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SELECTED ISSUES OF COAL-FIRED POWER GENERATION IN TERMS OF MAINTAINING ITS HIGH SHARE IN THE FUTURE STRUCTURE OF ELECTRICITY GENERATION IN POLAND

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Abstract:
The Polish economy is one of the most dynamically developing economies in Europe. However, this development over the next 30 years is threatened by the lack of adequate supply of cheap and reliable energy. This is due to an array of negligence and delays in the expansion and reconstruction of the energy system. Due to the increasingly urgent need to solve this problem, many concepts about the direction in which the development of the Polish power system should go have emerged. This article presents arguments emphasising the advisability of maintaining the maximum high share of coal-fired power plants in the future structure of power generation. There is proven that raw materials in Poland may ensure stable development of the economy for next 100 years. Also, thanks to new technologies, CO2 emissions may by reduced by half.

Keywords: coal power engineering, conventional power engineering, renewable energy sources, power generation system, European Union

Introduction

The coming years will be very important from the point of view of the development of the Polish power industry. This is due to a number of factors, including the need to secure energy supplies for a constantly developing economy, the need to meet international commitments to reduce greenhouse gas emissions, and the need to rebuild and expand the energy sector, which has been neglected since the political changes of the late 1980s and early 1990s.

The basis of the Polish power industry has always been coal. Currently, more than 80% of electricity is obtained from the combustion of this fuel. Therefore, the situation of Poland in comparison to other European countries is particularly difficult. The global trend of moving away from conventional energy is in contradiction with the needs of the Polish economy. This is because it needs a reliable and cheap energy supply – taking into account the growing demand and the changing load of the system on a daily and annual basis (Strupczewski 2018). The relatively low price per megawatt hour of energy on the primary market and a number of restrictions on pollutant emissions do not benefit investors in making decisions concerning the construction of new generation units. Therefore, it is very important to develop an appropriate scheme for the further development of the Polish power industry on the basis of the current situation and factors that will have an impact in the future.

The goal of the article is to present selected issues related to coal energy in terms of maintaining its high share in the future structure of electricity generation in Poland. Therefore, the current structure of power generation, the raw material base and the steps necessary to adapt the coal-fired units to the requirements of the EU concerning the reduction of emissions of pollutants into the atmosphere are discussed in detail. Authors try to find answers the questions: is it possible to cover future electricity demand in Poland by utilisation of steam coals from local

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coal basins in thermal power plants, what challenges need to be overcame in order to satisfy upcoming emission standards, what disadvantages may occur in Polish power system if current national power policy is continued?

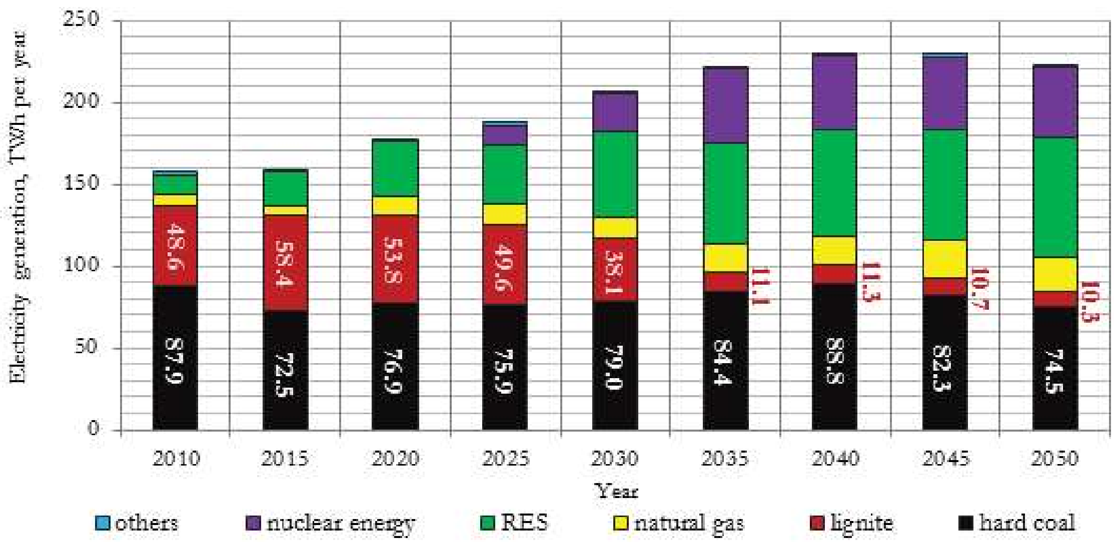
Facts concerning the use of coal fuels in Poland

Poland is an example of a country in which the economy is predominantly dependent on obtaining energy from coal. Long-term operation of coal-fired power plants has resulted in the development of specific technologies, production and service facilities, as well as a scientific base allowing for further intensive development of this technology. The fact that coal-fired power generation is a part of the cultural identity of many regions of the country would seem to be unique on a global scale. This stands in opposition to the current European trends supporting dynamic and profound changes in the structure of energy production in the Member States.

Current structure of electricity generation in Poland

Electricity generation in 2016 amounted to 162.6 TWh in Poland, with consumption of 159.1 TWh and an import-export balance of 2.0 TWh. Production was covered in 47.7% by hard coal-fired units, 30.5% by lignite, 4.7% by gas fuels, and 4.2% by biomass. The share of wind power in domestic production in 2016 amounted to 7.5%. At the end of 2016, installed capacity was 41,397 MW, 46.3% of which was concentrated in hard coal units, 22.5% in lignite units, 15.3% in wind power plants and other RES, 5.6% in utility water power plants, and 3.9% in gas units. The installed RES capacity has been increased by nearly 6.4 GW over 10 years. Average monthly capacity reserves ranged from 5 to 7.8 GW (annual: 5.87 GW), load: 20.6 to 34.6 GW (22.21 GW). In 2016, the ratio of achievable to installed capacity was 69.5%. Peak demand for electricity was recorded on December 15 (25,546 MW), and the lowest on August 15 (11,277 MW). The coefficient of utilisation of installed capacity in RES was only 21.2% (compared to units with a higher degree of controllability – 48.5% for hard coal, 62.6% for lignite) (PSE 2016).

Figure 1. Forecast level of electricity generation in Poland from individual energy sources [own elaboration based on (Ministry of Economy 2015)]



For the assessment of the use of thermal coals in electricity generation processes in the near future, the government plans contained in document (Ministry of Economy 2015) and presented in Figure 1 may be used. These assume a domestic increase in electricity demand by about 45% in 2015-2040 and an annual demand of 220-230 TWh after 2040. This change should take place with the supply of electricity from coal-fired units at the level of 75-90 TWh/year and with the gradual phasing out of lignite-fired units (from nearly 60 TWh/year in 2015 to a relatively constant value of 10-11 TWh/year after 2035). The production capacity of the less calorific coal-fired units is to be covered by renewable energy sources (mainly wind turbines), nuclear power generation and, to a small extent, gas-steam units. However, it should be remembered that the assumptions published in (Ministry of Economy 2015) should be treated only as an indication. A number of problems with the commencement of construction of the first Polish nuclear power plant, as well as economic and political perturbations in the area of renewable energy sources will constitute deviations from these plans, which are necessary to implement with a steadily growing demand for electricity. The assumed gradual phase-out of lignite-based power generation and the decrease in the share of hard coal-fired units in the power mix may be adjusted in the event of difficulties in meeting electricity demand or in regulating generation capacity with fluctuating demand and the supply of sources depending on weather conditions.

The shape of the future energy sector in Poland will also depend on the availability and prices of energy resources, profitability of exploitation of deposits, new infrastructural investments and the level of fees for the use of the environment (including CO_2 emissions) (Popławski, Dudek, Łyp 2015). An additional important variable, although often overlooked, is the social aspect. This concerns mainly nuclear power and environmental protection and is described in detail in paper (Stankiewicz 2014). The dynamically changing economic and technical situation on the European energy market makes it impossible to accurately predict the shape of the Polish power industry in the near future. However, it can be assumed that regardless of the total costs of electricity generation in coal-fired units, coal reserves will constitute an important element of national energy independence and may be decisive in maintaining a hot reserve in case of lack of supply from renewable sources (Dolega 2018).

Resources

Information reaching public opinion suggests that coal resources in Poland, whose extraction is economically viable, are already depleted (Tomaszewski 2018). However, a detailed analysis of the most recent data from 2016 presents a completely different picture of the situation. The current state of hard coal and lignite resources in Poland is presented below and their potential in terms of electricity generation is estimated. This may be one of the pillars of the legitimacy of continuing to base the production structure, from the point of view of energy independence, on these fuels.

Hard coal

As already indicated, hard coal is the most important fuel used to generate electricity in Poland. In 2016, out of 162.6 TWh fed into the grid, 47.7% were covered by power units using this mineral. This is justified by the considerable resources located in the country – according to the World Energy Council, there are 58.59 billion tonnes of hard coal in Poland – 8.3% of the more than 670 billion tonnes documented worldwide (Dolega 2018). Since the end of World War II, a total of 8.70 billion tonnes of this raw material has been mined in Poland. Currently, Poland is ranked 10th in terms of the amount of extracted coal in the world (Polish Geological Institute 2018).

According to the Polish Geological Institute (Polish Geological Institute 2018), by 2050 the annual use of hard coal for electricity generation is expected to reach 70-90 TWh per year. At the turn of 2017, there were 157 documented hard coal deposits in Poland, 46 of which were being exploited. 45.1% of them were well documented and 37.9% were subject to exploitation. 72% of Polish deposits were coal energy from groups 31-33.Industrial resources (fixed in deposit development projects) were estimated at 2.98 billion tonnes of raw material. The location of domestic hard coal deposits is mainly concentrated in 3 areas – the Coal Basins:

- Upper Silesian (GZW), located in an area of 5,600 km2 in the Śląskie and Małopolskievoivodeships, concentrating about 80.3% of the national balance sheet resources located in 140 deposits (45 of which were being exploited in 2016). The greatest still unexploited deposits are considered to be: Kobiór-Pszczyna (3.06 billion tonnes, initially identified), Oświęcim-Polanka (2.14 billion tonnes) and Studzienice 1 (1.34 billion tonnes), while the Janina deposit (1.57 billion tonnes) is the largest deposit currently being exploited,
- Lubelskie (LZW), occupying areas with deposit prospects on the area of 9,100 km2 (1,200 km2 are currently documented deposits), in the Lubelskievoivodeship. In 2016, 1 of 10 documented deposits (representing 19% of the hard coal in Poland) was being exploited in the LZW. The largest unexploited deposits are: KolechowiceNowe (2.26 billion tonnes, initially recognised), Lublin (2.28 billion tonnes, recognised in detail), and Orzechów (1.83 billion tonnes, initially recognied), while the only field being exploited is Bogdanka (764 million tonnes),
- Lower Silesia (DZW), in the southern part of the Lower Silesian Voivodship (120 km2 in close proximity to Wałbrzych and NowaRuda), which has not been exploited since 2000 (about 1% of the national coal is left here, which is divided into 7 local deposits). The largest unexploited deposits include the locations: NowaRuda Pole, PiastRejonWacław – Lech (179.3 million tonnes, recognised in detail), Victoria (123.3 million tonnes, abandoned), Wałbrzych – Gaj (46.0 million tonnes, abandoned). The geological balance sheet resources of the DZW amount to 423.98 million tonnes.

Domestic hard coal extraction in 2016, concentrated within the above-mentioned extraction areas, amounted to 66.48 million tonnes and increased by approx. 2.2% as compared to 2015, but was lower than in 2009 by approx. 10 million tonnes (Szuflicki, Malon, Tymiński 2017; Central Statistical Office 2016) Consumption in 2016 amounted to approx. 71 million tonnes. The main recipient of the coal was the power industry (51% of domestic production, including 66% of all extracted steam coal). This gives an annual coal consumption of 31-33 in the power industry of 35.2 million tonnes with a total domestic output of 54.9 million tonnes. Exports in 2016 exceeded imports of this raw material by 0.8 million tonnes. Applying these figures to the amount of energy generated, it gives an index of hard coal consumption in the power industry at the level of 0.43 tons per each 1 MWh net.

Table 1 presents the geological balance resources of hard coal in the first two basins, with a division into individual categories according to the Polish classification.

Table 1. Geological balance resources of coal (in million tonnes) type 31-33 together with the degree of development [own elaboration based on (Szuflicki, Malon, Tymiński 2017)]

Area	Share of steamcoals, %	overal	A+B	C_1	C_2	D	Off-balance sheet. A+B
Poland	71.6	41 921.30	4 086.46	13 448.45	23 283.82	1 102.58	11891.63
		30.2%	63.5%	44.7%	17.0%	7.9%	32.6%
GZW	68.4	32 066.0	4 007.50	10 339.23	16 616.69	1 102.58	6 992.99
		37.4%	62.8%	53.9%	22.9%	7.9%	50.1%
LZW	87.1	9 825.7	78.9	3 089.8	6 657.0	-	4 898.6
		6.8%	100.0%	13.9%	2.4%	-	7.7%

To evaluate the potential electricity generation from thermal power units supplied from balance resources highlighted in Tab. 1., further assessments were conducted.The operating parameters obtained in 2016 were referred to a model power plant, which reflects the operation of a modern base unit. To calculate the consumption of steam coal in coal-fired power units per 1 MWh and, as a result, identify possible electricity generation in thermal power stations supplied from Polish steam coals basins, the methodology presented in (Cholewiński 2018; Cholewiński 2017) was harnessed. In short, it is based both on the physicochemical properties of selected solid fuels and on the values of performanceparametersof power units, including gross or net thermal efficiency. As a result, the quality and quantity of the flue gas (on the basis of a stoichiometric calculations) can be assessed for every solid fuel and every type of power unit as well as the net and gross electricity generation, coal consumption and emission rates of CO_2, SO_2, NO_x, dust and Hg.

In further analysis it was assumed that a coal-fired unit generates electricity with an average annual total net efficiency of 38%, burns raw fuel with a calorific value of 23 MJ/kg (in working condition) with an annual availability of 82.2%. As a result, estimated consumption of hard coal equals to 3.61 thousand tonnes per year, calculated per 1 MW of power capacity. This corresponds to 0.412 tonnes of coal burned for every 1 MWh of electricity net. Interestingly, if total efficiency increases to 45.5% (the guaranteed value in the case of units 5 and 6 in the Opole Power Plant), with the remaining operating parameters maintained, this number can be reduced by approx. 600 tonnes annualy per each 1 MW of actual capacity and a 0.34 tonnes/ MWh_{net} ratio can be achieved (i.e. approx. 20% lower than that achieved in 2016 in the NPS).

Assuming a modern hard coal-fired unit with an average annual nominal capacity of 1075 MW and 82% availability, annual coal demand will amount to 2.66 million tonnes and will be accompanied by a net generation of 7.74 TWh of electricity.

In the case of doubling the amount of technically and economically viable deposits to be exploited and minimising mining losses, the amount of thermal hard coal that could be used in the domestic power industry would increase to 8.2 billion tonnes. Assuming that all documented deposits (A+B, C1, C2, D) of hard coal from the 31-33 group of 41,921 million tonnes are used, the net amount of energy generated in power plants would amount to nearly 121,862 TWh, which, with annual consumption at the level projected for 2040-2050 (220 TWh), would allow Poland's energy demand to be covered for over 550 years – based only on the combustion of this fuel group.

Analysing the above data, it can be concluded that the hard coal seams available in Poland are sufficient for many years of exploitation for the needs of the Polish power and heating industry. Importantly, even though the location, composition and abundance of deposits are well known, their operability and therefore their potential output in the future may differ. According to (Kassenberg, Wilczyński 2018) somewhat less than 14% of the undeveloped fields are profitable for production. Taking into account production losses of 30-60%, this gives a total production potential of 2.35-4.11 billion tonnes of unexploited deposits, which, while maintaining the utilisation rate in 2016, gives the potential lifetime of hard coal units of 33-58 years.

It should be noted, however, that along with the development of mining techniques and overcoming organisational, social and economic barriers, national coal reserves may increase significantly. Examples may be the following deposits: Kobiór – Pszczyna (GZW), where an estimated 3.06 billion tonnes of energy raw material is located, KolechowiceNowe (LZW, 2.26 billion tonnes), and Lublin (LZW, 2.28 billion tonnes); however, their exploitation would require undertaking integrated political, social and technical measures, difficult to implement in the still unclear situation on the domestic fuel market and environmental charges (e.g. CO_2 tax, fluctuating between 7.5 to even 45 EUR'10 for each 1 tonne of the material) (Ministry of Economy 2015).

Lignite

Geological deposits of lignite in Poland in 2016 amount to 23.45 billion tonnes. Out of 91 documented deposits, only 9 were being worked (they accounted for a total of 1.35 billion tonnes, which only corresponded to 6% of Poland's reserves of this raw material). Sources of lignite mining at the beginning of 2017 included the following mines (the most important deposits with coal mining in 2016 and estimated resources are noted in brackets): Bełchatów (BełchatówSzczerców – 23.94 million tonnes per year, with reserves equal to 813.66 million tonnes, Belchatow-Bełchatów fields - 16.24 million tonnes and 89.33 million tonnes) Turów (bed of the same name – 7.53 million tonnes 353.47 Mt), Adamów (bed of the same name – 2.94 m tonnes and 15.22 million tonnes, Koźmin – 0.51 million tons and 11.22 million tons), Konin (Pątnów IV – 5.19 million tonnes and 14.71 million tonnes, Tomisławice – 2.29 million tonnes and 44.92 million tonnes, Drzewce – 2.15 million tonnes and 9.83 million tonnes) and

Sienawa (Sienawa I – 0.07 million tonnes and 1.30 million tonnes).Outside the deposits already exploited, a huge amount of brown coal (with a minimum weighted average calorific value of 6.5 MJ/kg at 50% relative humidity) are in the balance of identified deposits in regions such as Lower Silesia (6,260 million tonnes in 14 beds, the Legnica field north 1,723 million tonnes, Ścinawa 1,767 million tonnes, Legnica-field west 864 million tonnes, Legnica-field east 830 million tonnes, Radomierzyce 349 million tonnes, Ruja 345 million tons), Kujawsko-Pomorskie (902 million tonnes in 8 deposits, including Więcbork 509 million tonnes), Lublin (180 million tonnes in two beds, including all of the balance in the Trzydnikbed) Lubuskie (5,909 Mt in 21 beds, including the bed: Gubin and 352 million tonnes, Gubin II 1,034 million tonnes, Gubin-Zasieki-Brody 2,019 million tons, Torzym 844 million tonnes, Lubsko 341 million tonnes), Łódź (2,241 million tonnes in 9 fields, including Rogóźno 419 million tonnes, and Złoczew 612 million tonnes), Mazowieckie (93 million tonnes in 4 beds), Opole (approx. 3 million tonnes in the three fields), and Wielkopolska (8,043 million tonnes in 31 fields, including: Czempin 1,035 million tonnes, Gostyń 1,989 million tons, Krzywin 667 million tonnes, Mosina 1,495 million tonnes, Oczkowice 996 million tonnes, Szamotuły 746 million tonnes, Trzcianka 300 million tonnes). In addition to the above-mentioned, in Poland there are 11 lignite deposits with resources of 100-300 million tonnes, 16 more concentrating from 10 to 100 million tonnes of raw material each and 18 from the range of 1-10 million tonnes (Szuflicki, Malon, Tymiński 2017).

Lignite mining in Poland in 2016 amounted to 60.27 million tonnes and decreased by 4.5% compared to 2015. Raw material management almost entirely took place in the neighbouring power plants (Bełchatów, Turów, Pątnów I and II, Konin, Adamów – until the closure at the beginning of 2018) and combined heat and power plants (Central Statistical Office 2017). In 2016, in the case of Polish lignite-fired power units, the fuel utilisation rate – converted into electricity generated – amounted to 1.18 tonnes of raw material per 1 MWh net in 2016.

The identified resources and consumption of lignite in Poland – as in the case of hard coals – referred to the model power station already mentioned (total net efficiency of 38% and an annual availability of 82.2%), burning coal with a calorific value of 8 MJ/kg would require 10.37 thousand tonnes of raw material for every 1 MW of net (1.18 tonnes per 1 MWh of net), and after raising the efficiency of up to 45.5% – 8.66 thousand. t/MWh (0.99 t/MWh_{net}– by approx. 16% less than estimated by the actual data of 2016). The 1,075 MW class unit would burn 7.65 million tons of fuel annually, giving 7.74 TWh of electricity to the grid. Thus, assuming that the power plant would operate for 30 years, the power project would require the concentration of approx. 230 million tonnes of recoverable fuel in the close vicinity of the power unit.

Assuming the use of all documented lignite (A+B, C1, C2, D) – in an amount of 23,451 million tonnes – the amount of energy generated in power stations of the above parameters would be close to 23,712 TWh.With an annual consumption level projected for the years 2040-2050 (220 TWh), this would allow – at the moment of basing the whole electricity on lignite

– would cover Polish energy needs for a period of nearly 108 years. If current production levels (51.2 TWh) were met, this time would be extended by nearly 300 years. When the share of lignite deposits with production potential is determined, the above values will be proportionally lower.

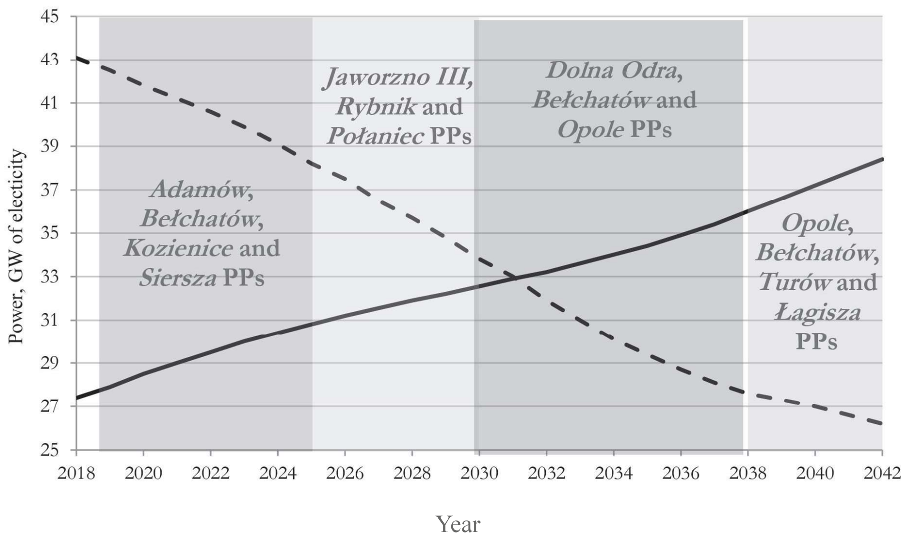
Challenges for coal-fired power generation

In the development programme published in (Ministry of Economy 2015), hard coal should, over the next 30 years, generate 75-90 TWh of electricity each year. The analyses assume that with the construction of a nuclear power plant and the development of RES, the amount of electricity fed into the grid from lignite-fired units will be reduced by 80% between 2040 and 2050 compared to 2015. This is due to the increasingly stringent environmental standards imposed by the EU and the lack of decisions on the exploitation of new deposits of this fuel. Significantly, however, the departure from this fuel group will be accompanied by a systematic increase in energy demand (from approximately 166 TWh in 2016 to nearly 230 TWh in 2045), which should theoretically replace lignite-fired units in PPS with units based on RES, natural gas or those using nuclear reactors.

Reconstruction of generation capacity

One of the main problems of the Polish conventional energy sector is the age of generation units. Only 25% of them were built earlier (?) than 20 years ago (Wierzbowski, Filipiak, Łyżwa 2017). Assuming that the average operating time of a coal-fired power plant is 40 to 45 years, we can speak of an alarming state of generation units, as 63% of them are already over 30 years old. A similar state of affairs applies to transmission lines, 47% of which are over 40 years old. This means that it is inevitable that individual units will have to be shut down from work for PSE (the PPS operator). Figure 2 shows an increase in electricity demand (continuous line) in relation to power losses due to the shutdown of individual power units. Analysing the course of the curves, it is obvious that after 2030 the situation of the Polish power system will become critical due to the decrease in generation capacity being below the demand of the economy.

Figure 2. Visualisation of the change in energy demand in Poland (continuous line) and the decrease in generation capacity (dashed line) as a result of shutting down part of the power units in individual coal-fired power plants. This elaboration is based on (Wierzbowski, Filipiak, Łyżwa 2017).



The response to this is, of course, the construction of new generation units. Such investments have indeed been undertaken. On 19 December 2017, the most modern power unit with a capacity of 1,050 MWe at the Kozienice Power Plant in Poland was commissioned. It is powered by hard coal. Units 5 and 6 of the Opole Power Plant are also in the final stage of construction, each with a capacity of 900 MWe. The first unit is to be commissioned in the second half of 2018 and the second in the first half of 2019. The construction of these units is the largest single infrastructure investment in Poland since 1989. Another large investment is the construction of a 950 MWe power unit at the Jaworzno power plant. Completion of construction is planned for the fourth quarter of 2019. These generating units are blocks for supercritical parameters. This means a high net efficiency of more than 45%. In addition, they will comply with all emission limits. However, these investments are the only ones that have been completed or are at an advanced stage of development. It should be remembered that the construction time of a power unit from the stage of investment analysis to commissioning is about 10 years (Pawlik 2013). These units will not replace those withdrawn from the system.It is therefore important to look for solutions to this problem. Some of the units to be shut down in the future may become an element of the cold reserve intervention system. This concept is based on the use of selected generation units in the event of a capacity shortfall. As a result of two tender procedures in 2013 and 2014, the transmission system operator obtained 830 MWe of intervention reserve owned by TAURON Wytwarzanie S.A.. The system can run until the end of 2019. However, these are ad hoc measures and they cannot in the long run determine the security of the energy supply. Confirmation of this fact is provided by the events of September 2015, when the combination of many factors such as high temperature, low water level, failures and planned renovations resulted in the first interruptions in the supply of energy for industrial customers in many years.

The issue of new investments in high-capacity generation units remains open. Investments in professional power engineering are extremely capital intensive. They are also based on an ROI period normally exceeding 20 years. In such a long period of time it is impossible to accurately determine the future situation on the dynamically changing market. An additional threat is also the fact that energy often serves as an element of pressure in local and global politics. This results in the implementation by state authorities of decisions that are contrary to the principles of the market economy.

Another factor hindering the development of coal-fired power generation is low energy prices in the competitive market (Tab.2). The answer to this phenomenon may be the introduction of an instrument such as differential contracts. It consists in providing investors with a fixed reference price at which the operator will buy back the energy produced by them. If the actual market price exceeds the amount specified in the contract, the investor returns the price difference to the operator. Such a solution increases the profitability of the investment and shortens the period for its return.

Table 2. Average electricity prices per MWh on the competitive market in individual years. (Information from the President of the Energy Regulatory Office No. 153/2014; 12/2015; 13/2016; 17/2017; 28/2018; 45/2018).

Year	2013	2014	2015	2016	2017	I quarter 2018
PLN/MWh	181.55	163.58	169.99	169.70	163.70	174.95

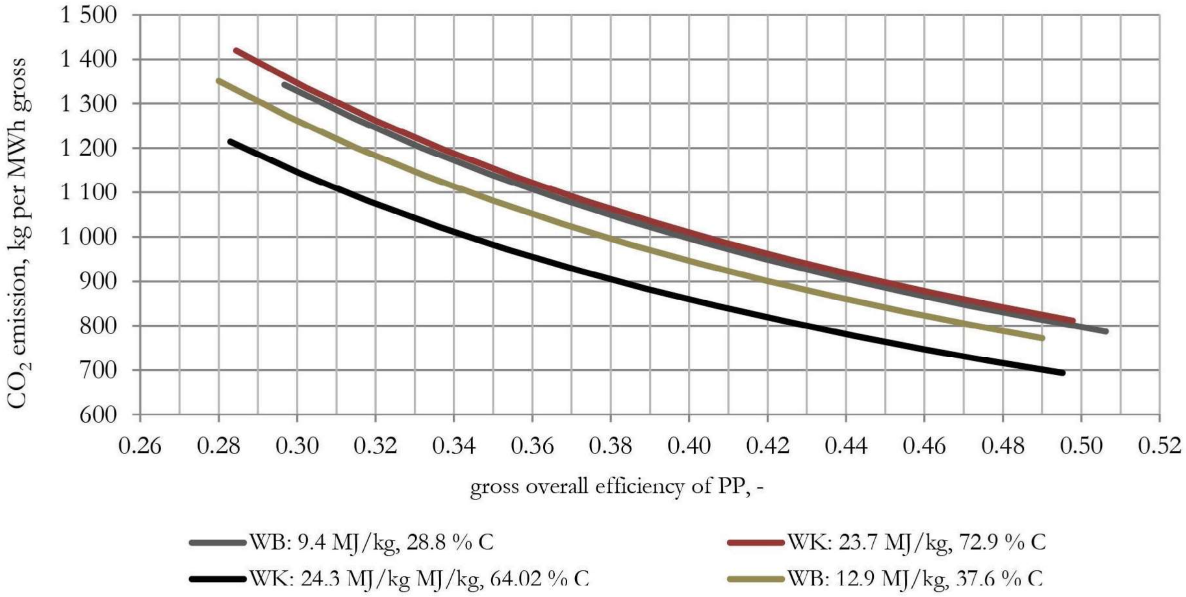
Reduction of pollutant emissions

Poland, as an EU member state, must adapt its energy sector to the requirements of the Energy and Climate Package.

The solution motivating the EU Member States to implement the declarations included in the package are, among others, charges for carbon dioxide emissions (carbon tax) (Czaplicki 2017). At present, the European Emissions Trading System (EU ETS) is a tool for controlling CO_2 emission levels in Poland, resulting from the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). Modelled on the American CCX exchange (Chicago Climate Exchange), it has been operating since 2005. It provides for the allocation of emission allowances to business and their turnover – buying or selling – depending on the actual level of emissions. However, it is being systematically reorganised over the next few years, imposing stricter emission limits on the member states (number of allowances allocated), as well as taking steps to alleviate the structural imbalance between supply and demand (due to the recession in allowance prices after the financial crisis in 2009). The changes will include the introduction of the MSR (Market Stability Reserve) sales mechanism, assuming the surpluses of allowances in order to maintain the level of their prices – in order to effectively promote changes within the high emission industry. Expected price levels per 1 tonne of carbon dioxide may reach 25-30 EUR already at the beginning of the 2020s (European Commission 2018; gramwzielone.pl 2018). Moreover, the so-called winter package assumes a final departure in 2031 from financial support on the market by power companies whose carbon dioxide emissions exceed 550-700 grammes per 1 kWh of generated power (wnp.pl 2017). This is to form the basis for the implementation of RES technologies in the national power system.

All the above changes will undoubtedly be a challenge for the Polish power sector using thermal coal. Importantly, in order to limit CO_2 emissions per MWh net generated electricity, it will be necessary to increase the total net efficiency of the power units, including reduced load operation. Fig. 3. presents an analysis of the CO_2 emission factor per MWh of electric energy depending on the achieved total efficiency, calculated for model units equipped with pulverised coal-fired boilers according to theabovementioned (section 2.2.1) model (Cholewiński 2018; Cholewiński 2017). As may be seen, it is becoming advisable to use solid fuels with the highest possible calorific value and the lowest carbon content (which is a substrate in the reaction to carbon dioxide formation) and to increase net efficiency (e.g. through the use of boilers for ultra-supercritical parameters, reduction in individual needs of blocks, adequate energy management, etc.). In the first case, differences in CO_2 emissions of 100-200 kg/MWh$_{net}$ were obtained for the same efficiency, while in the second case, it was shown that once the net efficiency of 46% was reached, the CO_2 emission factor could reach 750-850 kg/MWh$_{net}$ (in the case of 38% – 900-1050 kg/MWh$_{net}$).

Figure 3. Level of CO2 releases from a coal-fired power plant depending on the fuel being burned and the achieved net total efficiency of the unit – for the case of complete combustion and the content of pure carbon element in ashes and slags at the level of 4% (own elaboration)



Interestingly, even to meet the efficiency requirements of the new units (Tab. 3.), it seems impossible to achieve a CO_2 emission level of 550 kg/MWh. For example, for a gas-steam co-generation unit it is possible to achieve the ratio of 230 kg/MWh with the degree of chemical energy use of fuel at the level of 85% (Pawlik 2013). Therefore, assuming that the coal-fired units continue to be operated, it may be necessary to use CCS (Carbon Capture and Storage) technologies, e.g. oxygen combustion or carbon capture with the use of ethanolamines, which may prove justified even if account is taken of a significant net decrease in plant efficiency due to the supply of oxygen production facilities or the implementation of additional reactors.

Table 3. Suggested net overall efficiency of LCP units according to BAT-AELs (Commission Implementing Decision 2017)

Power	Hard coal		Lignite		Biomass and peat	
	new	existing	new	existing	new	existing
≥ 1000 MW$_t$	45 – 46	33.5 – 44	41.5 – 44	33.5 – 42.5	33.5–>38	28 – 38
< 1000 MW$_t$	36.5 – 46	32.5 – 41.5	36.5 – 44	31.5 – 39.5		

In addition to CO_2, the functioning of the national coal-based electricity sector also involves emissions of pollutants such as nitrogen oxides (NO, NO_2, N_2O), sulphur oxide (SO_2), mercury (elemental and oxidised), carbon monoxide, hydrochlorines, hydrofluorides, and dust.

Significantly, however, even despite the scale of combustion of steam coal in the country, the activities classified - according to SNAP classification, group 01 - as *Combustion Processes in the energy production and transformation sector*, throughout the country,in 2016 were only the major source of SO_2 (44.9% of the national emission determined at 581.3 thousand tonnes), NO_x (24.7% of the 726.4 thousand tonnes, with road transport – 31.8%) and mercury (50.1%, which amounted to 5,184 kg) (Kocoł 2017).

In accordance with the BAT conclusions adopted in 2017, all combustion installations of fuels with a capacity supplied with fuel > 50 MW will be obliged to use the best available techniques in the field of atmosphere protection and, on their basis, to comply with restrictive levels of pollutant emissions such as NO_x, SO_2, CO, HCl, HF, Hg and dusts (Kocoł 2017; wszystkooemisjach.pl 2018). In addition, in the case of coal-fired power plants with a thermal input of more than 300 MW, continuous monitoring of the emission levels of the following substances maintained or introduced will be required: NO_x, CO, SO_2, dust and mercury. At the same time, it should not be forgotten that simply adapting its technology to these emission standards does not relieve power plants of the need to pay for the use of the environment. According to (Commission Implementing Decision 2017) , each 1 kg of SO_2 or NO_x emitted costs 0.53 PLN, Hg – 190.68 PLN, dust – 0.35-0.58 PLN, and CO – 0.11 PLN. The conditions resulting from BAT can be met through the various types of technological measures listed in Table 4. Moreover, the emissions of the pollutants already mentioned can be significantly reduced by replacing old generation units with new ones and by co-combustion with coal of fuels treated as biomass in accordance with the applicable regulations. For example, a wood-based energy raw material can contain, per MJ of calorific value, much smaller amounts of sulphur, mineral matter and mercury, which, in addition to the introduction of "green energy" into the system, can have an additional environmental effect in the form of reduced emissions of mercury, sulphur oxides and fly ash.Due to this it will be possible to achieve lower pollutant emissions, and not only of CO_2 (tab.5).

Table 4. Summary of measures suggested, among others, as part of the BAT conclusions, aimed at limiting selected aspects included in the negative impact of coal-fired power plants with the Clausius-Rankine cycle on the environment [own elaboration on the basis of (Lecomte et al. 2017)]

Aspect	Suggested technological and organisational procedures
overall environmental effectiveness and combustion efficiency	composition of appropriate fuel mixtures; regular maintenance of the furnace; automation of the combustion process; integrated approach to combustion and subsequent capture of pollutants (e.g. NOx); appropriate selection of combustion equipment design; hybrid systems (e.g. associating heat sources within 2 and more thermodynamic circuits); use of highly efficient technologies for simultaneous capture of several pollutants in one process

energyefficiency	optimisation of combustion process parameters; increasing (at the turbine inlet) or decreasing (in the steam turbine condenser) the parameters of the working medium (e.g. through the use of high-strength materials); reduction of energy consumption and heat losses; careful recovery of heat, e.g. from exhaust fumes, by-products of combustion or steam, including the so-called waste heat and latent heat (for preheating air or fuel or as part of polygeneration; so-called „wet stacks" and chimney refrigeration exhaust systems may be used for this purpose); automation of combustion and thermo-flow processes, e.g. within the scope of work with a load other than nominal; carbonisation of water and steam cycle; storage of heat, e.g. within the scope of reducing the negative impact of the operation of blocks with a load lower than nominal on the utility ratios of power plants; increasing the efficiency of internal working machines (turbines, pumps); hybrid systems (e.g. associating heat sources within 2 and more thermodynamic cycles)
waste management	use of wasteless or similar technologies (e.g. production of synthetic gypsum in flue gas desulphurisation installations); recovery of by-products of incineration, e.g. in construction and road engineering; use of high-energy furnace waste in fuel mix; regeneration processes of used elements (e.g. catalysts)
noise emission	appropriate operation and control of equipment; reducing noise emissions by means of sound insulation or sound-absorbing structures and barriers (casings); use of machines with low noise emission coefficient; use of silencers; careful placement of machinery (e.g. in order to use natural sound barriers)
SO_x, HCl and HF emissions to air	optimisation of the combustion process in terms of preventing pollution (so-called low-emission furnaces), utilisation of selective catalytic or non-catalytic reduction of nitrogen oxides; use of highly efficient technologies for simultaneous capture of nitrogen oxides and CO
emissions of NO_x, N_2O and CO to air	use of sorbents fed into the furnace chamber or combustion route (depending on the furnace used); use of absorption techniques (dry, semi-dry and wet), including sea water; combined techniques to remove SO_x, HCl, HF; limitation of flue gas heating above dew point; appropriate selection of fuels (e.g. containing low amounts of sulphur, chlorine and fluorine)
emissions of dust and metal dust to air	use of high efficiency (as far as possible, fly ash grain size) electrostatic and bag filters; use of sorbents and ash agglomerators; use of wet reactors (e.g. absorbers).
emission of mercury to air	use of high efficiency dust collectors (for the capture of mercury adsorbed by fly ash); use of a plant for flue gas desulphurisation (for sorption and oxidation of mercury vapour, including through the use of additives to substrates for use in the removal of sulphur oxides from the boiler exhaust gas); the use of catalysts (eg. within the SCR, in order to oxidise mercury vapour); injection of sorbents of mercury vapour into the flue gas; addition of halogen additives to the flue gas or fuel; pre-treatment of fuels (eg. to remove mercury compounds or to transform fuels towards those more susceptible to reducing Hg emissions); choice of fuels (eg. it is appropriate to reduce the mercury and sulphur in the fuel and increase – in reasonable quantities – chlorine)

Table 5. Annual average (for blocks with operating time >1500 hours per year) permissible concentrations of individual pollutants in the flue gas according to BAT-AELs (Lecomte et al. 2017)

Pollutant	Power, MW_t	Fuel			
		steamcoals		biomass and peat	
		new	existing[4)]	new	existing[4)]
NO_x, mg/m^3_{ref}	< 100	100-150	100-270	70-200	70-250
	100-300	50-100	100-180	50-140	50-180
	≥ 300	50-85	65-175	40-140	40-160
SO_2, mg/m^3_{ref}	< 100	150-200	150-360	15-70	15-100
	100-300	80-150	95-200	< 10-50	< 10-100
	≥ 300	10-75	10-180	< 10-35	< 10-100
CO, mg/m^3_{ref}	< 100	30-140		30-250	
	< 300		30-160		
	≥ 300	5-140		30-80	
HCl[1)], mg/m^3_{ref}	< 100	1-6	2-20	1-15	1-25
	100-300	1-3	1-20	1-15	1-25
	≥ 300			1-15	1-25
HF[2)], mg/m^3_{ref}	< 100	< 1-3	1-7	< 1	< 1,5
	100-300	< 1-2	1-7	< 1	< 1
	≥ 300			< 1	< 1
pyły, mg/m^3_{ref}	< 100	2-5	2-18	2-5	2-15
	100-300	2-5	2-14	2-5	2-12
	300-1000	2-5	2-12	2-5	2-10
	≥ 1000	2-5	2-8		
Hg, $\mu g/m^3_{ref}$	< 300	< 1-3/5 [3)]	< 1-9/10 [3)]	< 1-5	
	≥ 300	< 1-2/4 [3)]	< 1-4/7 [3)]		

[1] gaseous chlorides, expressed as HCl, [2] inorganic gaseous fluorine compounds, expressed as HF, [3]value before slash for hard coals, after slash for brown coals, [4] ≥ 1500 h/year

The introduction of the capacity market

The centralised power market will have a significant impact on the shape of the future power sector in Poland. As a new regulatory tool, it is intended to prevent the occurrence of power shortages in the near future. It will also lead to the dual commodity character of the Polish power industry. Trade will take place on the basis of generated electricity and net disposable power. At present, producers base their activities (apart from possible support schemes) on the production and sale of electricity. The future system will also make it possible to obtain revenue for the provision of a service in the form of generation capacity (hot reserve).

The new model is to be based on auctions during which electricity producers are to offer the Transmission System Operator their available capacity, based on the so-called Dutch model (Pay-as-Clear - PAC). Auctions will be held to determine the price of market equilibrium on the basis of many rounds of classified listings with a decreasing price. According to the PAC formula, sellers submit bids using values which, in their opinion, are as close as possible to the expected market equilibrium price. Such a model will require appropriate risk management and thus the need to select the optimal strategy for participation in the power market (taking into account the assets held by the auction participants, market position, risk appetite, etc.). Participants will stop bidding when the price proposed in a round exceeds the player's tolerable remuneration. This is supposed to allow many smaller electricity producers to participate in covering the prospective demand for capacity and thus provide some kind of investment incentive for potential electricity producers (owners of physical units, power suppliers, transmission and distribution system operators, settlement managers). The auction will be won by entities offering the lowest price with full technological and ownership neutrality. Interestingly, the allocated "capacity" obligations can be traded on the secondary market. An alternative solution, not supported by the Legislator, may also be a discriminatory auction formula (Pay-as-Bid - PAB), promoting sources with the lowest production costs, but depriving bidders of incentives to submit bids reflecting their real marginal costs, which may result in obtaining prices higher than in the case of similar PAC auctions (Saługa 2017)

The introduction of the capacity market is a response to the progressive distortion of the single commodity energy market, which in turn results from the use of energy sources with significant generation instability (i.e. mainly subsidised RES currently having priority in the introduction of capacity into the system). The development of RES leads to a systematic reduction of the operating time of conventional power plants, the abandonment of nominal loads by the aforementioned control blocks (fired with solid, liquid and gaseous fuels) and creates the need to maintain an increasing hot reserve in the system in the event of a loss of supply from wind turbines or solar technologies. As a result, the operation of thermal power plants is becoming less and less cost-effective, and RES implementation poses a real threat to a stable electricity supply. The above-mentioned capacity market is another element which makes it impossible to accurately predict the future shape of the fuel and energy structure in Poland.

Conclusion

The article presents selected technological, economic and environmental aspects related to the further development of the Polish conventional energy sector. In the next 30 years it will be necessary to continue using coal-fired power plants, which – because of their high availability, wide load range, controllability, technological maturity and increasingly less invasive impact on the environment – are the only way to safeguard a secure energy supply. It was shown that the coal resources owned by Poland may, if properly managed, determine national energy security. However, taking into account the changing environmental standards and economic and legal tools implemented, it is necessary to create a national support programme for coal-based power units to support the development of flue gas cleaning technologies, valorisation of solid fuels and to enable the undertaking of steps towards the exploitation of further deposits of fuels in deposits in Poland. The focus should be on creating favourable technical and economic solutions, facilitating the undertaking of new, large investments in this sector – even with the current legal and organisational reality, which is less and less favourable from the point of view of coal-fired power units. One of the most important threats is the vision of not meeting the restrictive CO_2 emission limits, but the existing concepts of commercialisation of combustion in pure oxygen and sequestration of CO_2 from exhaust gases provide a basis for solving this problem in the future.

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