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Analyzing Supply Reliability Incentive in Pricing Regulation of Electricity Distribution Operators

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Abstract: In support of the global green transition, numerous policies have been introduced to efficiently address the increasing demand for reliable electricity. However, the impacts of these policies have received limited attention, despite the potential for unsuccessful policy targets to introduce inefficiencies into the energy system, subsequently diminishing societal wealth. This study bridges this research gap by conducting a comprehensive examination of a supply reliability incentive within electricity pricing regulation, aiming to contribute new insights for policy assessments. Analyzing data from all electricity distribution operators within a single jurisdiction, the study investigates the volume and distribution of economic steering to elucidate the overall societal impact. The findings suggest a rewarding system for positive developments in indices, regardless of the absolute interruption index levels, highlighting the importance of precise variable definitions in implementing incentive mechanisms. The assessment tools developed for this study will be valuable for further regulation and policy assessments.

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

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Citation: Seppälä, J.; Järventausta, P. Analyzing Supply Reliability Incentive in Pricing Regulation of Electricity Distribution Operators. *Energies* **2024**, *17*, 1451. https://doi.org/10.3390/en17061451

Academic Editor: Marco Merlo

Received: 23 February 2024
Revised: 10 March 2024
Accepted: 13 March 2024
Published: 18 March 2024

1. Introduction

With electricity playing an increasingly important role in the global green transition, societies are becoming more reliant on resilient and reliable electricity distribution. The overarching goal of electricity distribution regulation is to provide distribution services effectively. Consequently, policies have been introduced to ensure "good quality" and to meet the rising demand for reliable electricity. However, the impacts of these policies have been less often studied; setting the target too high or too low may lead to inefficiency in the economic system due to exaggerated investments or unreliable electricity distribution.

Studying the supply reliability data from the pricing decisions issued by the national regulation authority, which covers a whole jurisdiction, provides insight into the overall economic effects of regulation. Therefore, this research bridges the research gap between the studies on economic regulation and those on technical improvements by examining an exceptionally extensive dataset on electricity reliability in one jurisdiction (Finland). Given the well-documented application of revenue cap regulation in Finland, and the extensive regulator-published data used in this study, the results are repeatable. The approach introduced in this study will also be applicable in further research in the context of other regulatory frameworks.

This study comprises three parts. The first part offers a concise literature review of studies related to the regulation of supply security. The second part presents and analyzes the supply reliability incentive in Finnish pricing regulation, following the model introduced in the first part. Incentive data are clustered and enriched with additional data to identify underlying similarities. In the third part, the results are discussed considering the regulation rationales.

2. Literature Review

Broadly speaking, the security of supply (SoS) covers the whole energy value chain, from the extraction of primary energy (fuel) for electricity generation and supply. The term "Security of Electricity Supply" (SoES) can be used for more specifically assessing the security of supply in the electricity sector [1,2].

Though assessing and improving electricity distribution reliability is, in a broad sense, basic engineering, there is only scant quantitative research on assessing the complete SoES value chain. Larsen presented 12 dimensions for assessing the SoES value chain and its performance, including generation, grid reliability, and economic aspects [2]. The dimensions are aligned with the concerns of the International Energy Agency: "These trends call for a broader, widely encompassing approach to electricity security" [3]. Such a broader, but also complex, description and model for addressing the issues of our rapidly transforming energy system is presented by Georgiev et al. in [4].

Jamasb concludes in [5] that network regulation can play a crucial role in mitigating the security of supply risks. The approach and framework for SoES in the European Union (EU) is based on the directive 2019/944. Though energy security has been recognized as a dimension of the "Energy Union", the directive does not give explicit indicators for assessing SoES. Therefore, national implementations of quality regulation vary.

The quality of electricity supply can be divided into (1) availability (continuity of supply) and (2) electricity characteristics (voltage quality). In most countries, the continuity of supply is often implemented in pricing regulation, whereas the voltage quality is typically excluded from pricing regulation. The implementation of quality regulation varies between countries, though typical references for "quality" are international standards such as EN 50160. On the one hand, quality regulation in Europe is based on direct obligations; on the other, it is based on indirect economic steering [6]. As the latest standard does not define levels for the continuity of supply, extensive regulation may exist. In the Finnish regulation framework, for instance, customers must receive compensation for long interruptions (i.e., over 12 h) and quality standards for continuity of supply in certain extreme weather conditions are given [7].

Continuity of supply concerns interruptions in electricity supply. In the European standard EN 50160:2022 on voltage characteristics in public electricity networks, supply interruption is defined as the "condition in which the voltage at the supply terminals is lower than 5% of the reference voltage" [8]. Continuity of supply (CoS) is often measured with indices describing the annual interruption amount per customer ("SAIFI") or the annual interruption length per customer ("SAIDI"). Examples for calculating these indices are presented in [9]. According to European energy regulators, heterogeneous definitions are used for calculating interruption indices in Europe; therefore, the direct benchmarking of indices for all countries is not applicable [6]. Other issues exist regarding, for example, data collection techniques, as presented by Eto regarding data from the US [10].

The strategies for improving electricity distribution reliability are universal; Brint expressed these general strategies in [11] as follows: (1) decrease the fault rate of the conductors, (2) optimize the location and number of switches, (3) increase the level of interconnection, and (4) introduce automation. The next step involves mitigating any remaining effects on customers in the event of a fault, achieved through improved technologies such as earth fault current compensation [12] or network islanding [13]. The interruption indices of a distribution system operator (DSO) in the capital city of Finland were decreased by 50% using the strategies presented in the study by Siirto et al. [12].

A strategic approach for developing networks, including wider asset management viewpoints, for example, from ownership, legislation, and pricing regulation, is presented in [14]. While describing concepts and methods for the strategic development of electricity distribution networks, Lassila concludes that "There is no single universal model to be applied to strategic decision-making, but each development task has to be carried out case by case. This is due to the different operating environments and diverging targets set by the owners of the distribution companies [. . .]" [14]. The need for development tasks has been proven by numerous (Finnish) studies for preparing cabling and automation strategies [15], and for planning to improve overhead network reliability in rural and urban areas [16]. In a comprehensive case study in the US context (Florida), the undergrounding of electricity distribution structures was studied to assess the profitability of resiliency improvement methods. The central conclusion is similar to the European context: underground cabling is expensive and cannot always be justified by quantifiable benefits. Moreover, the assessment tool developed in the study can be considered as a calculator: "It is the responsibility of the user to make appropriate decisions about input parameters" [17–19].

The majority of electricity distribution interruptions in Finland are caused by weather [20] and the trend of increasing weather-related blackouts appears to be global [21]. Also, according to a comprehensive study in the US, covering 195 DSOs and 70% of sales in the US, by Larsen et al., the trend of reliability is decreasing over time due to severe weather-related increases in interruption indices [22].

Several types of models have been developed to evaluate and simulate the effects of weather on the electricity supply. Statistical models can provide accurate estimates regarding resiliency for a given (limited) spatial unit, whereas fragility-based models provide estimates for resiliency for a given point on a grid. A disadvantage of such simulations is the dependence on the actual network topology, which typically is not publicly available and therefore does not describe the actual reliability [23]. The topology is also constantly changing due to natural network development. Räisänen et al. further studied the estimates for a given point on a grid and developed advanced methods for predicting the snow load outage risk for overhead lines [24]. A model for Finnish electric grid resilience to extreme wind is presented in [25].

Methods for estimating the effects of interruptions on customers are presented in [26]. The indirect analytical method approaches the question from a macroeconomic perspective, for example, by dividing the annual gross national product by the total electrical consumption. Customer surveys are conducted to gather a sample from real customers—this method gives accurate but possibly biased data as the answers depend on the research questions. Case studies are the third method for evaluating interruptions and this is used especially after significant blackouts. In case studies, the timeframe of the interruption is typically clear and therefore the cost evaluation is more concrete than in an interview approach [26].

Though European energy regulators regularly publish a snapshot description of quality regulation in Europe, the effects of quality regulation constitute a less studied area. Joskow presents a comprehensive description of the development of incentive regulation and mentions that relatively little systemic analysis exists on the effects of inventive regulation mechanisms. They state of the evolution of regulation in the UK, that "While the initial focus was on reducing the operating costs, it has shifted to investment and various dimensions of service quality". They also challenge the implementation of quality incentive mechanisms: "Quality of service schemes appear to have been bolted onto schemes designed to provide incentives for cost reduction and do not effectively incorporate information on consumer valuations of quality and the costs of varying quality in different dimensions". The "menu of contracts" approach is proposed to provide efficient incentive properties [27].

Still, the data and experiences from the UK context are comprehensively studied, as the UK was a pioneer in implementing market restructuring policies in the 1980s and 1990s. Insights regarding legislation, regulation, the number of companies, and the quality of service for the early stages of reforms are given by Jamasb in [28]. Based on experiences in the UK, incentive regulation can be considered as wider policy reform. The conclusion regarding the continuity of supply is that the UK incentive system and the quality incentive, combining performance targets and a bonus/penalty system, have improved the service quality of UK utilities. An important note by Jamasb is that the UK incentive mechanism is different from a purely cost-oriented benchmark, which, according to Jamasb, "could lead to perverse economic incentives".

Schiavo presented experiences of regulation and incentives for improving continuity of supply in the Italian context in 2001 in [29]. The experience of such incentives appears encouraging, though concerns regarding the reliability of data are recognized. An implementation of the continuity of supply incentive in the Swedish context is presented in [30].

The relationship between maintenance costs and quality in Austria is studied in [31]. For the Finnish context, the authors of reference [32] presented the general experiences of the modern rate of return regulation in Finland. In a comprehensive assessment of the rate-of-return of the Finnish framework, Collan concludes that the returns in 2015–2019 were at a high level [33].

As performance benchmarking is an important part of modern regulation, the results of the significant efforts in developing data envelopment analysis (DEA), stochastic frontier analysis (SFA), and other stochastic models such as StoNED, for different regulation frameworks, are presented, for example, in [34]. In the study on steering signals and the benchmarking of the early Finnish regulation framework by Honkapuro, it is concluded that directing benchmarking signals is not only dependent on the parameters and methodology but also on the implementation of benchmarking in the regulatory framework [35].

This compact literature review encompasses academic studies on regulation, pertinent case studies, the regulatory policy background in Europe, and global electricity supply issues. While previous research extensively covers sections of the electricity distribution value chain, there is a dearth of studies regarding the effects of policy actions. Thus, this study addresses this gap by introducing a novel data-driven method for evaluating supply reliability within a modern pricing regulation framework covering a whole jurisdiction. The efficacy of the method is validated through an in-depth analysis of interruption indices from Finnish DSOs. Due to the public data and well-documented regulation and research methods, the repeatability of the results enhances the applicability of the method in further research and other regulatory frameworks.

3. Description of Economic Regulation Steering Reliability

The rationale for electricity distribution regulation is often described as protecting customers from the adverse effects of natural monopolies, while also being described as a mechanism to improve the efficiency of utilities. Other rationales include improving competition when possible and preventing the subvention of vertically integrated businesses. Today, regulation frameworks are typically based on (1) the obligations for supervised utilities, and (2) the powers of the regulator. The regulator should act according to the given powers, independent from state steerage [1,36].

In theory, the goal of a regulation framework is to maximize societal wealth. While reliable and reasonably priced energy acts as a catalyst for the economy and therefore increases the wealth produced, exaggerated investments may create a risk of economic inefficiencies in the form of unnecessary asset costs. Therefore, the ultimate challenge is to optimize the societal benefits and disadvantages. Since a comprehensive description of all the economic benefits needs a wider approach, this study concentrates on the direct societal costs incurred by interruptions.

The optimization problem of incurred costs derives from DSO costs, customers, and possible regulation costs. The fundamental idea is to minimize the incurred costs over time, as in (1):

$$\min f(t) = c_{DSO}(t) + c_{CUSTOMER}(t) + c_{REGULATION}(t) \tag{1}$$

The key element in supply reliability is the condition of the distribution network. Therefore, one of the preconditions for well-functioning regulation is to allow the regulated companies to cover reasonable costs for their network assets. Setting the allowed cost level under the total asset cost level may encourage utilities to postpone the investments required to maintain the condition of their network. Catching up the backlog of investments may lead to a sudden need for new capital and/or changes in pricing. Also, inefficiencies in investment procurement may appear.

The other extreme is to increase the investment levels over a reasonable level. One reason for exaggerated investments is the economic possibility of a high level of investments, for example, due to loose regulation. As such behavior increases the overall societal costs incurred, as in (1), it should be avoided.

The time scope plays a significant role when assessing utility regulations and processes. Due to the rather slow nature of infrastructure businesses, the changes in regulation take a long time to become visible in the actual supply reliability. Utilities may try to improve their short-term cost performance by lowering maintenance and/or investment levels. Similarly, the effect of increased investments may become visible long after the changes. Therefore, all steering effects are not always visible in the data from the evaluation period.

3.1. Typical Frameworks for Economic Regulation

Rate-of-return (RoR) regulation is considered entry-level regulation because the model itself can be run with little information on the company's processes and performance. Nevertheless, a set of substance rules is needed to ensure a certain service level, as companies with natural monopolies do not have incentives for maintaining good quality or efficiency [37].

The fundamental idea in RoR is to compensate the shareholder for its investment with a reasonable profit, while exaggerated compensation for investments would persuade unneeded investments. Exaggerated compensation for investments is called the Averch–Johnson effect. On the other hand, undercompensating increases the risk of avoiding or postponing the required investments. It is important to note that, although it is easy to show the mechanism of the Averch–Johnson effect, it is difficult to prove empirically [37]. An example of RoR is given in Figure 1, as a part of a revenue cap regulation.

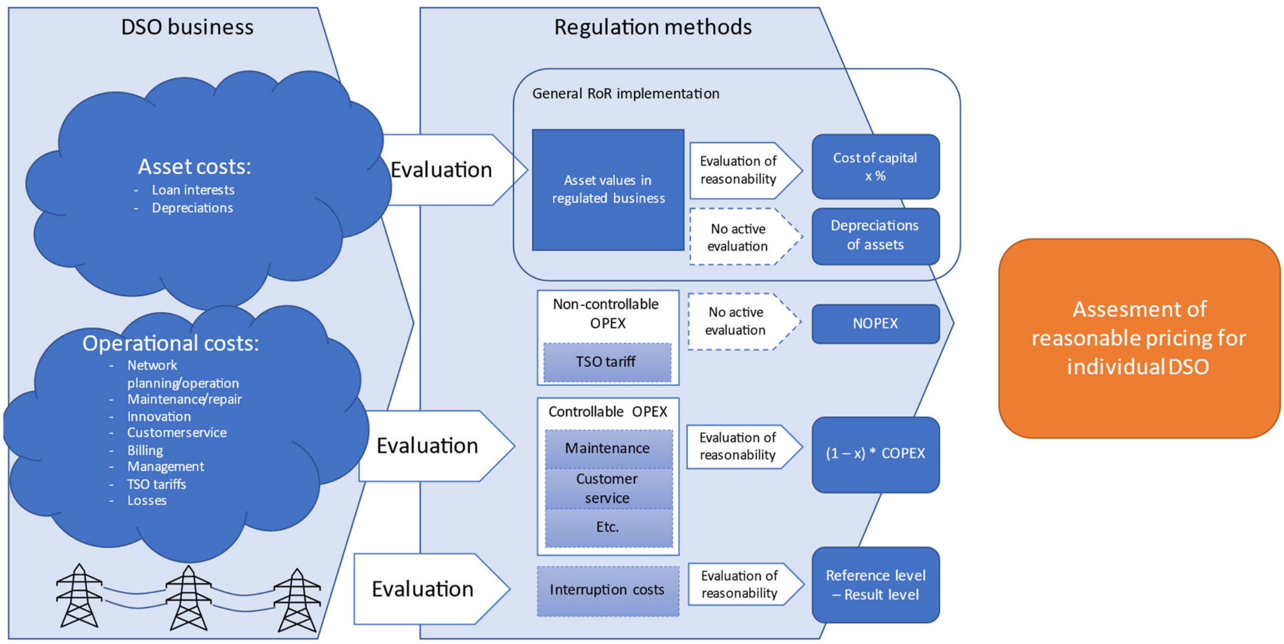


Figure 1. An example of revenue cap regulation. OPEX stands for operational expenses, COPEX for Controllable operational expenses, NOPEX for Non-Controllable operational expenses (Source: author).

While the RoR regulation implicitly steers utility turnover, the revenue cap (RC) regulation directly controls a company's allowed turnover level. In revenue cap regulation, the allowed turnover is typically based on the cost of assets and reasonable provision, similar to RoR regulation, but the adjustments are more visible and measurable than in the RoR approach. Since the adjustments to the elements of revenue cap regulation include subjective evaluations, putting the conceptually simple logic of revenue cap regulation into practice requires gathering and evaluating information regarding the regulated utilities. In Figure 1, to show points of evaluation, an example of a revenue cap regulation is presented.

3.2. Modeling the Reliability for Regulation

The common issue in regulation is the information asymmetry between the regulator and the utility. In short, the utility always has more information on the business. Though certain methods have been introduced to address the asymmetry, the fundamental issue in the regulation is the challenge of comprehensively describing the stochastic interaction between the utilities and society. Thus, utility operations and the effects of regulation must be studied from selected measurements, which may be incomplete or inaccurate. The underlying information issue is as in Plato's Allegory of the Cave: the shadows are the reality of the prisoners but are not accurate representations of the real world [38]. The regulation is similarly based on the shadows (measurements) of the objects (businesses) in the real world.

As utilities in natural monopolies have no incentives to reduce their marginal costs, regulation incentives encourage the regulated utilities to improve their efficiency to produce desired outputs. For optimizing societal economic wealth, the results of increased efficiency should be returned to society. A common straightforward method is to split the gained efficiency benefits between the utility and the customers. In general, a regulation incentive can be described as a process consisting of the measurement of the present situation, the control function, and the application function to steer the utilities toward the target situation, as can be seen in Figure 2.

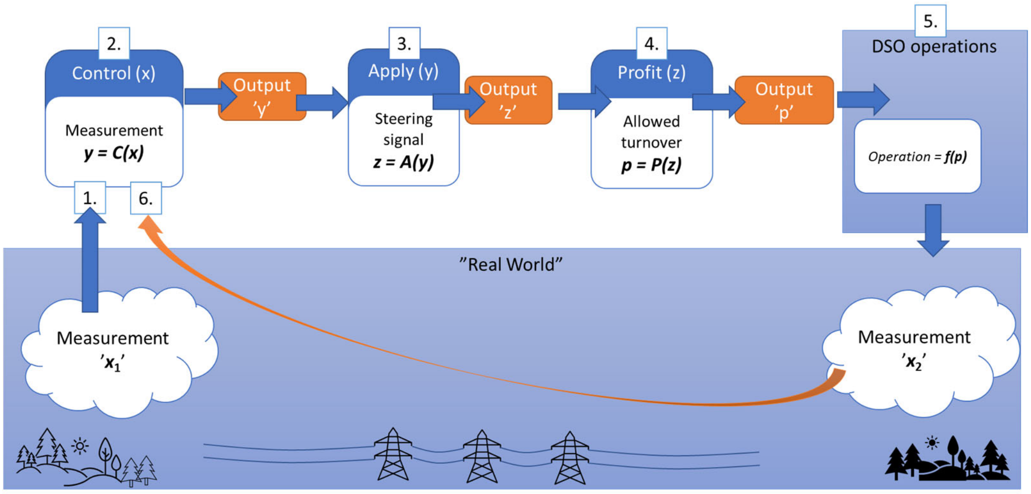


Figure 2. Conceptual description of incentive mechanism. (Source: author).

In the conceptual incentive process, an incentive takes in a sample measurement (1.) of a distribution process conducted in a dynamic reality; (2.) benchmarks the sample in a control function; (3.) adjusts the steering signal to implement in pricing; and (4.) is applied as a part of the pricing evaluation to define (5.) the allowed turnover of the DSO for conducting regulated business; altering the dynamic reality for a new sample measurement (6.). The incentive process is similar to the control functions of any general process in engineering, though the fundamental difference is that an economic incentive does not have the direct capability of altering reality. In pricing regulation, adjusting the turnover "*p*" is, in general, presumed to affect the operation of regulated utilities.

3.3. The Control and Application Functions in the Incentive Model

The control function in the model evaluates the measured performance against the target level. The target level may be defined as constant improvement, i.e., 5% per year. However, the control function is often an application of yardstick metering. The evaluation may compare the performance of a utility with its historical performance, or with other utilities directly or by applying advanced performance benchmarking methods (DEA, SFA, StoNED). The downside of such methods is that benchmarking can only describe the lowest assumed cost profile in the scope of the available measurements and therefore may not recognize potential outside these measurements. A less used method is to build a model of an optimal network for fulfilling the service demand, which has been applied, for example, in Sweden, Spain, Peru, and Chile. The Network Performance Assessment Model of Sweden was implemented in 2003, but was later discarded since it was not able to adequately capture all important network features; the model actually decreased efficiency [39].

The application function turns the result of the control function into money terms in order to affect the pricing of DSOs. In revenue cap regulation, the typical method is to introduce an adjustment term to the allowed turnover according to the result of the evaluation function. In practice, a bonus/malus term with top/roof levels is often introduced to adjust the allowed turnover. The top/roof levels are needed to avert exaggerated pricing adjustments: while utilities must recover from their mandatory costs, customers must be protected from high prices. The application function may adjust the allowed turnover (the pricing) of the utility, but it may also adjust the profit for assets if such an element is implemented in the framework. The volume of adjustment may equal or overcompensate for the adverse societal effects incurred.

3.4. Details of the Implementation of a Supply Reliability Incentive

The Finnish pricing regulation framework presents a modern combination of a rate of return and a revenue cap with incentives. The control function of the supply reliability incentive is based on the interruption costs, presenting the harm incurred to customers. The costs are calculated by the regulator for each DSO using both the number of interruptions and the interrupted power as input parameters. An example of interruption costs C_i of the momentary interruptions type is shown in (2):

$$C_i = n_i \times c_i \times P_i \tag{2}$$

where n_i is the annual number of interruptions, c_i is the unit price for the type of interruption and P_i is the interrupted power. A comprehensive list of the indices and background for calculating the interruption costs is presented in [40,41].

The Finnish framework uses a conventional approach as a control function by comparing the present interruption costs with the former interruption costs of the DSO. In some frameworks, interruption costs are adjusted, for example, by excluding major events. A major event is introduced in the IEEE Guide for Electric Power Distribution Reliability indices, to designate “an event exceeding reasonable design and/or operational limits of the electric power system” [9]. Other options for describing a solid reference level, by excluding certain years from the data, are presented in [42]. For the Finnish regulation methods’ fourth regulation period (2016–2019), major events are not excluded. Therefore, the “control function” of the Finnish framework is straightforward, as it subtracts the interruption costs of the current year from the reference interruption costs, as can be seen in (3):

$$C_{RES} = C_{REF} - C_{CURR} \tag{3}$$

The application function provides a steering signal to steer the DSO toward the target level of interruption costs. As the “applying function” simply adds the result of an evaluation (C_{RES}) to the allowed turnover, the applying function may be as shown in Figure 3.

In the Finnish regulation methods, the results of the control function are linearly connected to the decrease/increase in the reasonable profit. To provide predictability, the effects of the supply reliability incentive of Finnish pricing regulation methods are tied to the value of network assets by limiting the effect of the incentive to 15% of the annual reasonable asset profit. Moreover, the quality incentive is also symmetric to the system operator with a maximum quality bonus of less than 15% of the system operator's reasonable output for the year in question. As a result, a potential quality penalty can be no more than the maximum quality bonus. Instead of simple addition, the application function $A(y)$ could be nonlinear to amplify the steering signal, or the application function could take into account externalities such as the storm days of the given year. The application function could also affect elements other than the allowed turnover, for example, it could adjust the rate of reasonable profit.

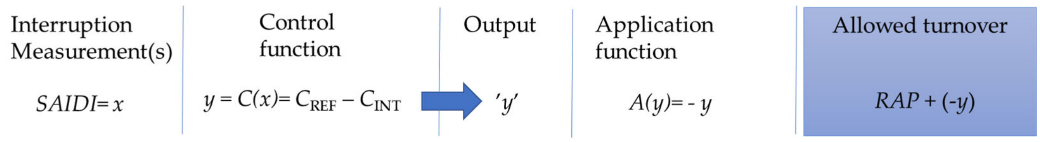


Figure 3. Mechanism of applying a quality incentive in Finnish regulation methods. RAP stands for "regulated asset profit".

4. Results of the Supply Reliability Incentive

The Finnish regulation framework presents a modern combination of a rate of return and a revenue cap with incentives. The regulation authority issues pricing decisions for each DSO regarding the given regulation period (i.e., 4 a). Characteristic of the Finnish regulation framework is the extensive public disclosure of DSO business and performance data, including interruption details, such as planned and unplanned occurrences, categorized as momentary or long interruptions [40]. Thus, the steering signal of the quality incentive is visible for every 77 DSOs.

4.1. The Results of Supply Reliability Incentive

The control function of the supply reliability incentive consists of the interruption costs and their reference levels. Prior to 2016, halved interruption costs and reference costs were considered in the incentive. The summarized interruption costs of DSOs are presented in Figure 4.

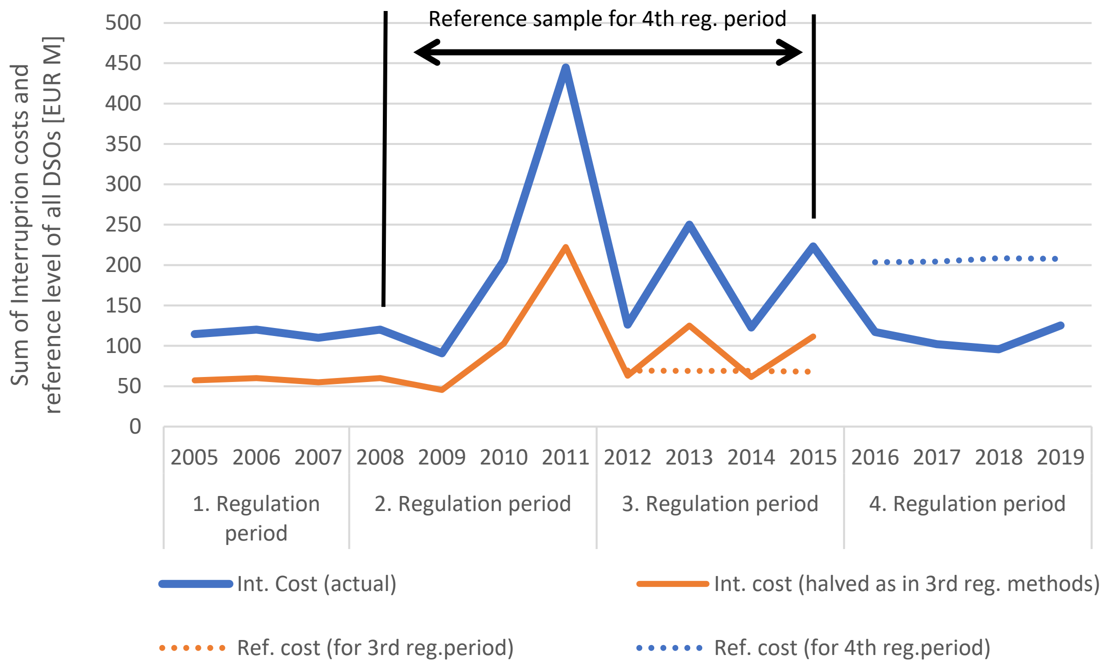


Figure 4. The actual interruption costs and interruption costs according to the reference level under regulation periods.

In Figure 4, the blue line presents the actual interruption costs, and the orange line represents the halved interruption costs according to the regulation methods prior to 2016. Since major events have not occurred under the fourth period, the interruption costs are systematically lower than the reference costs.

The application function limits the steering effect with top/floor levels. From the published data regarding each DSO, the summarized results over time show EUR 379 M of bonuses and EUR 114 M malus over time. The majority (EUR 281 M) of the bonuses ever provided by the incentive are from the fourth regulation period (2016–2019). The annual results of the incentive are shown in Figure 5.

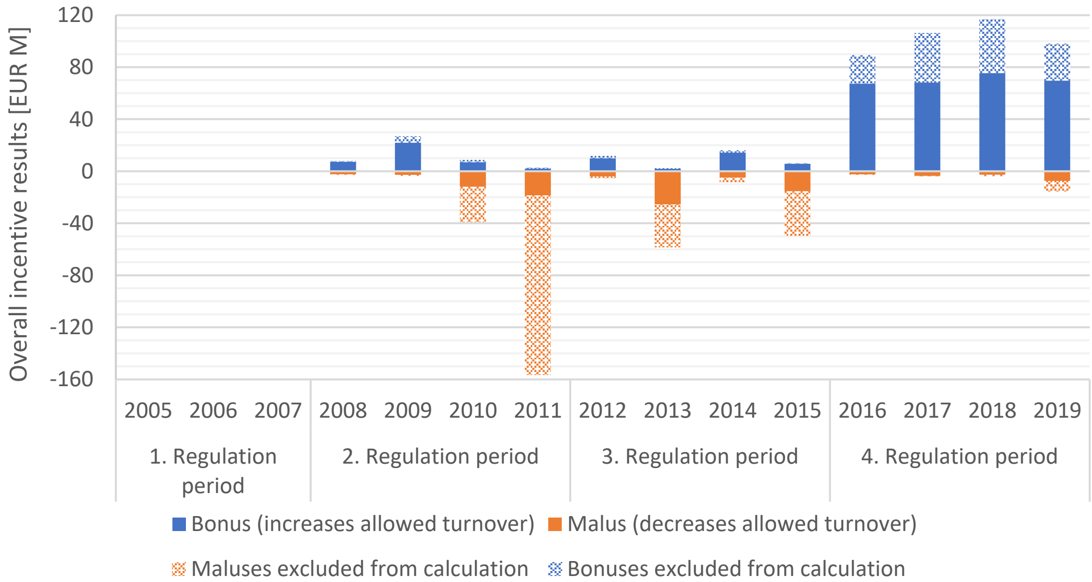


Figure 5. The supply reliability incentive results: the solid area represents the incentive result; the dotted area represents the top/floor adjustments.

In Figure 5, the actual interruption costs and adjustments of the incentive show the mechanism of Finnish regulation methods for the fourth and fifth regulation periods. The effect of exceptional interruption costs is cut in that year in the incentive, but the reasonability of supply reliability is later assessed according to the actual interruption costs. As a result, the level of maluses in 2011 was relatively low, but bonuses in the fourth regulation period were high. In the year 2011, as the top/floor adjustments excluded EUR 138 M of maluses, the incentive affected the pricing only by EUR 18 M. Over time, the maluses were cut by EUR 251 M and the bonuses by EUR 152 M, of which EUR 130 M was in the fourth regulation period.

Utilizing adjusted interruption costs for the DSO's future reference values would mitigate the biased behavior of adjustments in the incentive, as stated in [43]. According to the regulation methods for the sixth and seventh regulation periods, the adjusted interruption costs will be used as the reference level starting from the seventh regulation period in 2028.

Though the level of bonuses in the fourth regulation period is high due to the high interruption costs in the 2008–2015 sample period (see Figure 4), the quality indices actually also improved after introducing the quality standards in the Finnish legislation in 2013. The quality standards have made the DSOs increase the proportion of underground cables in medium voltage networks from 24% in 2013 to 45% in 2022. Therefore, the reference level describes the expected interruption costs of an earlier network structure rather than of the present network structure.

4.2. Tracking the Success Factors by Clustering

The regulator-published dataset examined in this study includes an extensive amount of data regarding interruptions by type. Relying solely on human interpretation for drawing conclusions may introduce risks of oversimplification and subjectivity. Using machine-based data extraction enables the identification of patterns, facilitating the discovery of novel insights within the dataset. Therefore, new observations regarding the interruption cost data can be searched by clustering, a powerful tool for classifying data by similarities. Insights for applying clustering to multidimensional datasets are presented and demonstrated in [44].

The summarized supply reliability incentive results show that, while most DSOs received significant bonuses, some received malus. As the Finnish regulator also publishes data on the structure of the network and the businesses of all individual DSOs, the success factors of the incentive results may be examined along with the network structure. While the absolute interruption costs of a DSO depend on the volume of the DSO business, interruption costs per network unit and interruption costs per customer are introduced to present the performance of a network and the effects of interruptions on customers.

The quality incentive result per medium voltage network length (EUR/MV-km) was calculated for every DSO and for every year of the fourth regulation period (2016–2019). The results are presented in a 77 × 4 table of data. A simple sorting of the table by the sum of the incentive results shows that the majority (69) of the 77 DSOs gained net bonuses in the fourth reg. period. Clustering the quality incentive results over 4 years for each DSO (4 × 77 table) into seven clusters with k-means clustering gives the results presented in Table 1:

Table 1. The first clustering of incentive results.

Cluster Index	Number of DSOs in Cluster	Average Cumulative Incentive Results in Cluster, 4th Regulation Period (EUR/km)
1	2	−1544.1
2	15	+26.8
3	25	+880.4
4	3	+1906.6
5	23	+2144.5
6	7	+3178.9
7	2	+5571.9
Total	77	+1382.7

In Table 1, a positive value (+) in the average incentive result means a bonus for the DSO, while a negative value (−) means a malus. The companies with the most bonuses are in clusters 6 and 7; the opposite is seen in cluster 1, with two DSOs with maluses. Two larger groups (clusters 3 and 5) include the majority of DSOs, which gained a bonus from the incentive. Cluster 2 is "in the middle", with the incentive only having a small effect. The clustered data for each DSO cluster are presented in Figure 6.

The results presented in Figure 6 show successful clustering: similar output vectors (interruption costs) have been classified in the same categories. Figure 6 also shows the reason for dividing clusters 4 and 5 into different clusters: while the average interruption costs are at the same level, the variation over the years is higher in cluster 4.

Insights from the Clustering Results

Since the identification of each DSO was preserved in clustering, the results can be enriched with additional data regarding individual DSOs. A common hypothesis is that interruption costs decrease as the proportion of underground cables increases; the clustering results are enriched with the increased rate of underground cables in the fourth regulation period in Table 2.

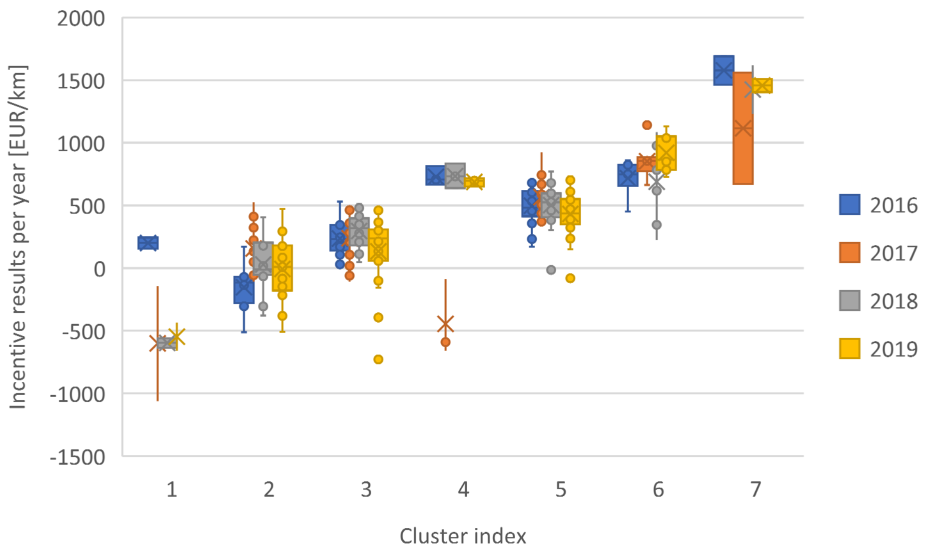


Figure 6. First clustering: annual quality incentive results as EUR/km for individual DSOs by cluster. Circles represent individual DSOs, and the cluster average is marked with an 'x'. The line indicates variation outside the upper and lower quartiles displayed in the box. Points outside of these lines are considered outliers.

Table 2. The first clustering result enriched by the proportion of underground cables.

Cluster Index	Number of DSOs in Cluster	Average of Annual Incentive Results in Cluster (EUR/km)	Average Increase in Cabling Degree (Percentage Point)	Average of Annual Actual Interruption Costs (EUR/km)
1	2	−386.0	12.4	773.5
2	15	+6.7	5.1	524.8
3	25	+220.1	8.3	534.5
4	3	+426.2	12.2	1349.7
5	23	+528.6	15.4	503.9
6	7	+794.7	16.7	588.6
7	2	+1393.0	18.3	1314.0

The data in Table 2 are aligned with the common hypothesis: companies that increased their proportion of underground cables the most (column 4) gained the highest quality bonus per medium voltage (MV) network length. The outcomes of the incentive exceed the actual interruption costs in clusters 5, 6, and 7. Nevertheless, the results are in line with the incentive design: DSOs are rewarded for decreasing interruption costs. The data on the cabling rates of individual companies in clusters are shown in Figure 7.

Figure 7 shows that DSOs that performed well (clusters 5, 6, 7) in the incentive, on average, increased their cabling rate more than DSOs in other clusters. The variation is considerable though, as the large cluster 3, for instance, includes DSOs from urban and rural areas. Some clusters of companies even significantly increased their cabling rate but are still categorized into a cluster with lower bonuses. This is characteristic of clustering: since clustering is based on similarities in interruption costs, the results of the quality incentive do not change uniformly for those receiving more bonuses.

While the interruption cost per network length describes the performance of the network in its environment, another approach is to describe the effects of interruptions on customers by calculating the interruption cost per customer. The incentive results and actual interruption costs per network length and per customer are presented in Table 3.

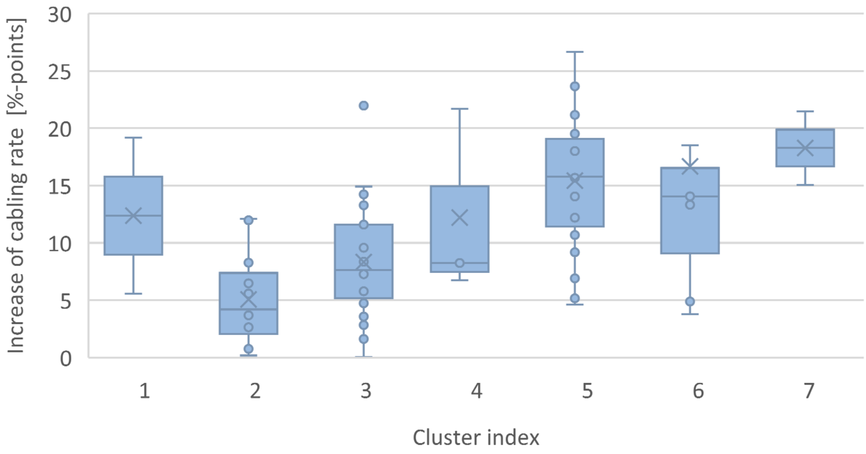


Figure 7. The increase in cabling rates for individual DSOs by clusters. Circles represent individual DSOs, and the cluster average (as shown in Table 2) is marked with an 'x'. The line indicates variation outside the upper and lower quartiles displayed in the box. Points outside of these lines are considered outliers.

Table 3. Actual interruption costs and incentive results for clusters.

Cluster Index	Incentive Result of DSO per Network Unit (EUR/km)	Actual Interruption Cost of DSO per Network Unit (EUR/km)	Incentive Result per Customer (EUR/Customer)	Actual Interruption Cost per Customer (EUR/Customer)
1	−386.0	773.5	−7.2	14.3
2	+6.7	524.8	+3.1	56.3
3	+220.1	534.5	+12.0	34.0
4	+426.2	1349.7	+13.8	46.6
5	+528.6	503.9	+25.2	27.5
6	+794.7	588.6	+15.4	12.1
7	+1393.0	1314.0	+18.9	16.1
ALL	+345.7	586.6	+14.3	33.9

According to Table 3, the annual interruption costs describing the effects on customers vary between EUR 12.20 and EUR 56.30 per customer, while the given bonuses vary between EUR 3.10 and EUR 25.20 per customer. DSOs in cluster 2 were rewarded with small bonuses, though the actual interruption costs per customer were the highest. The two DSOs in cluster 1 received maluses of EUR 7.20 per customer.

Table 4 shows how the results are altered when incentive results are clustered with, instead of being enriched by, an increase in the cabling rate.

Table 4. The second clustering results: incentive results clustered with the increase in cabling rate. Outliers (clusters 1 and 5) marked with (*).

Cluster Index	*n*	Average Cumulative Incentive Result of a DSO under 4th reg. Period (EUR/km)	Average Increase in Cabling Rate (%-Points)	Background Information: Average Cabling Rate in MV Network, (%)
1 *	1	−1887	19.2	79.5
2	10	+624	7.0	85.6
3	37	+672	6.7	15.8
4	20	+2212	18.5	40.7
5 *	1	+3101	47.5	62.8
6	6	+3129	10.2	69.7
7	2	+5572	18.3	72.1

The second clustering result in Table 4 includes two outliers (clusters 1 and 5, marked with (*)). The second result aligns with the first clustering result, but the distribution is steeper, dividing DSOs into clusters where the average result is more than EUR 2000/km and clusters where the average result is less than 1000/km. An illustration of the clustered data from Table 4 is shown in Figure 8 (outliers are excluded).

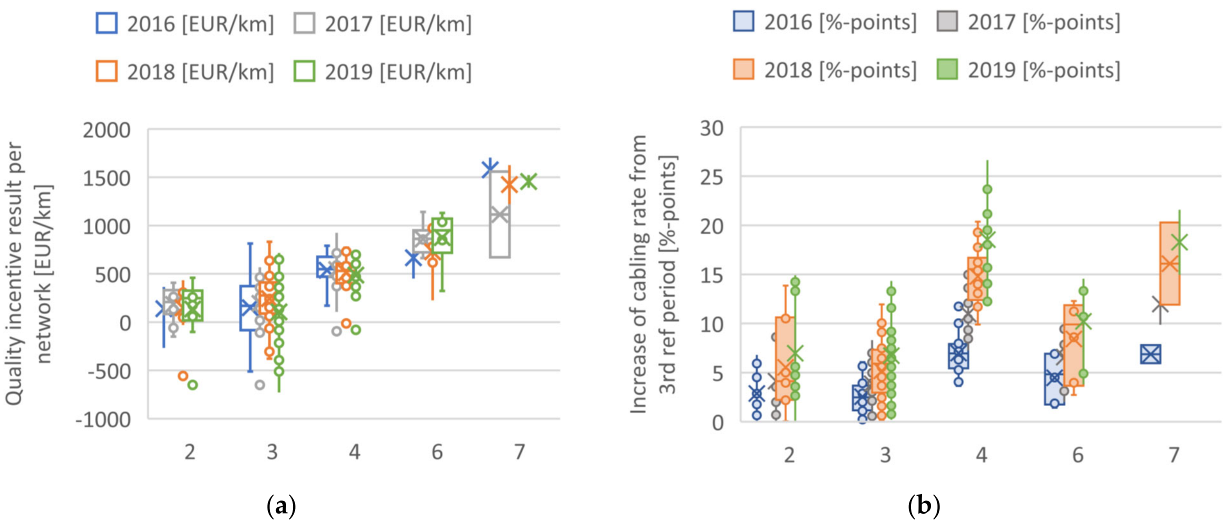


Figure 8. Illustrations of the second clustering data regarding the incentive results, the cabling rate, and clustered data: (**a**) the annual incentive results; and (**b**) the increase in the proportion of underground cables. Circles represent individual DSOs, and the cluster average is marked with an 'x'. The line indicates variation outside the upper and lower quartiles displayed in the box. Points outside of these lines are considered outliers.

It can be seen in Figure 8 that increasing the cabling rate correlates with greater bonuses from the quality incentive, especially in clusters 4, 6, and 7. The cabling rate also increased for some individual DSOs in clusters with lower bonuses, but, considering the features of clustering, the incentive progress is dissimilar from DSOs gaining the best bonuses (clusters 4, 6, and 7).

5. Discussion

The overall effect of a Finnish supply reliability incentive increased the allowed turnover by EUR 281 M in the fourth regulation period (2016–2019), which accounts for 3.7% of the collective DSO turnover under the same period. Breaking down the incentive mechanism into a control function and application function reveals that, without top/floor adjustments for individual bonuses, the effect could even have been as high as EUR 410 M. The general incentive model, presented in Figure 9, visualizes the cost of improving supply reliability.

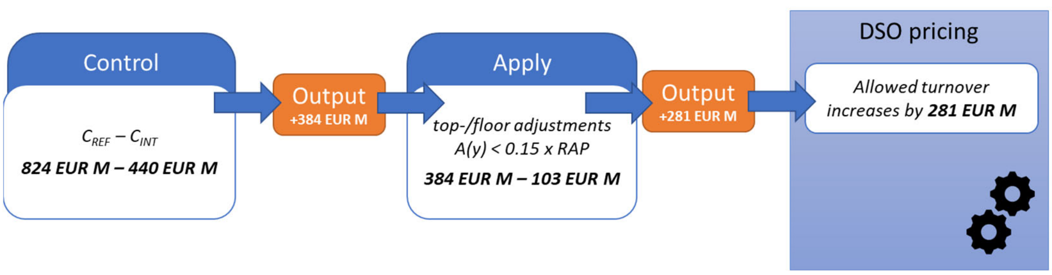
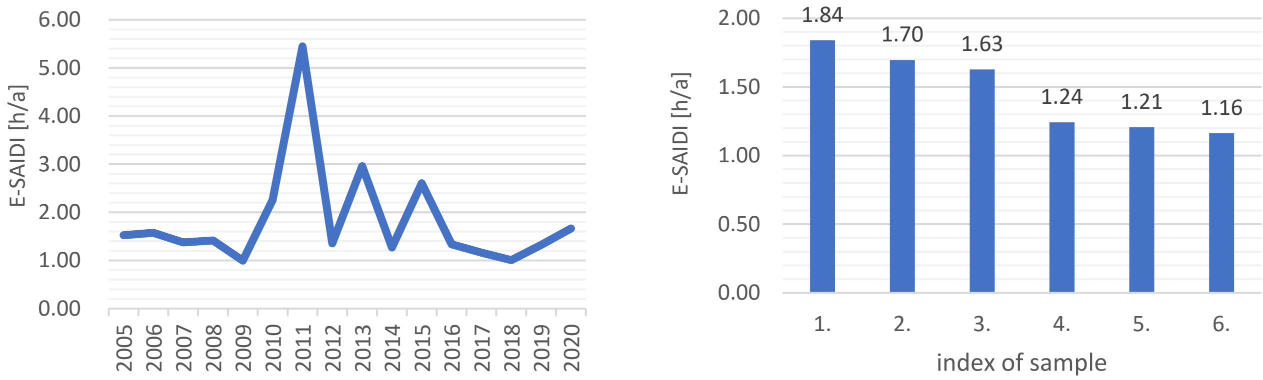


Figure 9. The incentive mechanism broken down according to the general incentive model.

A further examination of the incentive results reveals the distribution of bonuses across the jurisdiction. Classifying DSOs by the adjusted interruption costs and cabling rate shows that DSOs that have increased their proportion of underground cables the most were rewarded with the highest bonuses; the absolute cabling rate is less relevant in gaining bonuses. Comparing the adjusted interruption costs with the actual interruption costs confirms the result. Most bonuses (+25.2 EUR/customer) were given in the cluster with mediocre absolute interruption costs (27.5 EUR/customer). Moreover, bonuses were also rewarded with the highest absolute interruption costs (56.3 EUR/customer). Therefore, the supply reliability incentive mechanism appears to reward companies that still remain at a poor interruption cost level. The results show the importance of calibrating the incentive to aim at a specific target level, instead of straightforwardly rewarding an improving result.

As the interruption costs depend on the increase in the cabling rate of DSOs, the supply reliability incentive appears to be an extensive bonus for increased cabling, instead of a reward for a low interruption level. Since the "cabling bonus" is not achievable for utilities operating in urban areas with an already high proportion of underground cables, DSOs may be treated unfairly under this incentive. Introducing a target element into the control function would enable the steering of interruption costs toward the optimum level of societal cost. A scaling element in the application function would be adjusting the rapidity of steering for smooth progression toward the target level.

For evaluating the level of incentive results in reality, the long-time average SAIDI of all Finnish DSOs from 2005 to 2019 was 1.84 h. As the average SAIDI from 2016 to 2019 was only 34% lower (1.21 h), the all-time high bonuses of the fourth regulation period appear exaggerated. Adjusting the indices to exclude exceptional events could enable the study of the reliability index baseline, removing variations caused by weather conditions or other external factors. Using an extended time series could decrease the significance of variations across individual years but may introduce slowness into the incentive. The exaggerated effects of the incentive could also be efficiently avoided by excluding extreme years from the reference indices, as presented in [42]. Examples for defining the adjusted reference level are shown in Figure 10.



(a) (b)

Figure 10. (**a**) Average E-SAIDI of Finnish DSOs; (**b**) options for calculating the "average" E-SAIDI from the source data in (**a**). The options are as follows: 1: average SAIDI 2005–2019; 2: two worst years excluded from 2005 to 2019; 3: SAIDI 2012–2019; 4: two worst years excluded from 2012 to 2019; 5: SAIDI 2016–2019; and 6: the worst years excluded from 2016 to 2019.

The peaks in the national E-SAIDI, for the years 2011, 2013, and 2015, are due to major events. The reference level from the latest years (6: 1.16 h/a) would be 37% lower than the long-time actual average (1: 1.84 h/a) and could result in a more moderate bonus level. This underscores the fact that the resultant steering signal relies on the interpretation of the "reasonable" reference level.

However, overall, the supply reliability has improved, and the major storms that occurred from 2016 to 2019 (major storms: 2016: "Rauli", 2017: "Kiira", 2019: "Aapeli", "Tuuli", "Päivö", "Aila") did not cause disturbances on a similar scale to those seen in the past. Still, evaluating the "avoided disturbances" due to the structural improvements in the network would require advanced modeling, similar to the work by Jasuinas et al. in [25].

Generally, the outcomes of the supply reliability incentive in Finnish regulatory methods align with the incentive target and the actual interruption indices. However, direct steering may have a greater impact on supply reliability and thus on the calculated interruption costs. Nonetheless, the incentive remains a valuable tool for adjusting supply reliability towards a societal economic optimum. While the general incentive model can be used for assessing and adjusting the effects of a supply reliability incentive, it also provides tools for balancing the quality and asset costs of the electricity network in policy actions.

6. Conclusions

This study analyzed the exceptionally extensive reliability data of DSOs in one complete jurisdiction to present the effect of a supply reliability incentive. The concept involves differentiating the evaluation and applying mechanisms of the incentive to assess the volume and distribution of the steering signal.

The data regarding the quality incentive within the Finnish framework prove the logical correlation between bonuses and the adoption of underground cabling. More importantly, the evidence suggests that the incentive rewards companies for improving their supply reliability, notwithstanding the persistence of relatively low absolute supply reliability. Furthermore, DSOs with high rates of underground cabling and high supply reliability do not reap benefits from the incentive. Summarizing the average interruption costs, alongside the incentive outcomes, in order to describe the actual expenditure of experienced supply reliability reveals a significant variation in the theoretical cost ranging from EUR 7.10 to EUR 60.40 per customer.

An examination of this Finnish quality incentive generally shows that simple yardstick metering is sensitive to the selection of reference data and data adjustments. Possible errors in the source data, which establishes the reference level of interruptions and describes the current supply reliability, can impact the evaluation results of the incentive. Given that inconsistent results may diminish public acceptance of incentives, the tools presented here are valuable for conducting sensitivity analyses during incentive development. Ultimately, they help avoid unintended outcomes of incentives in the future.

Further research is needed to assess the overall steering of a complete set of incentives and the direct obligations of the regulation framework. The incentive model and enhanced clustering presented in this study offer valuable tools for systematic assessments of the regulatory framework.

Author Contributions: Conceptualization, J.S.; methodology, J.S.; software J.S.; validation, J.S.; formal analysis, J.S.; investigation, J.S.; resources, J.S.; data curation, J.S.; writing—original draft preparation, J.S.; writing—review and editing, J.S. and P.J.; 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.

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

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