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Structure of electricity production in Poland in the context of using energy carriers - actual condition and forecast

Streszczenie. *W referacie przedstawiono strukturę wytwarzania energii elektrycznej w Polsce z uwzględnieniem wykorzystywanego nośnika energii. Analizie poddano ilość energii wyprodukowanej na bazie węgla kamiennego, węgla brunatnego, gazu oraz w elektrowniach wodnych i wiatrowych. Opracowane zostały modele ekonometryczne produkcji energii elektrycznej. Przy ich wykorzystaniu dokonano prognozy produkcji energii elektrycznej na bazie poszczególnych nośników.* ***(Struktura wytwarzania energii elektrycznej w Polsce w kontekście wykorzystania nośników energii – stan obecny i prognoza****)*

Abstract*. The paper presents the structure of electricity production in Poland taking into account the energy carrier used. The amount of energy produced from hard coal, brown coal, gas, hydropower plants and wind power stations was analysed. Econometric models of electricity production have been developed. Authors present also a forecast of electricity production based on individual energy carriers. They used a results of econometric modelling then.*

Słowa kluczowe: struktura wytwarzania energii elektrycznej, modelowanie ekonometryczne, prognoza produkcji energii elektrycznej
Keywords: structure of electricity production, econometric modeling, forecast of electricity production

Introduction

The modern society is largely dependent on electrical energy. General economy, industry, services, science and administration units, and private lives rely on the universal use of electric, electronic, and IT devices and systems. It is not an overstatement that electrical energy is the basis of the development of the modern human and society. Therefore, the reliability of electrical energy supply is a priority regardless of the domain of human activity. In this context, the issues of access to energy carriers and diversification of electrical energy production using various carriers become relevant.

Utility power plant industry increased its output from 137,798 to 147,394 GWh in 2000–2015. This indicates that the Polish energy industry is growing as is the energy demand.

In Poland, electrical energy is still produced mainly in utility power plants. The installed capacity of power plants in Poland was 34,178 MW, including 30,710 MW in thermal power plants and CHP plants (as of 2015, according to [1]). They have, therefore, been the backbone of the electrical power system. There were 131 thermal utility power plants in Poland in 2015. Energy production in these power plants reached 147,394 GWh. Poland is a country where most electrical and heat energy is produced from fossil fuels, hard coal and brown coal. This provides a high degree of energy independence of about 80%. It can be perceived as a country independent of fuel import. According to the energy policy, coal will remain the primary energy fuel for Poland [2].

Despite the dominant position of coal, new hydropower, wind, gas, and other plants are being built. The number of hydropower plants, for example, increased from 128 in 2000 to 142 in 2015 [1].

The participation of individual types of energy sources in the total capacity in 2015 is shown in Figure 1.

The energy generation structure shown in Figure 1 is very unfavourable. The Polish electrical energy industry is dependent on two primary energy carriers, hard coal and brown coal. For environmental, financial, and economic reasons, the participation of the other carriers should be increased in the total electrical power production balance.

The paper focuses on results of an analysis of energy carrier diversification in the Polish electrical energy industry. It will analyse electrical energy production in utility power plants. Furthermore, it will attempt to build econometric models for the production of energy from various carriers including the impact of economic, financial, sociological, demographic, climatic, and other factors. The authors use the models to forecast energy production for the future.

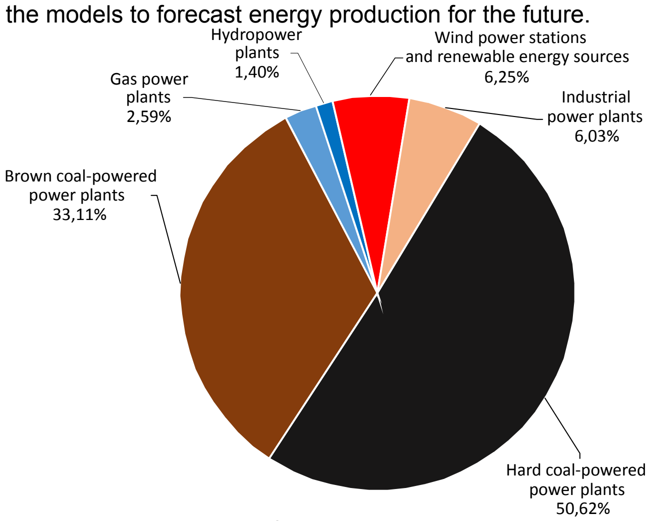

Fig. 1. Percentage share of individual power plant groups in total electrical energy output by fuel type in 2015 [1]

Econometric forecasting

Forecasting is one of the most important scientific methods for learning about the reality and controlling it. As the final result of the forecasting process, forecasts are intended to provide as objective and scientifically grounded information about the selected phenomena as possible and to create a basis for intentional activities aimed to direct the development of the phenomena [4, 8].

Forecasting methods can be divided into two basic groups, quantitative and qualitative methods.

Econometric analyses are of particular practical relevance. Their basic tool is the descriptive econometric model. It is an equation (a system of equations) which approximates key quantitative relationships between investigated phenomena or values. An individual phenomenon is usually affected by multiple varied phenomena (economic, social, demographic, environmental, technical, etc.). The strength of the influence different factors have on the investigated phenomenon is usually diverse; some factors affect it greatly, some a little, and other still, only accidentally. The econometric model is a formalised description of the investigated phenomenon, which takes into consideration only significant elements and leaves out less important ones. The model equation is the external manifestation of the description. The equation represents the relationship between the explained variable, which describes the phenomenon and predictor variables, which describe other phenomena (Fig. 2) [4, 10].

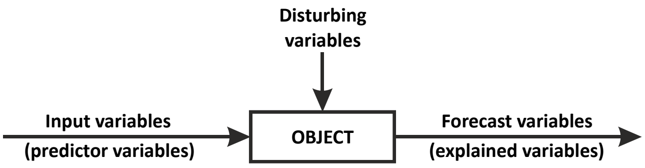

Fig. 2. Econometric model (own figure after [4])

The descriptive econometric model that represents the dependence of variable Y on variables $X_1, X_2, \ldots, X_k$ can be expressed in the general form [10]:

$$Y = f(X_1, X_2, \ldots, X_k, \varepsilon) \tag{1}$$

where: Y – explained variable, X_k – k-th predictor variable, ε – random deviation.

Symbol f above means the analytic notation of predictor variable function, which is determined when constructing the model. The inclusion of random deviations ε in the econometric model is related to its stochastic nature [10].

If relationship (1) is linear, it takes the following form:

$$Y = a_0 + a_1 \cdot X_1 + a_2 \cdot X_2 + \cdots + a_k \cdot X_k + \varepsilon \tag{2}$$

where: $a_0, a_1, a_2, \ldots, a_k$ – structural parameters of the model.

The study involved econometric linear models and thus the authors demonstrate the methods for constructing them further in the paper. The easiest way to determine individual parameters of a linear model is to apply the classic method of least squares. Using matrix notation [10]:

- matrix (vector) of observations of the explained variable:

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \cdots \\ y_k \end{bmatrix} \tag{3}$$

- matrix of observations of predictor variables:

$$X = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1k} \\ 1 & x_{21} & x_{22} & \cdots & x_{2k} \\ 1 & x_{31} & x_{32} & \cdots & x_{3k} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nk} \end{bmatrix} \tag{4}$$

- matrix (vector) of estimates of structural parameters:

$$a = \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_k \end{bmatrix} \tag{5}$$

- matrix (vector) of model reminders:

$$e = \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix} \tag{6}$$

then the least squares criterion is:

$$S = e^T \cdot e \rightarrow min. \tag{7}$$

where:

$$e = y - X \cdot a \tag{8}$$

The dependence with which the vector of estimates of structural parameters can be determined is [10]:

$$a = (X^T \cdot X)^{-1} \cdot X^T \cdot y \tag{9}$$

Random deviation variance is estimated with the following formula [10]:

$$S_e^2 = \frac{e^T \cdot e}{n-k-1} \tag{10}$$

and the matrix of variance and covariance of estimates of structural parameters with formula [10]:

$$D^2(a) = S_e^2 \cdot (X^T \cdot X)^{-1} \tag{11}$$

In matrix (11), elements on the main diagonal are variances $V(a_i)$ (i = 0,1,2,…k) of estimates of structural parameters. Values:

$$S(a_i) = \sqrt{V(a_i)} \tag{12}$$

are standard errors of estimates of structural parameters [10].

With model parameters estimated, it has to be verified whether it describes the investigated phenomena well. The verification involves testing three properties [10]:

- the degree to which the model conforms to empirical data,
- the quality of estimates of structural parameters,
- the distribution of random deviations.

In order to consider the estimators effective, linear regression model assumptions (so-called Gauss–Markov assumptions) must be met:

1) The regression function is linear and constant (its parameters do not change within the set of observations), i.e. the relationship between variables is stable,
2) Predictor variables are non-random; their values are defined real numbers,
3) Observation matrix X, $n\times(k+1)$ is of full rank: rz(X)=k+1<n, i.e.:
   - predictor variables are not collinear, i.e. there is no exact linear dependence between them

   and
   - the number of observations exceeds the number of estimated model parameters,
4) The random component has normal distribution, mean value of 0, and constant standard deviation, and
   - the random component is not autocorrelated,
   - the random component is not correlated with predictor variables,
5) The information in the sample is the only information used to estimate model parameters.

If the econometric model is verified to be correct, it may be used in research related to forecasting and drawing conclusions on the behaviour of the investigated value. There are three basic types of forecasts [3, 10]:

- the point forecast,
- the interval forecast of explained variable values,
- the interval forecast of explained variable expected values.

Statistical data on electrical energy production in Poland

In recent years, the electrical energy produced from individual carriers changed significantly. Electrical energy produced from hard coal, brown coal, gas, water energy, and wind energy is shown in Table 1. The data is shown in Figure 3 as well.

An analysis of the data shown in Table 1 and visualised in Figure 3 demonstrates that the Polish electrical energy sector relies heavily on hard coal and brown coal as was mentioned in the introduction. Although the amount energy from hard coal is being gradually reduced, it still constitutes 50–60% of the total national energy output. The share of brown coal in the energy mix is growing slightly year on year. Gas power plants clearly increased their share from 483 GWh in 2000 to 4,926 GWh in 2015. The amount of energy produced by utility hydropower plants was significantly reduced. It is first and foremost a consequence of excess production capacity in the system and reduced use of pumped storage power plants. The statistical data shows a significant increase in electrical energy produced by wind power stations. Its amount increased from 5.4 GWh in 2000 to 10,858.4 GWh in 2015.

Table 1. Electrical energy production in utility power plants in Poland, in GWh [1]

Year	Power plants				
	hard coal-powered	brown coal-powered	gas	hydro-power	wind-power
1998	79 153	51 797	9	4 203	4,1
1999	79 874	50 741	247	4 142	5
2000	83 671	49 677	483	3 967	5,4
2001	82 227	50 557	792	4 043	14
2002	81 321	48 906	2 124	3 702	61
2003	85 733	51 617	2 868	3 110	124
2004	86 729	52 159	3 263	3 462	142,3
2005	84 983	54 912	5 004	3 528	135,3
2006	92 144	53 559	4 543	2 770	388,4
2007	92 336	51 278	4 411	2 643	494,2
2008	86 600	53 795	4 588	2 465	790,2
2009	85 162	50 953	4 673	2 672	1029
2010	90 282	49 671	4 586	3 155	1664
2011	90 494	52 748	5 007	2 453	3205
2012	85 003	55 341	5 107	2 159	4747
2013	83 338	56 725	3 777	2 658	6004
2014	78 347	53 884	3 893	2 401	7675,6
2015	80 189	53 389	4 926	2 186	10858,4

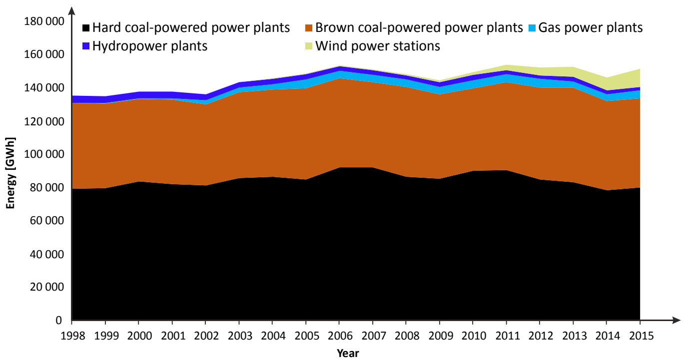

Fig. 3. Electrical energy production in utility power plants in Poland, in GWh (own figure after [1])

Econometric modelling of utility power plant production in Poland

Based on comprehensive statistical research and having analysed in-depth the factors influencing the production of energy in utility power plants, the authors selected over two hundred variables that may potentially affect the production. These included determinants both internal and external to the country. After careful investigation, the following were selected as the predictor variables in the models: X_1 – the population of Poland acc. to balances [thousand of people], X_2 – mean monthly gross salary [PLN], X_3 – mean monthly household's available income per capita [PLN], X_4 – residential resources [thousand pcs], X_5 – gross domestic product [million PLN], X_6 – investment outlays in industry [million PLN], X_7 – sold production in industry [million PLN], X_8 – number of shops [pcs], X_9 – number of catering establishments [pcs], X_{10} – registered business units [pcs], X_{11} – gas consumption from the mains [hm^3], X_{12} – mean monthly cost of household heating fuel per capita [PLN], X_{13} – retail prices of key goods and services – hard coal [PLN], X_{14} – mean annual air temperature [°C], X_{15} – expenditure on new fuel burning techniques and technologies [million PLN], X_{16} – expenditure on water reservoirs and barrages [million PLN], X_{17} – railroad cargo transport [thousand tonnes], X_{18} – private agricultural holdings [thousand pcs] X_{19} – national R&D expenditure [million PLN], X_{20} – apartments with dishwashers [pcs], X_{21} – number of registered unemployed persons [person], X_{22} – expenditures on fixed assets for environment protection [thousand PLN], X_{23} – the number of apartments with microwave ovens [pcs]

Econometric models for energy produced in individual groups of power plants were developed. Models with the highest coefficient of determination are (standard errors of estimates of structural parameters are given in parenthesis):

1. For hard coal-powered power plants:

- Model I

(13) $$Y = -\underset{(2,3471)}{6{,}1257} \cdot X_{15} + \underset{(2373,66)}{90875{,}27}$$

- Model II

(14) $$Y = \underset{(0,000445)}{0{,}000677} \cdot X_{23} + \underset{(2368,08)}{81881{,}09}$$

- Model III

(15) $$Y = \underset{(0,003746)}{0{,}005010} \cdot X_7 + \underset{(3141,72)}{81168{,}28}$$

2. For brown coal-powered power plants:

- Model I

(16) $$Y = \underset{(0,001580)}{0{,}004778} \cdot X_7 + \underset{(1324,87)}{48466{,}02}$$

- Model II

(17) $$Y = \underset{(0,001192)}{0{,}003303} \cdot X_5 + \underset{(1395,89)}{48589{,}47}$$

- Model III

(18) $$Y = \underset{(0,113972)}{0{,}314868} \cdot X_{19} + \underset{(1006,04)}{49762{,}75}$$

3. For gas power plants:

- Model I

(19) $$Y = \underset{(0,000086)}{0{,}000643} \cdot X_{23} - \underset{(0,510512)}{1{,}589758} \cdot X_{15} + \underset{(683,30)}{1648{,}90}$$

- Model II

(20) $$Y = \underset{(0,000768)}{0{,}005208} \cdot X_7 - \underset{(0,548812)}{1{,}880259} \cdot X_{15} + \underset{(822,07)}{887{,}79}$$

- Model III

(21) $$Y = \underset{(0,461478)}{1{,}918232} \cdot X_2 - \underset{(0,000615)}{0{,}000040} \cdot X_{21} - \underset{(2293,56)}{1678{,}39}$$

4. For hydropower plants:
- Model I

(22) $$Y = -\underset{(0,000262)}{0{,}002203} \cdot X_7 + \underset{(220,10)}{4895{,}64}$$

- Model II

(23) $$Y = -\underset{(0,000031)}{0{,}000266} \cdot X_{23} + \underset{(167,21)}{4430{,}65}$$

- Model III

(24) $$Y = -\underset{(0,124092)}{0{,}743420} \cdot X_2 + \underset{(0,000165)}{0{,}000193} \cdot X_{21} + \underset{(616,74)}{4649{,}00}$$

5. For wind power stations:
- Model I

(25) $$Y = \underset{(0,044713)}{0{,}566707} \cdot X_{19} - \underset{(394,68)}{2925{,}87}$$

- Model II

(26) $$Y = \underset{(0,000191)}{0{,}002018} \cdot X_{20} - \underset{(313,97)}{939{,}74}$$

- Model III

(27) $$Y = \underset{(1,205141)}{11{,}660637} \cdot X_{16} - \underset{(471,70)}{2466{,}35}$$

Variables most often used to build models were: X_7 – sold production in the industry [million PLN] (four models),

Table 2. Coefficients of determination and standard errors of estimate for the econometric models of electrical energy production

Power plants:	Model	R^2 [-]	S_e [GWh]
hard coal-powered	I	0,5123	3703,66
	II	0,3337	4156,89
	III	0,1066	4221,46
brown coal-powered	I	0,6788	780,20
	II	0,5385	837,09
	III	0,3372	838,78
gas	I	0,8312	803,54
	II	0,8040	865,99
	III	0,6187	1207,72
hydropower	I	0,8245	295,73
	II	0,8271	293,53
	III	0,8025	324,76
wind power	I	0,9146	721,38
	II	0,8813	850,49
	III	0,8619	917,32

X_{15} – expenditure on new fuel burning techniques and technologies [million PLN] (three models), and X_{23} – apartments with microwave ovens [pcs] (three models). Most of the constructed models are causal models. Some models, however, are symptomatic models (models 14, 19, 23, 24, 26, and 27).

For these models, adjusted coefficient of determination R^2 and standard error of estimate S_e, were determined as measures of model quality. The coefficient of determination specifies what part of the variability of the investigated explained variable is the part determined by the predictor variables used in the model. The standard error of estimate indicates how much the actual value of the explained variable differs on average from the value determined by the model. Values R^2 and S_e for the models are shown in Table 2.

Forecast of utility power plant energy production in Poland

A medium-term forecast of electrical energy production for 2015–2025 was created based on the econometric models. The forecast values are shown in Table 3 and visualised in Figures 4–8.

The forecasts assume constant trend of all predictor variables. The above-mentioned assumption was made following an in-depth analysis of the statistical data and numerous consultations with economic experts.

The values in Table 3 and Figures 4–8 are point forecast values for energy production. The mean forecast error S_{pT} and forecast interval limits are important elements of the forecasting process. The mean forecast error specifies the value by which forecasts will differ on average from the actual values of the forecast variable. Forecast interval limits determine, with an a priori known probability called the forecast reliability, the interval that contains the unknown value of the forecast variable in the forecast period. The interval is defined as follows:

(28) $$P\{dy_T^* < y_T < gy_T^*\} = \beta$$

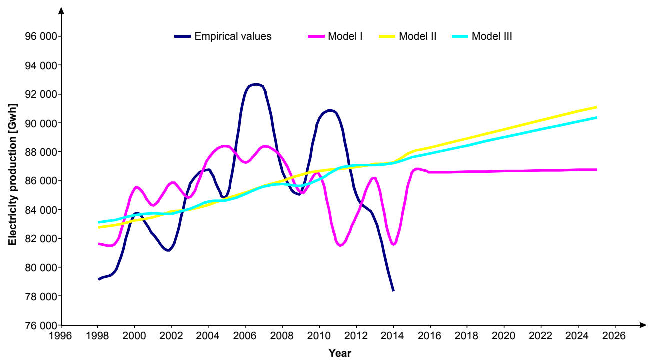

Fig. 4. Empirical values and forecast of electrical energy production in utility hard coal power plants

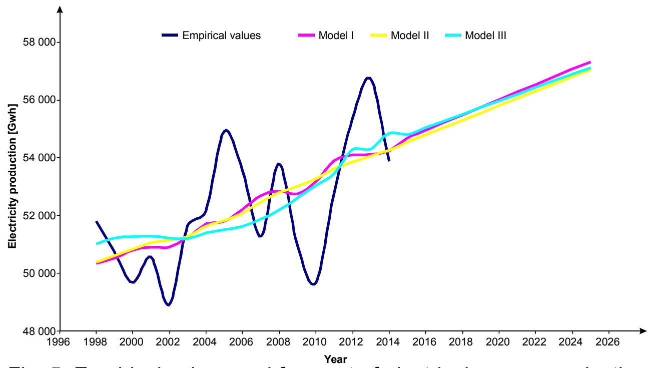

Fig. 5. Empirical values and forecast of electrical energy production in utility brown coal power plants

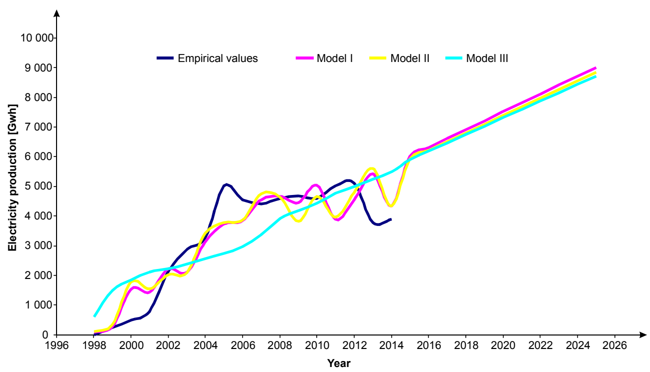

Fig. 6. Empirical values and forecast of electrical energy production in gas utility power plants

Table 3. Forecast electrical energy production in utility power plants in Poland for 2015–2025, in GWh

Year	Hard coal-powered power plants			Brown coal-powered power plants			Gas power plants			Hydropower plants			Wind power stations		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
2015	86556	87990	87632	54689	54547	54808	6013	5905	5901	2054	2029	2033	6803	7385	7601
2016	86577	88301	87909	54953	54798	55040	6314	6199	6184	1932	1906	1914	7996	8415	8778
2017	86598	88612	88185	55217	55049	55273	6615	6493	6466	1811	1784	1794	9266	9508	10043
2018	86619	88923	88462	55481	55300	55505	6916	6787	6749	1689	1662	1674	10613	10663	11394
2019	86640	89234	88739	55745	55551	55737	7217	7081	7032	1567	1540	1555	12036	11882	12831
2020	86661	89545	89016	56008	55802	55969	7517	7376	7314	1445	1417	1435	13535	13163	14355
2021	86682	89856	89292	56272	56053	56201	7818	7670	7597	1324	1295	1315	15112	14507	15966
2022	86703	90167	89569	56536	56303	56433	8119	7964	7879	1202	1173	1196	16764	15914	17663
2023	86725	90478	89846	56800	56554	56665	8420	8258	8162	1080	1051	1076	18494	17383	19447
2024	86746	90789	90123	57064	56805	56897	8721	8552	8444	959	928	956	20300	18915	21318
2025	86767	91100	90399	57328	57056	57129	9022	8846	8727	837	806	837	22183	20510	23275

Table 4. Mean error and forecast interval limits for the forecast of electrical energy production in utility power plants in Poland for 2015–2025, in GWh

Year	Hard coal-powered power plants			Brown coal-powered power plants			Gas power plants			Hydropower plants			Wind power stations		
	I	II	III	I	II		I	II	III	I	II		I	II	III
S_{pT}	3861	5800	5859	2471	2565	2587	1121	1203	1692	410	410	455	1015	1998	2435
dy^*_{2025}	79198	79732	78916	52485	52029	52058	6824	6489	5411	33	4	0	20193	16595	18503
gy^*_{2025}	94335	102467	101883	62170	62083	62200	11219	11203	12043	1642	1609	1728	24172	24426	28047

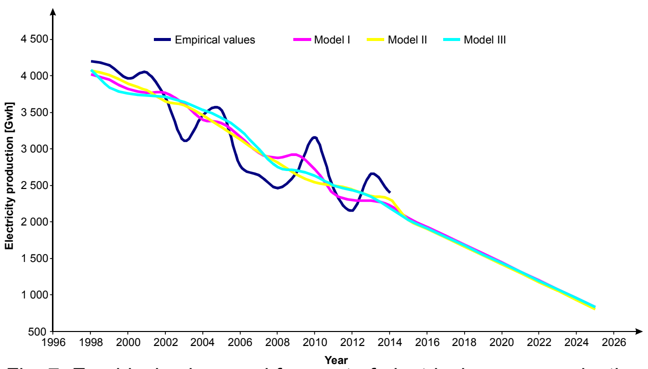

Fig. 7. Empirical values and forecast of electrical energy production in utility hydropower plants

Mean forecast error and forecast intervals for the assumed forecast reliability β = 0.95 are shown in Table 4. Due to text length limitations, the forecast intervals were limited to the last year of the forecast, i.e. 2025.

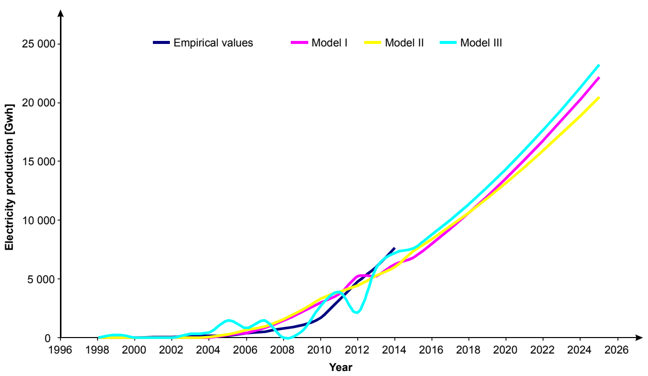

Fig. 8. Empirical values and forecast of electrical energy production in utility wind power plants

Summary

The current structure of electrical energy production is very unfavourable. Its analysis indicates that the Polish electrical power industry is dependent on two primary energy carriers, hard coal and brown coal. The study was designed to build econometric models of electrical energy production in various power plants in Poland. They were used in forecasts and to attempt to answer the question whether a change in the energy production structure can be expected in the nearest future. The analyses yielded the following conclusions:

1. Although negative effects of thermal power plants are widely recognised, electrical energy production from hard and brown coal will continue to increase in the years to come. It is forecast that the output of electrical energy from hard coal in Poland will not be affected significantly by gradually increasing coal production costs.
2. The output of gas power plants will increase as well. These power plants are more environmentally friendly than coal power plants. Apart from environmental issues, the increase of the capacity of these power plants will be affected by slightly more stable gas market related to the operation of the gas terminal in Świnoujście.
3. The production of electrical energy in utility hydropower plants has been dwindling for several years. It is first and foremost a consequence of excess production capacity in the power system and reduced periods of use of pumped storage power plants and the amount of energy produced by them. Note that energy production in large run-of-river hydropower plants is relatively stable.
4. The largest growth in energy production is forecast for wind power stations, which results from numerous investments in such objects in the recent years.

5. Electrical energy production models for brown coal, gas, hydropower, and wind plants can be considered very good, models for hard coal power plants are rather unreliable (maximum R^2 = 0.5123). It is related to the lack of significant correlation between the amount of electrical energy produced from hard coal and any economic, financial, sociological, etc. factors. The production is affected by numerous determinants simultaneously, including state and international policy and fuel prices on international markets.
6. Although the econometric models are based on various predictor variables, their forecasts yield similar results. It demonstrates a good reliability of the forecasts.

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