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COMPARATIVE STUDY ON ELECTRIC ENERGY LOSSES IN POLISH DISTRIBUTION SECTOR

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ABSTRACT

Accurate calculation of energy losses, technical as well as commercial, in real power systems is a complex issue that requires consideration of many various factors.

The analysis of electric energy losses in different distribution companies with respect to chosen characteristics (area size, number of recipients, load density, recipients density, network density, and others) is presented in this paper.

In order to carry out a detailed analysis of losses characteristics and to examine the influence of different factors on the level of losses several classical methods of multidimensional data analysis have been applied. Additionally, a new method of graphic representation of the full structure of multidimensional data is proposed by the authors.

The carried out analysis can be a meaningful voice in the ongoing discussion on shaping tariffs for electric energy. It is especially important in the context of deregulation of electric energy markets in Poland and Europe because losses reduce economic efficiency of a company thus worsen its competitiveness on the market.

KEY WORDS

Power distribution, electric energy market, electric energy losses, multidimensional data analysis, visual methods of multidimensional data analysis

1. Introduction

Polish energy sector undergoes deep structural, organisational and proprietary transformation. Measures to form a market for electric energy and introduce competition in this sector are being taken.

Functioning of Polish energy sector is regulated by the Act of 10 April 1997 Energy Law (Journal of Laws No 54 of 4 June 1997, Item 348 as amended) which enables the introduction of market mechanisms in this sector and, at the same time, the protection of recipients' interests. In accordance with the Act an organ for the regulation of fuels and energy sectors and the promotion of competitiveness was established. This organ is the President of the Energy Regulatory Authority of Poland (ERAP) and operates as a central organ of the state administration. One of the most important tasks of the organ for the regulation of energy sector is approval and control of tariffs for electric energy, fuels and heat. The President of the ERAP is mandated by the Act to balance in his regulatory actions the interests of energy suppliers and consumers. Detailed rules of tariff setting and calculation are included in the Decree of the Minister of Economy of 14 December 2000 concerning detailed principles for setting and calculating tariffs and the principles of settlements in trade in electric energy (Journal of Laws No 1 of 2001, Item 7). Quoted acts state that the electric energy tariffs should on one hand ensure the coverage of energy enterprises' costs including the costs of modernisation, development and protection of the environment and on the other protect the recipient from unreasonable price level. New directions of legal, organisational and technological solutions will have an increasing influence on further development of the power sector.

Polish power distribution sector is made up of 33 distribution companies. Currently the distribution companies are dealing with the transmission, distribution and trading of electric energy. They all use similar technology but vary in operational conditions. They operate in different geographical environments, supply and demand conditions, have various numbers and structures of clients and differ in network property and its technical condition.

The carried out research proves the existence of the correlation between the operational conditions and the costs of power utilities. Electric energy losses occurring in power networks are an essential element of every power utility's balance. In Polish conditions they reach a dozen or so percent and in extreme cases may gain several dozen percent of the whole energy flowing through all network levels [1, 2]. Costs resulting from energy losses are a charge both to power utilities and individual recipients. They influence companies' economic efficiency and electric energy prices. This fact is of particular importance as far as the diversification of energy prices is concerned.

Limiting of energy losses costs occurring in power distribution networks is a potential source of significant savings. The fundamental problem is the correct estimation of different kinds of energy losses occurring in distribution networks and localisation of their sources. Simple comparison of the values of energy losses in examined companies without taking into consideration the market conditions in which they operate cannot be a basis for inference of justified level of energy losses. For this reason the application of econometric comparative methods *{benchmarking)* in determining the justified level of energy losses is valid.

Analysis of electric energy losses in selected distribution companies with respect to selected market, geographic, organisational and technical indicators is presented in this paper, in order to carry out a detailed analysis of the losses indicators and grasp the influence of different factors on the level of losses an original method of graphic representation of multidimensional data proposed in paper [3] and the analysis of multivariable linear regression [4] have been applied.

2. Source data

Occurrence of electric energy losses is intrinsic to the process of energy generation, transmission and distribution. Losses depend on many various factors of technical, economic, geographic or social nature. Accurate calculation of energy losses in real power systems is a complex issue that requires consideration of numerous factors. Accessibility and reliability of measurement data and information on network structure are of primary importance.

The results and the precision of electric energy losses calculation depend mainly on the type and the quality of available input data which, in case of distribution networks, is formally diversified and varies in accessibility and reliability [1].

Balance losses and losses and balance differences ratio are basic parameters characterising distribution companies according to technical and economic criteria.

Balance losses (AE_b) include actual technical losses and all commercial losses defined as deviations in energy trading with the recipients as well as with other organisational units. Balance losses are also called reported losses because they are indicated in distribution company's reporting.

Losses and balance differences ratio ($AE°_O$) describes balance losses in distribution companies' networks in percentage terms

Companies' distribution networks can be divided into two voltage categories: 1 JOkV networks and medium and low voltage networks (MV+LV). Because the operation of networks of different voltage levels is rather autonomous, losses occurring in them can be analysed separately.

Analysis of data on balance energy losses in absolute and percentage terms indicates substantial diversification among the companies (Table 1).

Describing commercial losses one has to conclude that there is no particular method of calculating them. They can be only determined as a difference between balance losses and calculated technical losses. Additionally, it is not possible to calculate technical losses either, even with use of computer technology. Therefore, methods of statistical analysis are widely applied in the calculation of electric energy losses.

Table 1. Balance energy losses in selected distribution companies [2]

No.	Company	$\Delta E_{b(110)}$	$\Delta E_{b\%(110)}$	$\Delta E_{b(MV+LV)}$	$\Delta E_{b\%(MV+LV)}$	No.	Company	$\Delta E_{b(110)}$	$\Delta E_{b\%(110)}$	$\Delta E_{b(MV+LV)}$	$\Delta E_{b\%(MV+LV)}$
		GWh	%	GWh	%			GWh	%	GWh	%
1	2	3	4	5	6	1	2		4	5	6
1.	SD 1	162.00	1.69	437.50	13.12	18.	SD 18	46.90	2.33	136.10	9.14
2.	SD 2	106.30	3.38	390.50	14.42	19.	SD 19	133.20	2.50	261.30	11.19
3.	SD 3	117.00	3.24	175.40	7.81	20.	SD 20	38.60	1.42	322.10	18.15
4.	SD 4	107.60	2.82	355.40	13.51	21.	SD 21	76.60	1.28	907.40	15.36
5.	SD 5	96.60	3.06	319.40	16.36	22.	SD 22	147.40	2.45	311.10	12.46
6.	SD 6	14.20	1.04	167.50	18.29	23.	SD 23	68.10	1.23	723.10	21.15
7.	*SD 7*	26.10	0.60	616.60	17.20	24.	SD 24	18.20	1.06	105.90	11.53
8.	SD 8	661.60	4.42	605.20	10.09	25.	SD 25	62.90	1.92	309.40	12.08
9.	SD 9	62.00	3.75	115.10	7.58	26.	SD 26	53.70	2.20	200.20	17.99
10.	SD 10	31.20	1.55	166.70	13.75	27.	SD 27	109.10	2.33	290.30	13.56
11.	SD 11	99.90	1.65	401.50	15.62	28.	SD 28	36.40	1.56	196.70	12.17
12.	SD 12	19.50	1.21	197.00	15.02	29.	SD 29	88.40	1.39	495.40	11.34
13.	SD 13	107.20	1.76	751.60	17.55	30.	SD 30	203.10	2.84	698.30	15.14
14.	SD 14	25.20	0.60	139.10	12.99	31.	SD 31	92.80	2.25	342.50	12.98
15.	SD 15	53.70	1.83	329.40	15.02	32.	SD 32	38.10	1.77	214.50	12.37
16.	SD 16	44.70	1.20	500.00	17.13	JJ.	SD 33	33.00	1.76	208.60	12.38
17.	SD 17	89.20	1.46	588.70	17.47	34.	Average	93.05	1.99	363.02	14.00

3. Graphic analysis of the structure of distribution companies with respect to chosen characteristics

Searching for the relation between the value of electric energy losses and the operational conditions of the distribution companies defined by chosen indicators, the authors have applied in first step the graphic analysis of the structure of objects (distribution companies) with respect to their chosen characteristics. The set of indicators selected through an essential analysis) has been presented in Table 2. Selected indicators can be determined on the basis of data from [4]. Additionally, the distribution companies have been divided into four categories according to the amount of losses (in percentages) in the networks of both voltage levels.

In case of 110kV networks (Fig. la) following classes can be identified: {S8}, {S2, S21}, {S13, SI7, S22, S23, S30}, {S4, S6, S7, S11, S14, S19, S27, S31}, {S29} and other.

Main characteristics differentiating the companies with respect to the conditions of network operation are X7 (length of the 110kV lines), X5 (energy transformed into the MV network), X8 (Capacity of 110kV/MV transformers), X4 (energy introduced into the 110 kV network), XI (area of company's operation). Remaining characteristics reveal no significant influence on the diversification of distribution companies as far as the conditions of 110kV network operation are concerned.

In case of the MV+LV networks (Fig. lb) following groups can be identified: {S8}, {S21}, {S29}, {S30}. *{S2,* S22, S23}, {S7, S13, S15, S17}, {S6, S10, S12, S14, S24} and other.

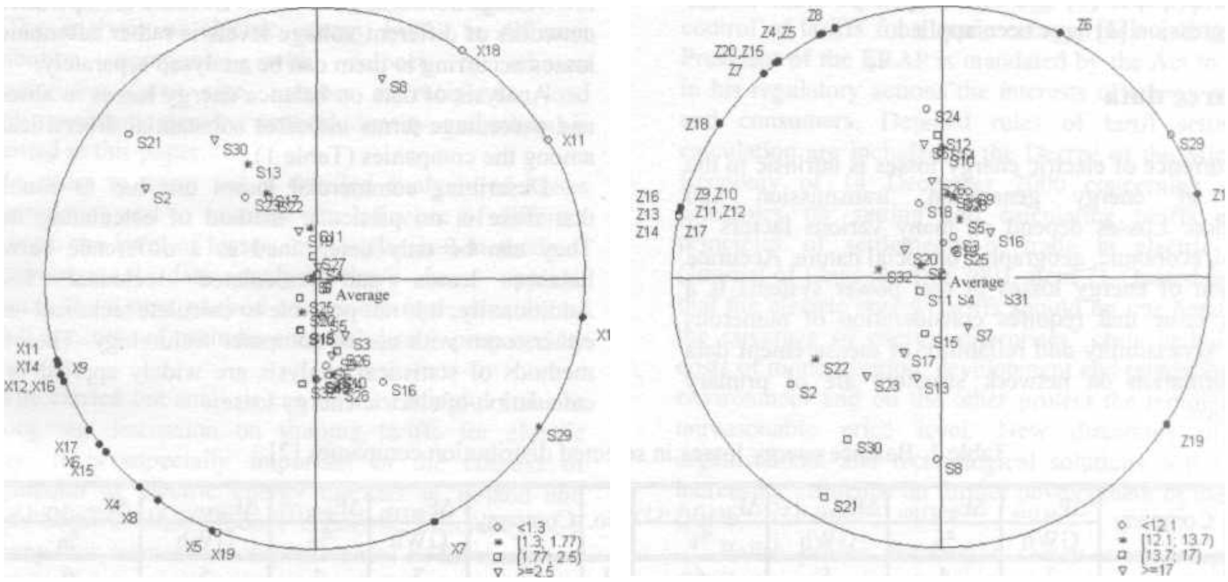

Fig. 1. Structure of distribution companies with respect to conditions of network operation: a) 110 kV network, b) MV+LV network

In the 110kV network the categories comprise of the companies with losses: below 1.3%, between 1.3% and 1.8%, between 1,8% and 2,5% and above 2,5%. In the MV+LV network the categories comprise of the companies with losses: below 11.1%, between 11.1% and 12.1%, between 12.1% and 13.7%, between 13.7% and 17.0% and above 17.0%. Preliminary analysis has proven no substantial diversification of losses levels with respect to geographic location of the companies.

Results for 110kV and MV+LV networks obtained from a computer program, which presents the structure of multidimensional data on the on the plane [3], are shown in Figure 1.

Analysis of the distribution of objects and characteristics in relation to each other leads to the division of the distribution companies into several classes with respect to the conditions of network operation on both voltage levels.

Main characteristics differentiating the companies with respect to the conditions of the MV+LV network operation are Zl, Z4, Z5, Z6, Z7, Z8, Z15, Z20. Remaining characteristics reveal no significant influence on the diversification of distribution companies as far as the conditions of MV+LV network operation are concerned.

Further analysis shows that the level of percentage energy losses in 110kV and MV+LV networks of selected distribution companies is not connected with the diversification of the companies with respect to the selected characteristics. Companies with different levels of losses could be found in one class. This leads to the conclusion that the selected set of factors in the analysed system doesn't provide a significant explanation to the percentage level of losses in the selected distribution companies.

Table 2. Set of indicators characterising operational conditions of selected distribution companies

Characteristic	Symbol [unit]	Description	Characteristic	Symbol [unit]	Description
XI	S [km^2]	Area of operation	Z1	S [km^{2}l	Area of operation
X2	$\Delta E_{b(110)}$ [GWh]	Balance losses in the 110kV network	Z2	$\Delta E_{b(MV+LV)}$ [GWh]	Balance losses in the MV+LV network
X3	$\Delta E_b\%_{(110)}$ [GWh]	Percentage balance losses in the 110kV network	Z3	$\Delta E_b\%_{(MV+LV)}$ [GWh]	Percentage balance losses in the MV+LV network
X4	E_{110} [GWh]	Energy supplied to the 110 kV network	Z4	$E_{(MV+LV)}$ [GWh]	Energy introduced into the MV+LV network
X5	$Et_{(110\rightarrow MV)}$ [GWh]	Energy transformed from the 110kV network into the MV+LV network	Z5	$L_{ODB(MV+LV)}$ [unit]	Number of recipients in the MV+LV network
X6	$L_{0(110)}$ [unit]	Number of recipients in the 110 kV network	Z6	L(MV+LV) [km]	Length of the MV+LV lines
X7	$L_{(110)}$ [km]	Length of the 110kV lines	Z7	$TR_{HV/MV}$ [MVA]	Capacity of WN/SN transformers
X8	$Tr_{hv/mv}$ [MVA]	Capacity of HV/MV transformers	Z8	$Tr_{(MV/LV)}$ [MVA]	Capacity of HV/LV transformers
X9	E/S [GWh/km^2]	Spatial density of the energy supplied into company's area of operation	Z9	E/S [GWh/km^2]	Spatial density of the energy supplied into company's area of operation
X10	E_{110}/S [GWh/km^2]	Spatial density of the energy supplied to the 110kV network	Z10	$E_{(MV+LV)}/S$ [GWh/km^2]	Spatial density of the energy supplied to the MV+LV network
Xll	$Et_{(110\rightarrow MV)}/E_{110}$ [MWh]	Energy transformed from the 110kV network into the MV+LV network in relation to the energy supplied to the 110kV network	Zll	$L_{o(MV+LV)}/S$ [unit/km^2]	Spatial density of the recipients in the MV+LV network
X12	$L_{O(110)}/S$ [unit/km^2]	Spatial density of the recipients in he 110kV network	Z12	$L_{(MV-LV)}/S$ [km/km^2]	Spatial density of the MV+LV lines
X13	L_{110}/S [km/km^2]	Spatial density of the 110kV lines	Z13	$Tr_{(HV/MV)}/S$ [MVA/km^2]	Spatial density of capacity of HV/MV transformers power
X14	$Tr_{(HV/MV)}/S$ [MVA/km^2]	Spatial density of capacity of HV/MV transformers	Z14	$TR_{(MV/LV)}/S$ [MVA/km^2]	Spatial density of MV+LV transformers power
X15	E^2_{110} [GWh^2]	Square of the energy supplied to the 110kV network	Z15	$E^2_{(MV+LV)}$ [GWh^2]	Square of the energy supplied o the MV+LV network
X16	E^2_{110}/S [GWh^2/km^2]	Spatial density of the square of the energy supplied to the 110 kV network	Z16	$E^2_{(MV+LV)}/S$ [GWh^2/km^2]	Spatial density of the square of *he* energy supplied to the MV+LV network
X17	E^2_{110}/L_{110} [GWh^2/km]	Square of the energy supplied to the 110kV network per km of 110 kV lines	Z17	$E_{(MV+LV)}/L_{o(MV+LV)}$ [GWh/recpt.]	Average energy consumption of the recipients in the MV+LV network
X18	$Tr_{(HV/MV)}/E_{110}$ MVA/GWh]	Capacity of HV/MV transformers in elation to the energy supplied to the 110kV network	Z18	$E^2_{(MV+LV)}/L_{(MV+LV)}$ [GWh^2/km]	Square of the energy supplied o the MV+LV network per km of MV+LV lines
X19	$E^2_{110}/L_{o(110)}$ [GWh^2/recpt.]	Square of the energy supplied to the 110kV network divided by the umber of the 110kV recipients	Z19	$Tr_{(MV/LV)}/E_{(MV+LV)}$ [MVA/GWh]	Capacity of MV/LV transformers in relation to the energy supplied to the MV+LV network
X20	$E_{110}/L_{(110)}$ [GWh/recpt]	Energy supplied to the 110kV network divided by the number of the 110kV recipients	Z20	$E^2_{(MV+LV)}/Lo_{(MV+LV)}$ [GWh^2/recpt]	Square of the energy supplied o the MV+LV network divided y the number of the MV+LV recipients

4. Analysis of electric energy losses with use of multivariable linear regression

In order to distinguish a group of factors that will better explain the diversification of energy losses levels in selected distribution companies further analysis with use of multiple regression has been carried out [4].

Numerous models using different sets of explanatory variables have been analysed. Regression analysis has been conducted with use of the procedures of standard regression, backward stepwise, forward stepwise which are available in STATISTICA software.

Unfortunately, the carried out analysis hasn't resulted in a model that would in a satisfactory way explain the diversification of the distribution companies with regard to the percentage level of electric energy losses and at the same time have a rational physical and organisational interpretation. All variables included into models are significant ($p<0.05$).

The regression model for a 1 lOkV network chosen for further presentation and analysis has the following form:

$$AE_b\%_{(110)} = 0.53213 + 0.00060\,X7 - 2.06654\,XI1 + 8.85E\text{-}9X15 + 5.67698X18 \qquad (1)$$

Corrected coefficient of determination of the model for a MV+LV network equals 0.175 (p=0.051). This means that in case of MV+LV networks merely 17.5% of variance of percentage energy losses is explained by the constructed regression model.

In order to further explore the structure of the models additional graphic analysis has been carried out (Fig. 2). The analysis comprised only those characteristics which were included as explanatory variables in the regression models.

The analysis of both structures indicates the concentration of the objects (companies) into several clusters. In case of the 110 kV networks following classes of objects can be identified: {S4, S9, S16, S24, S29}, {S8}, {S2, S15, S21, S32, S33} and other. Companies characterised by various levels of losses are mixed in each class, which supports the conclusion that analysed parameters have a weak influence on the level of energy losses. For the MV+LV networks following classes of objects can be identified: {S7, SI 1, S13, S15, S17, S21, S23, S30}, {S8, S9}, {S18, S22, S26, S27, S32}, {S2} and other.

Although the set of companies' characteristics has been limited only to those significantly explaining the percentage level of energy losses in the regression model a clear division into classes with the homogenous levels of energy losses hasn't been achieved.

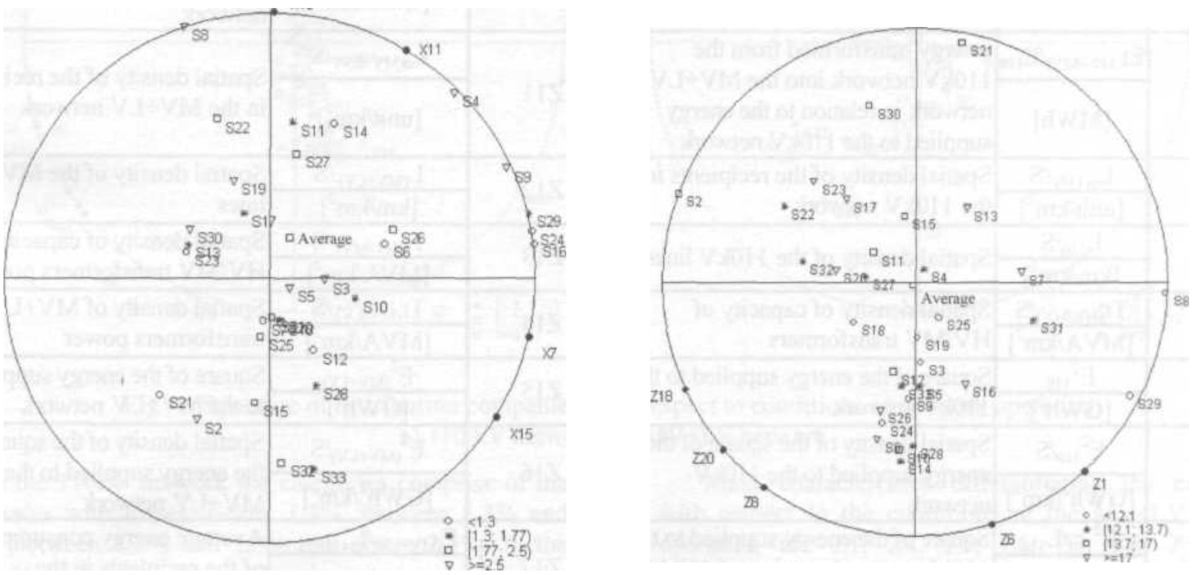

Fig. 2. Structure of distribution companies with respect to the characteristics included as explanatory variables in the regression model: a) 110 kV network, b) MV+LV network

Corrected coefficient of determination of the model equals 0.365 (p=0.0024). This means that only 36.5% of variance of percentage energy losses is explained by the constructed regression model.

The model for a MV+LV network has the following form:

$$\Delta E_b\%_{(MV+LV)} = 12.7599 - 0.00035\,Z1 + 0.00043\,Z6 - + 0.00509\,Z8 + 0.09244\,Z20 \qquad (2)$$

On the contrary, companies with different levels of losses could be found in one class. It is however noteworthy that the first class which is characterised by the high level of all five parameters contains only companies with high losses. This means that a higher level of analysed characteristics influences higher energy losses. There is however no basis to claim that a lower level of these parameters is connected with lower losses.

5. Conclusions

In case of the power distribution sector a comparative statistical analysis is justified due to the large number of analysed objects and very similar scope of their operation. Multidimensional data analysis has enabled to determine the similarities and differences between the distribution companies and to specify the groups of characteristics that are significant or insignificant in the differentiating.

The objective of the research was to conduct a comparative study on electric energy losses in Polish distribution sector. Unfortunately, the carried out analyses haven't delivered a complete answer as far as the recognition of the factors significantly differentiating selected distribution companies with respect to the percentage levels of energy losses is concerned. Cause and effect relationship between the variables present in the developed models of energy losses for the networks of both voltage levels and the level of losses occurring in power networks can be observed. The direction of this influence is in accord with technical and organisational interpretation of the phenomenon. Despite that fact the variables explain only a small part of the variability of losses level in selected distribution companies.

Obtained results may suggest that the high percentage of energy losses in Polish distribution companies belongs to the category of commercial losses, including illegal power consumption. This presumption is supported by a relatively high level of energy losses in Polish companies in comparison to the companies in the European Union [2].

The results point at the advisability of further research in this field. On one hand, attempts should be made to broaden the scope of explanatory variables describing company's operational conditions. On the other hand, it seems essential to undertake an in-depth analysis of the commercial losses and their sources.

In authors' opinion, the presented study can be a meaningful voice in the ongoing discussion on shaping tariffs for electric energy.

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