulation Authority. Secondly, it offers a solid and repeatable assessment framework to explore the formation of the total costs of electricity distribution. This study extends the data-driven research on the regulation framework presented in [13,24] and, therefore, does not discuss the issues on clustering and specific performance indicators.

3. Methodology

The efficiency of investments must be assessed in relation to their targets. Logical evaluation questions include the following: Is the investment necessary? Does it reliably serve customers in its specific surroundings? How much maintenance does it require? What are the alternatives for the investment? Does the owner of the network have other strategic objectives? [25] Evaluating every single investment would require extensive data processing capabilities, making the evaluation process complex. Despite this, the evaluation of individual actions may not provide clear-cut answers to efficiency questions. Therefore, a benchmarking approach is used in this study to encapsulate the given inputs and outputs to evaluate the results of the electricity distribution process.

The supply reliability is typically considered a function of investments: The more a DSO invests in the network, the more reliable the network becomes. Since interruptions in the distribution service can be quantified in monetary terms, the total cost of the distribution service for customers can be expressed as the sum of the investment costs and interruption costs [1]. The third part of the total costs is traditionally referred to as the cost of regulation.

According to Decker, the cost of regulation is more and more being considered as policy cost, presenting wider policy targets related, for example, to enhancing clean transition or avoiding energy poverty. Minimizing the societal costs can be expressed as a function of time, as in [1,13], but extended with fundamental policy costs, as in (1):

$$min f(t) = C_{DSO}(t) + C_{CUSTOMER}(t) + C_{POLICY}(t) \tag{1}$$

However, the global minimum for this function is zero if the system does not exist. By reversing the function according to the rationale of natural monopolies—natural monopolies may exist if they produce a net wealth increase—this approach, adopted from Decker [7], presents the wealth-increasing function in the context of average cost pricing. In this concept, a utility produces a service with a production cost (PC) and sets the pricing to cover the PC and provide the asset owner with a profit (π). Referring to the wealth increase function, the profit (π) must be positive for the utility to cover its PC, but if π′ >> π, it increases prices and reduces the surplus in wealth production. Therefore, the regulator's objective is to define such a π to maximize the total surplus, i.e., the wealth increase (W) over time, as shown in (2).

$$max f(t) = W(t) - C_{DSO}(t) - C_{CUSTOMER}(t) - C_{POLICY}(t) \tag{2}$$

Equation (2) represents the maximizing of the produced wealth (W), which could also be achieved with higher costs—not only minimizing the costs. Since wealth production is a stochastic function, an explicit solution for maximizing wealth is not known. Therefore, benchmarking through historical measurements [11,26] is proposed to assess the elements of Equation (2). For benchmarking, the electricity distribution process can be described as a set of inputs producing outputs:

$$\begin{bmatrix} C_{asset} \\ C_{opex} \end{bmatrix} \xrightarrow{yields} \begin{bmatrix} n_{customers} \\ d_{network} \\ W_{energy} \\ C_{interruptions} \end{bmatrix} \tag{3}$$

Equation (3) fundamentally describes the process where a DSO invests in assets (in terms of money) and produces outputs such as connected customers, network volume, and transferred energy, along with a negative output in the form of interruption costs. In other words, the input vector represents the costs incurred by the DSO, while the output vector represents the enablers of wealth increase and the interruption costs. As the scope of this study focuses on the total costs incurred by society (rather than the wealth increase), the produced wealth is excluded from this initial assessment. Therefore, the assets of a DSO are considered to produce interruption costs, expressed as follows:

$$f\left(c_{asset}, c_{opex}\right) = c_{interruptions} \tag{4}$$

The Finnish regulator provides data on actual asset costs, operational expenses, interruption costs, and reasonable profit calculations upon request, presenting a comprehensive database of all 77 DSOs' costs for producing the selected outputs—in this case, interruption costs.

This study's approach is based on assessing the costs as in (2), formed from the costs of DSOs (C_{DSO}), incurred costs for customers of interruptions C_{INT}, and cost of policies (incentivizing activities) C_{POLICY} in (2). These costs are marked as total costs (TC). Allowed profit is the regulator's perception of reasonable profit after operational costs. Therefore, the allowed revenue (AR) is calculated 'backwards' from the allowed profit (AP). The real costs of DSOs are calculated from the regulation data to present the break-even cost (BC), meaning the revenue DSO must be equal to reach a net zero result/profit. As every increment for revenue (R) (where (BC < R < AR)) increases the utility's profit by increasing the collected revenue, the adjustable difference between AR and BC can be considered as the regulator's steering (ST). In this study, minor regulatory costs (e.g., personnel costs) are ignored as they do not directly provide steering. The formation of the cost elements is depicted in Figure 1.

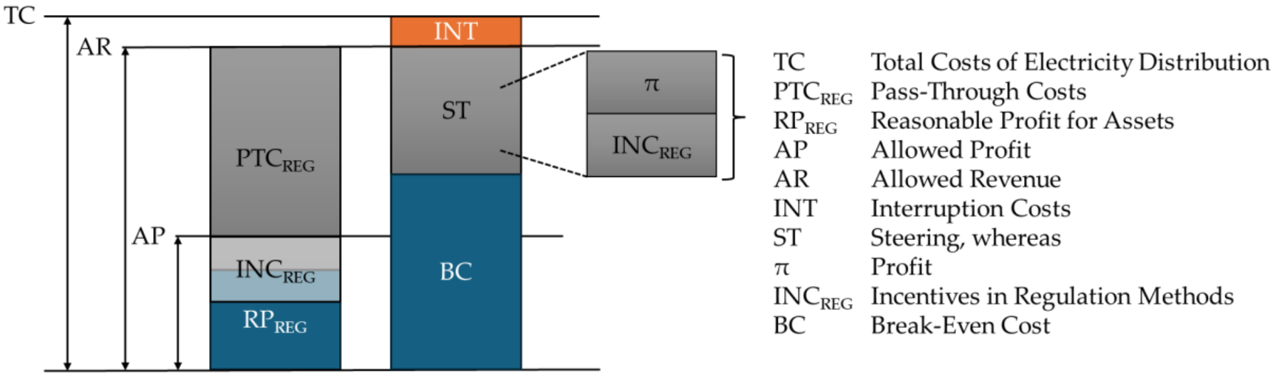


Figure 1. The formation of the elements of total costs incurred to the society. Source: Author.

The steering potentially reduces the wealth incurred to the society (see (2)) but may also lead to wealth increment by allowing a utility, for example, to invest in reliability/efficiency and, therefore, adjust the interruption costs/break-even costs of a utility. This shows the stochastic nature of the electricity distribution business and its operation environment: Neither BC nor AR are constant; they are functions of given inputs and the operation environment. This must be considered when discussing the results: The reasonable profit is defined only for the given inputs and outputs. Moreover, as the costs depend on the customer volume, they are to be presented as unit costs, i.e., proportional, for example, to customer volume, network length, or transferred electricity.

3.1. Description of the Finnish Pricing Framework and the Data Collection

The Finnish pricing regulation focuses on controlling the revenues of Distribution System Operators (DSOs) rather than directly regulating prices. This regulation combines rate of return (RoR) and performance-based regulation (PBR), where the reasonable profit for network assets is compared to the 'allowed profit' (AP). The AP results from an adjusted profit calculation by the regulator to assess DSO performance. This calculation includes five incentives: investment, efficiency, quality, security of supply, and innovation. The difference (surplus or deficit) between allowed profit and adjusted profit is calculated separately for every year of operation and the binding authoritative decision is issued after the regulation period, mandating that any surplus be returned to customers in the next regulation period, and any deficit be recovered similarly. A surplus indicates that a DSO has collected excess revenue, which must be returned to customers. Conversely, a deficit allows the DSO to recover the shortfall by increasing revenue collection [27].

The rationale for collecting data on DSOs' business activities lies in the regulator's duty to evaluate pricing. Performance and background data for this study are collected by the regulator, as every DSO is required to provide information for pricing evaluation purposes. Consequently, the dataset covers the entire jurisdiction of Finland. Regulatory data is collected annually for the previous year and verified and published by the regulator. Thus, in 2024, the data encompasses the entire fourth regulation period (2016–2019) and part of the fifth regulation period (2020–2021 of 2020–2023). The technical and economic source data of each individual DSO, along with pricing assessment data, were combined into a single database for further examination. The data preparation included replacing null values with zeros, integrating different files into a master file, and error checking.

3.2. Clustering as a Grouping Method

To understand a new object or phenomenon, people typically identify its key characteristics and then compare these with those of familiar objects or phenomena. This comparison is based on how similar or different they are, following specific standards or rules. Clustering is a mathematical grouping method, in which data objects are divided into groups by their similarities. While thousands of clustering methods are available for different purposes and new ones appear continuously, the optimal clustering method for each application is to be defined according the purpose of clustering [28–30].

The k-means algorithm used in this study is a partitional clustering method. It minimizes the mathematical distances between data vectors by iteratively organizing them around central vectors (centroids) until the sum of errors—the distances between the vectors and centroids—no longer decreases. As a mathematical method, clustering provides repeatable and objective ways to analyze the results of the electricity distribution process, as described by the given data objects. Although clustering is not yet widely applied in electricity distribution research, it is used in non-parametric benchmarking (StoNED) [31] and gathering insights from DSO's interruption indices [24].

The operational environment in Finland indicates that DSOs should be categorized into at least three classes: urban, rural, and mixed areas. Previous studies recommend using four to seven classes to prevent the emergence of outliers (clusters of individual DSOs) [13,24]. Although the literature suggests ignoring or setting aside outliers, especially when the number of data objects is large [29], this study includes them. Including all DSOs provides a comprehensive view of the entire jurisdiction and offers valuable insights into the clustering results.

3.3. Error Sources and Limitations

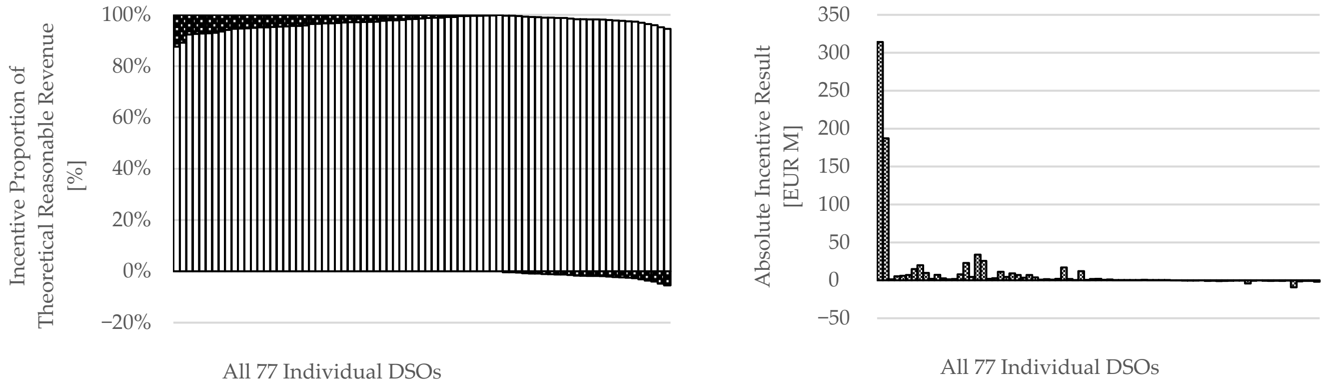
The regulation data regarding the economy and performance of DSOs is initially generated by the DSOs themselves. Interruption and other performance data are considered reliable as they are based on the automatic data collection processes of DSOs. The average indices delivered to the regulator are annually controlled by the regulator. Economic data is based on legal bookkeeping obligations and is deemed reliable. The allowed profit calculations, subject to administrative decisions, are also considered reliable. However, certain anomalies in the business processes of DSOs may cause inconsistencies in the allowed profit calculations and, consequently, in the calculation of the theoretical allowed revenue in this study. For instance, some DSOs have altered the ownership of the networks they operate, and a DSO may lease network assets from a third party. Additionally, although rare, some subsidies may cause anomalies in the data.

A general limitation of clustering is that clustering only assigns the input data into groups according to the pre-defined parameters. Firstly, clustering itself does not add anything on the data, and secondly, the result depends on the predefined parameters of clustering: for example, the number of clusters and the initial centroids of the clustering process.

When clustering classifies data sets through a numerical iterative process, verifying the explicit correctness of clustering is challenging. Therefore, clustering results are evaluated by analyzing both clustering-specific and source data indicators. Given that clustering results are fundamental to subsequent conclusions, two different clustering environments (MATLAB and Python) were applied to verify the results. To ensure successful clustering, source data indicators such as the minimum, maximum, and average values for each cluster are calculated and manually assessed for cluster homogeneity.

4. Results

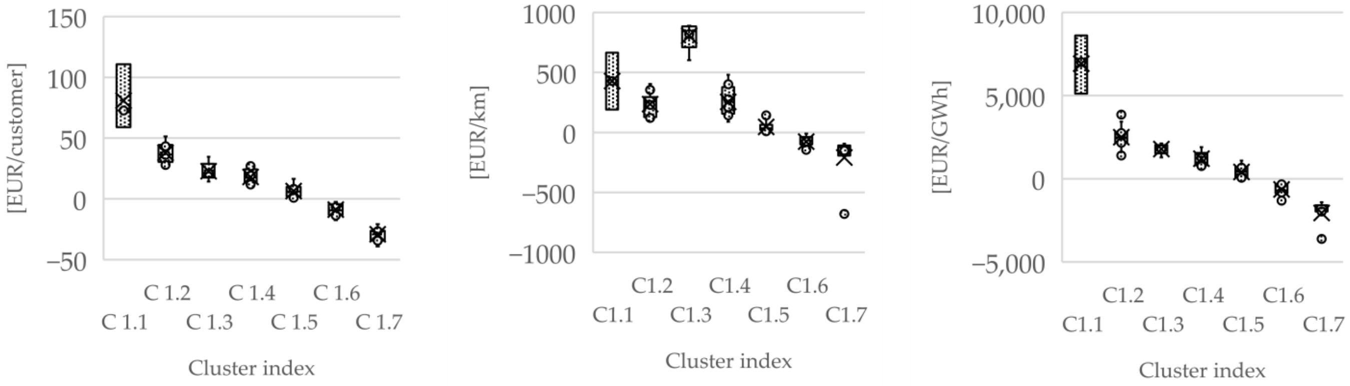
The first approach to the total costs of distribution is to define and present the proportion of incentives within the revenue allowed to be collected from customers. Calculating the allowed revenue (AR) from the 'allowed profit' (AP) enables the assessment of the impact of incentives on the prices paid by customers. The incentives as a proportion of the AR are presented in Figure 2.



(**a**) (**b**)

Figure 2. (**a**) The distribution of the allowed revenues (AR) for the years 2016–2021 for each DSO, starting from the base level of allowed revenues (light areas) and adjusted with the incentives (dark areas) to determine reasonable revenue. (**b**) The net total of incentives for each DSO from 2016 to 2021.

In Figure 2a, the formation of the allowed revenue illustrates the variation in incentive effects across different DSOs. Incentives range from −6% to +14% of the allowed revenue for each DSO. For 44 out of 77 DSOs, pricing regulation increases the AR through incentives. However, the absolute impact is significantly skewed, as shown in Figure 2b: The sum of bonuses amounts to EUR 768 million, while maluses total EUR 27.6 million. Moreover, two of the largest DSOs account for EUR 501 million of all bonuses. Given that DSOs vary in customer volume, network size, and electricity transferred, the incentive results are calculated in proportion to these variables. The relative incentive results are clustered to identify similar outcomes, as shown in Figure 3:



(**a**) (**b**) (**c**)

Figure 3. The incentive results in proportion to the various factors. (**a**) EUR per customer (Table A1 of Appendix A) (**b**) EUR per km (**c**) EUR per GWh.

Figure 3a–c are all based on clustering the incentive result per customer and indicate that increased bonus levels for certain groups of DSOs are evident in every aspect considered. Cluster 1.3 includes DSOs operating in urban areas with a low network volume per customer, which increases the incentive result in proportion to the network volume, as seen in Figure 3b. The numerical details of the clustering results are provided in Table A1 of Appendix A.

The incentive effect represents only a portion of the overall impact of pricing regulation. The absolute steering (ST) per customer is calculated as the difference between break-even costs and allowed revenue (AR). Combined with the interruption costs per customer, the total costs of electricity distribution incurred by society are presented in Figure 4.

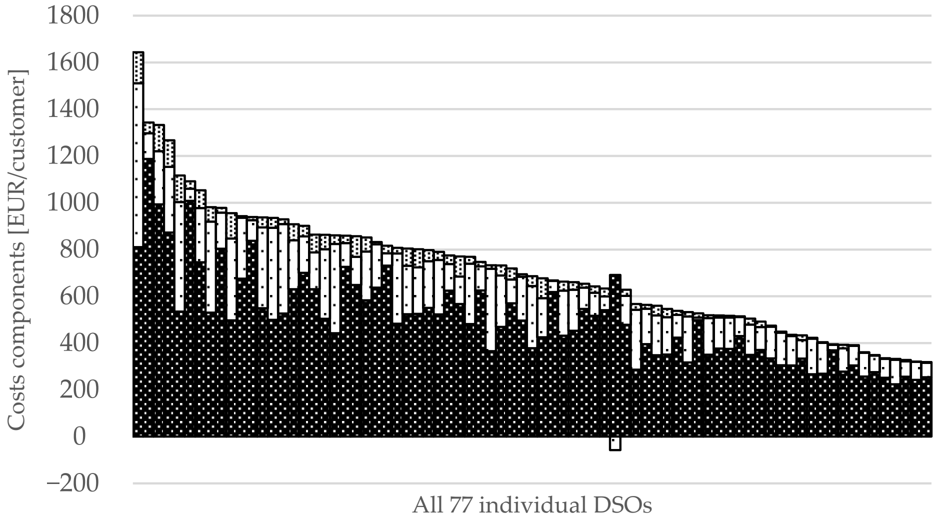


Figure 4. The formation of total of electricity distribution cost per customer for each DSO. (Break-even cost (BC) in dark, steering cost (ST) as white, and interruption costs (INT) in grey).

Figure 4 illustrates that the total cost of electricity distribution from 2016 to 2021 ranges between EUR 320 and 1620 per customer, with varying cost components. The majority of these costs are break-even costs, followed by steering costs, while interruption costs constitute a minor portion. The anomaly in (negative) steering costs in Figure 4 for one DSOs indicates that the break-even costs (BC) have exceeded the allowed revenue (AR) due to ownership transactions of network assets.

To gain insights, the total costs of electricity distribution (BC, interruption costs, incentives, and the linear trend of interruption costs) are classified into seven clusters based on similarities in cost formation. Figure 5a displays the total break-even and steering costs for each DSO, representing the costs borne by customers. Figure 5b depicts the interruption costs incurred by customers for the corresponding clusters.

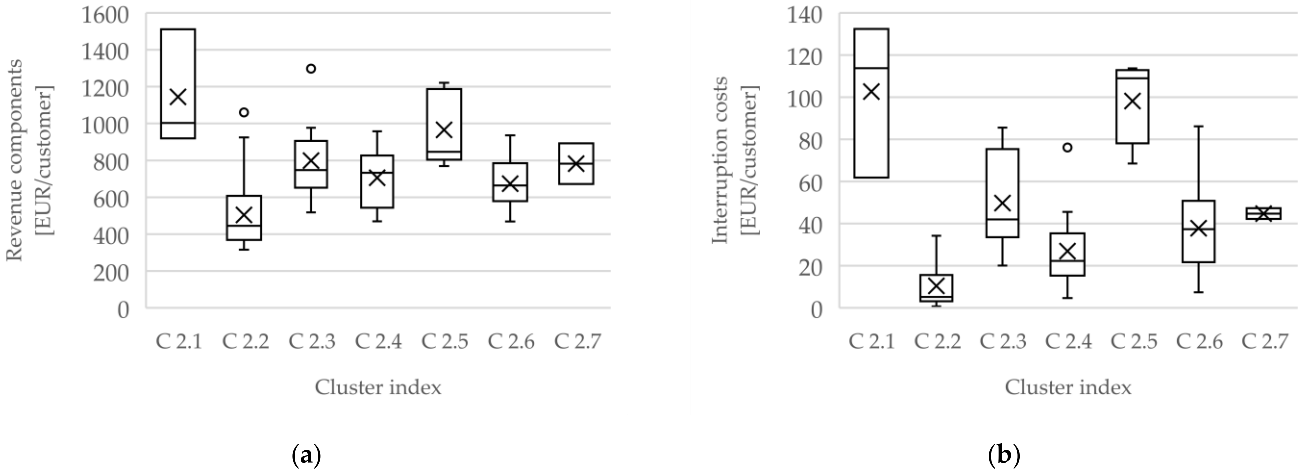


Figure 5. (**a**) The sum of break-even costs and steering costs in each cluster. (**b**) The interruption costs for the same clusters.

In Figure 5a, the break-even costs (BC) for clusters 2.1 and 2.5 are above the average per customer, yet these clusters perform worse in terms of interruption costs (Figure 5b). Specifically, for cluster 2.1, the interruption costs per customer are higher than those in the lower half of the clusters. The numerical details of the clustering results are provided in Table A2 of Appendix A. Given the dual nature of the resulting interruption costs, the linear trend of interruption costs was calculated for 2016–2021 and is presented in Figure 6.

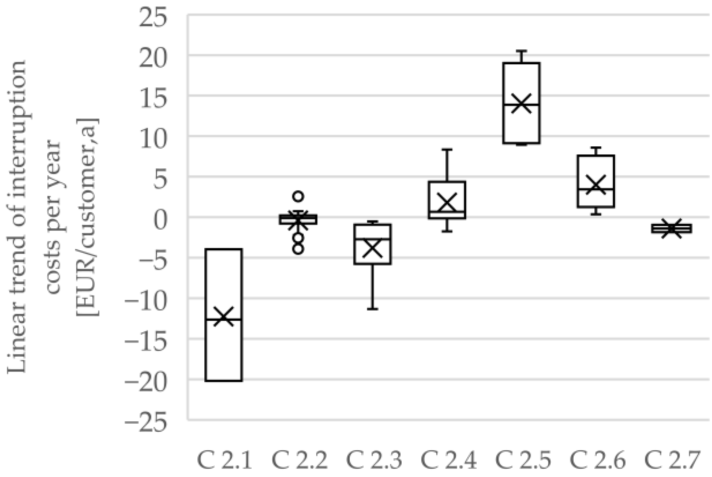


Figure 6. The linear trend of annual interruption costs from 2016 to 2021.

The linear trend in Figure 6 shows a decreasing trend in interruption costs for the DSOs in cluster 2.1, whereas interruption costs in cluster 2.5 continue to rise. The clustered cost-formation data is combined with additional information to explain these results (Table A4 of Appendix B). The analysis reveals that cluster 2.1 comprises five relatively small DSOs with an above-average network volume per customer. The DSOs in cluster 2.5 have 10 times the volume of those in cluster 2.1.

Given that the identification of DSOs is preserved in the background data, the results indicate that geographically, the DSOs in cluster 2.1 are located in northern Finland, whereas the majority of those in cluster 2.5 operate in eastern Finland. Both clusters have a higher network volume per customer than the Finnish average. The geographical location of a DSO defines the challenges for network structures. In northern Finland, the growing season is short due to lower solar radiation, reducing the risk of trees and branches falling on overhead lines. However, snow conditions can negatively impact reliability. Eastern Finland, characterized by deep forests and snowy winters, presents challenging conditions for electricity distribution reliability.

Given the differing trends in interruption costs, a third approach is introduced to define the impact of recent investments on the total costs incurred by society. The average replacement investments are obtained from the regulator for each DSO, compared to the linear trend of the total costs (break-even costs, steering, and interruption costs) from 2016 to 2021, and clustered in the third clustering, shown in Figure 7. The numerical details of the clustering results are provided in Table A3 of Appendix A.

The linear trend of total costs is negative for 56 out of 77 DSOs, meaning decreasing total costs. While the conventional hypothesis suggests that increased investment levels decrease interruption costs, Figure 7 shows that not all DSOs have succeeded in converting investments into reduced total distribution costs.

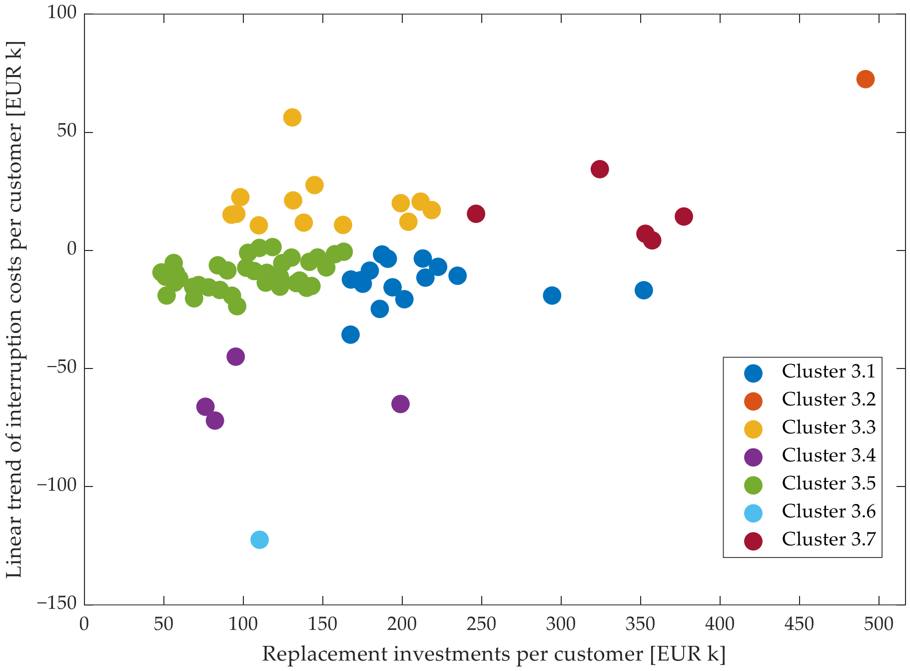


Figure 7. The linear trend of total distribution costs resulting from replacement investments. The different colors represent different clusters in the third clustering, based on similarities in input (investments) and output (linear trend of total costs).

5. Discussion

According to earlier studies on the quality incentive of Finnish pricing regulation methods [9], DSOs have been generously rewarded by the quality incentive for improving their supply reliability. The comprehensive regulation data analyzed in this study show that pricing regulation has, overall, increased the allowed revenue of DSOs: From 2016 to 2021, the net total of incentives amounted to EUR 740 million. The two largest DSOs received about two thirds of all bonuses. While increasing reliability is generally a highly preferable trend, recent legislative changes suggest that customers have experienced excessively high price increases. At first glance, the results support this, as the bonuses from incentives have been even as high as EUR 100 per customer. This perception also aligns with the findings of Collan [32], where the profits of DSOs were criticized for being high compared to other industries. Given that the resulting absolute reliability level remains at an average level for these DSOs [13], the discrepancy between the bonuses and the results may cause customer dissatisfaction.

Improving resilience through investments comes at a cost, and customers also benefit from the enhanced reliability in form of lower interruption costs. The distribution of the total costs incurred by society shows that the overall impact of incentives, while generating some dissatisfaction, constitutes a relatively small portion of the total costs, as shown in Figure 8.

While the break-even costs, stemming from actual utility expenses, present the majority (68%) of the overall cost of electricity distribution, a substantial reduction in the total costs of electricity distribution would necessitate fundamental improvements in network construction and operation efficiency. However, decreasing the break-even costs could affect the reliability or even safety of the electricity distribution, and therefore, potentially decrease the wealth increase. Therefore, the fairness of prices should be assessed together with the wealth increase derived from improved distribution reliability.

To gain a comprehensive view of the total costs incurred by society, data on pricing and interruption costs for all DSOs in Finland were acquired and analyzed through clustering. Assuming that the fairness of pricing is based on the assets of DSOs, it is evident that in sparsely populated areas, the absolute price for electricity distribution is higher than in urban areas with higher population density. However, population density increases capacity density and construction costs in urban environments. Therefore, it is natural to find frontiers of DSOs operating in different environments. The clustered total costs of electricity distribution in this study identified at least a few of these frontiers. DSOs at urban areas have the lowest annual total costs, at EUR 490 per customer, while the highest total costs are for DSOs operating in Northern Finland, at EUR 1250 per customer. DSOs operating in challenging environments in Eastern Finland and the Western coast of Finland also have high costs, at EUR 1120 per customer. For the two largest DSOs gaining the majority of the absolute incentive bonuses, and that also operate partly in challenging environments, the annual total cost of distribution is EUR 820 per customer.

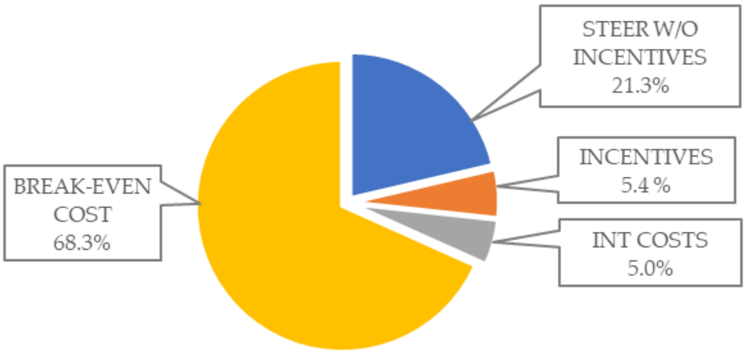


Figure 8. The distribution of total costs incurred by society, calculated for the entire country (Finland).

Based on the linear trend in interruption costs from 2016 to 2021, the most significant improvement in interruption costs was achieved by a group of relatively small companies in Northern Finland (EUR −20 per customer per year). Correspondingly, the linear trend of total costs is also decreasing, at EUR −36 per customer per year. For DSOs in urban areas, replacement investment levels are low to moderate, resulting in minimal changes in total distribution costs. However, the results align with the shadow prices of DSOs in [20], where the shadow prices for interruption minutes for DSOs in urban areas were higher than for those operating in sparsely populated areas.

Overall, the results for the total costs of distribution are twofold. On one hand, some DSOs have succeeded in converting investments into decreased total costs. On the other hand, some DSOs seem to struggle with reliability. While this study does not systematically account for the operating environment of DSOs, the known geographic location of DSOs with standout total costs indicates that environmental factors explain the higher costs. According to the shadow prices of improving reliability [20], relatively small investments would increase reliability and, hence, decrease the total costs (TC) of some DSOs. The potential for decreasing total costs also indicates the potential for harmonizing the total costs of distribution in the jurisdiction. However, the significance of some DSOs having higher costs than other should be assessed in relation to maximizing the total wealth in Equation (2): Higher TC of electricity distribution may produce the maximum wealth.

The global energy system is undergoing a complete transformation towards cleaner and more distributed energy generation, while customer expectations for reliability are simultaneously increasing. This transformation challenges the conventional asset-based regulation applied to capital-intensive utilities due to rapid changes in capacity demand. Since new electricity generation sources (e.g., solar) and consumption sites (e.g., district heating via electric boilers) are lightweight and more flexible in terms of location compared to centralized energy systems, the establishment of new sites and decommissioning of old ones can rapidly alter capacity demand, potentially leading to stranded network investment costs. The RIIO-2 model in the UK represents a shift towards TOTEX regulation, focusing on the outcomes of the electricity process—specifically, the ability to efficiently connect users to the electricity market. While network assets remain a crucial part of the energy system, flexibility could provide efficient solutions for connecting customers to the electricity market, given the pace of transformation.

The results of this study, which describe the formation and progress of the total costs of the electricity distribution cost incurred to the society, could inform the development of a technology-neutral TOTEX pricing model by providing cost information to be compared to the wealth gains as formally presented in Equation (2). Due to inconsistencies in estimating outage costs among EU regulators [1], the harmonization of data collection across different regulatory frameworks is needed. The method of clustering regulatory data can simultaneously handle multivariate data regarding DSOs. This allows for the use of SAIDI and SAIFI to assess interruptions, while also incorporating other dimensions, such as policy targets, into the assessment. As noted in this research, though, direct comparison without considering the environment may be irrelevant.

6. Conclusions

This study fills a gap in the research regarding information and methods for assessing the total costs of electricity distribution producing wealth for the society. The research gap is addressed by providing a data-driven analysis of the total costs of real-world DSOs and the regulatory impact on these costs. The study is based on public regulation data provided by the regulatory authority, and the methodology is described to ensure the results are repeatable. The research data covers asset costs, interruption costs, and policy costs, within a one entire jurisdiction, Finland.

The main contribution to the research area is in acquiring knowledge of the cost formation of electricity distribution through reproducible objective analysis, instead of straightforward price comparison. The results of this study indicate that the average overall cost of electricity distribution per customer ranges from EUR 490 for DSOs in urban areas to EUR 1250 for those in rural areas of Northern Finland. The break-even costs, based on actual utility expenses, account for the majority (68%) of the total distribution costs. Regulated costs contribute 26%, while interruption costs make up 5% of the overall distribution costs. The clustered results for the progress of interruption costs also indicate that relatively small investment levels in certain environments may decrease the total incurred costs to society, while some DSOs appear to be already closer to the optimal point of investment and interruption costs. The description of wealth increase unfolds the importance of considering the costs of distribution as part of the macroeconomic optimization problem.

Although this empirical study is based on the Finnish environment, the methodology for assessing and understanding the total costs of electricity distribution can be applied in other contexts. The focus on total costs is increasingly important, especially as the clean energy transition challenges traditional network investments with flexible, technology-neutral alternatives. However, comparative research is needed to refine the method and data collection process for other frameworks. The results from the Finnish environment still provide a valuable benchmark for further research.

Author Contributions: Conceptualization, J.S.; methodology, J.S.; software, J.S. and J.K.; validation, J.S. and J.K.; formal analysis, J.S.; investigation, J.S.; resources, J.S.; data curation, J.S. and J.K.; writing—original draft preparation, J.S.; writing—review and editing, J.S.; visualization, J.S.; supervision, P.J.; project administration, J.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original source data is public and available on request from Finnish Energy Authority.

Acknowledgments: The authors thank the Finnish Energy Authority for providing the regulation data and the anonymous reviewers for valuable feedback to improve our original article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

The same clustering method and parameters are applied for all clustering within this study—K-value of 7, centroid initialization with k++ (pre-clustering), Euclidean distance metering, and 500 iterations —to ensure consistency of the results.

Table A1. Details of clustering result 1 (variable: incentive results per customer). Values in EUR/customer.

Cluster Index	**C 1.1**	**C 1.2**	**C 1.3**	**C 1.4**	**C 1.5**	**C 1.6**	**C 1.7**
DSOs in cluster	3	11	5	16	16	19	7
average	80.8	37.9	22.8	18.1	6.4	−8.8	−29.2
maximum	110.7	51.4	34.7	27.1	16.4	−2.4	−20.9
minimum	59.0	27.5	14.3	9.6	0.1	−17.5	−39.1
deviation	26.8	7.8	7.4	5.7	4.7	4.6	6.0

Table A2. Details of clustering result 2. Variables: BC, incentives, interruption costs, and linear trend of interruption costs. Values in EUR/customer.

Variable	**Cluster Index**	**C 2.1**	**C 2.2**	**C 2.3**	**C 2.4**	**C 2.5**	**C 2.6**	**C 2.7**
	DSOs in cluster	3	29	12	12	5	14	2
BC	average	625.0	410.4	560.8	539.8	728.3	491.8	534.8
	deviation	160.3	197.3	219.0	179.9	200.3	90.4	49.6
INT	average	102.7	10.4	49.8	27.0	98.2	37.8	44.7
	deviation	36.5	10.1	22.2	19.2	19.6	21.2	3.6
STEER	average	519.4	93.8	238.2	166.3	237.7	181.8	247.6
	deviation	162.1	50.9	88.5	71.9	85.2	85.6	205.7
INT.trend	average	−12.3	−0.4	−3.8	1.8	14.0	4.0	−1.4
	deviation	8.1	1.2	3.3	2.9	5.0	3.0	0.6
INC	average	5.5	8.4	2.4	36.7	25.0	−17.4	91.7
	deviation	8.9	10.8	12.4	8.4	29.1	13.6	26.9

Table A3. Details of clustering result 3. Variables: replacement investments, linear trend of total cost of electricity distribution. Values in EUR/customer.

Variable	**Cluster Index**	**C 3.1**	**C 3.2**	**C 3.3**	**C 3.4**	**C 3.5**	**C 3.6**	**C 3.7**
	DSOs in cluster	16	1	13	4	37	1	5
Replacement investments	average	210	492	149	113	103	110	332
	maximum	352		219	199	163		377
	minimum	168		93	76	49		246
	deviation	50	-	46	58	34	-	51
Linear Trend for Total Cost	average	−14	72	20	−62	−10	−122	15
	maximum	−2		56	−45	1		34
	minimum	−36		11	−72	−24		4
	deviation	9	-	12	12	6	-	12

Appendix B

Table A4. Descriptive background information regarding DSOs. The Cluster Index refers to the clusters in second clustering (See Table A2 of Appendix A for details regarding clustered variables).

Cluster Index		**Annual Transferred Energy [GWh]**	**Customer Volume [pcs]**	**Network Volume [km]**	**Proportional Network Volume [m/Customer]**	**Proportional Actual Revenue [EUR k/Customer]**
C 2.1	min	28	1.835	629	234	573
	avg	97	6.946	1.772	310	678
	max	220	16.535	3.877	441	847
	med	43	2.468	809	255	616
	std	107	8.310	1.826	114	147
C 2.2	min	85	6.627	487	16	307
	avg	802	60.140	2.563	68	467
	max	4.379	395.369	7.919	219	1.015
	med	429	27.149	2.143	58	402
	std	965	81.455	1.953	46	161
C 2.3	min	24	759	140	128	430
	avg	241	15.684	2.555	195	635
	max	1.282	103.091	13.213	292	1.007
	med	73	5.298	928	184	621
	std	385	28.764	3.830	54	142
C 2.4	min	77	5.835	837	42	436
	avg	301	19.884	2.729	154	631
	max	747	57.918	6.238	264	897
	med	284	18.260	2.702	158	646
	std	185	14.724	1.713	63	147
C 2.5	min	24	3.529	901	169	496
	avg	830	63.379	15.864	247	824
	max	1.861	118.018	27.470	311	1.152
	med	1.055	87.528	22.489	257	780
	std	778	54.886	13.718	52	261
C 2.6	min	17	1.786	445	58	371
	avg	233	16.118	2.501	176	580
	max	972	72.441	13.467	282	821
	med	146	7.999	952	175	582
	std	294	21.878	3.632	76	145
C 2.7	min	6.097	429.367	72.793	167	604
	avg	6.781	451.185	75.780	168	694
	max	7.465	473.004	78.767	170	783
	med	6.781	451.185	75.780	168	694
	std	967	30.856	4.224	2	127

References

1. Nepal, R.; Jamasb, T. Incentive Regulation and Utility Benchmarking for Electricity Network Security. *Econ. Anal. Policy* **2015**, *48*, 117–127. [CrossRef]
2. Rothwell, G.; Gómez, T. *Electricity Economics: Regulation and Deregulation*; John Wiley & Sons: Hoboken, NJ, USA, 2003; ISBN 0-471-23437-0.
3. Jamasb, T.; Pollit, M. Incentive Regulation of Electricity Distribution Networks: Lessons of Experience from Britain. *Energy Policy* **2007**, *35*, 6163–6187. [CrossRef]
4. Reichel, J.; Kollmann, A.; Tichler, R.; Schneider, F. The Importance of Incorporating Reliability of Supply Criteria in a Regulatory System of Electricity Distribution: An Empirical Analysis for Austria. *Energy Policy* **2008**, *2008*, 3862–3871. [CrossRef]
5. European Commission. *A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy*; European Commission: Brussels, Belgium, 2015.
6. European Parliament. *Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the Internal Market for Electricity (Recast)*; European Parliament: Brussels, Belgium, 2024.

7. Decker, C. *Modern Economic Regulation: An Introduction to Theory and Practice*; University Printing House: Cambridge, UK, 2015.
8. Jamasb, T. Incentive Regulation of Electricity and Gas Networks in the UK: From RIIO-1 to RIIO-2. *Econ. Energy Environ. Policy* **2021**, *10*, 181–196. [CrossRef]
9. Jooshaki, M.; Abbaspour, A.; Fotuhi-Firuzabad, M.; Moeini-Aghtaie, M.; Lehtonen, M. MILP Model of Electricity Distribution System Expansion Planning Considering Incentive Reliability Regulations. *IEEE Trans. Power Syst.* **2019**, *34*, 4300–4316. [CrossRef]
10. CEER. *7th CEER-ECRB Benchmarking Report on the Quality of Electricity and Gas Supply 2022*; Council of European Energy Regulators (CEER) and Energy Community Regulatory Board (ECRB): Brussels, Belgium, 2022.
11. Kuosmanen, T.; Johnson, A. Modeling Joint Production of Multiple Outputs in StoNED: Directional Distance Function Approach. *Eur. J. Oper. Res.* **2017**, *262*, 792–801. [CrossRef]
12. Sappington, D.E.M. Regulating Service Quality: A Survey. *J. Regul. Econ.* **2005**, *27*, 123–154. [CrossRef]
13. Seppälä, J.; Järventausta, P. Analyzing Supply Reliability Incentive in Pricing Regulation of Electricity Distribution Operators. *Energies* **2024**, *17*, 1451. [CrossRef]
14. García Cooper, R.A.; Sitiriche, M.C.; Rivera, A.I.; Rengifo, F.A. True Cost of Electric Service: What Reliability Metrics Alone Fail to Communicate. *Electr. J.* **2024**, *37*, 107386. [CrossRef]
15. Linares, P.; Rey, L. The Costs of Electricity Interruptions in Spain. Are We Sending the Right Signals? *Energy Policy* **2013**, *61*, 751–760. [CrossRef]
16. Kufeoglu, S.; Lehtonen, M. Cyclone Dagmar of 2011 and Its Impacts in Finland. In Proceedings of the IEEE PES Innovative Smart Grid Technologies, Europe, Istanbul, Turkey, 12–15 October 2014; IEEE: Istanbul, Turkey, 2014; pp. 1–6.
17. Finnish Parliament. *Government Proposal for Electricity Market Act (HE20/2013 vp)*; Finnish Parliament: Helsinki, Finland, 2013.
18. Finnish Parliament. *Government Proposal for Electricity Market Act (HE265/2020 vp)*; Finnish Parliament: Helsinki, Finland, 2020.
19. Kufeoglu, S.; Lehtonen, M. A Review on the Theory of Electric Power Reliability Worth and Customer Interruption Costs Assessment Techniques. In Proceedings of the 2016 13th International Conference on the European Energy Market (EEM), Porto, Portugal, 6–9 June 2016; IEEE: New York, NY, USA, 2016; Volume 2016, pp. 1–6.
20. Küfeoğlu, S.; Gündüz, N.; Chen, H.; Lehtonen, M. Shadow Pricing of Electric Power Interruptions for Distribution System Operators in Finland. *Energies* **2018**, *11*, 1831. [CrossRef]
21. Färe, R.; Grosskopf, S.; Weber, W.L. Shadow Prices and Pollution Costs in U.S. Agriculture. *Ecol. Econ.* **2006**, *56*, 89–103. [CrossRef]
22. Molinos-Senante, M.; Mocholí-Arce, M.; Sala-Garrido, R. Estimating the Environmental and Resource Costs of Leakage in Water Distribution Systems: A Shadow Price Approach. *Sci. Total Environ.* **2016**, *568*, 180–188. [CrossRef] [PubMed]
23. Coelli, T.J.; Gautier, A.; Perelman, S.; Saplacan-Pop, R. Estimating the Cost of Improving Quality in Electricity Distribution: A Parametric Distance Function Approach. *Energy Policy* **2013**, *53*, 287–297. [CrossRef]
24. Seppälä, J.; Kari, J.; Mutanen, A.; Järventausta, P. Methods for Studying the Steering Effects of Supply Regulation (Paper 619). In Proceedings of the CIRED 2021—The 26th International Conference and Exhibition on Electricity Distribution, Online, 20–23 September 2021; pp. 3150–3154.
25. Lassila, J. *Strategic Development of Electricity Distribution Networks: Concept and Methods (Dissertation)*; Lappeenranta University of Technology: Lappeenranta, Finland, 2009.
26. Korhonen, P.J.; Syrjänen, M.J. Evaluation of Cost Efficiency in Finnish Electricity Distribution. *Ann. Oper. Res.* **2003**, *121*, 105–122. [CrossRef]
27. Energy Authority. *Regulation Methods on the Fourth 1.1.2016–31.12.2019 and the Fifth 1.1.2020–31.12.2023 Regulation Period*; Energy Authority: Helsinki, Finland, 2021.
28. Jain, A.K. Data Clustering: 50 Years beyond K-Means. *Pattern Recognit. Lett.* **2010**, *31*, 651–666. [CrossRef]
29. Mutanen, A. Improving Electricity Distribution System State Estimation with AMR-Based Load Profiles. Ph.D. Thesis, Tampere University, Tampere, Finland, 2018.
30. Xu, R.; Wunsch, D. *Clustering*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2009; ISBN 978-0-470-27680-8.
31. Xiaofeng, D.; Kuosmanen, T. Best-Practice Benchmarking Using Clustering Methods: Application to Energy Regulation. *Omega* **2014**, *2*, 179–188.
32. Collan, M.; Savolainen, J.; Lilja, E. Analyzing the Returns and Rate of Return Regulation of Finnish Electricity Distribution System Operators 2015–2019. *Energy Policy* **2022**, *160*, 112677. [CrossRef]