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STRUCTURAL ANALYSIS OF VARIATION OF ELECTRICITY TRANSMISSION MARGINAL COSTS

Abstract: The paper presents a surface model of the accounting costs of electricity transmission over the 220 kV and 400 kV networks. A structural analysis of marginal costs variation was carried out. Variogram functions (isotropic, directional variogram, variograms roses) were used to build the model. The model describes well the considered phenomenon, i.e. the area and time variation of marginal costs, and has great potential in the electrical power sector, especially in the context of the development of market mechanisms in electric energy trading. The model has made it possible to observe the existing tendencies in cost (directional and time) variation, which is useful for setting electricity transmission tariffs correctly stimulating the behaviour of the electric power network users – the electricity suppliers and consumers.

Keywords: marginal transmission costs, variation of costs, electric energy, isotropic variogram, directional variogram.

1. Introduction

By creating models representing the observed reality, one can gain a deeper insight into the different phenomena involved. This applies particularly to the power industry because of the complexity of the correlations and interactions between the electricity generation and transmission technology and the consumption of electric energy in the conditions of developing market mechanisms. A model of nodal marginal prices makes it possible not only to faithfully represent the cost pattern, but also to apply a proper methodology of investigating and analyzing cost variation and the directionality of variation trends, using geostatistical methods. Spatial analyses of cost distribution were carried out to confirm the viability of using nodal electricity transmission prices instead of a transmission tariff uniform for the whole country.

2. Application of marginal costs in the electric power sector

Since investments in the electric power sector are highly capital-intensive, increasingly more emphasis is placed on improving the effectiveness of managing this sector. This is particularly important in the context of developing market mechanisms in the sale of the various energy carriers. In the traditional approach, the emphasis was placed on improving the technical and financial efficiency of the planning of the long-term development of power systems in accordance with the lowest cost criterion, optimizing short and middle-term systems operation and improving the management of power companies. All of the above are supply-side measures – but the effectiveness of the power sector to a large extent depends on the demand side actions. This issue has been attracting an increasing amount of attention, particularly when a proper pricing policy in which electricity tariffs are determined on the basis of marginal costs is to be adopted. In many western countries, alternative (marginal) costs have become the starting point for debates on an electric power sector development policy [2; 6; 11].

For a few years now, specialists in electricity transmission tariffs have been considering the adoption of nodal tariffs [2; 3; 5; 12; 13] instead of a uniform tariff for the whole country, based on the so-called "copper plate" concept. The nodal tariff varies depending on the cost level in the particular nodes of the electric power network. In order to determine nodal costs one can use the category of marginal costs. Marginal costs of electricity are divided into short-term marginal costs and long-term marginal costs.

The short-term marginal cost is a minimal additional cost of producing and transmitting a unit of electricity needed to cover an increment in demand, using the existing productive and transmission capacities.

The long-term marginal cost is a change in the electricity production and transmission cost, caused by a change in the load over a time long enough for all the electricity supply (generation and transmission) capacities to change. This cost is created by an increment in the total costs entailed with the generation of an additional electricity unit in the future. Besides short-term marginal cost components, this includes the costs of increasing the power and the transmission capacity. The power cost component takes into account changes in investment costs and the fixed operational and maintenance costs needed to cover an increment in demand [6].

This paper discusses short-term electricity transmission costs and their surface and time variation, using as an example the national electric power system. In order to estimate the variation in the costs, geostatistical methods such as: the (isotropic and directional) variogram function and the ordinary (block) kriging, taking into account the unique and moving "neighbourhood" (a sample search subarea), were employed.

3. Estimation of basic marginal cost statistics

In the preliminary stage of the spatial analyses of marginal costs in the nodes of 220 kV and 400 kV networks, the basic statistical parameters for the winter and summer night off-peak period and morning peak (Tables 1, 2) were estimated and cost distribution histograms were computed using 106 data items for the area of the whole country (Figures 1–4). The cost distribution histograms for the summer season and the winter season have a three or two-modal character with a very distinct one-modal class (Figures 1–4). The modal class values are within the following ranges: the summer night off-peak period – 35.68÷35.95; 36.22÷36.49; 38.37÷38.64 [PLN/MWh]; the summer morning peak– 49.98÷50.39 as well as 50.81÷51.22 and 54.12÷54.53 [PLN/MWh]; the winter night off-peak period – 54.04÷54.78; 58.45÷59.19 [PLN/MWh]; the winter morning peak – 56.38÷56.96; 58.13÷58.71 as well as 59.29÷59.88 and 61.63÷62.21 [PLN/MWh], depending on the particular time instant, appropriately higher for the morning peak (Figure 2). All the cost distribution histograms show slight positive skewness g_1, which is more pronounced for the winter season, especially for the night off-peak period (Tables 1, 2). The low kurtosis coefficients g_2 (higher for the winter season) indicate a considerable degree of flattening of the four histograms (Tables 1, 2).

Generally, much higher minimal X_{min}, maximal X_{max} and average costs for the summer morning peak than for the night off-peak period attract attention (Table 1). The above cost statistics are highest in the winter season during the morning peak and slightly lower during the off-peak hours in this season (Table 2), which slightly differs from the observations made during the summer season (Table 1). The standard deviations of the costs are larger in the summer morning peak and in the winter night

Table 1. Basic statistical parameters of marginal costs in nodes of 220 kV and 400 kV networks for the summer season of 2000

Analyzed parameter	X_{min} [PLN/MWh]	X_{max} [PLN/MWh]	Average $\overline{X}$ [PLN/MWh]	Standard deviation S [PLN/MWh]	Variation coefficient V [%]	Skewness g_1	Kurtosis g_2
Summer night off-peak period	35.15	39.17	36.99	1.06	2.87	0.39	1.95
Summer morning peak	49.16	55.35	51.93	1.74	3.36	0.25	1.63

Source: own calculations.

Table 2. Basic statistical parameters of marginal costs in nodes of 220 kV and 400 kV networks for the winter season of 2000

Analyzed parameter	X_{min} [PLN/MWh]	X_{max} [PLN/MWh]	Average $\overline{X}$ [PLN/MWh]	Standard deviation S [PLN/MWh]	Variation coefficient V [%]	Skewness g_1	Kurtosis g_2
Winter night off-peak period	51.85	62.85	55.56	2.79	5.02	1.04	2.98
Winter morning peak	55.80	64.54	59.16	2.28	3.85	0.56	2.06

Source: own calculations.

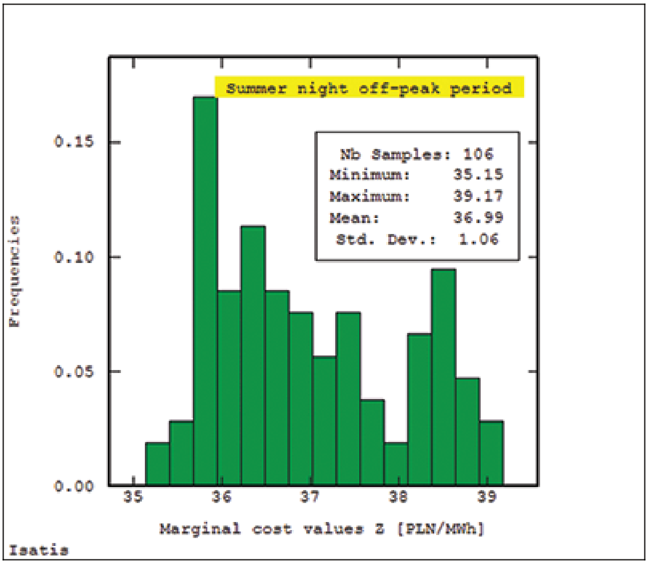

Figure 1. Histogram showing distribution of original marginal cost values *Z* [PLN/MWh] in nodes of 220 kV and 400 kV networks for the summer night off-peak period

Source: own calculations.

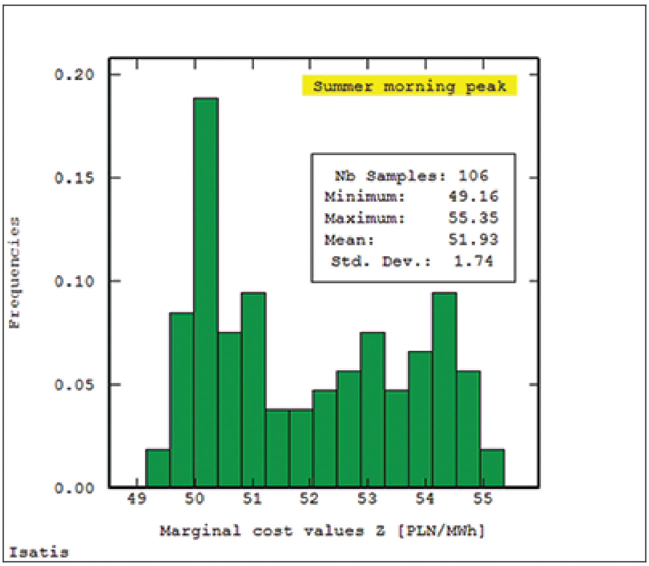

Figure 2. Histogram showing distribution of original marginal cost values *Z* [PLN/MWh] in nodes of 220 kV and 400 kV networks for the summer morning peak

Source: own calculations.

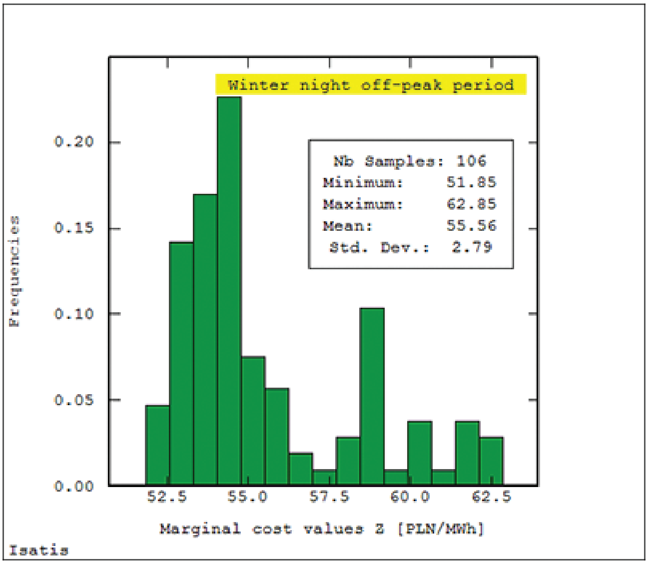

Figure 3. Histogram showing distribution of original marginal cost values *Z* [PLN/MWh] in nodes of 220 kV and 400 kV networks for the winter night off-peak period

Source: own calculations.

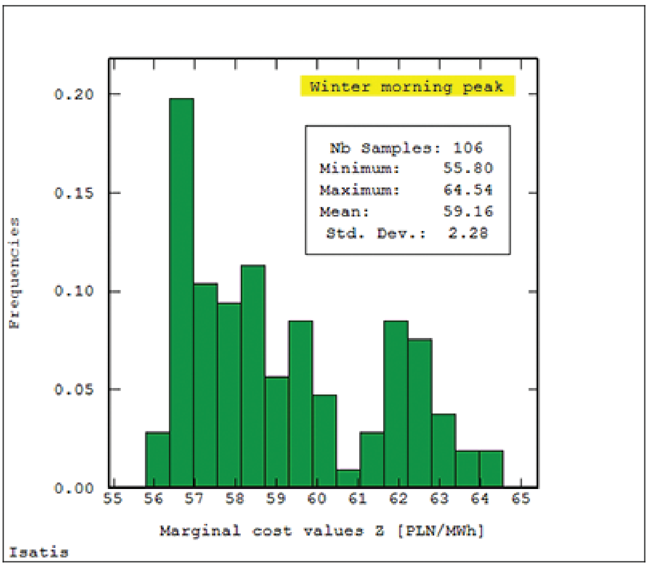

Figure 4. Histogram showing distribution of original marginal cost values *Z* [PLN/MWh] in nodes of 220 kV and 400 kV networks for the winter morning peak

Source: own calculations.

off-peak period (Tables 1, 2). Against the low cost variation coefficients V for the considered time instants, coefficients V in the winter season stand out, being distinctly higher for the night off-peak period (Table 2).

4. Investigative methodology

This paper proposes the geostatistical methods and procedures which were used here to analyze spatially correlated data on marginal transmission costs. The geostatistical analysis was carried out using the isotropic variogram function, the directional variogram function and the ordinary (block) kriging technique, in the 2D system [10].

The distinguishing feature of the proposed methodology is the use of the isotropic variogram function and the directional variogram function for the quantitative representation and modelling of the spatial structure of the studied process, i.e. cost variation.

Use of variogram function to study cost variation structure

The principal tool of geostatistics is the variogram function. It is used to determine the type of surface or spatial correlation between studied variables. The empirical variogram is modelled by means of a theoretical analytical function. The variogram function enables one to obtain the best (as regards the minimal estimation error) picture of the structure of the variation of the studied variable, i.e. marginal costs in 2D [1; 4; 7].

The empirical semivariogram, characterizing the correlation between cost values on a surface (in 2D), is represented by the following relation:

$$\gamma^*(h) = \frac{1}{2n_h} \sum_{i=1}^{n_h} \left[z(x_i + h) - z(x_i) \right]^2, \tag{1}$$

where: $z(x_i + h)$, $z(x_i)$ – cost values in points x_i and $x_i + h$, i.e. separated by distance h; n_h – the number of pairs (x_i, $x_i + h$) of cost values in points separated by distance h, used in calculating semivariogram function $g^*(h)$.

Empirical variograms describe the character of the variation in the considered regionalized variable, i.e. marginal electricity transmission costs in 220 and 400 kV network nodes.

Since isotropic variograms do not give a full picture of the character of cost variation, directional variograms showing the variation of the analyzed parameter in the particular directions were determined. As part of this study, (averaged) isotropic variograms were computed, taking into account all the measurement data, while directional variograms were computed on the basis of measurements oriented along specified directions (bands).

The isotropic cost variograms show sharp directional changes in the value of function $\gamma(h)$ for the considered distance. Actually, an almost unlimited increase in the value of function $\gamma(h)$ is observed. For this reason the J-Bessel model, the spherical model and the nugget-effect model were used to model the isotropic empirical cost variograms.

Only when the number of sample pairs is considerably reduced did the isotropic and directional variogram values begin to decrease sharply.

5. Study of anisotropy of marginal electricity transmission costs

A structural analysis of cost variation was carried out on the basis of the isotropic and directional variograms of marginal costs, calculated for the considered sample population (n = 106 data).

5.1. Isotropic variograms of marginal costs

Figures 5–8 show the isotropic cost variograms computed for the whole considered distance (500 km). Owing to them one can precisely trace the character and degree of variation of function $\gamma(h)$ values for a considerable distance. This means that variograms improve the quality of estimation in comparison with the averaged (omnidirectional) variograms determined for only 1/3 of the distance (150 km),

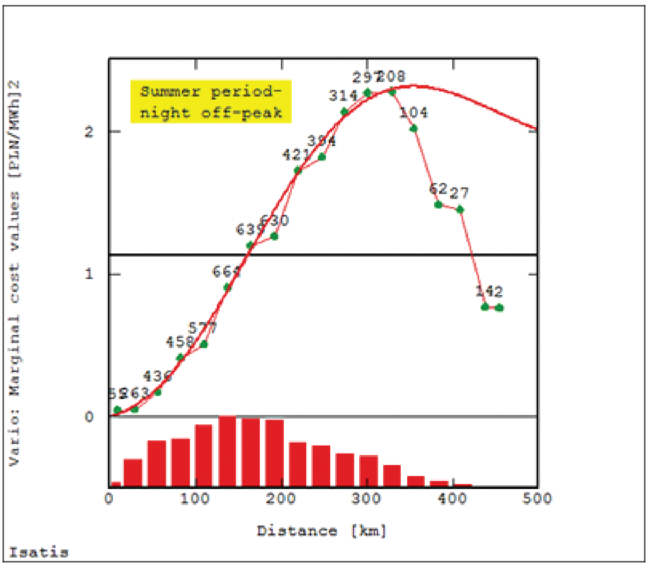

Figure 5. Isotropic variogram of marginal costs [PLN/MWh]^2 in nodes of 220 kV and 400 kV networks for the summer night off-peak period, approximated with theoretical model (J-Bessel model and spherical model); histogram of distribution showing pairs' size

Source: own calculations.

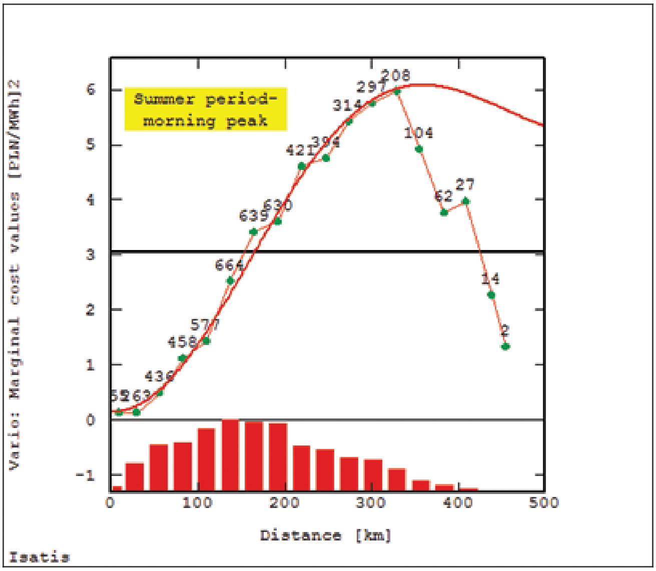

Figure 6. Isotropic variogram of marginal costs [PLN/MWh]^2 in nodes of 220 kV and 400 kV networks for the summer morning peak, approximated with theoretical model (J-Bessel model with nugget effect); histogram of distribution showing pairs' size

Source: own calculations.

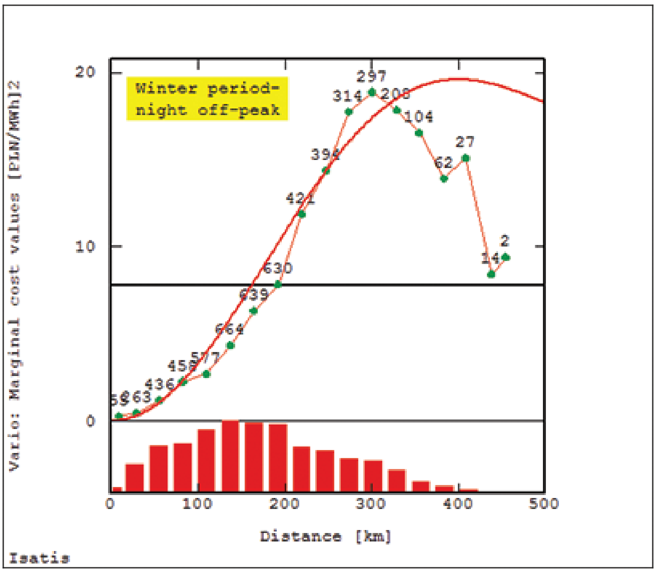

Figure 7. Isotropic variogram of marginal costs [PLN/MWh]^2 in nodes of 220 kV and 400 kV networks for the winter night off-peak period, approximated with theoretical model (J-Bessel model with nugget effect); histogram of distribution showing pairs' size

Source: own calculations.

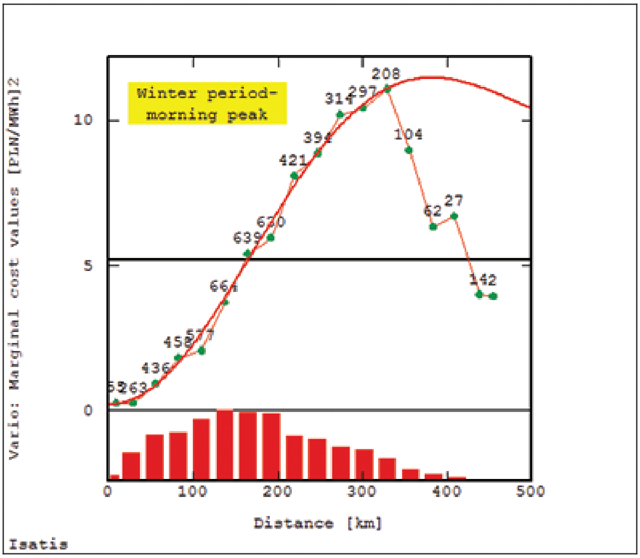

Figure 8. Isotropic variogram of marginal costs [PLN/MWh]^2 in nodes of 220 kV and 400 kV network for the winter morning peak, approximated with theoretical model (J-Bessel model with nugget effect); histogram of distribution showing pairs' size

Source: own calculations.

presented in [8; 9]. In the bottom part of the figures, below the variograms, there are histograms showing the distributions of the numbers of pairs of measured cost values (samples) (Figures 5–8).

The isotropic variograms were computed for the whole considered sample population, i.e. for all the available data ($n = 106$). In all the isotropic variograms one can see a very strong upward trend of the values of variogram function $\gamma(h)$ in both the seasons, particularly strong in the summer and winter morning peak (Figures 5–8). The values of isotropic variogram function $\gamma(h)$ noticeably decline for a distance of 325÷350 m as the number of pairs of measured cost values (presented as histograms in the lower part of Figures 5–8) decreases.

The isotropic variograms of marginal costs were usually approximated with the J-Bessel model combined with the nugget effect model (Table 3). The exception is the isotropic variogram computed for the summer night off-peak period, which was fitted by means of a model structure consisting of the J-Bessel model and the spherical model (Table 3). In the summer season, the highest threshold (sill) variance C appears in the variogram determined for the morning peak. Whereas in winter, the highest threshold (sill) variance is found in the variogram computed for the night off-peak period. Also the strongest nugget effect C_0 occurs in the latter variogram (Table 3). Effect C_0 is also present in the variograms computed for the summer and winter morning peaks, but its share is much smaller (Table 3). The largest influence ranges (a) of 40–50 km occur in the variograms obtained for both the summer and winter night off-peak periods (Table 3).

Table 3. Comparison of geostatistical parameters for models of isotropic variograms of electricity transmission costs in highest voltage nodes for two time instants and seasons for the area of Poland

Time instant, season	Nugget effect C_0 [PLN/MWh]^2	Partial sill variance *C'* [PLN/MWh]^2	Total sill variance *C* [PLN/MWh]^2	Range of influence *a* [km]	Basic model structures
Summer night off-peak period	–	2.01 0.04	2.05	0.03 (scale par.) 0.02	J-Bessel, spherical
Summer morning peak	0.144	5.245	5.39	0.03 (scale par.)	J-Bessel, nugget effect
Winter night off-peak period	–	–	17.30	0.03	J-Bessel
Winter morning peak	0.200	9.94	10.14	0.03	J-Bessel, nugget effect

Source: own calculations.

5.2. Directional variograms of marginal costs

Directional cost variogram roses were analyzed to describe specific trends in the studied process of electricity transmission costs for the area of Poland. The directional variograms were computed for the following directions of investigation: W-E, NW-SW, N-S and NE-SW (Figures 9–12) for a distance of about 500 km, similarly as in the case of the isotropic variograms. Below the directional variograms there are histograms showing the distribution of the number of measured cost pair values (samples) (Figures 9–12).

The directional variograms confirmed the cost variation trends previously observed in the isotropic variograms. In the summer period the values of function $\gamma(h)$ change most markedly along the W-E and NW-SE lines of investigation, especially in the summer morning peak. At the same time in this case the $\gamma(h)$ graphs are much steeper (Figures 9, 10) for the two considered time instants. Whereas the directional variograms (NE-SW, N-S) show a weak variation in $\gamma(h)$ values. For a distance of about 325 m the values of directional variogram function $\gamma(h)$ begin to sharply decrease (Figures 9–12).

The directional variograms for the winter season show slightly different variation trends, i.e. the most marked variation occurs along the three lines: W-E, NW-SE and NE-SW (Figures 11, 12), with the strongest growth along the W-E direction, similarly as for summer. The variation in the values of function $\gamma(h)$ along the directions NW-SE and NE-SW is less distinct. The least variation in costs occurs along the N-S direction. The NE-SW variation direction becomes most apparent in the winter morning peak (Figure 12). Similarly as was found for the summer morning peak (Figure 10), steeper diagrams of directional variogram function $\gamma(h)$ are observed for the winter morning peak (Figure 12).

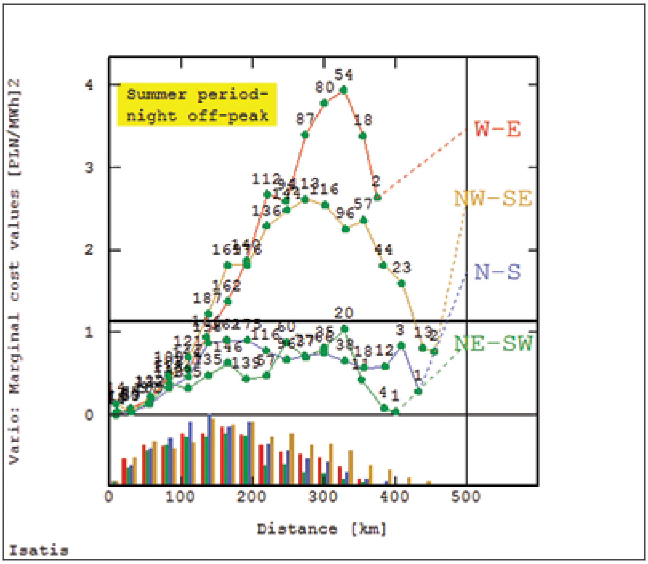

Figure 9. Directional variograms rose for marginal costs [PLN/MWh]^2 in nodes of 220 kV and 400 kV networks for the summer night off-peak period; histogram of distribution showing pairs' size

Source: own calculations.

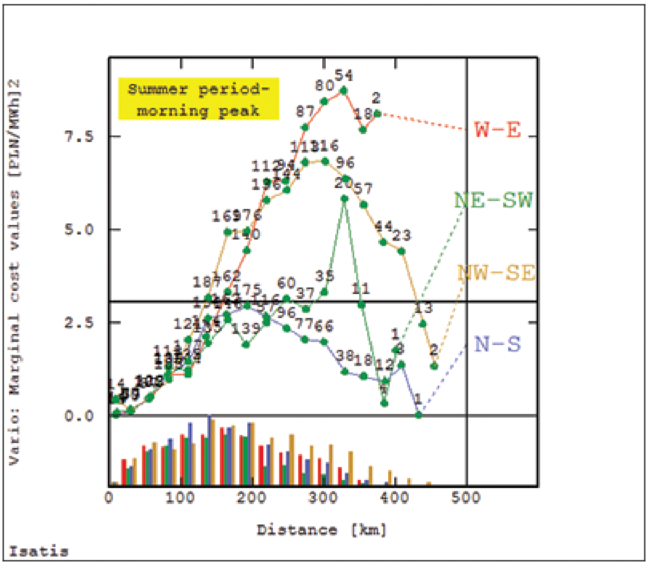

Figure 10. Directional variograms rose for marginal costs [PLN/MWh]^2 in nodes of 220 kV and 400 kV networks for the summer morning peak; histogram of distribution showing pairs' size

Source: own calculations.

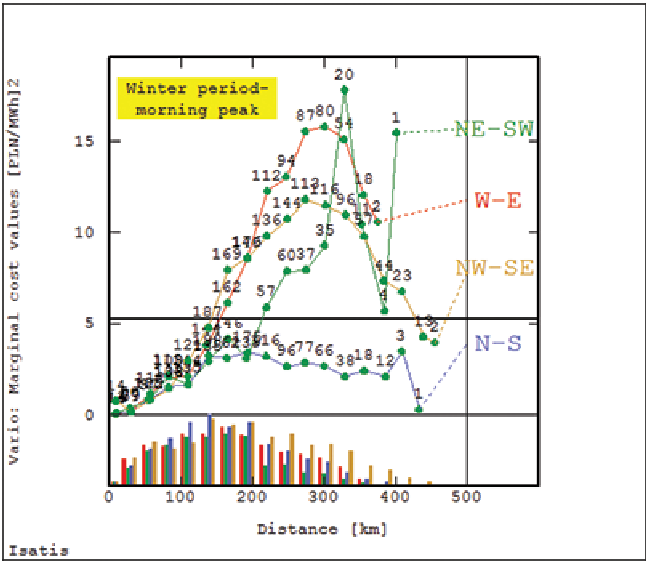

Figure 11. Directional variograms rose for marginal costs [PLN/MWh]^2 in nodes of 220 kV and 400 kV networks for the winter night off-peak period; histogram of distribution showing pairs' size

Source: own calculations.

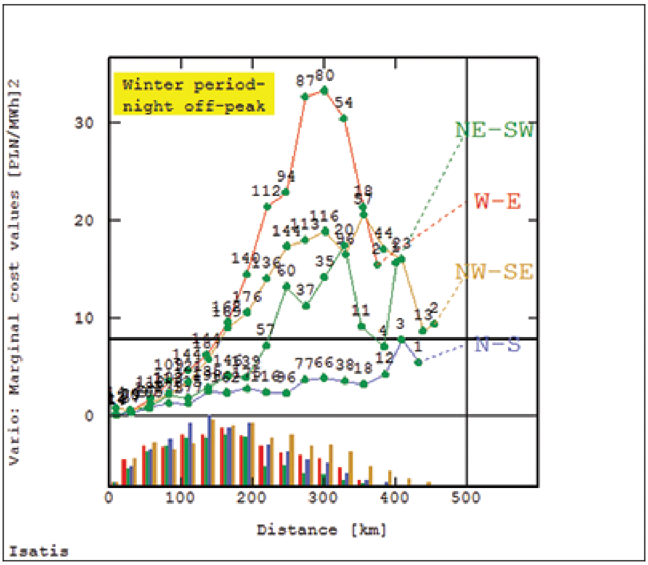

Figure 12. Directional variograms rose for marginal costs [PLN/MWh]^2 in nodes of 220 kV and 400 kV networks for the winter morning peak; histogram of distribution showing pairs' size

Source: own calculations.

6. Conclusions

A model of the distribution of electricity marginal costs for the area of Poland has been created. The 2D geostatistical model of cost variation made it possible to obtain accurate characteristics of the parameter values for the whole area of Poland for two time instants in the summer and winter seasons in the year 2000. The isotropic variogram function, the directional variogram function and the ordinary (block) kriging procedure were used to build the model.

Geostatistical studies showed the behaviour of the cost values to vary. The cost variation trends were found to be: W-E, NW-SE in the summer season and W-E, NW-SE, NE-SW in the winter season. The costs increased most strongly in the W-E direction.

The (2D) geostatistical model made it possible to determine estimated averages Z^* (together with the corresponding value of estimation standard deviation σ_k) in the particular nodes of the two-dimensional grid covering the area of the country and in selected points within this area at a given time.

The proposed methodology constitutes a new approach to the characterization and analysis of network operating conditions for the purposes of network development and designing tariffs. It enables one to indicate locations for new generating and consuming nodes and electric power network connections.

The surface estimation of the costs gives an objective picture of their variation in the particular places of the electric power network, and as the results of the computations show, the costs vary considerably across the country. At the same time, it becomes apparent that the electricity transmission tariff with equal rates for the whole area is a faulty approach to transmission service billing. A much better solution is the nodal tariff, which reflects the actual costs occurring in the particular nodes of the electricity transmission network, or the so-called layered tariff proposed by the authors in [12, 13]. Such transmission tariffs correctly stimulate the behaviour of the network users (electricity consumers and producers), contributing to, among other things, the elimination of network constraints and the reduction of transmission losses.

In the dynamically changing electricity market conditions, the use of the surface methods of estimating marginal costs is one of the factors minimizing the system costs of electricity supply. The proposed methods can be useful for the planning of investments in the electric power network infrastructure.

Literature

[1] Armstrong M., *Basic Linear Geostatistics*, Springer, Berlin 1998.

[2] Albouy Y., *Guidelines for Marginal-cost Analysis of Power System*, World Bank, Energy Department, Washington, D.C., 1984.

[3] *EPRI – Marginal Costing Within Transmission Networks. Optimal Power Flow. MCTN Users Manual*, Laurits R. Christensen Associates, Inc. December 1998.

[4] Isaaks E.H., Srivastava R.M., *An Introduction to Applied Geostatistics*, Oxford University Press, New York, Oxford 1989.

[5] *Marginal Costing Within Transmission Networks. Optimal Power Flow. MCTN Users Manual*, Laurits R. Christensen Associates, Inc. Dec 1998.

[6] Munasinghe M., Warford J.J., *Electricity Pricing, Theory and Case Studies*, World Bank, Johns Hopkins University Press, Baltimore and London, 1982.

[7] Namysłowska-Wilczyńska B., *Geostatystyka – teoria i zastosowania*. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2006.

[8] Namysłowska-Wilczyńska B., Wilczyński A., *Badanie anizotropii zmienności kosztów krańcowych przesyłu energii elektrycznej z użyciem funkcji wariogramu*, XI Międzynarodowa Konferencja Naukowa nt. Aktualne problemy w elektroenergetyce APE'03, Politechnika Gdańska, Gdańsk-Jurata 11–13 czerwca 2003, pp. 225–232.

[9] Namysłowska-Wilczyńska B., Tymorek A., Wilczyński A., *Modelowanie zmian kosztów krańcowych przesyłu energii elektrycznej z wykorzystaniem metod statystyki przestrzennej*, XI Międzynarodowa Konferencja Naukowa nt. Aktualne problemy w elektroenergetyce APE'03, Politechnika Gdańska, Gdańsk-Jurata 11–13 czerwca 2003, pp. 217–224.

[10] Namysłowska-Wilczyńska B., Wilczyński A., *3D electric power demand as a tool for planning electrical power firm's activity by means of geostatistical methods*. Econometrics. Forecasting No 28, Research Papers of Wrocław University of Economics No 91, Wrocław 2010, pp. 95–112.

[11] *Teoria i praktyka kalkulacji kosztów krańcowych w elektroenergetyce*, Fakty i dokumenty Nr III/1997 (7), Polskie Sieci Elektroenergetyczne S.A., Warszawa 1997.

[12] Tymorek A., Wilczyński A., *Transmission Tariff Structure – Assessment and Modification Suggestions*, Proceedings of the International Symposium "Modern Electric Power Systems" MEPS'02, Wrocław University of Technology, Wrocław, 11–13 September, 2002, pp. 31–35.

[13] Tymorek A., Namysłowska-Wilczyńska B., Wilczyński A., Koncepcja warstwowej taryfy przesyłowej, *Rynek Energii* nr 2 (93), 2011, pp. 106–111.

ANALIZA STRUKTURALNA ZMIENNOŚCI KOSZTÓW MARGINALNYCH PRZESYŁU ENERGII ELEKTRYCZNEJ

Streszczenie: W artykule przedstawiono sposób budowy powierzchniowego modelu kosztów marginalnych przesyłu energii elektrycznej siecią 220 kV i 400 kV. Przeprowadzono analizę strukturalną zmienności tych kosztów. Zastosowano w tym celu funkcje wariogramu izotropowego i kierunkowego oraz sporządzono róże wariogramów. Opracowany model dobrze opisujący badane zjawisko, tj. zmienność obszarową i czasową kosztów marginalnych, ma duże walory aplikacyjne w sektorze elektroenergetycznym, szczególnie w sytuacji rozwijania mechanizmów rynkowych w obrocie energią elektryczną. Model ten umożliwił zaobserwowanie istniejących tendencji zróżnicowania kosztów, tj. kierunkowej i czasowej zmienności, co jest przydatne do tworzenia taryf przesyłowych energii elektrycznej, właściwie stymulujących postępowanie użytkowników sieci elektroenergetycznej – dostawców oraz konsumentów energii elektrycznej.

Słowa kluczowe: koszty krańcowe przesyłu, zmienność kosztów, energia elektryczna, wariogram izotropowy, wariogram kierunkowy.