Energy Policy Studies

1(2) / 2018

IGNACY LUKASIEWICZ
ENERGY
POLICY
INSTITUTE

Cover design: Aku Studio

Typesetting: Aleksandra Szewczyk

Proofreading: Robin Gill

Publisher: Ignacy Lukasiewicz Energy Policy Institute

Morawskiego 19 street, 35-321 Rzeszów
eps@instytutpe.pl
tel. + 48 17 85 77 907
http://www.instytutpe.pl/eps/

http://www.instytutpe.pl/en/eps-en/

e-ISSN: 2545-0859

The electronic version of the journal is the original version.

Rzeszów 2018

Ministry of Science and Higher Education
Republic of Poland

"Energy Policy Studies – English language e-edition as a tool for disseminating science" and "Energy Policy Studies – transfer of the best foreign pracities and echange of experience" – the tasks financed as part of contract 687/P-DUN/2018 with the resources of the Minister of Science and Higher Education for science promotion activity.

Contents

ANALYSIS OF CHEMICAL AND PHASE COMPOSITION OF COPPER OXIDE PREPARED BY DIRECT CURRENT SPUTTERING FOR PHOTOVOLTAIC APPLICATIONS

Paulina Sawicka-Chudy[1], Marek Wielgosz[2], Andrzej Wal[1], Bogumił Cieniek[2], Grzegorz Wisz[2], Łukasz Głowa[1], Marian Cholewa[1], Joanna Sawicka[3]

Abstract

This paper presents the application of X-ray fluorescence and X-ray diffraction methods for the study of copper oxide structures as an absorber layer in thin-film solar cells. The layers of copper oxide were applied by direct current magnetron sputtering. Quantitative and qualitative analysis of oxide layers were performed using XRF (X-ray fluorescence). The studies showed a high copper content in both samples, amounting to 98% and 96%, as well as trace amounts of other elements (nickel, lead). The XRD (X-ray diffraction) study showed Cu_2O and Cu_8O phases, amorphism ranging from 24% to 44%, and crystallinity from 55% to 75%. Crystallites of 30 nm were also determined. The aim of the study was to determine the chemical and phase composition of the layers obtained and to determine the degree of their contamination depending on the parameters of the manufacturing technology in terms of their application in photovoltaics. One of the samples showed an advantage both in terms of material and structural composition.

Keywords: XRF, XRD, copper oxide, photovoltaics

Introduction

Copper (II) oxide, (CuO), and copper (I) oxide, (Cu_2O), are materials with semiconductor properties, which are characterized by a p-type semiconductor, with a simple energy interruption (about 1.4 eV for CuO and about 2.2 eV for Cu_2O). Differences in the gap value result from the construction of the crystalline structure (Korkmaz et al. 2016, p. 142; Serin et al. 2005, p. 398). Scientists use many techniques to produce a copper oxides. These include the PLD (Pulse laser deposition) method (Chen et al. 2009, p. 927), magnetron atomization (Sawicka-Chudy et al. 2018, p. 715), or chemical methods (Markworth et al. 2001, p. 2408). The authors decided to verify the parameters of the Cu_2O obtained by DC magnetron sputtering in order to improve the efficiency of the heterojunction based on copper oxide as an absorber in the structure of thin-film solar cells. The aim of the study was to determine the chemical and phase composition of the layers obtained and to determine the degree of their contamination depending on the parameters of the manufacturing technology in terms of their application in photovoltaics.

Sample preparation and test methodology

Series Cu_2O thin film was deposited by DC magnetron sputtering using a modular *PREVAC* platform. N-type Si (100) wafers and glass slides were used as the substrate materials with dimensions of 5x4 and 6x5 mm, respectively. Cu_2O layers were deposited in an Ar (99.9999%) and O_2 (99.999%) mixed atmosphere in different process parameters from a Cu target. The chamber was cleaned thermally before the experiment and the base pressure of the

[1] Department of Biophysics, Faculty of Mathematics and Natural Sciences, University of Rzeszow, 1 Pigonia Street, 35-317 Rzeszow, Poland.
[2] Department of Experimental Physics, Faculty of Mathematics and Natural Sciences, University of Rzeszow, Pigonia 1 Street, Rzeszow 35-317, Poland.
[3] University of Rzeszow, Medical Faculty, Kopisto 2a Street, Rzeszow 35-359, Poland.

vacuum system was $1 \cdot 10^{-5}$ Pa. They were selected on the basis of earlier studies and numerical simulations (Sawicka-Chudy et al. 2018, p. 715; Sawicka-Chudy 2017, p. 71).

The authors present representative layers (P1, P2) from the series. The process parameters are shown in Table 1.

Table 1. Process parameters

Parameter	P1	P2
The distance between the source and substrate [mm]	38	58
Pressure process [Pa]	1.73	2.5
Power [W]	~80	~70
Time [min]	40	60
Oxygen flow rates [cm^3/s]	3	8
Argon flow rates [cm^3/s]	2	2
Substrate temperature [K]	473.15	473.15

In order to determine the chemical composition of the layers, the XRF method was applied. The measurements were made with a Thermo spectrometer type ARL QUANT'X EDXRF Analyzer. To determine the phase composition, the XRD method was applied using a D8 Advance diffractometer with CuKα radiation (α mean = 1.54178 Å) at a constant X-ray tube current of 40kV and 40mA. Peak dilatation and Scherrer's formula were used to determine the average size of crystallites of compounds.

For the determination of elements, the modelless method was implemented in UniQuant ED software. The software records the spectra obtained for different radiation energies and, on the basis of the model, determines the elemental composition that best matches the results obtained. The range of elements detected by the spectrometer starts with fluorine and ends with uranium. In the next stage of the work, the structures of the analyzed oxide layers were examined using X-ray diffraction. The XRD measurement was carried out in coupled theta/2theta mode. The ICDD PDF-2 2012 database was used for Phase Matching.

Results and discussion

XRF analysis of layers

In the case of both samples, due to the low layer thickness (about 220 nm), a signal from the emission of silicon was also obtained. Examples of XRF spectra for both layers at 20 kV X-ray energy are shown in Fig. 1a-1b (for sample P1) and Fig. 1c-1d (for sample P2). The average results obtained from the whole measurement are collected in Table 2. On their basis, it can be concluded that the layer contains only a few traces of metals other than copper.

Figure 1a. Spectrum of elemental composition of the examined micro-area, layer on glass, sample P1

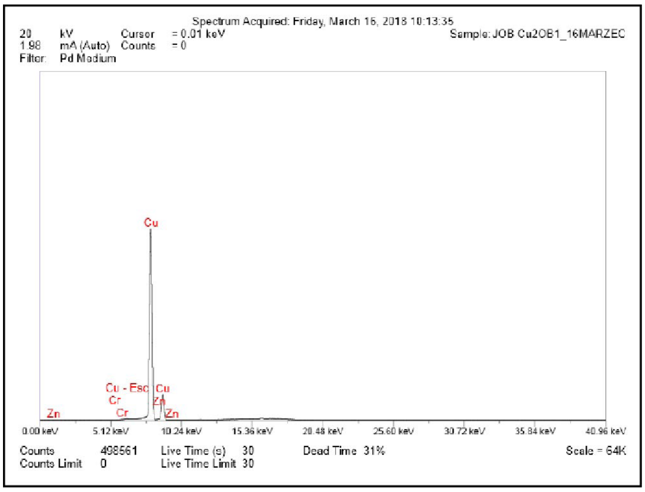


Figure 1b. Spectrum of elemental composition of the examined micro-area, layer on silicon, sample P1

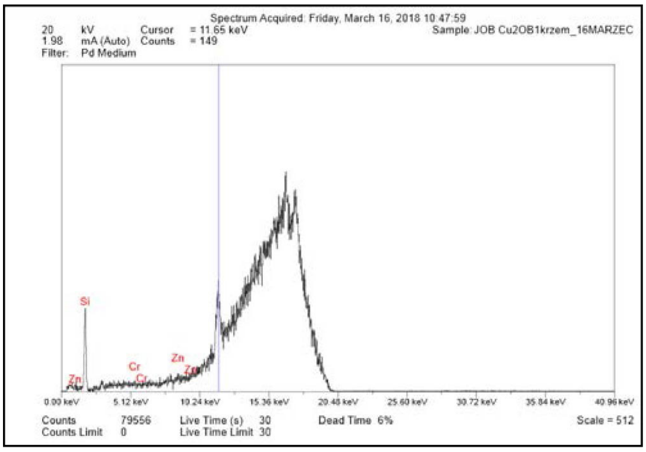


Figure 1c. Spectrum of elemental composition of the examined micro-area, layer on glass, sample P2

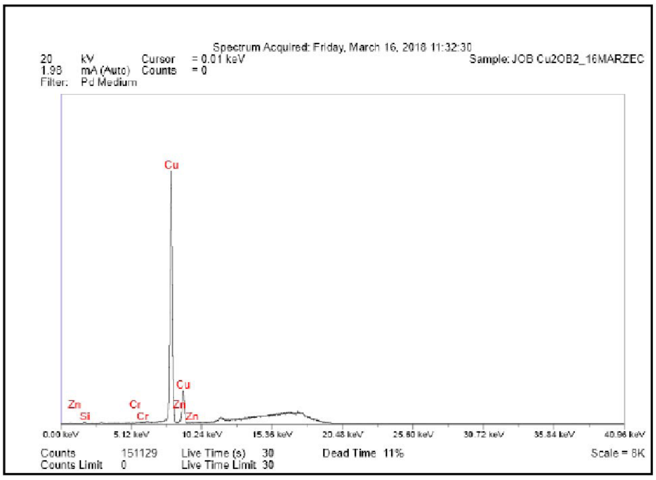


Figure 1d. Spectrum of elemental composition of the micro-area under investigation, layer on silicon, sample P2

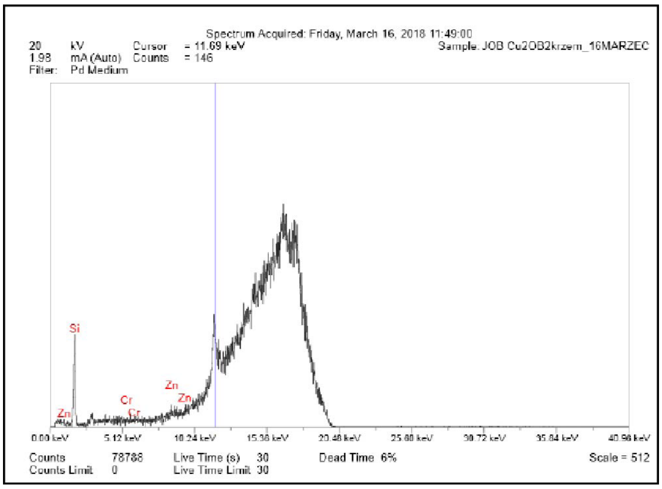


Table 2. Percentage analysis of the composition of copper oxide layers deposited on silicon

Determined element	Content by quantitative analysis XRF [%].	
	P1	P2
Cu	98.94	96.330
Ni	1.020	0.966
Pb	0.030	-
Px	0.010	-
Fe	-	0.648
Mn	-	0.630
Co	-	0.577
Cl	-	0.310
Cr	-	0.226
Zn	-	0.166
V	-	0.082
Ti	-	0.063

A quantitative analysis study showed a high copper content in both samples, 98% and 96%, as well as trace amounts of other elements such as nickel and lead. Despite the fact that the samples were produced by the same method and only the parameters of the apparatus changed, the quantitative composition of the elements differs significantly.

XRD analysis of layers

Figures 2 and 3 show the XRD spectra obtained in the studies of copper oxides on the glass substrate (a), and the silicon substrate (b).

Figure 2. XRD spectra for Cu_2O samples deposited on glass

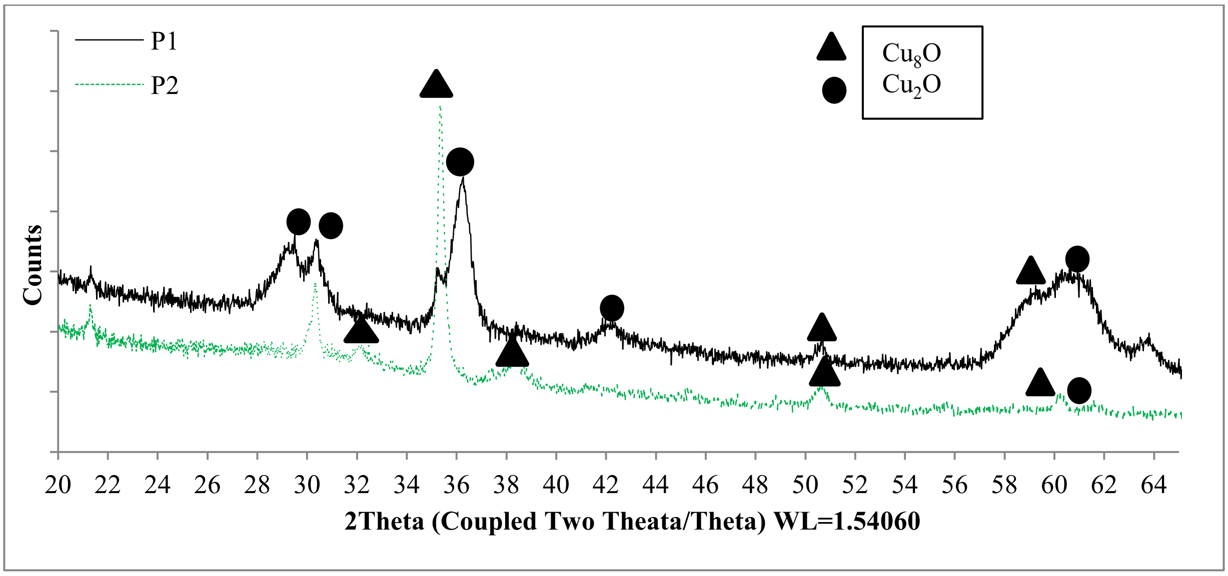
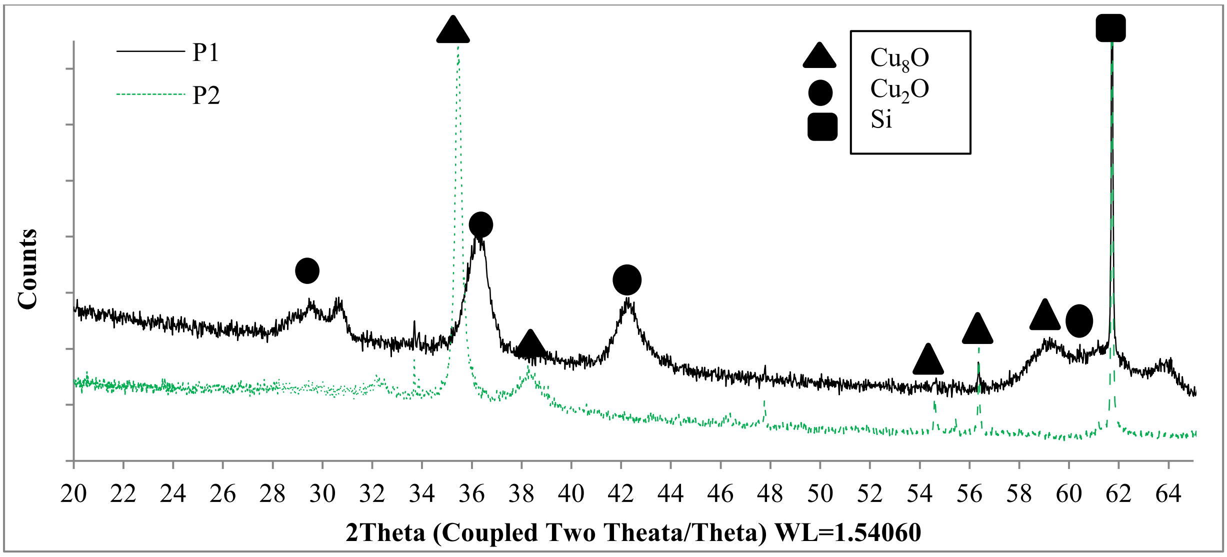


Figure 3. XRD spectra for Cu_2O samples deposited on silicon



As the XRD diffraction graphs show, the structures differed significantly, indicating the influence of the preparation method. On the basis of the position of the diffraction line, it was found that they originated from phases Cu_2O and Cu_8O. Several researchers also reported Cu_8O in their study (Yonglong 2014; Guan, Hashimoto, Kuo 1984). Table 3 shows the phases detected, grain size, and the crystallinity and amorphicity of the samples.

Table 3. Parameters obtained during the XRD test

Sample	Crystal direction	Grain size	**Crystalline**	**Amorphous**
P1 (*glass*)	Cu_2O, Cu_8O	-	75,8%	24,2%
P1 (*silicon*)	Cu_2O	-	70,2%	29,8%
P2 (*glass*)	Cu_8O	31,8 nm	69.8%	30.2%
P2 (*silicon*)	Cu_8O	28,0 nm	55.7%	44.3%

For sample P1 it was not possible to measure the grain size, due to the combination of reflections from different phases. Higher crystallinity values were obtained on glass, but on silicon a more homogeneous layer was obtained. At the same time it can be stated that sample P1 in both measuring systems shows a higher content of crystalline structure in relation to amorphous structure, which is very important in the construction of solar cells.

Conclusion

The paper presents the results of investigations of two layers of copper oxide prepared by direct current magnetron sputtering. The chemical and phase composition of the obtained layers was analyzed in order to improve the efficiency of the heterojunction based on Cu_2O as an absorber layer. The measurement results of fluorescence spectra (quantitative analysis) give the main element as copper for P1 and P2 at 98% and 96% respectively. However, this analysis also showed traces of other elements. The XRD test showed the dominant phase of Cu_2O for P1 sample and its higher crystallinity for both types of substrates. Considering the sum of the results obtained, the advantage of the P1 sample in terms of both material composition and structure should be confirmed. For this reason, the important parameters of the magnetron application process for Cu_2O layers are high purity in the working chamber (lower pressure), and lower oxygen content. It also seems essential to choose the right distance between the material source and the layer to be deposited, which reduces the number of defects that occur.

Acknowledgments

The work was carried out thanks to the support of the Centre for Innovation and Transfer of Technical and Natural Knowledge of the University of Rzeszow.

Bibliography

1. S. Korkmaz, B. Geçici, S. Deniz Korkmaz, R. Mohammadigharehbagh, S. Pat, S. Ozen, V. Senay, H. Hakan Yudar, *Morphology, composition, structure and optical properties of CuO/Cu_2O thin films prepared by RF sputtering method*, "Vacuum" 131/2016.
2. Serin N., Serin T., Horzum Ş., Celik Y, *Annealing effects on the properties of copper oxide thin films prepared by chemical deposition*, [in:] Semicond. Sci. Technol. No. 20, 2005.
3. Chen A., Long H., Li X., Li Y., Yang G., Lu P., *Controlled growth and characteristics of single-phase Cu_2O and CuO films by pulsed laser deposition*, [in:] Vacuum No. 83, 2009.
4. Sawicka-Chudy P., Wisz G., Górny S, Głowa Ł, Sibiński M., Cholewa M., *Numerical simulation and analysis of experimental TiO2/Cu2O thin film for photovoltaic structures*, [in:] Journal of Nanoelectronics and Optoelectronics No. 13, 2018.
5. Markworth P., Liu X., Dai J., Fan W., Marks T., Chang R., *Coherent island formation of Cu_2O films grown by chemical vapor deposition on MgO (110)*, [in:] J. Mater. Res., No. 16, 2001.
6. Sawicka-Chudy P., Sibiński M., Wisz G., Rybak-Wilusz E., Cholewa M, *Numerical Analysis and Optimization of Cu_2O/TiO_2, CuO/TiO_2, Nanostructures PV using SCAPS*, [in:] Official Proceedings MICROTHERM, 2017.
7. Yonglong S, Development of thin filmphotovoltaic cells based on low cost metal oxides, [in:] PD thesis 2014.
8. Guan R., Hashimoto H., Kuo K. H., Electron-Microscopic study of the structure of metastable oxides formed in the initial stage of copper oxidation. II. Cu_8O, [in:] Acta Crytallographica Section B: Structural Science No. 40, 1984.

Paulina Sawicka-Chudy, MA, Eng.
ORCID: 0000-0002-5931-6566

Paulina Sawicka-Chudy is a master of science Faculty of Civil and Environmental Engineering, Environmental Engineering, Technical University of Rzeszow, and PhD student of Physics at University of Rzeszow and Electronics at Technical University of Lodz. Her research is concentrated around optimization and development of semiconductor devices and particularly TiO_2/Cu_2O solar cells structures.

Marek Wielgosz
ORCID: 0000-0001-8769-7864

Marek Wielgosz – Material engineering engineer, graduate of the University of Rzeszow and the School of Electronics in Rzeszow. Since January 2018 he works as a Composite Repair Mechanic in a company from the aviation industry. Responsibilities: works related to the repair of composite elements of the aircraft and its components, painting work, certification of performed activities and tasks in the required documents and computer systems. In 2017-2018 he was an active member of the Student Scientific Club of Flyers operating at the Rzeszow University of Technology. He was responsible for making composite materials for the analogue of the Mars rover - for the international competition University Rover Challenge, which takes place every year in the USA. In 2014-2015 he was active in the international student organization AIESEC. He was involved in the organization of language workshops run by native speakers. He helped the ward from Taiwan move around the city of Rzeszow. He links his professional future with the polymer composites industry. Enthusiast of electric cars and 3D printing technology. In his free time, he chases with go-carts.

Andrzej Wal, DSc, Associate Professor
ORCID: 0000-0002-8560-1045

Andrzej Wal, Faculty of Mathematics and Natural Sciences, University of Rzeszow

Bogumił Cieniek, MSc
ORCID: 0000-0001-7687-6867

Bogumił Cieniek is a master of science Faculty of Mathematics and Natural Sciences. His research is concentrated around magnetic properties of diluted semiconductors, and structural and optical properties of zinc-oxides thin films.

Grzegorz Wisz, DSc
ORCID: 0000-0003-1029-4359

Grzegorz Wisz is a PhD in physical sciences, academic teacher, entrepreneur. In 2003 he became a PhD at the Institute of Physics of the University of Rzeszow. In 1998, he studied Computer Science, and in 2013 - Innovation and Knowledge Transfer Management. External expert of the National Center for Research and Development, member of the Supervisory Board of the Polish Institute of Innovation and Technology Transfer, member of the Working Group on National Intelligent Specialization, member of the Cluster Council of the Polish Clusters Employers' Association, head of the Protective Technology Laboratory of the University Center for Innovation and Technical and Natural Knowledge Transfer, Director of Technology Transfer Center of the University of Rzeszów, an initiator and creator, and currently a President of the Subcarpathian Renewable Energy Cluster. Initiator and animator of the Smart Eco-Estate 2020 concept. Author and co-author of over fifty publications and scientific studies in the field of physics, energy management and clusters.

Łukasz Głowa
ORCID: 0000-0001-5511-5057

Łukasz Głowa graduated from the University of Rzeszow in the field of Applied Sciences, specialization: lasers and optoelectronics, first cycle studies. Now he is a Master's Degree student of Physics, specialization: radiological protection with dosimetry and detection of flaws. He cooperates with University Centre for Technology Transfer https://www.ctt.rzeszow.pl/index.php and Subcarpatian Renewable Energy Cluster https://energia.rzeszow.pl/ and is a shareholder of Ecoeffect Ltd. His scientific interests are solar cells, electronics and scanning electron microscopy.

Marian Cholewa, DSc, Associate Professor
ORCID: 0000-0002-8717-0779

Marian Cholewa – Professor at the University of Rzeszow in Rzeszow, Poland. Head of the Biophysics Department. Author or co-author of over 180 publications with Hirsch Index of 19. Co-author of 3 patents. Research interests involves development and applications of: (a) development and application of new materials for green energy research, (b) development of new nanomaterials for enhanced secondary electron emission (c) novel methods of imaging in Biology and Medicine including MRI, PET, PET/MR, CT and synchrotron radiation, (d) development and applications of novel analytical techniques with electron, ion, laser and X-ray microbeams. Has been working in research establishments around the Globe including: Australia (Melbourne and Monash Universities), Germany (GSI and KIT), JAEA in Japan, Poland (INP, RUT and UR), Singapore (NUS) and USA (BNL). Supervisor of multiple Diploma, MSc and PhD students around the world.

Joanna Sawicka
ORCID: 0000-0003-3314-2278

University of Rzeszow, Medical Faculty, al. Kopisto 2a, 35-359 Rzeszow, Poland,
e-mail: sawicka199623@wp.pl

EFFICIENT USE OF ENERGY IN WASTEWATER TREATMENT PLANTS

Adam Masłoń[1], Marta Wójcik[2], Krzysztof Chmielowski[3]

Abstract

Saving energy and increasing energy efficiency constitutes a rationalisation of energy use, which is becoming increasingly important in the context of sustainable development and security of energy supply, as well as the fight against global climate change. In line with the global trend, the issue of energy intensity of water and wastewater management is currently dynamically developing in terms of research. Consideration is therefore being given to the use of electricity in wastewater treatment systems, as well as the assessment of the energy efficiency of wastewater treatment plants.

This paper presents the issues of electricity consumption in wastewater treatment systems and the possibilities of improving the energy efficiency of wastewater treatment plants.

Keywords: wastewater treatment, energy intensity, energy consumption, biogas, aeration

Introduction

The largest consumer of electricity in cities is the water and wastewater infrastructure, which is responsible for 25-40% of its total consumption. The entire water sector is currently responsible for around 4% of global electricity consumption. Water demand will continue to grow over the next 25 years, so energy efficiency measures are needed in this sector (Danfoss 2018). Electricity accounts for as much as 40% of the operating budgets of water companies and about 20% of the costs associated with the supply and treatment of water intended for consumption. Over the next 15 years a further increase in energy consumption of 60-100% is expected (Biedrzycka 2016, p. 14).

The need to intensify the removal of pollutants from wastewater, which has been observed in recent years, translates into increased costs associated with the operation of wastewater treatment systems – both for the main part of wastewater, as well as for the treatment and disposal of sewage sludge. The observed systematic increase in pollutant loads in wastewater flowing into municipal treatment plants, which makes it difficult to maintain the stability of technological processes, additionally results in a further increase in the plant's operating costs. In order for a wastewater treatment plant to operate properly, it is necessary to supply significant amounts of electricity, which is necessary for the transport of wastewater, technological processes and the operation of administrative facilities (Masłoń 2017, p. 332).

The energy consumption of wastewater treatment systems varies greatly. It depends on the technological system used and varies from year to year. The research indicates that the demand for electricity in wastewater treatment plants amounts to almost 1% of total domestic consumption, e.g. in Poland (Orchowski et al. 2017, p. 68-69), Germany (Reinders et al. 2012), or in Italy (Faladori et al. 2015, p. 1007) In other countries, e.g. Spain, electricity consumption in wastewater treatment plants is already higher and accounts for 2-3% of national energy

[1] PhD, Eng., Rzeszow University of Technology, Department of Chemistry and Environmental Engineering, e-mail: amaslon@prz.edu.pl

[2] PhD, Eng., Rzeszow University of Technology, Department of Materials Forming and Processing

[3] DSc, PhD, Eng., Uniwersity of Agriculture in Krakow, Department of Sanitary Engineering and Water Management

consumption (Fundación OPTI 2012, p. 6). In the USA, electricity consumption for municipal wastewater treatment plants accounts for as much as 5.4% of total domestic energy consumption and may increase by 20% over the next 20 years (Gromiec 2016). At present, the energy demand in Poland in wastewater treatment plants is not high compared to other countries, as it amounts to approx. 1TWh/year (Orchowski et al. 2017, p. 68). For comparison, wastewater treatment plants in Germany, Great Britain and the United States use 3.49 TWh/year, 3.7 TWh/year and 21 TWh/year respectively (GWRC 2008 p. 45). However, forecasts for the development of municipal infrastructure indicate an increase in energy consumption for wastewater treatment in Poland to the level of 5.5 TWh/year, which will then constitute about 2.5-3.5% of national electricity consumption (Wójtowicz 2013).

The high energy consumption of wastewater treatment plants (WWTP) determines the need to optimise technological processes, as well as the purposeful use of wastewater or sewage waste, such as sewage sludge, for the production of electricity and heat. It is becoming appropriate to develop energy audits for wastewater treatment plants, on the basis of which the energy intensity of individual wastewater treatment processes can be determined, and thus energy intensity guidelines for other investments can be defined. Creating a database of indicators is a valuable activity. Reducing electricity consumption can never be the overriding objective in the management of a wastewater treatment system, but there is a possibility to reduce the energy intensity of the installation without compromising the quality of the treated wastewater (Masłoń 2017, p. 332). Therefore, it is necessary to look at comprehensive solutions to the municipal wastewater treatment system in a different way from previously. Nowadays, the minimisation of energy consumption and the ecological sourcing of energy from alternative sources is gaining in importance and constitutes an important element of sustainable development, also in relation to water and wastewater management. Improving the energy efficiency of wastewater treatment plants is one of the challenges posed by the idea of a closed-circuit economy (Rytelewska-Chilczuk 2017).

The aim of this paper is to present the issue of energy intensity of wastewater treatment systems in the aspect of rational and efficient use of energy.

Energy balance of wastewater treatment plants

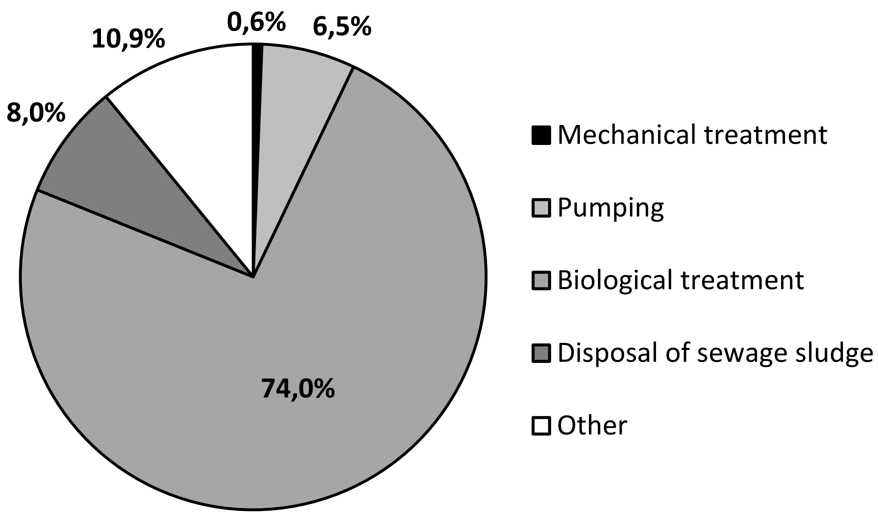
The wastewater treatment structure should be considered as a heat and power system. Electricity is used in the wastewater treatment plant to supply electric drives, among other things. Electric drive systems consist mainly of electric motors, which are used for increasing pressure (compression), pumping and transporting liquids and gases by means of pumps, fans, compressors and are additionally used in mixers, presses and other equipment for processing waste from wastewater (debris, sand, and sewage sludge). At each stage of wastewater treatment electric drive systems are used, so all technological operations such as mixing, aeration, and pumping, which are part of the wastewater treatment system, determine the consumption of electric energy. Thermal energy, in turn, is used for sewage sludge processing – in fermentation chambers and sludge dryers, etc. In a wastewater treatment plant, electricity and heat are also used for the social needs of employees, heating of technical and administrative buildings, and illumination of the area, etc.

The urban wastewater treatment process consists of two main stages – mechanical treatment (removal of floating or dragged impurities, suspended solids) and biological treatment (removal of organic pollutants, nitrogen and phosphorus compounds). It is also possible to use the third stage of wastewater treatment, which includes the removal of refractive contamination and the disinfection of wastewater. The first stage of treatment is the pumping of wastewater (wastewater pumping stations), removal of debris in travelling screens, removal of mineral suspension in the sandbox and sedimentation of easily falling suspension in the primary settling tanks. These processes display a relatively low electricity demand (with the exception of pumping the wastewater). Mechanical wastewater treatment devices consume less than 1% of the energy consumed by the entire plant (Orchowski et al. 2018, p. 71). The first degree of energy consumption data indicated in the literature varies considerably. Energy consumption for pumping raw wastewater depends mainly on the pumping height and is 0.02-0.1 kWh/m^3 (Canada), 0.045-0.14 kWh/m^3 (Hungary) and 0.1-0.37 kWh/m^3 (Australia), 0.041 kWh/m^3 (Poland) (Bodík and Kubaská 2013, p. 16; Orchowski et al. 2018, p. 72). According to a WssTP report (2011), electricity consumption in European countries up to the biological stage of wastewater treatment with activated sludge is between 0.15 and 0.7 kWh/m^3. In the biological stage of wastewater treatment the most energy-intensive process is aeration of aerobic chambers (nitrification). Aeration accounts for up to 60% of energy consumption in the biological pipeline and 44% of energy consumption in the entire wastewater treatment plant (Orchowski et al. 2018, p. 72). In addition to aeration of bioreactors, a large energy consumer is also the mixing of activated sludge in anaerobic and anoxic chambers and sludge recirculation. Conventional activated sludge processes consume on average 0.46 kWh/m^3 (Australia), 0.269 kWh/m^3 (China), 0.33-0.60 kWh/m^3 (USA), 0.30-1.89 kWh/m3 (Japan) (Bodík and Kubaská 2013, p. 16), and 0.53 kWh/m^3 (Poland) (Orchowski et al. 2018, p. 72). The processes used in the third stage of the treatment consume the most electricity (e.g. UV lamps, ozone generators, pumps, etc.). The literature review indicates a highly diversified energy intake for the so-called "advanced processes" of wastewater treatment. For example, in Japan, advanced wastewater treatment processes have an energy demand of between 0.39 and 3.74 kWh/m^3. In the USA, this third degree of purification consumes an average of 0.43 kWh/m^3. This value is similar to the energy consumption reported in the literature for treatment plants in Taiwan (0.41 kWh/m^3), New Zealand (0.49 kWh/m^3) and Hungary (0.45-0.75 kWh/m^3) (Bodík and Kubaská 2013, p. 16).

One of the inseparable elements of the wastewater treatment process is the treatment and disposal of sewage sludge. The sludge management loop, unlike the rest of the wastewater treatment plant equipment, usually operates in a cyclical manner. The processes of compaction, aerobic or anaerobic stabilisation (methane fermentation) and sludge dewatering are used here. In large wastewater treatment plants, methane fermentation processes and additional drying or incineration of sewage sludge are used. The production of biogas from sewage sludge in fermentation chambers allows for its use for power generation. Biogas production from sewage sludge for energy production is justified in large wastewater treatment plants with an average capacity of more than 8-10,000 m^3/day. The biogas produced by anaerobic digestion consists of methane (40% to 70%), carbon dioxide (about 40-50%) and a small amount of other gases, e.g. hydrogen sulphide, ammonia, etc. (Kołodziejak 2012, p. 1036-1037). Biogas after desulphurisation can be used for energy purposes (production of heat, electricity) or in other technological processes (heating of buildings). The energy consumption of sewage sludge treatment varies and depends on the size of the wastewater treatment plant, the type of technology used and the nature of the plant's operation. For example, the energy intensity of the sludge management loop in the Sandomierz WWTP (Poland) amounts to 0.055 kWh/m^3, which accounts for 8% of the energy consumed by the entire plant (Orchowski et al. 2018, p. 73).

The analysis of electricity consumption in individual units of the wastewater treatment plant technological line allows the structure of energy consumption, and thus the possibilities of its rationalisation, to be determined. Figure 1 shows an example of the structure of electricity consumption in the different stages of wastewater treatment.

Figure 1. Structure of electricity consumption in individual parts of the Sandomierz WWTP (Poland)



Source: own research

The energy balance of wastewater treatment plants should be considered as a whole, taking into account the energy consumption of wastewater treatment and sludge treatment processes as well as the use of energy for non-technological and social purposes. To assess the energy intensity of wastewater treatment plants, it is helpful to determine the KPIs (energy key performance indicators) in relation to the amount of wastewater, the equivalent number of inhabitants or the load of organic pollutants discharged during wastewater treatment (Tab. 1).

Table 1. Electricity consumption indicators in the wastewater treatment plant

Abbreviation	Unit
KPI_1	kWh/m^3
KPI_2	kWh/(p.e.·year) or kWh/(p.e.·day)
KPI_3	kWh/kg COD_{rem} lub kWh/kg $BOD_{5\ rem}$

p.e. – equivalent population
COD_{rem} – quantity COD removed
$BOD_{5\ rem}$ - quantity of BOD_5 removed

Source: Longo et al. 2016, p. 1253-1254

According to Wróblewski and Heidrich's (2017b) studies, unit electricity consumption in municipal wastewater treatment plants in Poland ranges from 0.45 to 1.29 kWh/m^3, with the average value equal to 0.84 kWh/m^3. The report of the Chamber of Commerce "Polish Waterworks" determined the average energy intensity index for Polish wastewater treatment plants at the level of 0.77 kWh/m^3 in 2015. (Benchmarking 2016). According to Gromiec (2016), the average values of the energy intensity index of the process of collecting and treating wastewater are 0.84 kWh/m^3 for facilities for 20-100 thousand inhabitants and 0.62 kWh/m^3 for facilities of more than 100 thousand inhabitants. Table 2 presents detailed energy intensity indices of wastewater treatment plants determined for selected installations.

Table 2. Unit electricity consumption in selected wastewater treatment plants in Poland

Location; name of the treatment plant	Average daily amount of wastewater [m^3/d]	P.E.	Indicators of specific electricity consumption		
			KPI_1 kWh/m^3	KPI_2 kWh/(p.e.·day)	KPI_3 kWh/kg $BOD_{5\ rem}$
Błonie	4 211	33 605	1.034	0.137	2.279
Sandomierz	4 258	42 090	0.69	0.071	1.2
Biała Podlaska	8 991	56 035	0.879	0.163	2.714
Skarżysko Kamienna	9 333	43 596	0.361	0.077	1.283
Otwock	12 352	94 415	0.801	0.125	2.08
Kalisz	16 997	153 679	0.631	0.07	1.162
Kołobrzeg	17 278	214 381	0.698	0.065	1.088
Krosno	21 000	117 000	0.510		
Koszalin	26 952	342 961	0.398	0.032	0.533
Chorzów; the Klimzowiec WWTP	29 200	200 000	0.620	-	-
Rzeszów	42 631	276 099	0.468	0.07	-
Kraków; the Kujawy WWTP	54 990	388 178	0.35		0.88
Gdynia, the Dęgoborze, WWTP	57 200	463 000	0.69	0.085	1.57
Kraków; the Płaszów WWTP	144 600	630 670	0.42	-	1.7
Warszawa; the Czajka WWTP	410 200	-	0.43	-	-

Source: Wróblewski and Heidrich 2017a, p. 328-329; Banaszek 2014, p. 28; Orchowski et al. 2018, p. 71; Trojanowicz and Karamus 2016, p. 51; Masłoń 2017, p. 4; Styka et al. 2017, p. 331-332; Bisak et al. 2017, p. 372-373; ETV4WATER Raport 2017, p. 36

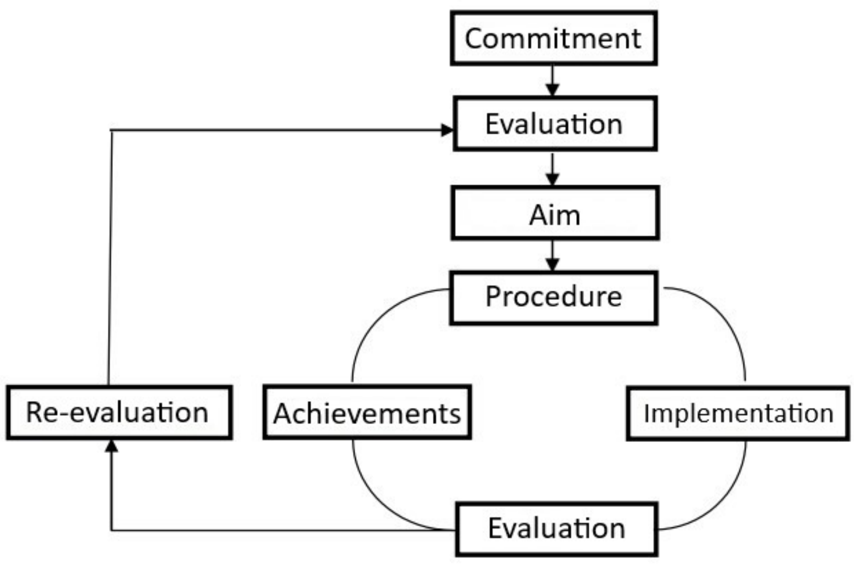
Electricity consumption depends primarily on the type of wastewater flowing in and the technological system of the wastewater treatment plant. The analysis of the topic indicates that the energy intensity of wastewater treatment varies greatly from country to country (Maktabifard et al. 2018).

Improving the energy efficiency of wastewater treatment plants

High energy consumption of wastewater treatment plants translates into the need to optimise technological processes, as well as the search for alternative energy sources, thanks to which the purchase of electricity from the distribution network can be minimised.
Recognising current and future energy consumption is important to identify opportunities for energy efficiency improvements and financial benefits. It is necessary to identify the activities and operations that consume the most energy or are inefficient. A key aspect of the wastewater treatment plant strategy in the near future will be to minimise the energy intensity of the technological process, taking into account ecological, economic and innovation criteria. Apart from the traditional role of water and wastewater systems, i.e. wastewater treatment and sewage sludge treatment, the production of resources (e.g. phosphorus recovery from sewage) and energy is playing a new role (Gromiec 2016, ETV4WATER Report 2017, p. 6).

The basic analytical method of energy demand assessment in a wastewater treatment plant is energy audits. They make it possible to assess the total energy demand of a given system, in addition to determining the most important processes and operations in terms of energy. Evaluation of the energy efficiency of the technology makes it possible to determine the energy saving procedure in the wastewater treatment plant. Based on the results of the energy audit, an energy improvement strategy should be identified, evaluated and established (Figure 2).

Figure 2. Energy management strategy for wastewater treatment plants



Source: ETV4WATER Raport 2017, p. 11

Energy savings in wastewater treatment plants are primarily related to the improvement or replacement of energy-intensive equipment (pumps, mixers, blowers) and the introduction of intelligent control and monitoring systems for wastewater treatment processes. This should be followed by the production of electricity and heat from wastewater sludge (thermal hydrolysis, fermentation, co-fermentation, sludge incineration) as well as the recovery of energy from wastewater (heat pumps, water turbines). Intensification of electricity production can be additionally achieved through the use of small cogeneration systems, photovoltaic panels or wind turbines. However, wastewater treatment processes have the greatest potential for improving energy efficiency (Table 3).

Table 3. Energy saving matrix in a wastewater treatment plant

Device, technological process	Wastewater pumping, wastewater transport	Wastewater treatment	Treatment and disposal of sewage sludge
Energy consumption in %	**25**	**60**	**15**
Pumping	X		
Pre-sedimentary settling tank		X	
Mixing/coagulation		X	
Removal of biogenic compounds		X	
Recirculation of activated sludge		X	
Sludge compaction/dewatering		X	
Fermentation/co-fermentation of sludge		X	
Sludge drying		X	
Biogas production/generation		X	
Solar energy		X	
Mini water turbines	X		
Wind turbines			X

Source: ETV4WATER Raport 2017, p. 17

The use of innovative wastewater treatment methods with simultaneous energy efficiency leads to an energy self-sufficient facility. However, in order to meet the expectations in the field of sustainable development and a closed-circuit economy, it is also possible to produce electricity and heat in excess of the facility's demand. The surplus electricity and heat can then be transferred to the distribution grids. The potential energy savings in the wastewater treatment plant are shown in Table 4.

Table 4. Distribution of energy consumption and energy saving potential in a selected wastewater treatment plant with activated sludge system

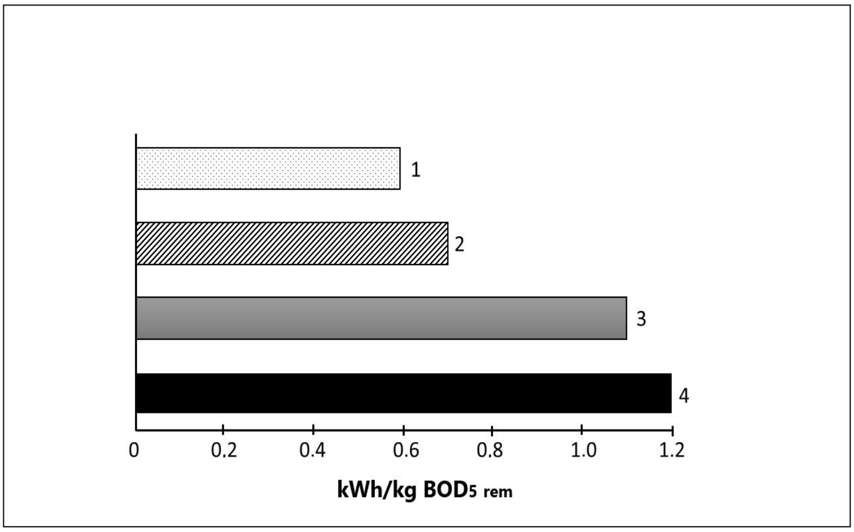
Purification stage	Share in energy consumption [%]	Energy saving potential	Comments
Wastewater collection (pumping station)	10	5-10% by retrofitting existing pumps; up to 30% by better maintenance and adaptation to capacity	Dependent on the share of gravity-induced collection
Biological wastewater treatment	55	20-50% through optimization of technological parameters, aeration optimization, online control application	Mostly for aeration of wastewater
Treatment and disposal of sewage sludge (sludge dewatering, sludge transport)	35	30% energy efficiency can be achieved by using classic mesophilic fermentation with additional cogeneration. Sludge pre-treatment or thermophilic fermentation can increase energy efficiency by up to 50%. Further application of advanced integrated co-fermentation processes, high-efficiency cogeneration can increase efficiency by up to 80%.	Anaerobic fermentation energy production

Source: Parsons et al. 2012, p. 41

The aeration system in the activated sludge chambers in wastewater treatment plants is the dominant electricity receiver. The share of the installed aeration system capacity in the total installed capacity of the wastewater treatment plant is usually at the level of 30 to 70% (Roksela and Heidrich 2017, p. 366). Properly selected devices and the operating parameters of the aeration system determine the consumption of electricity.

The electricity consumption for aeration of activated sludge depends mainly on the depth of the bioreactors and the type of equipment used (fig. 3). According to the literature, the consumption of electricity by aeration equipment in selected treatment plants is as follows: 0.46 kWh/m^3 in the Tychy-Urbanowice WWTP (Roksela and Heidrich 2017, p. 366), 0.421 kWh/m^3 in the Hajdów WWTP in Lublin (Kurek 2018, p. 58), 0.318 kWh/m^3 in Sandomierz (Orchowski et al. 2018, p. 72), 0.23 kWh/m^3 in the Dęgoborze WWTP in Gdynia (ETV4WATER Report 2017, p. 36). This represents up to 50% of the energy consumption of the entire wastewater treatment plant.

Figure 3. Electricity consumption of selected activated sludge aeration systems; 1-spinners, 2-small bubble diffusers, 3-thick and medium-bubble diffusers, 4-surface mechanical operators

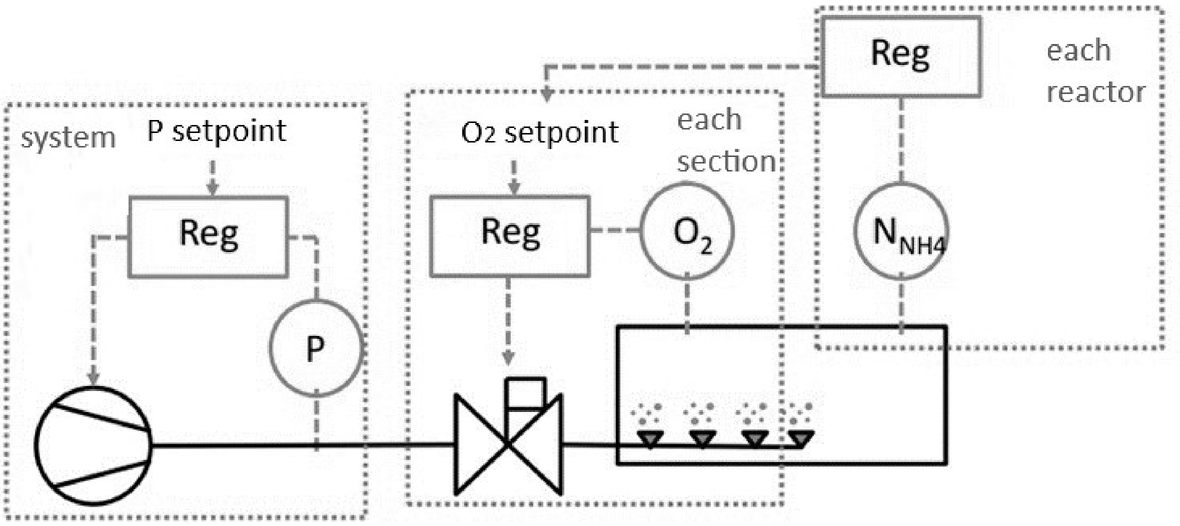


Source: Masłoń and Tomaszek 2017, p. 80.

The simplest example of improving the energy efficiency of an aeration system is the optimisation of equipment time control. At the Bad Oeynhausen WWTP (Germany), periodic shutdown of aeration in the nitrification chamber resulted in savings of 105 MWh/year without adversely affecting wastewater treatment efficiency (Szklarz and Reclaff 2016, p. 33). In turn, the replacement of blowers, diffusers and improved control of wastewater treatment plants in Sternö (Sweden, 26,000 p.e.) led to a reduction in the electricity consumption of bioreactors by as much as 65%. In the entire energy balance of the wastewater treatment plant, due to the modernisation of the aeration system, the energy consumption of the wastewater treatment plant was reduced by 13%. These savings corresponded to savings of 178 MWh/year, with an ROI (Return on Investment) period of 3.7 years for the modernisation of the aeration and control system (Larsson 2011).

The energy efficiency of aeration can also be intensified by using online measurements of ammonium nitrogen concentration (Fig. 4) (Masłoń and Tomaszek 2017, p. 115; Dąda and Pacuła 2018, p. 32). This control system reduces the amount of electricity despite the increase in the amount of wastewater and the pollution load in the inlet. The use of intelligent control of aeration blowers allowed the total energy consumption to be reduced to <0.4 kWh/m3 in the Kujawy WWTP (Kraków) (Łuszczek 2016) and from 3.5 kWh/p.e. to <2.0 kWh/p.e. in the Otwock WWTP (Jabłoński and Lech 2018, p. 29). In turn, the change in the method of controlling the operation of bioreactors in the Płaszów WWTP in Kraków allowed for savings in electricity consumption at a level of 20% (Biedrzycka 2016, p. 17).

Figure 4. The idea of aeration control using online measurements of ammonium nitrogen concentration; Reg-regulator, P - flow measurement, O2 – oxygen probe, NNH4- ammonium nitrogen probe



Source: Łuszczek 2016

Due to the significant energy potential of the organic fraction in wastewater, which is 5÷10 MJ/m^3 and 1.4÷2.8 kWh/m^3 (Wójtowicz 2015) and 4.92-7.97 kWh/kg COD (Heidrich et al. 2011, p. 381), it is advisable to use anaerobic fermentation of sewage sludge. The use of biogas in high-efficiency cogeneration processes leads to the generation of both electricity and heat. Co-fermentation of sewage sludge with other organic substrates (e.g. fatty waste) intensifies biogas production in fermentation chambers. Studies show that the use of additional co-fermentation leads to an increase in the amount of biogas from 100% to as much as 300% (Barbusiński 2017). Biogas production is a very important element in the operation of wastewater treatment plants. Thanks to this, the treatment plant becomes self-sufficient in terms of securing the supply of heat for technological and heating purposes (Biedrzycka, Lager 2012, p. 31).

Continuous optimisation of wastewater treatment processes and energy efficiency are essential today. An inseparable element of the energy strategy of a wastewater treatment plant should be the search for further, often innovative, ways of recovering energy from sewage. An example of this is the production of electricity by means of water turbines installed in the outlet drain from the wastewater treatment plant. In order to improve the energy balance in the wastewater treatment plant, it is possible to use photovoltaic farms on the premises.

Modernisation of wastewater treatment plants in Poland in recent years has led on the one hand to high efficiency in removing pollutants from wastewater and on the other to the minimisation of electricity consumption. Although the primary objective of wastewater treatment plants is to reduce pollution in wastewater, comprehensive technological and energy modernisation is possible, as evidenced by various examples of investment projects. The wastewater treatment plant in the Tychy-Urbanowice WWTP has been fully modernised in recent years, resulting in significant energy savings (Table 5).

Table 5. Reduction of energy consumption in the Tychy – Urbanowice WWTP

Type of operation	Level of energy intensity reduction [%]	Energy savings per year [MWh]
Modernisation of the main wastewater pumping station	47,0	241,0
Highly efficient interior lighting of rooms	41,0	3,0
Modernisation of aeration in bioreactors	29,0	1 223,0
Modernisation of activated sludge pumping station (recirculation)	78,0	512
Replacement of external lighting of the treatment plant	61,5	58,0

Source: RCGW 2018

The total installed capacity and electricity consumption after the modernisation of the plant was reduced by 25% with a 2-fold increase in the number of devices installed in the plant. Currently, the Tychy-Urbanowice WWTP is completely self-sufficient in terms of energy, and the average annual production of renewable energy is 150% in relation to the facility's own energy consumption. The amount of energy produced can satisfy the energy needs of a city of 16,000 inhabitants. In order to fully utilise this energy potential, the surplus energy covers the energy demand of the Tychy Water Park. The Tychy Water Park is the first facility in Poland that is entirely powered by electricity and is heated by the energy generated from biogas induced by the treatment of sewage sludge in the Tychy WWTP. The Tychy-Urbanowice WWTP is the first passive wastewater treatment plant in Poland (RCGW 2018).

Conclusion

The issue concerning the energy intensity of water and wastewater management is currently becoming one of the most dynamically developing research areas. Consideration is therefore being given to the use of electricity in wastewater treatment systems, as well as the assessment of their energy efficiency. Electricity is used in the wastewater treatment plant to supply electric drive systems, among other things. Electricity consumption depends on the type of wastewater and the technological system used in the treatment plant. Additionally, electric and thermal energy are used for the social needs of employees, heating of technical and administrative buildings, lighting of the area, etc.

The high energy consumption of wastewater treatment plants translates into the need to optimise technological processes, as well as the search for alternative energy sources, due to which the purchase of electricity from the distribution network can be minimised. It is necessary to identify the activities and operations that consume the most energy or are inefficient, which may result in the implementation of an energy saving procedure in the wastewater treatment plant.

Energy savings in wastewater treatment plants are primarily related to the improvement or replacement of energy-intensive equipment (pumps, mixers, blowers) and the introduction of intelligent control and monitoring systems for wastewater treatment processes. The optimisation of individual processes and the operation of machinery and equipment allows for energy savings in the purchase of several to a dozen or so percent. This is followed by the production of electricity and heat from sewage sludge (thermal hydrolysis, fermentation, co-fermentation, sludge incineration), in addition to energy recovery from wastewater (heat pumps, water turbines). The use of innovative wastewater treatment methods with simultaneous energy efficiency leads to an energy self-sufficient facility. Modern wastewater treatment plants should now be seen as technological and energy works, because on the one hand they remove pollutants from wastewater, and on the other they can be producers of raw materials (phosphorus recovery, fertiliser production) as well as electric and thermal energy.

Bibliography

1. Banaszek P., *Klimzowiec według algorytmu,* Kierunek Wod-Kan, 2014, 4, p. 26-29.
2. Barbusiński K., *Samowystarczalność energetyczna oczyszczalni*, Konferencja pt. Nowoczesne polskie rozwiązania w gospodarce wodno-ściekowej, Poznan, 16.10.2017.
3. *Benchmarking. Wyniki Przedsiębiorstw Wodociągowo-Kanalizacyjnych w Polsce*. Izba Gospodarcza „Wodociągi Polskie", 2016.
4. Biedrzycka A., *Kierunek: pasywna oczyszczalnia Płaszów,* Nowoczesne Budownictwo Inżynieryjne, 2016, No. 6(69), p. 14-17.
5. Biedrzycka A., Langer A., *Zielona energia w Wodociągach Krakowskich*, Nowoczesne Budownictwa Inżynieryjne, 2012, No. 6, p. 28-31.
6. Bisak A., Cyganecka-Wilkoszewska A., Raszkiewicz D., *Efektywność energetyczna warszawskich oczyszczalni ścieków*, Gaz, Woda i Technika Sanitarna, 2017, No. 9, p. 372-381.
7. Bodík I., Kubaská M., *Energy and sustainability of operation of a wastewater treatment plant*, Environment Protection Engineering, 2013, No. 39(2), p. 15-24.
8. Danfoss Poland, *Oczyszczalnie ścieków: od dużego konsumenta energii do jej producenta* http://www.danfoss.pl/newsstories/cf/oczyszczalnie-sciekow/?ref=17179918848#/ [access 06.09.2018].
9. Dąda H., Pucuła K., *Wdrożenie systemu sterowania napowietrzaniem od azotu amonowego z modułem optymalizującym ilość dostarczanego powietrza w oczyszczalni ścieków PGKiM w Sandomierzu Sp. z o.o. w 2017/2018 r*. Forum Eksploatatora, 2018, No. 4(97), p. 32-36.
10. ETV4WATER Raport. *Analiza ścieżek odzysku energii i poprawy efektywności w komunalnych oczyszczalniach ścieków*, (Eds) Szatkowska B., Paulsrud B., Neczej E., Oslo, 2017.
11. Faladori P., Vaccari M., Vitali F., *Energy audit in small wastewater treatment plants: methodology, energy consumption indicators and lesson learned*, Water, Science and Technology, 2015, No. 72(6), p. 1007-1015.
12. Fundación OPTI, *Estudio de Prospectiva. Consumo energético en el sector del agua*, 2012.
13. Global Water Research Coalition, *Water and Energy. Report of the GWCR Research Strategy Workshop.* London, 2008 http://www.waterrf.org/resources/Lists/SpecialReports/Attachments/2/GWRC_report_water_energy_workshop.pdf [access 04.09.2018].
14. Gromiec M., *Nowa rola gospodarki wodno-ściekowej w rozwoju miast i ograniczaniu zmian klimatycznych,* II Forum Ochrony Środowiska Ekologia stymulatorem rozwoju miast, Warsaw, 15-16.02.2016 r.
15. Heidrich E.S., Curtis T.P., Dolfing J., *Determination of the internal chemical energy of wastewater*. Environ. Sci. Technol. 2011, No. 45, p. 827-832.
16. Jabłoński J., Lech P., *Modernizacja oczyszczalni ścieków w Otwocku*, Forum Eksploatatora, 2018, No. 4(97), p. 24-31.
17. Kołodziejak G., *Możliwości wykorzystania potencjału energetycznego biogazu powstającego w trakcie procesu oczyszczania ścieków. Analiza opłacalności proponowanych rozwiązań*, Nafta-Gaz, 2012, No.12, p. 1036-1043.
18. Kurek E., *Wykorzystanie strącania wstępnego do poprawy funkcjonowania gospodarki osadowej w oczyszczalni ścieków Hajdów w Lublinie*, Forum Eksploatatora, 2018, No. 5(98), p. 50-58.
19. Larsson V*., Energy savings with a new aeration and control system in a mid-size Swedish wastewater treatment plant.* Uppsala University, 2011, No. 78 pp.
20. Longo S., d'Antoni B.M., Bongards M., Chaparro A., Cronrath A., Fatone F., Lema J.M., Mauricio-Iglesias M., Soares A., Hospido A., *Monitoring and diagnosis of Energy consumption in wastewater treatment plants. A state of the art. And proposals for improvement,* Applied Energy, 2016, No. 176, p. 1251-1268.
21. Łuszczek B., *Możliwości sterowania procesami w biologicznej oczyszczalni ścieków.* Konferencja Techniczna pt. „Innowacyjne rozwiązania w oczyszczaniu ścieków i zagospodarowaniu osadów ściekowych w oczyszczalni ścieków Rzeszów", Rzeszow, 14-15.11.2016.
22. Maktabifard M., Zaborowska E., Makinia J., *Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production*, Reviews in Environmental Science and Bio/Technology, 2018, https://doi.org/10.1007/s11157-018-9478-x
23. Masłoń A., *Analysis of energy consumption at the Rzeszów Wastewater Treatment Plant*, E3S Web of Conferences, 2017, vol. 22, 00115.
24. Masłoń A., Tomaszek J.A., *Sekwencyjne reaktory porcjowe. Podstawy technologii, zasady projektowania i przykłady zastosowań*. Wydawnictwo Seidel-Przywecki, Warsaw. 2017.
25. Orchowski M., Masłoń A., Heidrich Z.,. *Energochłonność oczyszczalni ścieków w Sandomierzu,* Gaz, Woda i Technika Sanitarna, 2018, No. 2, p. 68-73.
26. Parsons D., Cabrera Marcet E., Jeffrey P., *Carbon sensitive urban water future. D 21.1,* 2012 https://www.trust-i.net/, [access 15.10.2018 r].

27. Regionalne Centrum Gospodarki Wodno-Ściekowej S.A. Materiały informacyjne, http://www.rcgw.pl [access 10.10.2018].
28. Reinders M., Greditgk-Hoffamnn S., Risse H., Lange M., *Solution approaches for energy optimization in the water sector,* IWA World Congress on water, Climate and Energy, Dublin, Ireland, 2012, May 13-18.
29. Roksela M., Heidrich Z., *Energochłonność napowietrzania w procesie osadu czynnego*, Gaz, Woda i Technika Sanitarna, 2017, No. 9, p. 366-371.
30. Rytelewska-Chilczuk N., *Jak wyprodukować energię w oczyszczalni?* Portal Teraz Środowisko, https://www.teraz-srodowisko.pl/aktualnosci/jak-wyprodukowac-energie-w-oczyszczalni-3503.html [access 18.10.2017].
31. Styka W., Beńko P., Łuszczek B., *Efektywność energetyczna oczyszczalni ścieków MPWiK Kraków*, Gaz, Woda i Technika Sanitarna, 2017, No. 8, p. 330-335.
32. Szklarz P., Reclaff W., *Energooszczędność oczyszczalni ścieków. Neutralna energetycznie oczyszczalnia w Bad Oeynhausen*, Forum Eksploatatora 2016, No. 6 (87), p. 32-34.
33. Trojanowicz K., Karamus Ł., *Energetyczna utylizacja biogazu jako element gospodarki osadowej w oczyszczalni ścieków w Krośnie,* Forum Eksploatatora, 2016, No. 4(85), p. 46-53.
34. Wójtowicz A., *Potencjał energetyczny gospodarki komunalnej ze szczególnym uwzględnieniem gospodarki ściekowej*, VIII Forum Energetyczne, Sopot, 16-18.12.2013.
35. Wójtowicz A., *Strategia inwestycyjna współczesnych przedsiębiorstw komunalnych wykorzystujących środki funduszy ochrony środowiska*, Warsztaty z instytucjami finansowymi i samorządem lokalnym i regionalnym, Słupsk, 9.11.2015.
36. Wróblewski J., Heidrich Z., *Energochłonność miejskich oczyszczalni ścieków. Cz. I. Analiza i ocena danych literaturowych*, Gaz, Woda i Technika Sanitarna, 2017a, No. 8, p. 325-329.
37. Wróblewski J., Heidrich Z., *Energochłonność miejskich oczyszczalni ścieków. Cz. II. Badania własne*, Gaz, Woda i Technika Sanitarna, 2017b, No. 9, p. 363-365.
38. WssTP, *Water and energy: strategic vision and research needs. The Water Supply and Sanitation Technology Platform*, 2011.

Adam Masłoń, PhD, Eng.
ORCID: 0000-0002-3676-0031

Assistant Professor of Department of Chemistry and Environmental Engineering at Rzeszow University of Technology. The author of many scientific articles, analyses, reports and books. The area of scientific interests related to wastewater technology (activated sludge technology, sequencing batch reactors, aerobic granular sludge, energy consumption of wastewater treatment) as well as sewage sludge utilisation.

Marta Wójcik, PhD, Eng.
ORCID: 0000-0003-3764-1058

She is an assistant professor on the Department of Materials Forming and Processing at Rzeszow University of Technology. In 2015, she graduated with a Master's degree at Rzeszow University of Technology. In 2018, she received a doctoral degree in the field of environmental engineering. She is an author of several papers associated with the environmental and mechanical engineering. Her academic research is related with sewage sludge and waste management, recycling as well as fuzzy sets theory in engineering applications.

Krzysztof Chmielowski, DSc, PhD, Eng.
ORCID 0000-0001-9758-0854

In the period of 2002-2007 he completed doctoral studies at the Faculty of Environmental Engineering and Land Surveying of the University of Agriculture in Krakow. In 2007 at the home department, he defended his doctoral thesis entitled „Effectiveness of treatment using vertical flow sand filters in domestic sewage treatment plants" obtaining the PhD degree in agricultural sciences in the field of environmental development. By decision of the Faculty Board, the doctoral dissertation was awarded a distinction. He obtained the degree of habilitated doctor in agricultural sciences, in the field of environmental protection and development, specialty of water and wastewater management, at the same Faculty, based on the habilitation thesis „Effectiveness of sewage treatment in a domestic treatment plant using a modified gravel-sand filter".

ENERGY-EFFICIENT ARCHITECTURE, I.E. A COMBINATION OF FUNCTIONALITY AND ENVIRONMENTAL ASPECTS

Natalia Marciniak[1], Weronika Hyjek[2]

Abstract

The paper presents the concept of energy-saving architecture as a way to increase the use of renewable energy sources in the energy economy and increase the level of eco-innovation in Poland. Solutions leading to the minimisation of costs of energy supply and consumption in the internal building system are presented. The paper shows basic forms of building optimization and the possibility of their adjustment to the existing directives and regulations of the European Union using modern technologies. The reflections have been supported by examples of good practice in the field in Europe and worldwide.

Keywords: energy-saving architecture, optimization, "ZEB" buildings, eco-innovations, renewable energy sources

Introduction

The concept of functionality is the basis for the design and construction of modern buildings, but increasingly often there are also ecological and economic aspects. In order to reduce the negative impact of human beings on the environment and to meet the requirements imposed by the European Union in the field of energy-efficient construction, a variety of technologies are used which exploit renewable energy sources and allow the costs of producing energy to be reduced.

The aim of this paper is to show the best practices of energy-efficient construction, which in the future may become widely used to achieve not only self-supply of individual buildings with energy obtained from renewable energy sources, but also global benefits resulting from the reduction of fossil fuel consumption and minimization of carbon dioxide emissions. The paper presents legal requirements in the field of energy-efficient construction, and examples of technologies used, as well as economic aspects of implementation of new systems in architecture.

Definition of terms:

a) Eco-innovation – this is a term that links ecology with innovation, i.e. phenomena related to the implementation of ever more modern eco-technologies aimed at improving human health, as well as maintaining the natural order. The scope of activities is focused on environmental protection and maximizing the benefits of RES use.

b) ZEB (Zero-Energy Buildings), nZEB (Net Zero Energy Buildings) – buildings in which the applied technology makes it possible to produce an amount of energy from renewable sources that at least covers the energy demand of the building. The aim of sustainable construction is to achieve a balance between energy demand and production. Currently, nZEB buildings are considered to be the most beneficial long-term projects in terms of environmental efficiency (Sowa 2017).

[1] Student, Natalia Marciniak, University of Rzeszow, member of Student Science Club „Eurointegracja", Rzeszow University of Technology, nmarciniak98@gmail.com

[2] Student, Weronika Hyjek, University of Rzeszow, member of Student Science Club „Eurointegracja", Rzeszow University of Technoology, h.weronika1122@gmail.com

Directives and Regulations

The regulations governing energy efficiency standards are: Directive 2006/32/EC of the European Parliament and of the Council of 05.04.2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC, and also Directive 2002/91/EC of the European Parliament on the energy performance of buildings. On the basis of both the directive of 1 January 2009 and of the construction law, the requirement to prepare an energy certificate has come into force. Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (Official Journal of the European Union L 153 of 18.06.2010, p. 13). The main objectives of this directive were to reduce energy consumption and the use of energy from renewable sources, and to adopt standards such as "keeping the global temperature increase below 2 °C and the commitment to reduce by 2020 – total emissions of greenhouse gases by at least 20% below 1990 levels and by 30% in the event of an international agreement, and to reduce the Union's energy consumption by 20% by 2020" (European Council meeting in March 2007) and to achieve 20% energy efficiency by 2020 and to reduce greenhouse gases (Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009).

The year 2014 was a breakthrough legal year for energy-efficient construction through the newly binding Ordinance of the Minister of Infrastructure of 12 April 2002 (and subsequent amendments) on the technical conditions to be met by buildings and their location. The Regulation of the Minister for Infrastructure contains, inter alia, new requirements for thermal insulation of building envelope, i.e. specific requirements (mainly U_{MAX}) and general requirements (e.g. EP) for non-renewable primary energy, in addition to requirements for the design and, at a later stage, construction of such buildings in order to reduce the risk of overheating in summer. The Regulation also specifies the requirements for the use of general mechanical ventilation systems or in air conditioning systems with an efficiency of 500 m^3/h or more, devices which will be aimed at recovering heat from the extracted air with a minimum temperature efficiency of 50%, or the use of recirculation where this is allowed.

The Regulation of the Minister of Infrastructure of 6 November 2008 concerns the methodology of calculating the energy performance of a building and a residential unit or a part of a building constituting an independent technical and usable unit, besides both the method of preparing and templates of energy performance certificates.

This Regulation implements Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings (Official Journal of the European Union L 1 of 04.01.2003, p. 65; Official Journal of the European Union Polish special edition, Chapter 12, Volume 2, p. 168). The Regulation of the Minister of Infrastructure and Development on the methodology of determining the energy performance of a building or part of a building and energy performance certificates of 27 February 2015. (Official Journal Dz.U., 3025, item 376). The Act of 29 August 2014 on the energy performance of buildings on the basis of Directive 2010/31/EU of the European Parliament and of the Council of 19 May

2010 on the energy performance of buildings (recast). In Poland, the given standard will apply to all buildings as of 1 January 2021, while for buildings occupied by public authorities, which are their property, it will be applied from 1 January 2019.

Concepts and assumptions of plus-energy construction and its impact on the environment

Nowadays, traditional residential buildings are beginning to be replaced by "zero-energy" or "plus-energy" buildings, not only in terms of functionality, but above all in terms of ecology and economy. The main objective of introducing this type of building is to reduce the depletion risk of renewable energy sources. One of the most important assumptions is maximum energy efficiency with minimal energy consumption and costs. Energy construction has many goals. The most important is to protect the environment and strive for its sustainability, while at the same time benefiting health by reducing negative and dangerous phenomena occurring in the atmosphere. An example of actions leading to the implementation of this assumption is the reduction of the number of coal-fired furnaces and boilers, which results in the reduction of the amount of pollutants emitted to the atmosphere. However, the reduction of the use of renewable raw materials is an important aspect – well-thought-out construction and wall sealing allows for the preservation of heat, which in turn leads to a reduction in the design heat load.

Energy-efficient architecture plays an increasingly important role in the Polish construction industry due to the regulations and directives introduced by the European Union, which require Member States to maintain appropriate procedures, concerning not only the method of construction itself, but also the initial design process, taking into account the economic and ecological aspects. As a result, not only are modern eco-housing estates built from scratch, but steps are also being taken to rebuild and modernise existing facilities such as the Beddington Zero Energy Development – Bed ZED in London, which has been rebuilt from a sewage treatment plant to one of the most efficient eco-housing estates.

In countries such as the United Arab Emirates and Germany, energy-efficient construction is well known and promoted, while in Poland projects are beginning to be implemented especially in places where energy efficiency can help to rebuild the local environment. One example of world-class technology implementation is the Klimaty housing estate in Kraków, which is an energy-efficient and ecological type of construction, consuming only 27.5 kWh/m^2 annually (completion of construction in 2017). Heating costs vary, at around 450 PLN per apartment with an average area of 120m^2 and a height of more than 3 metres. This is possible thanks to the use of innovative technology using renewable energy sources by means of heat pumps. These apartments are only 5.5 km away from the city centre, but they are distinguished by the surrounding greenery, silence and protection against the annoying smog, which is an inherent problem for the inhabitants of Kraków. Meanwhile, the energy consumption at the "Sielanka" housing estate in Tarnowskie Góry (Lower Silesia) amounts to 40 kWh/m^2/year. It consists not of apartments, as in the case of the Klimaty estate, but of single-family houses with an area of 92 to 186 m^2 (completion of the first stage of construction in 2012 – 26 energy-saving houses).

The houses are located at a distance of 22 to 27 metres from each other, and the whole estate is located only 4 km from the city centre, which provides full access to public transport with other parts of the city or the surrounding area. On the other hand, passive houses are becoming more and more popular in Poland, thus ensuring minimum heat consumption – which amounts to only 15 kWh/m² due to the use of thermal insulation walls with appropriate sealing (U-value for walls is below 0.15 W/(m²K)), and also because of the use of mechanical ventilation with heat recovery (recuperator) and appropriate construction of the building and location in relation to light.
In newly-built residential buildings, a number of technological solutions are applied, leading to the highest possible amount of energy from RES. The following technologies are used for this purpose: solar collectors, photovoltaic cells, small and micro wind turbines, compressor heat pumps, biomass-fired installations, and cogeneration.

In the use of renewable energy sources, particular attention should be paid to biomass, the share of which in the fuel balance of renewable energy is still growing. It is currently the most widely used renewable energy source (Sala 2017). This is due, among other things, to the possibility of direct combustion in the form of solid biofuels (wood, straw, pellets), gaseous fuels (biogas) or after conversion into liquid fuels (oil, alcohol).
Water also plays an important role. It is the longest used renewable energy source in Poland, although, due to unevenly distributed annual rainfall, small land falls and high soil permeability, it is not very effective.
Solar energy is the least used. This is due to the uneven distribution of solar radiation over the year (about 80% of the annual amount of sunshine falls in the spring-summer season, i.e. less than six months). However, this allows the use of collectors for heating water in single or multi-family houses and public buildings.

Effective ways to optimise buildings. Presentation of local energy production capacity

Public buildings have the largest share in reducing energy consumption costs and increasing the level of eco-innovation in Poland. However, due to the lack of profitability, it is not possible to convert them completely into ZEB buildings. The opportunity to meet the requirements of the EU and government in the field of energy-saving architecture is in their partial reconstruction and the installation of specialised installations.

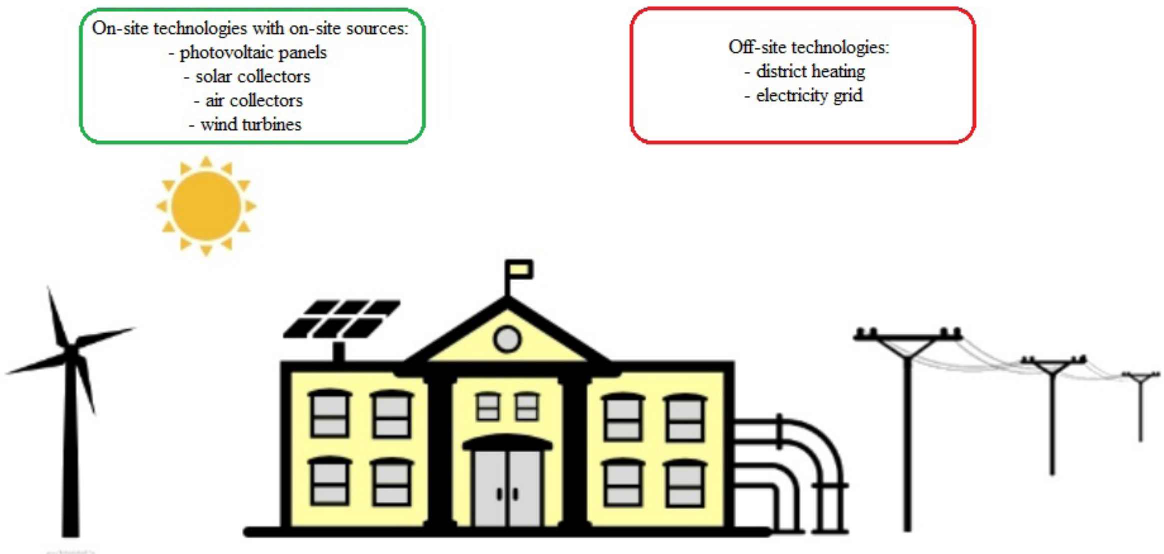
One of the ways to optimise buildings, using the potential of solar energy, is to rebuild the building so that it is exposed to light as long as possible and the heated air is maintained due to the use of modern technologies in sealing walls and windows. However, each redevelopment requires individual consideration and evaluation, so that all implemented energy-saving systems bring the greatest possible benefits without incurring any losses (accumulation of an adequate amount of heat and, in the case of possible surpluses, management for other energy-consuming sources).

Examples of effective ways to optimise the energy performance of buildings are based on selected buildings from around the world and Poland. The choice was not determined by a specific criterion, but only by popularisation and innovation among energy-plus architecture.

The application of the following solutions contributed to the achievement of the effect of energy efficiency: a recuperation system, which is based on the recovery of heat from the reconstruction of the mechanical air ventilation system. An example of using this system is the Klimaty housing estate in Kraków, which not only provides energy efficiency but also protects residents from urban smog, as well as heat pumps, using renewable energy sources. Minimisation of thermal energy consumption in passive buildings – passive kindergartens in Slovenia in the municipality of Preddvor, which were put into operation in 2012. The annual energy demand is 61 kWh/m²/year. Among other things, the following were used: a ventilation system with heat recovery at the level of 80%, a biomass boiler that provides heating for kindergartens, and photovoltaic panels on the roof with an output of 96.7 kW; which is a mechanism tracking the daily course of the sun – this is an example of the first building that maximises the absorption of natural light, and such a project was first developed in Germany in 1994. A "heliotrope" can produce 6 times more energy per sunny day than it consumes.

The concept of zero-energy architecture assumes that the energy needs of buildings should be covered by the energy produced within the building's balance sheet limits. This can take place using on-site technology, i.e. on the premises of a given building, or off-site, i.e. with the use of fuels located on its premises or supplied from outside. It is also possible to combine these two technologies through devices such as heat pumps that draw energy from external sources (e.g. grid electricity) and internal (e.g. ground).

Figure 1. Types of devices using on- and off-site technology. Source: own elaboration



Economic aspects of building renovation

Upgrading public buildings to nearly zero-energy building standards requires capital expenditure, which needs to be properly assessed in order to be able to identify the sources of financing.

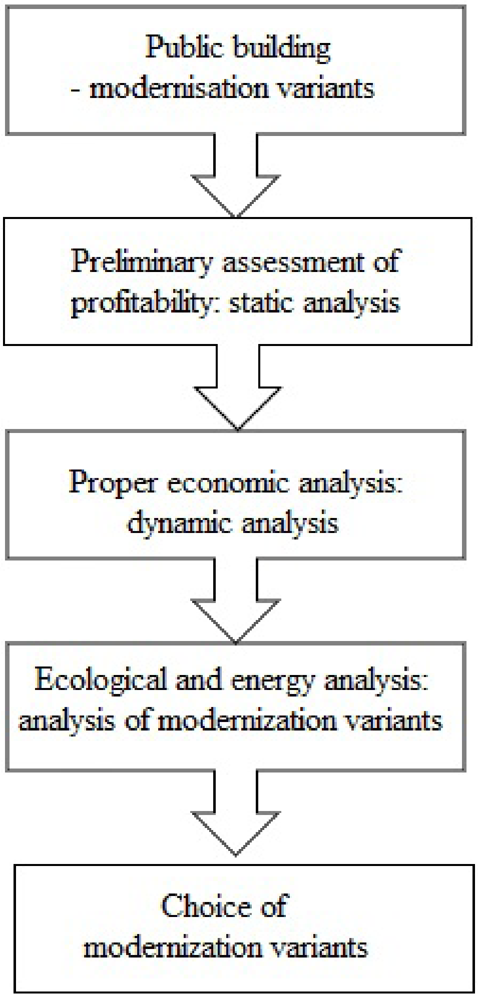
In the initial phase of calculation, the investment costs include: energy audit and technical design, obtaining permits, technical supervision, purchase of materials, and salary costs. An important element of the cost estimate is also the financial reserve, which will protect the budget against unexpected expenses.

In addition to investment, the costs of operating the building should also be determined, which are different in each case and should be determined after taking into account the configuration of the system, local energy costs, the location of the building and its financing sources. The components of operating costs include:

- purchase of: fuel or heat, electricity, and other utilities,
- environmental charges,
- maintenance and consumables,
- wages and salaries.

In order to determine the profitability of the planned investment, a static economic analysis (at the initial stage of project planning) and a dynamic analysis (to determine the actual profitability of the investment, taking into account the change in the value of money over time) are carried out.

Figure 2. Schema of valuation and selection of the building modernisation variant. Source: own elaboration



<u>Static analysis indicator:</u>

– Formula 1: Simple return time:

SPBT - simple return time,
I – investment outlays incurred in the base year,
K – the economic effect, i.e. the sum of profits (i.e. savings resulting primarily from a reduction in the costs of purchasing energy carriers and revenues from the sale of electricity generated) less tax, depreciation and costs of financing investments at base year prices,
R – possible increase in maintenance and repair costs in base year prices.

<u>Dynamic analysis indicators:</u>

– Formula 2: Real discount rate:

r_r – real discount rate,
r_{dep} - rate of return on risk-free investments,
r_i - inflation rate.

– Formula 3: Discount rate of increase in energy prices:

r_e – discount rate of increase in energy prices,
r_r – real discount rate,
r_{per} – energy price increase index.

– Formula 4: Net present value

NPV – net present value,
n – year of operation of the investment,
N – economic life of the investment,
K – the economic effect in specific periods, i.e. the sum of profits (i.e. savings resulting primarily from a reduction in the costs of purchasing energy carriers and revenues from the sale of electricity generated) less tax, depreciation and costs of financing investments at base year prices,
R – possible increase in maintenance and repair costs in individual periods,
I – investment outlays in individual periods,
r – discount rate.

– Formula 5: Net updated value:

NPVR – net updated value,
NPV – net present value,
t – period of incurred expenditures,
N – economic life of the investment,
I - investment and replacement outlays in individual periods,
r – discount rate.

– Formula 6: Profitability ratio:

PI – profitability ratio,
n – year of operation of the investment,
N – economic life of the investment,
I – investment and replacement outlays,
K – the economic effect, i.e. the sum of profits (i.e. savings resulting primarily from a reduction in the costs of purchasing energy carriers and revenues from the sale of electricity generated) less tax, depreciation and costs of financing investments at base year prices,
R – possible increase in maintenance and repair costs in individual periods,
r – discount rate.

Benefits from the buildings modernization by the example of the thermo-modernization program for Poland

According to experts from the Buildings Perfomance Institute Europe (BPIE), the potential reduction of greenhouse gas emissions by 2030 (compared to 2010) can reach 8-59%. It will be achieved as a result of thermal modernization of buildings. Air pollution will also decrease significantly due to reduced combustion of low quality solid fuels in domestic inefficient furnaces. As a result of thermo-modernization, it is also possible to reduce the emission of harmful substances. The table shows the estimated social benefits from the program.

Table 1. Estimation of the social benefits of thermo-modernization. Source: Own elaboration based on "Strategia modernizacji budynków: mapa drogowa 2050"

	PLN billion
Energy saving	185
Health benefits	185
Benefits for power grids	185
Economic stimulus	277
Environmental benefits	18
Total benefits (gross)	849
Minus total investment	122
Net social benefit	227
Saving for consumers (net)	63

Next table presents results of research on thermo-modernization of buildings in Poland by 2030 conducted by the Buildings Perfomance Institute Europe. It shows the results of the most effective solution including fast and free decarbonization.

Table 2. Results of research on thermo-modernization of buildings in Poland by 2030. Source: Own elaboration based on "Strategia modernizacji budynków: mapa drogowa 2050"

Description	Value	Unit
Annual energy saving in 2030	75	TWh / year
Savings in 2030 as % of present values	26	%
Investment costs (present value)	122	PLN billion
Savings (present value)	185	PLN billion

Net savings for the consumer	63	PLN billion
Net savings for society - without external effects	828	PLN billion
Net savings for society - with external effects	920	PLN billion
Internal rate of return	13,2	%
FAST DECARBONIZATION		
Annual CO_2 savings in 2030	65	Mt CO_2 / year
CO_2 saved in 2030 (% of 2010 values)	59	%
Cost of CO reduction	-131	PLN/ t CO_2
FREE DECARBONIZATION		
Annual CO_2 savings in 2030	32	Mt CO_2 / year
CO_2 saved in 2030 (% of 2010 values)	28	%
Cost of CO_2 reduction	-516	PLN/t CO_2

Advantages and disad

Every new idea or new construction process implemented involves positive and negative aspects, which are not always predictable, but after a certain period of time, there is a certain pattern through which the already existing methods can be improved. Plus-energy building is discovering increasingly streamlined solutions every year; however, despite this, there are still drawbacks or underefinements, which do not necessarily depend on the originator but on a wider group of individuals. A special case is the desire to reduce the number of coal-fired stoves and boilers. An individual inhabitant of a housing estate or city, after replacing a heating source, will not minimise the emission of pollutants into the atmosphere through coal-fired buildings located around them. Therefore, some problems need to be resolved on the macro scale. On the other hand, the application of systemic solutions for a whole housing estate or city will promise significant effects, which will be felt not only by the whole society, but additionally will mainly contribute to the reconstruction of the environment, which with every next century is facing an increasing number of threats. The introduction of such a solution is particularly necessary for cities threatened by smog. Another profitability is the reduction of heat energy consumption, which results in a reduction of heating costs. However, regardless of the introduction of modern technologies, there is the risk of equipment failure, which entails repair costs. An example of solving the problem of failure, although used only in some facilities (e.g. hospitals) due to high costs, is the construction of two sources of heat. When one of them fails, the other one is used. On the other hand, a cheaper and more frequent method is the introduction of devices with high reliability and guaranteed undisturbed operation, which do not assume failure rates.

Conclusion

The implementation of detailed legal requirements imposed by the European Union concerning energy-efficient construction is a big challenge for state policy. At the same time, however, it causes an increase in interest in this field among Polish architects, who are trying to implement innovative technologies in public and residential buildings. Thanks to appropriate calculation of investment profitability ratios, it is possible to select solutions in such a way as to minimise the costs of energy generation, while at the same time achieving the expected results. The use of energy-saving techniques initially in individual buildings gives an opportunity for their large-scale implementation, which will bring us closer to achieving energy balance not only in the country, but perhaps even in the world.

Bibliography

1. "Kierunki rozwoju budownictwa energooszczędnego i wykorzystania odnawialnych źródeł energii na terenie Dolnego Śląska" [Directions of development of energy-efficient construction and the use of renewable energy sources in Dolny Śląsk], Bać A. Kasperski J., Oficyna Wydawnicza Politechniki Wrocławskiej.
2. "Budynki o niemal zerowym zużyciu energii" [Buildings with almost zero energy consumption], Sowa J., Oficyna Wydawnicza Politechniki Warszawskiej, Warsaw 2017.
3. Mastalerska M., *Jak zaoszczędzić energię w domu? Budynek „plus-energetyczny" w Polsce*, „Energetyka Cieplna i Zawodowa" [How to save energy at home? "Plus-energy" building in Poland] No. 3/2011, https://www.cire.pl/pokaz-pdf-%252Fpliki%252F2%252Fbudynek_plus_energet.pdf.
4. Tytko R., Odnawialne źródła energii, [Renewable energy sources], OWG, Warsaw 2009.
5. Sala K., *Przemysłowe wykorzystanie biomasy w Polsce. Przesłanki i bariery*, [Industrial use of biomass in Poland. Premises and barriers], Prace Komisji Geografii Przemysłu Polskiego Towarzystwa Geograficznego, No. 31[4], 2017.
6. Rozporządzenie Ministra Infrastruktury z 12 kwietnia 2002 r. (wraz z późniejszymi zmianami) w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie. [Regulation of the Minister of Infrastructure of 12 April 2002 (as amended) on the technical conditions which should be met by buildings and their location].
7. Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (Official Journal of the EU L 153 of 18.06.2010, p. 13).
8. Directive 2006/32/EC of the European Parliament and of the Council of 05.04.2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC.
9. Directive 2002/91/EC of the European Parliament and of the Council on the energy performance of buildings.
10. Rozporządzenia Ministra Infrastruktury z dnia 6 listopada 2008 r. w sprawie metodologii obliczania charakterystyki energetycznej budynku i lokalu mieszkalnego lub części budynku stanowiącej samodzielna całość techniczno-użytkową oraz sposobu sporządzania i wzorów świadectw ich charakterystyki energetycznej. [Regulation of the Minister of Infrastructure of 6 November 2008. On the methodology for calculating the energy performance of the building and dwelling or part of the building constituting an independent whole technical-utilitarian and the preparation of the certificates and their energy].
11. Gevorkian P., Sustainable Energy Systems in Architectural Design, McGraw-Hill 2006.
12. De Garrido L., Artificial nature architecture, Instituto Monsa de Ediciones, Barcelona 2011.
13. Johnston D., Gibson S., Towards a zero energy home: a complete guide to energy self-sufficiency at home, The Taunton Press, Newtown 2010.
14. "Strategia modernizacji budynków: mapa drogowa 2050", [Strategy for the modernization of buildings: road map 2050] Kraków 2014 http://www.renowacja2050.pl/files/raport.pdf.
15. W Krakowie powstaje ekologiczne i energooszczędne osiedle mieszkaniowe, [An ecological and energy-saving housing estate is being built in Krakow]https://www.muratorplus.pl/inwestycje/inwestycje-mieszkaniowe/w-krakowie-powstaje-ekologiczne-i-energooszczedne-osiedle-mieszkaniowe-aa-hF8B-vH7w-FBXr.html [access: 26.04.2017].
16. Przedszkola pasywne na Słowenii, Passive kindergartens in Slovenia][https://architektura.info/index.php/architektura_zrownowazona/budynki_zrownowazone/przedszkola_pasywne_na_slowenii [access: 31.01.2016].
17. Nieruchomość dnia: Heliotrope, Niemcy, [Property of the day: Heliotrope, Germany] https://dominteligentny.pl/2015/nieruchomosc-dnia-heliotrope-niemcy/ [access: 5.01.2015].
18. Osiedle „Sielanka" – budujący przykład z Górnego Śląska, [„Sielanka" housing estate - building example from Górnego Śląska][http://www.chronmyklimat.pl/projekty/energooszczedne-4-katy/aktualnosci/osiedle-sielanka-budujacy-przyklad-z-gornego-slaska [access: 23.05.2014].
19. Wiśniewska L., Eco-Innovation Observatory, „ Country Profile 2016-2017 : Poland ", https://ec.europa.eu/environment/ecoap/sites/ecoap_stayconnected/files/field/field-country-files/poland_eio_country_profile_2016-2017.pdf.

Natalia Marciniak
ORCID: 0000-0002-3064-9746

Natalia Marciniak is a student of the Ignacy Łukasiewicz Rzeszow University of Technology, Faculty of Management, Faculty of Finance and Accounting. Member of student scientific circles: Eurointegration SKN, Ubezpieczeń SKN and Young Economists SKN. Co-author of the poster entitled "System approach to energy management on the example of TAURON Wytwarzanie S.A - Branch Elektrownia Stalowa Wola" presented during the 3rd National Scientific Conference "Energy Security - Pillars and Development Perspective" in Rzeszow.

Weronika Hyjek
ORCID: 0000-0003-4081-4482

Weronika Hyjek is a student of the Ignacy Łukasiewicz Rzeszow University of Technology, Faculty of Management, Faculty of Finance and Accounting. In 2018 she participated in the 3rd National Scientific Conference "Energy Security - Pillars and Development Perspective" in Rzeszow and presented a poster entitled "Energy Security - Pillars and Development Perspective" in Rzeszow. She presented the poster entitled "Strategic approach to energy management in selected regional environmental protection directorates".

EVALUATION OF THE QUALITY OF TITANIUM OXIDE AND COPPER OXIDE LAYERS BY MEANS OF OPTICAL MICROSCOPY

Angelika Głuszek[1], Paulina Sawicka-Chudy[2], Grzegorz Wisz[3], Maciej Sibiński[4], Marian Cholewa[1]

Abstract

The aim of this paper is to analyse high-resolution optical images of the surface layers of titanium oxide and copper oxide. The materials were produced using the PREVAC Modular Platform for layer deposition located at the University of Rzeszow. Images with a magnification of 50x were obtained using an optical microscope. On the basis of the results obtained, the quality of the layers was evaluated based on the image analysis. The quantitative method of analysis was applied, as a result of which the conditions of the manufacturing process for which the obtained layers had the highest homogeneity were indicated. The minimum range of grey shade counting was from 65 to 150 and the maximum range from 135 to 220. The standard deviation was from 8 to 40%.

Keywords: Titanium oxide, Copper oxide, Optical microscopy, Histograms

Introduction

The paper presents the results of research on titanium oxide and copper oxide as potential material for the construction of new types of solar cells based on TiO_2/CuO and TiO_2/Cu_2O connectors. The paper presents a qualitative analysis of optical images of the oxide layers produced. To determine the quality of the structures, images were obtained using the Nikon Eclipse MA 200 light microscope with the NIS-Elements software. This allows the surface of opaque materials in reflected light to be observed. In an optical microscope, an enlarged image of the examined object is generated with the use of light passing through a special optical system usually consisting of a set of several to a dozen or so optical lenses. Fig. 1 shows the photo and structure of the microscope Eclipse MA 200 microscope. The basic parts of the optical microscope are: eyepiece (1), micrometer screw, „revolver" (2), lens (3), macroscrew (4), and workpiece table (5). It is the most advanced metallurgical microscope in the reverse system, optimised for sharpness, aberration correction and ergonomics.

Histograms were created to evaluate the quality of the tested TiO_2 and Cu_2O layers using the online „Image Histogram Generator" software. (www.dcode.fr 2018). The Gauss greyscale curves for each image and the standard deviation were determined on the basis of these curves.

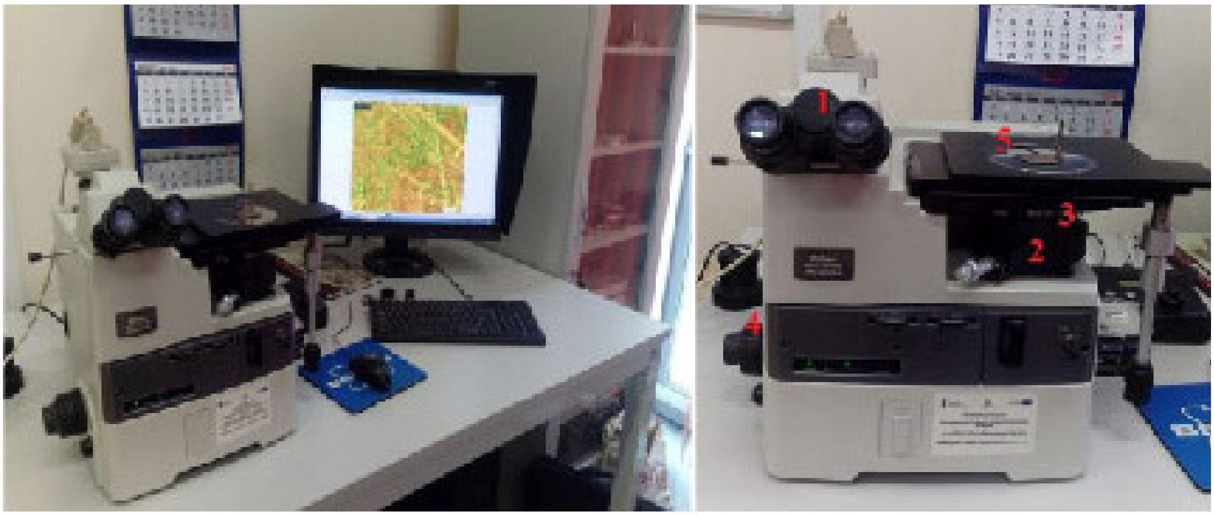
[1]University of Rzeszow, Tadeusza Rejtana 16C, 35-959 Rzeszow

[2] Department of Biophysics, Faculty of Mathematics and Natural Sciences, University of Rzeszow, 1 Pigonia Street, 35-317 Rzeszow, Poland.

[3] Department of Experimental Physics, Faculty of Mathematics and Natural Sciences, University of Rzeszow, Pigonia 1 Street, Rzeszow 35-317, Poland.

[4] Lodz University of Technology, Wólczańska 211/215, 90-924 Lodz

Figure 1. Nikon Eclipse MA 200 microscope with NIS-Elements software



Preparation of samples

For the purpose of the experiment 4 structures of copper oxide and titanium oxide were created. The layers investigated were produced by reactive magnetron atomisation of titanium and copper disks with the use of a modular PVD platform. N Si (100) type tiles and glass with dimensions of 5x4 and 6x5 mm, respectively, were used as substrates. The samples were produced in an atmosphere of argon Ar and oxygen O_2 in different process parameters. The atomisation time was 10, 20, 30 and 40 minutes. The process parameters are shown in Table 1.

Table 1. Process parameters for creating Cu2O and TiO2 layers

Parameters	P1	P2	P3	P4
Type of substrate	Silicon/glass			
Distance between source and ground [mm]	53	38	38	53
Pressure [mbar]	$1,58 \cdot 10^{-2}$	$2,41 \cdot 10^{-2}$	$1,9 \cdot 10^{-2}$	$2,78 \cdot 10^{-2}$
Power [W]	120	110	80	70
Time [min]	30	20	40	10
Oxygen flow [cm^3/s].	5.0	1.5	2.0	8.0
Argon flow [cm^3/s].	1.5	4.0	3.0	4.0
T [^{o}C]	20	150	200	20

Results and discussion

The Image Histogram Generator software (Sekatskii et al. 2001) was used for numerical analysis of the images obtained. This allows numerical greyscale data to be collected for each image based on its bitmap. On this basis histograms, Gauss curves, and the standard deviations for each sample were calculated, as shown in Table 1. The brightness scale is in the range from 0 to 255. In the literature many scientists have analysed the histogram (Scuderi et al. 2017; Rokhmat et al. 2017; Boissenin et al. 2007; Pires et al. 2013; Delbem et al. 2015; Kottler et al. 1997; Sekatskii et al. 2001; Wieclawek 2018).

Figure 2a. Photo and histogram of the structure P1 deposited on silicon

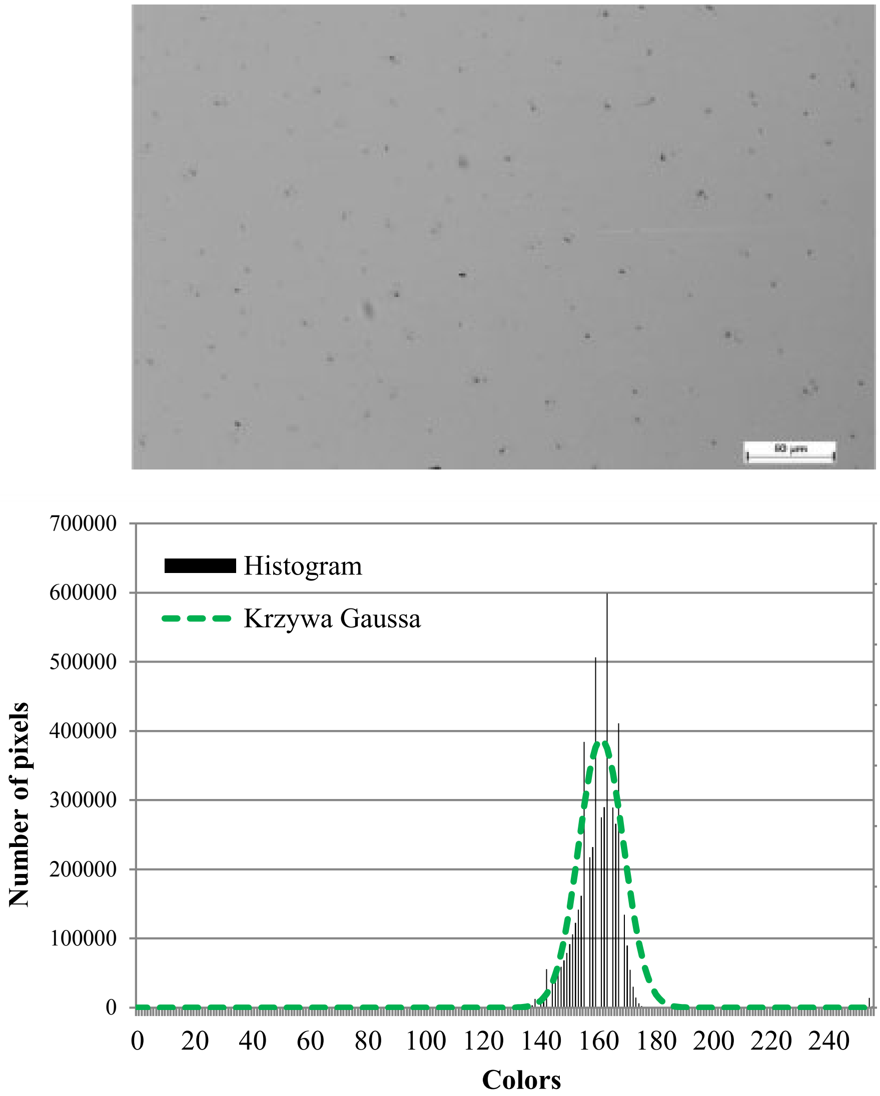
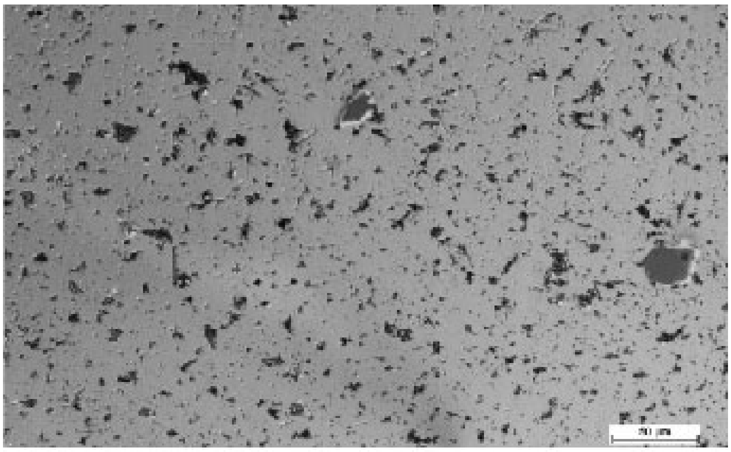


Fig. 2a. shows that the structure is homogeneous with a small number of point defects, which reflect the characteristic lines of the histogram. Its small blurring indicates the high homogeneity of the layer. The largest number of counts in this case is in the range 140-170.

Figure 2b. Photo and histogram of structure P1 deposited on glass



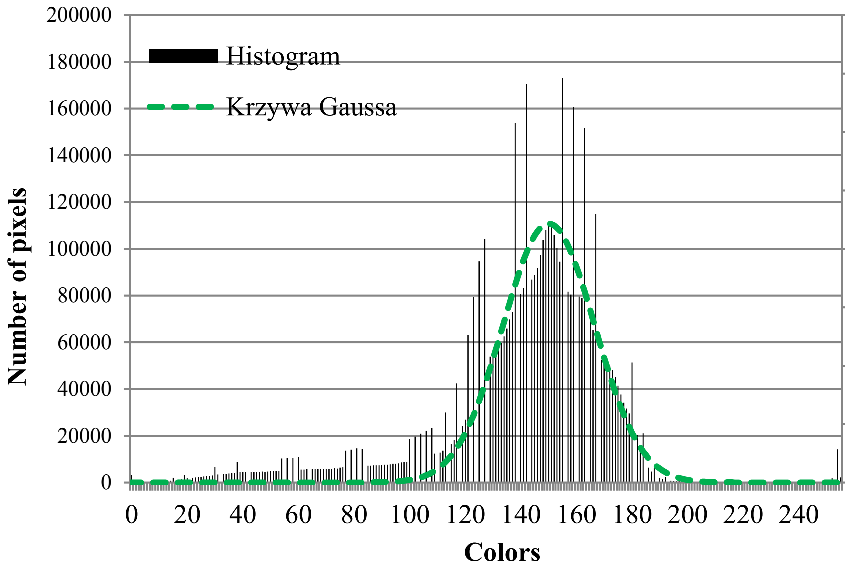
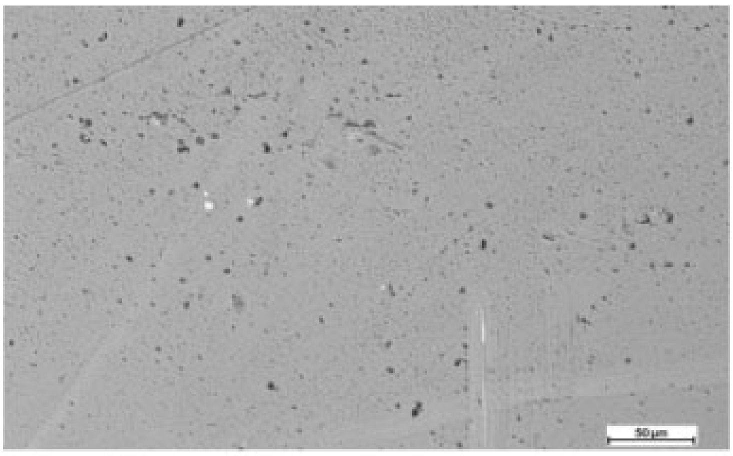
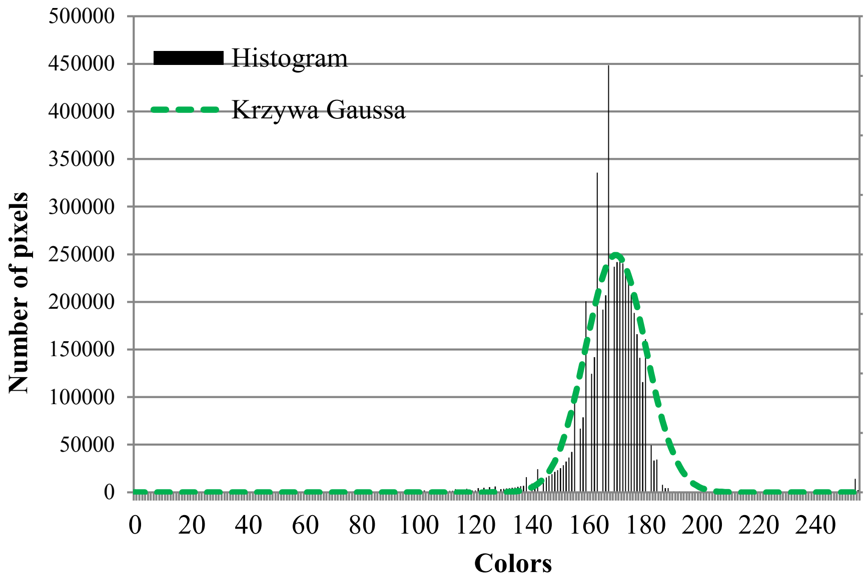


Fig. 2b clearly shows that in the case of this structure we can observe a much greater blurring of the histogram. This is due to the large number of point defects. The highest number of counts in this case is in the range of 120-180, which indicates the heterogeneity of the coating.

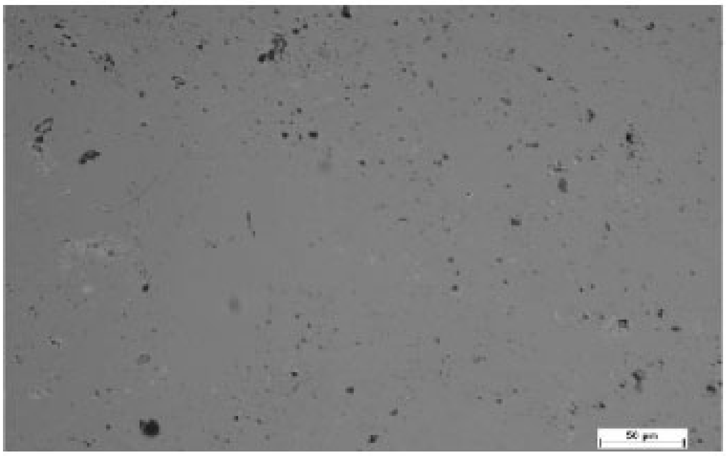
Figure 3a. Photo and histogram of the structure P2 deposited on silicon

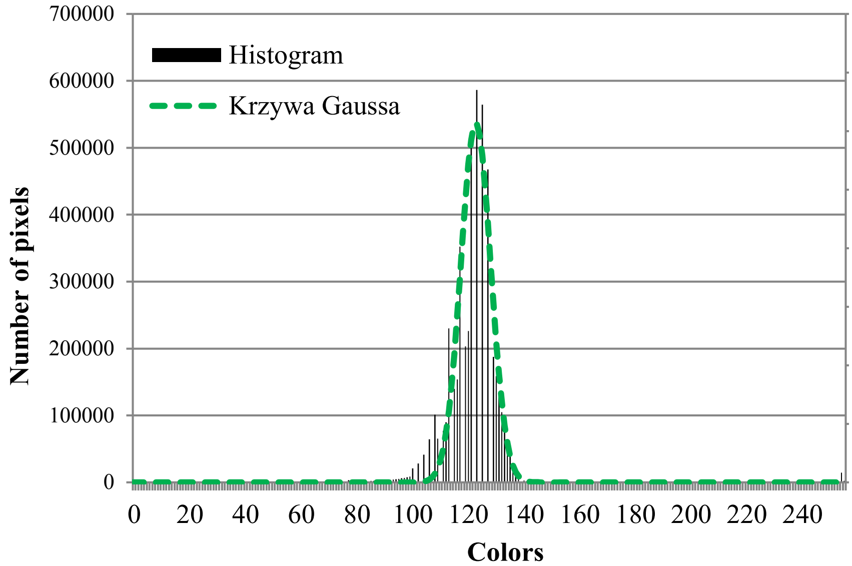




The structure is homogeneous with a small number of point defects of several µm in size. On the surface of the structure there are also surface defects in the form of longitudinal streaks, which probably result from errors in the substrate preparation. It should be emphasised that the streaks are not reflected in the histogram, because their greyscale is very similar to the colour of the layer. The two histogram lines to the left of the histogram illustrate several bright points in the image, the occurrence of which is probably the optical effect of the interaction of the microscope radiation with the layer. The largest number of counts in this case is in the range 150-180.

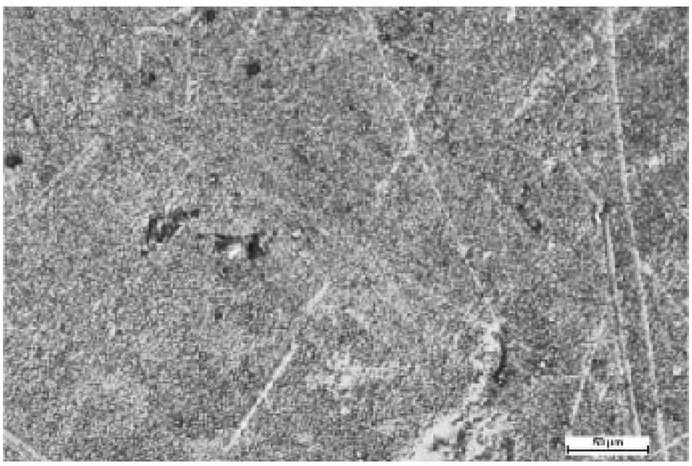
Figure 3b. Photo and histogram of structure P2 deposited on glass

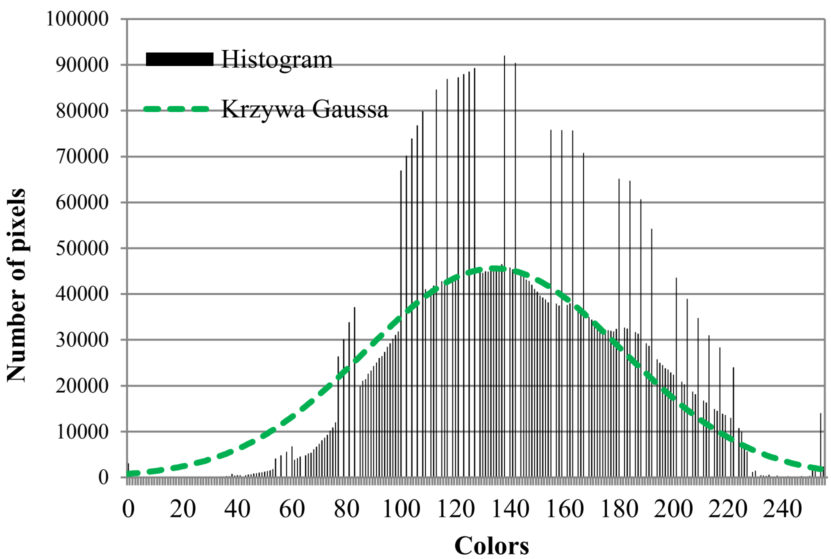




Figures 3a and 3b show that the structure P2 on silicon and glass is very similar. The layer on glass is homogeneous and has fewer point defects than the structure on silicon (Fig. 3a), but they are larger. The highest number of counts in the case of structure P2 deposited on glass is in the range of 110-135; the small range of greyscales indicates a good application of the coating on the substrate and confirms its homogeneity.

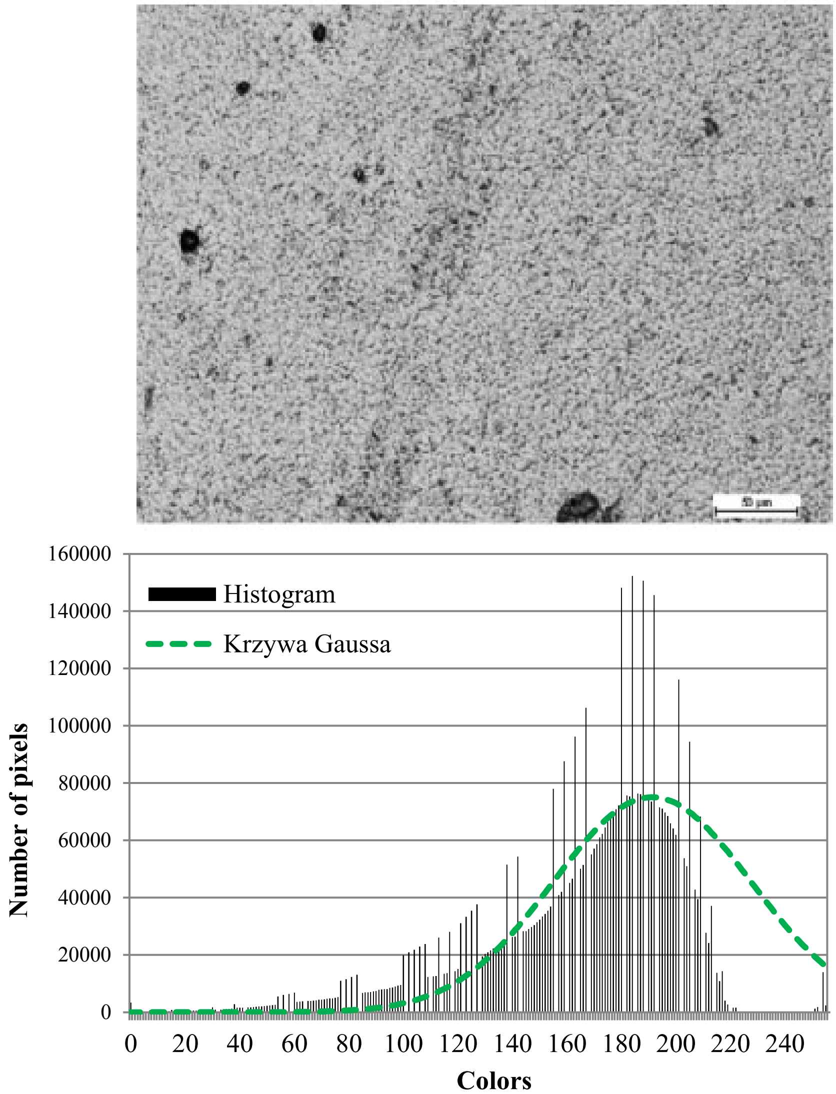
Figure 4a. Photo and histogram of the structure P3 deposited on silicon





The wide distribution of greyscales means that the sample is highly granular and, to some extent, this reflects a defect in the substrate. We conclude that the fine-graininess is due to the optical effect in the form of strong light scattering. The wavelength of the light is comparable to the characteristic grain size. The histogram detected surface defects with a lighter shade (a strong characteristic line on the left, towards the light pixels). The largest number of counts in this case is in the range of 65-220; the wide range of grayscale confirms the heterogeneity of the coating.

Figure 4b. Photo and histogram of structure P3 deposited on glass



Analysing the image obtained during the examination of the coating with the optical microscope, it can be stated that, similar to the structure P3 deposited on silicon, the coating is fine-grained. From the histogram for layer P3 deposited on glass we can see that the layer is characterised by a large variety of surfaces. The greyscale counting range from 80 to 220 shows that there are many phases and surface defects. The largest number of counts in this case is in the range 150-210.

Figure 5a. Photo and histogram of P4 structure deposited on silicon

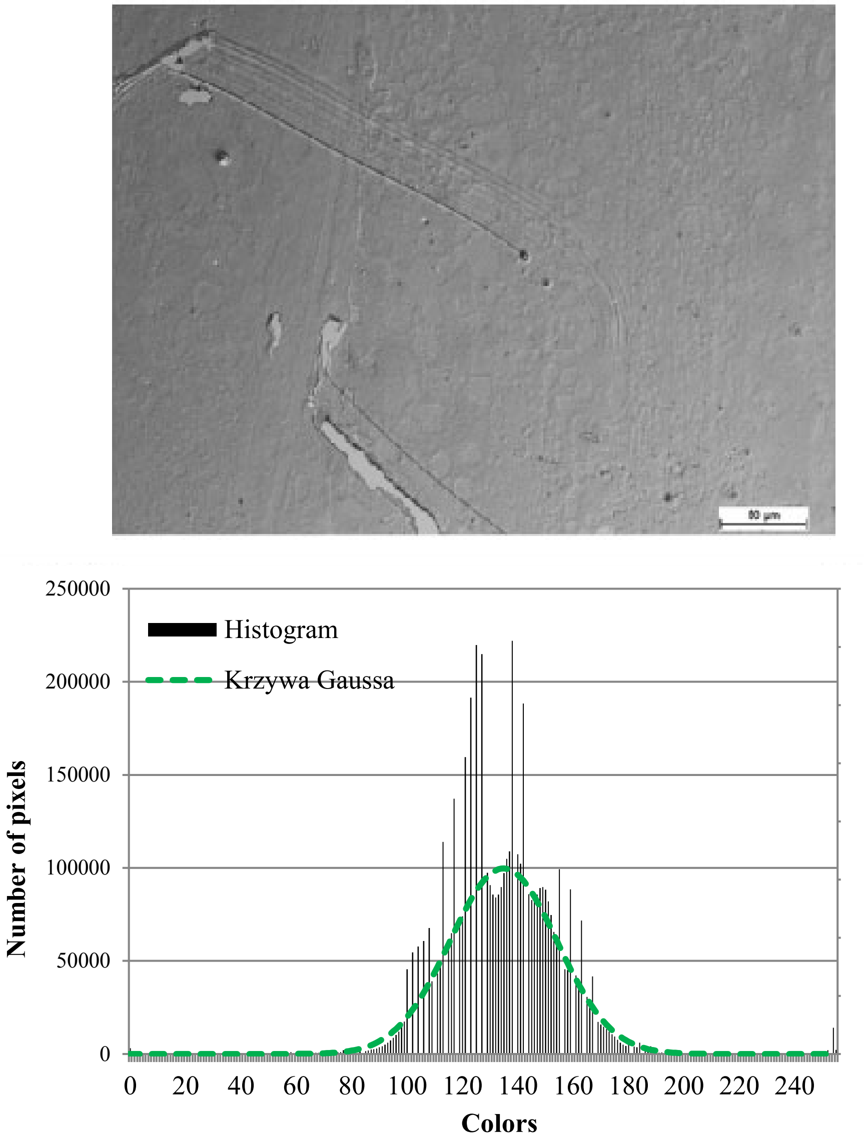
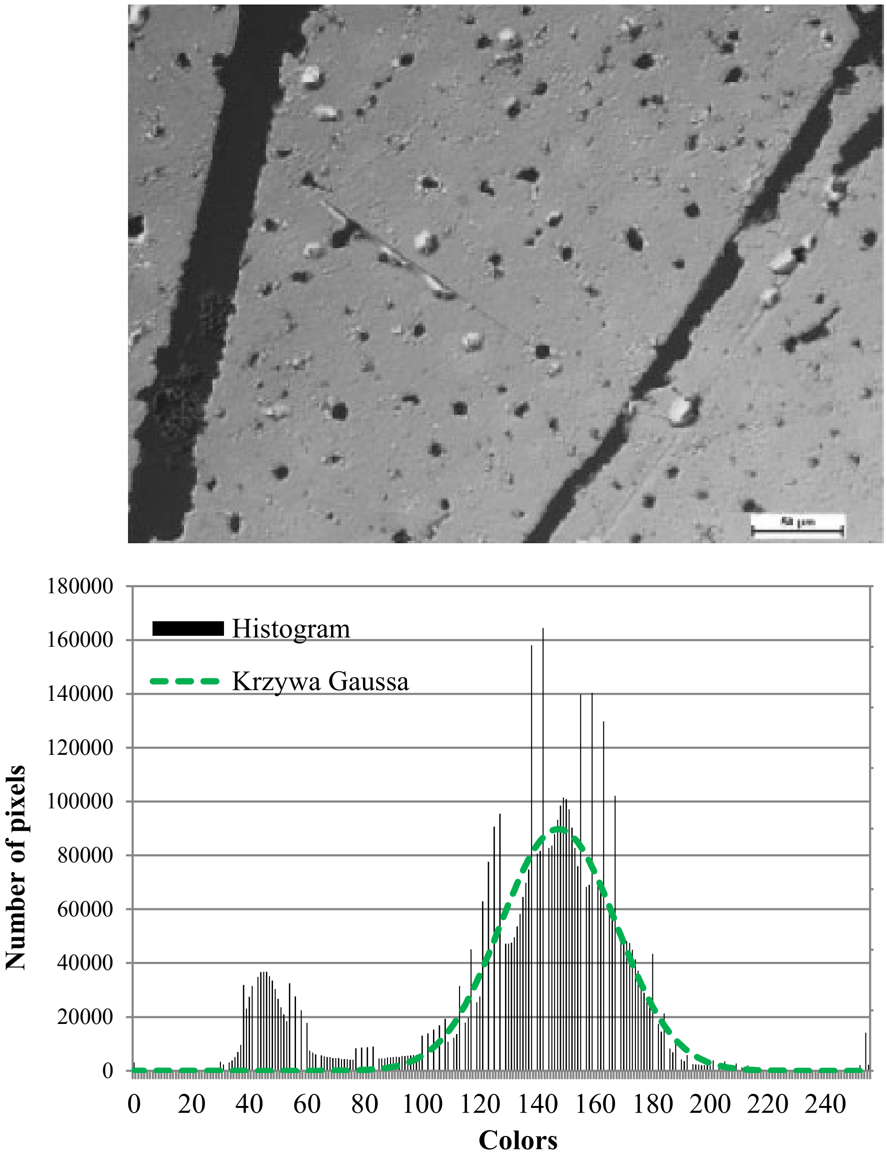


Figure 5a shows that the structure is heterogeneous. There are point defects arising from the manufacturing process and large surface defects in the form of scratches probably of a physical nature, which are not the result of the applied deposition process, but of subsequent tests carried out on the sample. The histogram shows that the analysed layer is homogeneous, but the counting observed in the range 100-160 of greyscales indicates slight deviations in the surface parameters of the analysed structure.

Figure 5b. Photo and histogram of P4 structure deposited on glass



From the histogram for layer P4 we can see that, apart from the dominant homogeneous structure giving greyscales from the range 110-180, a large number of counts in the range 40-55 illustrates the lack of continuity of the layer (uncovered substrate). In addition, it should be noted that in this case we are dealing with mechanical damage to the layer resulting from the scratch--test test (two clear scratches shown in Fig. 5b). The picture and histogram (Fig. 5b) show that the material is heterogeneous, there are a significant number of point defects of a large size of 10 µm, in addition, there are two characteristic scratches formed mechanically.
Table 2, with the minimum and maximum value of greyscale counts and the calculated standard deviation for all structures imposed by magnetron atomisation on silicon and glass, is presented below.

Table 2. Greyscale range and standard deviation

Greyscale range	P1		P2		P3		P4	
	Silicon	Glass	Silicon	Glass	Silicon	Glass	Silicon	Glass
Min	140	120	150	110	65	150	100	110
Max	170	180	180	135	220	210	160	180
Standard deviation [%]	10	20	15	8	40	25	20	30

The grayscale ranges and standard deviations listed in Table 2 allow the surface quality of the analysed layer to be assessed. The greatest heterogeneity is observed for the P3 layer deposited on silicon and glass. In this case there is the largest dispersion of values and the largest value of standard deviation. The best homogeneity is observed for layer P1 on silicon and layer P2 on glass. In the case of layer P4 on glass, the interpretation of the results and evaluation of the quality of the layer is difficult due to the clear mechanical scratches on the layer.

Conclusion

The paper presents a method of quantitative analysis of surface defects of samples by applying histograms of greyscales. The analysis technique used has certain advantages. The distributions presented quite effectively reflect particular types of defects, although the disadvantage of the method is the fact that the overlapping of similar greyscales from particular types of defects may lead to misinterpretations. The largest greyscale range was determined for structure P3 deposited on silicon and amounted to 65-220 (sample with fine grain structure with defects), whereas the smallest number of counts was determined for structure P2, deposited on glass and amounting to 110-135 (homogeneous sample with a small number of defects). The smallest standard deviation is shown by the structure P1 deposited on the silicon substrate and P2 applied to the glass substrate, which indicates the highest uniformity of its surface. This is consistent with the optical image made on the microscope and the histogram placed next to it (Fig. 2a, 3b).

Further studies on this analytical method are necessary, as it appears to be effective, but its weaknesses and methods for correcting errors should be learned, as well as clearly linking the nature, number and size of defects and the shape of histograms.

Bibliography

1. https://www.dcode.fr/image-histogram [access:18.05.2018].
2. Scuderi V., Amiard G., Sanz R., Boninelli S., Impellizzeri G., Privitera V.*: TiO_2 coated CuO nanowire array: Ultrathin p–n heterojunction to modulate cationic/anionic dye photo-degradation in water*,„Applied Surface Science" 416, p. 885-890, 2017.
3. Rokhmat M., Wibowo E.,Sutisna, Khairurrijal, Abdullah M.: *Performance Improvement of TiO2/CuO Solar Cell by Growing Copper Particle Using Fix Current Electroplating Method*,„Procedia Engineering" 170, p. 72-77, 2017.
4. Boissenin M., Wedekind J., Selvan A. N, Amavasai B. P., Caparrelli F., Travis J. R: *Computer vision methods for optical microscopes*,„Image and Vision Computig" 25, p. 1107-1116, 2007.
5. Pires L. F, Borges F. S., Passoni S., Pereira A. B.: *Soil Pore Characterization Using Free Software and a Portable Optical Microscope* „Pedosphere" 23, p. 503-510, 2013.
6. Delbem I. D., Galéry R.,BrandãoP. R. G.,PeresA. E. C.: *Semi-automated iron ore characterisation based on optical microscope analysis: Quartz/resin classification*, „Minerals Engineering" 82, p. 2-13, 2015.
7. Kottler V., Essaidi N., Ronarch N., Chappert C., Chen Y.*: Dichroic imaging of magnetic domains with a scanning near-field optical microscope* „Journal of Magnetism and Magnetic Materials" 165, p. 398-400, 1997.
8. Sekatskii S. K., Mironov B. N, Lapshin D. A, Dietler G., Let V. S.: *Analysis of fiber probes of scanning near-field optical microscope by field emission microscopy*, „Ultramicroscopy" 89, p. 83-87, 2001.
9. Wieclawek W.: *Information granules in image histogram analysis* „Computerized Medical Imaging and Graphics" 65, p. 129-141, 2018.

Angelika Głuszek
ORCID: 0000-0001-5221-0745

Angelika Głuszek is a student of Material Engineering at the University of Rzeszow - Masters studies. She graduated in engineering studies in Material Engineering at the Rzeszow University.

Paulina Sawicka-Chudy, MA, Eng.
ORCID: 0000-0002-5931-6566

Paulina Sawicka-Chudy is a master of science Faculty of Civil and Environmental Engineering, Environmental Engineering, Technical University of Rzeszow, and PhD student of Physics at University of Rzeszow and Electronics at Technical University of Lodz. His research is concentrated around optimization and development of semiconductor devices and particularly TiO2/Cu2O solar cells structures.

Grzegorz Wisz, DSc
ORCID: 0000-0003-1029-4359

Grzegorz Wisz is a PhD in physical sciences, academic teacher, entrepreneur. In 2003 he became a PhD at the Institute of Physics of the University of Rzeszow. In 1998, he studied Computer Science, and in 2013 - Innovation and Knowledge Transfer Management. External expert of the National Center for Research and Development, member of the Supervisory Board of the Polish Institute of Innovation and Technology Transfer, member of the Working Group on National Intelligent Specialization, member of the Cluster Council of the Polish Clusters Employers' Association, head of the Protective Technology Laboratory of the University Center for Innovation and Technical and Natural Knowledge Transfer, Director of Technology Transfer Center of the University of Rzeszow, an initiator and creator, and currently a President of the Subcarpathian Renewable Energy Cluster. Initiator and animator of the Smart Eco-Estate 2020 concept. Author and co-author of over fifty publications and scientific studies in the field of physics, energy management and clusters.

Maciej Sibinski, DSc, Eng.
ORCID: 0000-0002-9752-3400

Maciej Sibinski was born in Zgierz. In 1994 he has finished grammar school (in mathematic-physics educational profile) and started his studies at the Electronics and Electrical Engineering Faculty at the Technical University of Lodz. During the individual course of studies (1997-1999) he took part in TEMPUS program, visiting many European Universities and Scientific Centers. He has completed technology practices in Technische Universitat in Berlin, EU Joint Research Center in Ispra and State University of Gent - Belgium. In 1999 he prepared and defended his diploma thesis: „Cadmium telluride solar cells". From 1998 he was employed in Institute of Electronics at the position of trainee assistant and assistant and from 2008 after defense of his PhD diploma in Department of Semiconductor and Optoelectronic Devices as the assistant professor. His research is concentrated around optimization and development of semiconductor devices and particularly solar cells structures. His main field of interest is elaboration of thin-film polycrystalline solar cells, optimized towards low production costs and wide application range.

Marian Cholewa, **DSc, Associate Professor**
ORCID: 0000-0002-8717-0779

Marian Cholewa – Professor at the University of Rzeszow in Rzeszow, Poland. Head of the Biophysics Department. Author or co-author of over 180 publications with Hirsch Index of 19. Co-author of 3 patents. Research interests involves development and applications of: (a) development and application of new materials for green energy research, (b) development of new nanomaterials for enhanced secondary electron emission (c) novel methods of imaging in Biology and Medicine including MRI, PET, PET/MR, CT and synchrotron radiation, (d) development and applications of novel analytical techniques with electron, ion, laser and X-ray microbeams. Has been working in research establishments around the Globe including: Australia (Melbourne and Monash Universities), Germany (GSI and KIT), JAEA in Japan, Poland (INP, RUT and UR), Singapore (NUS) and USA (BNL). Supervisor of multiple Diploma, MSc and PhD students around the world.

LEAKING AWAY THE FUTURE: THE ROLE OF METHANE EMISSION AND NATURAL GAS SUPPLY CHAINS IN GLOBAL WARMING

Andreás Molnár[1]

Abstract

Natural gas is being considered as a "bridging fuel" that plays a crucial role in implementing the transition to a low-carbon economy and society. This study reviews an aspect of the natural gas industry that has been neglected for far too long, in spite of the growing importance of countering global warming and climate change. Reducing methane emissions from natural gas production, processing, transportation and consumption is becoming a more and more important aspect of reducing greenhouse gas emissions, and may contribute significantly to the goals of the United Nations Climate Change Conference of 2015. The key question this study aims to answer is to what degree does a stronger emphasis on natural gas consumption contribute to the fulfilment of the climate goals of the Paris Agreement per se? Is promoting natural gas consumption really the key to avoid a climate catastrophe? Is there sufficient time left to avoid such a catastrophe?

Keywords: natural gas, global warming, climate change, greenhouse gases, methane

Introduction

In December 2015 at the United Nations Climate Change Conference in Paris world leaders once again agreed – just as they did before, in Cancun, Copenhagen, Kyoto and Rio de Janeiro – to try to put a halt to climate change and its constantly aggravating consequences. The 196 signatory states of the Paris Agreement committed to "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (United Nations Framework Convention on Climate Change, 2015:2). But, despite the global understanding that urgent steps are needed to avert the worst-case scenarios of climate change, the world remains on track towards further global warming and, along with it, suffering from increasingly unpredictable and extreme weather conditions. According to the United Nations Environment Programme (UNEP), even if all of the current Paris pledges are kept, the world will still warm up by more than 3°C (UNEP, 2016:7).

The main reason behind this continuing failure to meet the challenge of climate change is the world's insatiable dependence on and appetite for fossil fuels: coal, oil, and natural gas. Almost every country burns these hydrocarbons at an accelerating pace, which gives incentives to the fossil fuel industry to explore for more. Yet there is a visible shift underway in global energy politics: although investments in coal and oil remain strong, over the last decade there has been an investment boom in natural gas, which led to a global increase in natural gas extraction and consumption. It started with the shale gas boom in the late 2000s in the United States whereby the level of natural gas production of the US increased from 543,2 billion cubic meters in 2000 to 734,5 billion cubic meters in 2017. This was accompanied by constantly growing natural gas consumption globally. Today, the five biggest natural gas consumers are the United States, Russia, China, Japan and Iran, accounting for almost half of all global natural gas consumption, with 1736,2 billion cubic metres out of 3670,4 billion cubic meters of total consumption worldwide in 2017 (British Petroleum 2018, p. 28).

[1] András Molnár is a PhD candidate at the Faculty of Social Sciences and International Relations at Corvinus University of Budapest (Hungary).

Since combustion of natural gas emits 50 to 60 percent less carbon dioxide (CO_2) when combusted in efficient natural gas power plants as compared to the emissions from a typical new coal plant, the image of natural gas extraction became strongly coupled with the fight against global warming and the goal of less pollution (National Energy Technology Laboratory 2010, p. 41-43). Thus, based on political, economic and environmental reasons, more and more countries plan to increase the share of natural gas as compared to other fossil fuels. The best example for this is the European Union as a whole, where natural gas plays a crucial role in the establishment of the so-called Energy Union, an ever-closer cooperation of member states with the aim of boosting energy security, creating a fully integrated internal energy market, improving energy efficiency, and pursuing the goal of decarbonisation (European Commission 2016b).

However, the question arises: *To what degree does a stronger emphasis on natural gas consumption contribute to the fulfilment of the climate goals of the Paris Agreement*? Is promoting natural gas consumption really the key to avoid a climate catastrophe until mankind finds a way to overcome its addiction and dependence on fossil fuels in energy generation and transport? Is there sufficient time left?

The severe consequences of climate change

It has been shown by scientists that a 2°C rise in temperatures worldwide can have devastating effects on the local and global scales, hitting the most vulnerable the hardest, and affecting tens of millions of people mainly in Africa, the Middle East and Asia. Even a 1.5°C rise in average global temperatures carries major risks, by threatening the very existence of some small island states, such as Tonga, Tuvalu, Palau, and the Solomon Islands, and low-lying coastal regions of Vietnam, Bangladesh, The Netherlands, and Japan through the accelerated melting of polar ice.

According to the National Oceanic and Atmospheric Administration (NOAA) and NASA, since record-keeping began in 1895, the hottest year on record worldwide was 2016. In that year, the Earth's surface temperature was one-degree Celsius warmer than the average across the entire 20th century. Before 2016, 2015 and 2014 were the warmest years on record, globally. According to NASA, 16 out of the 17 warmest years on record occurred since 2001 (NASA 2017).

Climate dynamics often strongly affect some regions more than others, so not every part of Earth experienced above-average temperatures in the last years. However, some outstanding anomalies should be mentioned. The last years have brought numerous reminders that the world is drifting towards a climate emergency. Floods in South Asia, heavy storms in the Atlantic Ocean region, severe drought in East-Africa, and island states in the Pacific Ocean region starting to disappear because of rising sea levels. All this shows the devastating impact of climate change on human lives and livelihoods, particularly in the poorest and most vulnerable countries. Hurricanes Harvey and Irma – the strongest ever recorded in the Atlantic region –

devastated large parts of the Caribbean, and Texas and Louisiana in the US, showing that even the most-developed countries are vulnerable to climate disasters.

There is evidence of climate change in Europe and its vicinity as well. Europe experienced the “Lucifer heatwave” in August 2017, which affected millions and saw temperatures as high as 42°C in Croatia and 44 °C in Spain.

CO2 is not the only problem

As mentioned earlier, burning natural gas instead of oil or coal where and when possible can significantly reduce the emissions of carbon dioxide (CO_2) and thereby contribute to a lessened greenhouse effect. However, CO_2 is not the only problem when it comes to natural gas that contributes to global warming. Significantly less attention is paid to the fact that natural gas production is also responsible for large amounts of methane emissions. Methane, one of the components of natural gas, is also a potent greenhouse gas that contributes to global warming and climate change. Though more short-lived in the atmosphere than CO_2, it still contributes to approximately 20% of the anthropogenic warming impact on the climate (Anderson and Broderick 2017, p. 20).

With the amount of natural gas extracted, the level of methane emission is also steadily increasing. According to Anderson and Broderick, increases in atmospheric methane concentrations have been observed since 2006, as well as regional increases in emissions. These are in line with the most pessimistic of the Intergovernmental Panel on Climate Change’s[2] emissions scenarios for future greenhouse gas emission levels (Anderson and Broderick 2017, p. 20-23).

Methane is a potent greenhouse gas, with a global warming potential 34 times higher than CO2 on a 100-year time horizon, and 86 times higher for a 20-year timeframe. Although it degrades over a period of about 12 years, and thereby has a relatively short half-life in the atmosphere as compared to CO_2 (of which between 65 and 80% dissolves into the ocean over a period of 20–200 years), the persistently high emissions of methane will replenish this loss and maintain the initial warming effect. This leads to a continuous wave of additional short-term temperature increases, which add to the warming effect of CO_2 (Anderson and Broderick 2017, p. 31-32).

Due to its longer lifespan in the atmosphere, CO_2 emission will remain the main catalyst of global warming, and the reduction of methane emissions can have a significant short to medium-term impact. As Schwietzke et al. conclude, “reducing methane emissions now will reduce climate forcing in only a few years – it takes much longer for CO_2. And since fossil fuel methane emissions are higher than previously thought, the potential to reduce climate forcing from this specific source is also greater” (Schwietzke et al. 2016, p. 90). This means that if mankind wants to limit global warming to below 2°C and avoid the worst-case scenarios of climate change, it must reduce CO_2 and methane emissions at the same time.

[2] See more about this: Intergovernmental Panel on Climate Change:Global Warming of 1.5°C– Special report

Main sources and types of methane emission

Methane is emitted by numerous, diverse sources into the atmosphere. These can be grouped by their provenience – natural or anthropogenic (man-made) origin, - or by the emitting process – thermogenic, biogenic, pyrogenic. (Saunois et al. 2016, p. 702-703).

- *Thermogenic methane* is formed due to the pressure and heat deep in the Earth's crust by the breakdown of buried organic material. It reaches the surface during natural gas and oil extraction or coal mining through geologic seeps.
- *Biogenic methane* is the by-product of the decomposition of organic matter predominantly in swamps, landfills, marine sediments, landfills, rice paddies, and waste-water facilities.
- *Pyrogenic methane* is produced by the incomplete combustion of biomass. The main sources of it are biofuel usage, biomass burning and peat fires.

However each of the three process categories can have both anthropogenic and natural components. According to estimates, aproximately 40% of the total methane emission comes from biogenic sources, while the other 60% are anthropogenic (Saunois et al. 2016, p. 702). The main source of anthropogenic methane emissions is agriculture, followed by industrial activity, and fossil fuel use. The oil and gas sector contribute roughly a quarter of the world's methane emissions.

If we look at the main types of methane emission, three categories can be identified.

- *Vented emission* is the intentional release of methane into the athmosphare mainly due to operational procedures, technical design, or safety deliberations. The most common form of vented emmission is the flaring of naural gas as a byproductof oil extraction.
- *Fugitive emissions* is the consequence of unintentional methane "leaks" from not sufficiently insulated valves and gas taps, or acures do to pipeline damage. These sources of methane emission are the most challenging to detect and quantify, because of the size and complexity of the netural gas infrastructure.
- *Un-combusted emission* derives from un-combusted methane in the exhaust of equipment in the production, processing and transmission segments.

Stages of natural gas flow and methane emission

Greenhouse gas emissions occur across the full supply chain of natural gas, from its exploration to its consumption. Generally, the natural gas life cycle can be broken down into three parts of which each has separate sub-stages with separate sources of emissions. Production can be divided into three activities, namely exploration, extraction and processing. The second stage is transport, which consists of four activities: transmission through pipelines, LNG (Liquefied Natural Gas), storage, and distribution. The third stage is end-usage, referring to residential or industrial consumption.

Production

In the production or upstream stages of natural gas production, three main sources of methane emissions can be identified (Le Fevre 2017, p. 16):

- Emission during well completion
- Fugitive emission from gathering pipelines
- Flaring is also a prominent sources of methane emission though it primarily steams from the gas accompininig oil production that is not gathered and utilised. Therefore it could be considered as not a direct result of natural gas production and supply, it nevertheless plays an important role in methane gas emission.

Howarth notes that because on average 3,6 – 7,9 per cent of shale gas escapes into the atmosphere it has a larger green house gas footprint than coal if used in power generation (Howarth 2011, p. 681).

Transmission and distribution

During the transmission stage methane emission mainly arises from above ground installations such as gathering and long distance transport pipelines, compressor and pressure regulation stations and liquified natural gas terminals. In all cases the age of the infrastructure and the level of maintenance is crucial with regards to the levels of fugitive methane gas during operations. The highest amount of emissions arising during maintanence and repair operations of gas in pipelines occurs when natural gas is vented to the atmosphere prior to work commencing. In 2015 Gazprom reported 1.3 million tonnes of methane emission of which 77 per cent arose from venting during repairs pf pipelines and other transport infrastructure (Gazprom 2016, p. 22). Leakage rates can vary widely however. A recent study by DBI (2016) assessed leakage rates for gas exported by Russie trough Ukraine as 0.38 per cent of sales gas. At the same time an European transmission operator reported a reduction in measured pipeline leakage from 0.024 per cent of sales gas to 0.01 per cent after a major repair programme was carried out between 2015 and 2017 (Le Fevre 2017, p. 17).

If we look at the distribution segment the main source of methane emission can be tracked back to the composition and insulation of pipelines. Methane leakages are more common in the case of older, metallic mains compared to polyethylene pipelines. In the case of metallic pipelines methane leakages typically arise from cracks in the iron, or from leaking joints and valves with old, worn out gaskets.

Table 1. Stages and sources of methane emission during the natural gas live cycle

Stage	Source	Example
Pre-extraction	Drilling and hydraulic fracking	Gas vented to atmosphare while drilling
	Well construction	Gas vented during the completion process

Extraction	Flaring	Unburned methane
	Workovers	Intentional venting
	Fugitive	Leaks caused by insufficient sealing
Processing	Flaring	Unburnd methane
	Fuel production	Unburned methane leaking to atmosphare
	Fugitive	Equipment failure
Transmission and distribution	Fuel	Unburned methane leaking from engines
	Fugitive	Unsufficient equipment sealing
Utilisation	Leakages	Unburned methane leaking during residential and industrial activity

(Balcombe 2015, p. 8).

Europe is involved in all of the stages of the natural gas life cycle, which also means that it has to deal with methane emissions from all three dimensions of the gas industry. However, the biggest and most important segment of it is transportation.

The Netherlands and the United Kingdom are the largest producers of natural gas in the European Union, representing approximately 70% of production. However, most gas consumed in the EU is imported, with an energy dependency ratio of approximately 70%. Currently, four sources dominate imports: pipeline gas from Russia (42% of imports to the EU in 2016), Norway (34%), Algeria (11%) and Liquified Natural Gas (13%) from diverse regions but mainly from Qatar, Algeria and Nigeria (European Commission 2016a).

According to Anderson and Broderick, the greenhouse gas emissions in the European natural gas supply chain, from lowest to highest, are: 1) conventional North Sea production, 2) short-distance pipelines, 3) LNG, 4) long distance pipelines (from Russia). The additional emissions of LNG and long-distance pipelines are approximately double those from short-distance conventional production. However, more factors must be considered when comparing and calculating the greenhouse gas emissions of different types of natural gas transportation. According to Abrahams (Abrahams 2015, p. 3239), upstream emissions from Russian production and transmission have an additional 3% methane leakage over US gas (speaking in average terms) and concludes that LNG exports from the US to Europe are more favourable than long-distance pipelines. Heath (Heath 2014, p. 3169) identified pipeline distance and pipeline leakage rate as the dominant factor of emissions, whereby a doubling of distance would lead to a 30 to 35 percent increase in greenhouse gas emissions. Balcombe (Balcombe et al. 2017, p. 8-10) suggest that the additional energy required for liquified natural gas (for liquefaction, cooling, shipping, transportation, and regasification) increases total emissions of LNG by about 20%.

End use accounts for the largest share of the climate change impact from natural gas, except for the very highest end of the liquefied natural gas range. As to transportation, the *lowest* absolute emissions of pipelines range from 94% to 53%, versus 86% to 43% for the *highest* absolute emissions for LNG, respectively.

Totalling 8%, transmission, storage and distribution are next on the list of sources of harmful emissions, followed by processing at 7%. All other stages of the natural gas supply chain represent less than 1% of total absolute emission (Anderson and Broderick 2017, p. 11).

However, supply chains with poorly regulated and enforced production and transportation standards – especially in the case of the long-distance pipelines from Russia – may still have the highest leakage rates.

LNG and climate change

The fracking boom in the US and high levels of natural gas consumption in the European Union between 2003 and 2010, and from 2014 onwards, have contributed to the rise of a new source of threat for the climate. The revival and constant output growth of the LNG industry has significantly contributed to global greenhouse gas emissions. Natural gas is more easily and cost-effectively transported across great distances in liquid form than through pipelines, but the climate impact of LNG has received little attention so far.

LNG creates additional methane emissions through the additional steps that are needed to produce it, ranging from liquefaction to the special processes and arrangements needed for transport and the regasification process. To make LNG, natural gas first needs to be cooled down to minus 160°C, and then warmed up again to convert it back to its gaseous form. Both procedures are highly energy-intensive, and therefore emissions-intensive. Anderson and Broderick conclude that although "there are large uncertainties in the emissions associated with natural gas supply chains, the additional emissions of LNG and long-distance pipelines are approximately double those of short distance conventional production" (Anderson and Broderick 2017, p. 39). According to Balcombe et al. (Balcombe et al 2017, p. 9) there is "greater confidence in the conclusion that the additional energy required for LNG transportation (for liquefaction, shipping and regasification) adds a burden for LNG of approximately an additional 20% over emissions from combustion and short-distance pipeline transport." Research firm Wood Mackenzie estimates that with the present year-on-year growth of the liquefied natural gas sector of around 5%, it will be the biggest source of carbon emissions growth for the world's top oil and gas companies by 2025 (Wood Mackenzie 2017). All this makes LNG a particularly dangerous kind of energy source for the climate; one which sees increases in investments from both exporting and importing countries, because they see it as a way of strengthening their energy security and diversifying their energy mix.

Conclusion

Climate change is driven by the continuously high amount of fossil fuel production, distribution and consumption needed to power our everyday lives. If we are to achieve the objectives of the Paris Agreement – to hold global average temperatures to below 2°C above pre-industrial levels – it is essential that within the coming three to four decades massive steps be taken in the direction of full global decarbonisation. This means that there is no room for the current consumption of high-level greenhouse gas emitting fossil fuels, such as coal and oil. Neither of these energy sources ought to play a substantial role on the global scale beyond 2035.

Methane emissions from the gas industry are a threat to the climate, and especially to people most at risk from the adverse effects of climate change. Whether produced and consumed domestically, or exported by pipeline or by ship as LNG, the gas industry contributes significantly to climate change by uncontrolled methane leaks.

Even though there is no reliable data on how extensive and how dangerous these leaks are, cutting methane emissions is nonetheless a necessary step to cut greenhouse gas emissions. Given the extent of existing greenhouse gas emitting infrastructure, it is highly unlikely that the Paris 2°C commitment is a viable mitigation objective.

Whereas currently carbon dioxide may be the main source of, and contributor to, climate change. However, methane released during natural gas production, distribution and consumption, means that, in the long run methane has a much greater warming effect. Its amount is greatly influenced by factors such as locations, production technologies, and the type and length of transportation infrastructure. Since recent trends allow for the projection of a further increase in the production and shipping of LNG, this also implies an additional greenhouse gas emission burden for the environment.

Therefore, natural gas cannot be considered as a short- or medium-term solution to climate change. Decades of political inaction has led to the urgent need for action today. Time is running out fast for a fossil fuel-based transition to renewable energy resources, which could avert a catastrophic climate change. The world needs to act and cut back significantly on its fossil fuel dependency before it is too late to do so.

Bibliography

1. Abrahams S. Leslie et al. (2015): Life cycle greenhouse gas emissions from U.S. liquefied natural gas exports: implications for end uses. *Environmental Science and Technology No.* 49(5), February 2015, p. 3237–3245.
2. Anderson, Kevin – Broderick, John (2017): Natural gas and climate change. *Friends of Earth Europe.* https://www.foeeurope.org/sites/default/files/extractive_industries/2017/natural_gas_and_climate_change_anderson_broderick_october2017.pdf [access 08.09.2018].
3. Balcombe, Paul., Anderson, Kris., Speirs, Jamie., Brandon, Nigel., Hawkes, Adam., (2015): Methane and CO_2 emissions from the natural gas supply chain – and evidence assessment, Sustainable Gas Institute | Imperial College London, https://www.sustainablegasinstitute.org/wp-content/uploads/2015/09/SGI_White_Paper_methane-and-CO2-emissions_WEB-FINAL.pdf?noredirect=1 [access 12.09.2018].
4. Balcombe, Paul et al. (2017): The Natural Gas Supply Chain: The Importance of Methane and Carbon Dioxide Emissions, *ACS Sustainable Chemistry & Engineering 5*(1), p. 3-20.
5. British Petroleum (2018): *BP Statistical Review of World Energy*. Available at: https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf [access 05.09.2018].
6. Energy Sector Planning and Analysis (2015): "Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3". *United States Department of Energy*. Available at: https://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Rev3Vol1aPC_NGCC_final.pdf [access 12.08.2018].
7. European Commission (2016a): *Quarterly Report on European Gas Markets, Market Observatory for Energy*, 9:4.
8. European Commission (2016b): "Towards Energy Union: The Commission presents sustainable energy security package, Brussels, 16 February 2016".Available at: http://europa.eu/rapid/press-release_IP-16-307_en.htm [access 29.08.2018].
9. Gazprom 2016; PJSC Gazprom Environmental Report, 2016. http://www.gazprom.com/f/posts/53/331565/gazprom-ecology-report-2016-en.pdf [access 02.09.2018].
10. Heath, A. Garvin (2014): "Harmonization of initial estimates of shale gas life cycle greenhouse gas emissions for electric power generation." *Proceedings of the National Academy of Sciences of the United States of America, 111*(31), pp. E3167-E3176.
11. Howarth, R., Santoro, R., and Ingraffea, A.: Methane and the greenhouse-gas footprint of natural gas from shale formations, Climatic Change, 106, 679–690, doi:10.1007/s10584-011-0061- 5, 2011.
12. Le Fevre, Chris (2017): Methane Emissions: from blind spot to spotlight, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2017/07/Methane-Emissions-from-blind-spot-to-spotlight-NG-122.pdf [access 19.08.2018].
13. NASA (2017): "NASA, NOAA Data Show 2016 Warmest Year on Record Globally, 19 January 2017". Available at: https://www.nasa.gov/press-release/nasa-noaa-data-show-2016-warmest-year-on-record-globally [access 20.08.2018].
14. National Energy Technology Laboratory (NETL). 2010. Cost and performance baseline for fossil energy plants, Volume 1: Bituminous coal and natural gas to electricity. Revision 2. November. DOE/NETL-2010/1397. United States Department of Energy.
15. Saunois, Marielle et al. (2016): The global methane budget 2000–2012, https://www.earth-syst-sci-data.net/8/697/2016/essd-8-697-2016.pdf, doi:10.5194/essd-8-697-2016, [access 10.09.2018].
16. Schwietzke, Stefan et al. (2016): "Upward revision of global fossil fuel methane emissions based on isotope database." *Nature, 538*(7623), pp. 88-91.
17. United Nations Environment Programme (2016): *The Emissions Gap Report 2016: A UNEP Synthesis Report.* Available at: https://europa.eu/capacity4dev/unep/document/emissions-gap-report-2016-unep-synthesis-report [access 10.09.2018].
18. United Nations Framework Convention on Climate Change (2015): *Adoption of the Paris Agreement, 21st Conference of the Parties.*
19. Wood MacKenzie (2017): Global LNG long-term outlook 2017. Available at: https://www.woodmac.com/reports/lng-global-lng-long-term-outlook-2017-50294119 [access 01.09.2018].

András Molnár, MSc
ORCID: 0000-0001-6512-4061

András Molnár is a PhD candidate at the Faculty of International and Security Studies of Corvinus University Budapest, Hungary. His main area of research is Russian foreign energy policy, with a special focus on natural gas in terms of Central Asia.

He is currently working for the Hungarian Ministry of Foreign Affairs and Trade.

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

Wojciech Pospolita[1], *Maciej Cholewinski*[2]

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

[1] Wroclaw University of Science and Technology, Faculty of Mechanical and Power Engineering, Department of Mechanical Engineering and Energetic Systems,e-mail: wojciech.pospolita@pwr.edu.pl
[2] Wroclaw University of Science and Technology, Faculty of Mechanical and Power Engineering, Department of Cryogenic, Aeronautic and Process Engineering, e-mail: maciej.cholewinski@pwr.edu.pl

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?

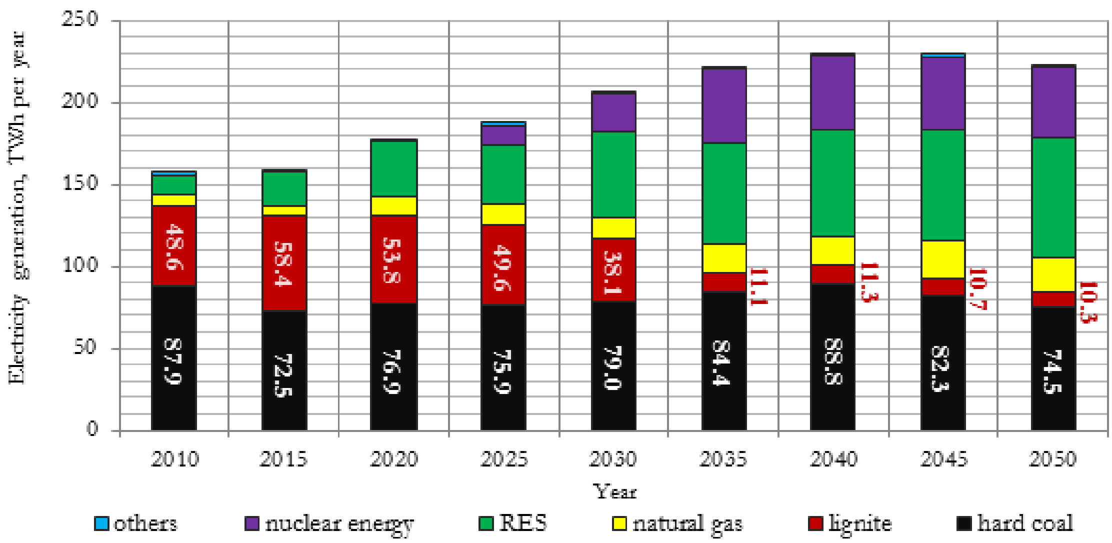
Facts concerning the use of coal fuels in Poland

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.

<u>Current structure of electricity generation in Poland</u>

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.

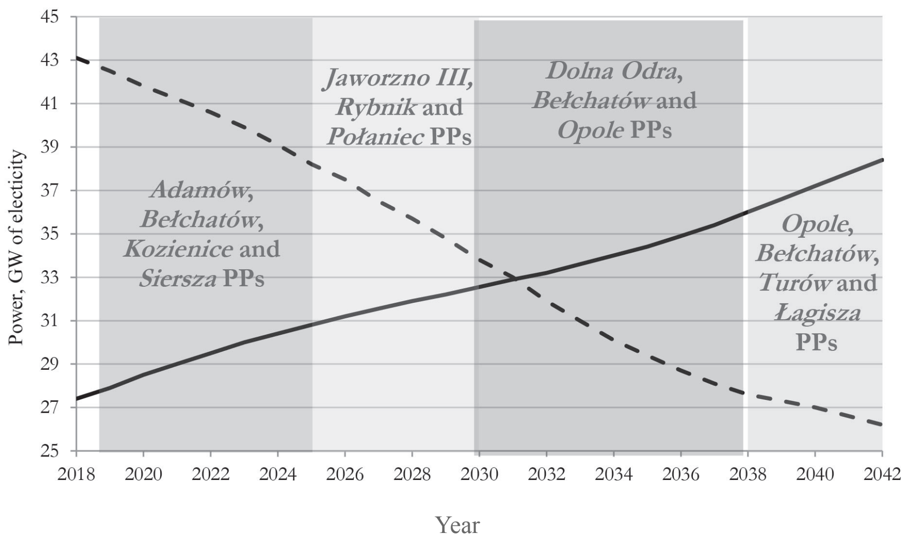
Challenges for coal-fired power generation

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

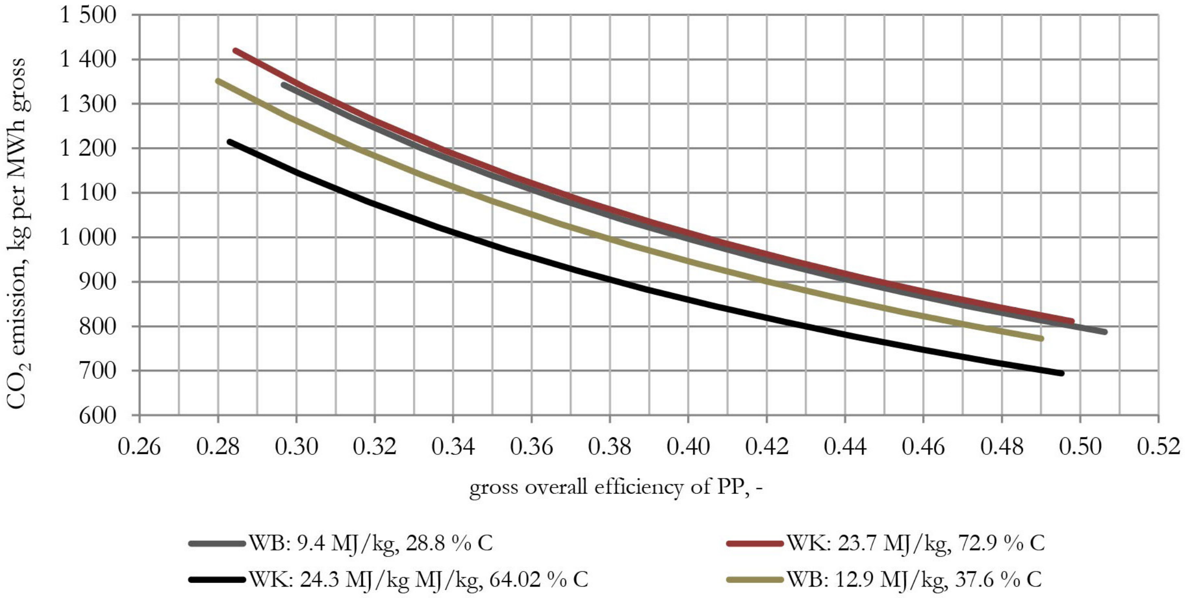
Reduction of pollutant emissions

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 cogeneration 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)

<table>
<tr><th rowspan="3">Pollutant</th><th rowspan="3">Power, MW_t</th><th colspan="4">Fuel</th></tr>
<tr><th colspan="2">steamcoals</th><th colspan="2">biomass and peat</th></tr>
<tr><th>new</th><th>existing4)</th><th>new</th><th>existing4)</th></tr>
<tr><td rowspan="3">NO_x, mg/m^3_{ref}</td><td>< 100</td><td>100-150</td><td>100-270</td><td>70-200</td><td>70-250</td></tr>
<tr><td>100-300</td><td>50-100</td><td>100-180</td><td>50-140</td><td>50-180</td></tr>
<tr><td>≥ 300</td><td>50-85</td><td>65-175</td><td>40-140</td><td>40-160</td></tr>
<tr><td rowspan="3">SO_2, mg/m^3_{ref}</td><td>< 100</td><td>150-200</td><td>150-360</td><td>15-70</td><td>15-100</td></tr>
<tr><td>100-300</td><td>80-150</td><td>95-200</td><td>< 10-50</td><td>< 10-100</td></tr>
<tr><td>≥ 300</td><td>10-75</td><td>10-180</td><td>< 10-35</td><td>< 10-100</td></tr>
<tr><td rowspan="3">CO, mg/m^3_{ref}</td><td>< 100</td><td>30-140</td><td></td><td colspan="2">30-250</td></tr>
<tr><td>< 300</td><td></td><td colspan="2">30-160</td><td></td></tr>
<tr><td>≥ 300</td><td colspan="2">5-140</td><td colspan="2">30-80</td></tr>
<tr><td rowspan="3">HCl1), mg/m^3_{ref}</td><td>< 100</td><td>1-6</td><td>2-20</td><td>1-15</td><td>1-25</td></tr>
<tr><td>100-300</td><td rowspan="2">1-3</td><td rowspan="2">1-20</td><td>1-15</td><td>1-25</td></tr>
<tr><td>≥ 300</td><td>1-15</td><td>1-25</td></tr>
<tr><td rowspan="3">HF2), mg/m^3_{ref}</td><td>< 100</td><td>< 1-3</td><td>1-7</td><td>< 1</td><td>< 1,5</td></tr>
<tr><td>100-300</td><td rowspan="2">< 1-2</td><td rowspan="2">1-7</td><td>< 1</td><td>< 1</td></tr>
<tr><td>≥ 300</td><td>< 1</td><td>< 1</td></tr>
<tr><td rowspan="4">pyły, mg/m^3_{ref}</td><td>< 100</td><td>2-5</td><td>2-18</td><td>2-5</td><td>2-15</td></tr>
<tr><td>100-300</td><td>2-5</td><td>2-14</td><td>2-5</td><td>2-12</td></tr>
<tr><td>300-1000</td><td>2-5</td><td>2-12</td><td rowspan="2">2-5</td><td rowspan="2">2-10</td></tr>
<tr><td>≥ 1000</td><td>2-5</td><td>2-8</td></tr>
<tr><td rowspan="2">Hg, $\mu g/m^3_{ref}$</td><td>< 300</td><td>< 1-3/5 3)</td><td>< 1-9/10 3)</td><td rowspan="2" colspan="2">< 1-5</td></tr>
<tr><td>≥ 300</td><td>< 1-2/4 3)</td><td>< 1-4/7 3)</td></tr>
</table>

[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.

Bibliography

1. Strupczewski A., Why renewable energy sources are not enough for Poland?, 13.06.2018, https://www.cire.pl/item,164657,2,0,0,0,0,0,dlaczego-odnawialne-zrodla-energii-nie-wystarcza-dla-polski-.html [access: 31.07.2018]
2. PSE, Report 2016 Polish Power System, https://www.pse.pl/dane-systemowe/funkcjonowanie-rb/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2016 [access: 31.07.2018]
3. Ministry of Economy, Conclusions from prognostic analyzes for the needs of Poland's Energy Policy until 2050, Annex 2 to the Energy Policy of Poland until 2050, Project - version 0.2, Warsaw, June 2015
4. Popławski T., Dudek G., Łyp J., Forecasting methods for balancing energy market in Poland. Electrical Power and Energy Systems 65, p. 94 -101 October 2015
5. Stankiewicz P., We will build a power plant for you (a nuclear one!). Technology assesment in development of nuclear energy in Poland. Studia socjologiczne 212, p.77-108, 2014
6. Dolega W., Energy eggiciency – Case study Poland. Innovative Materials and Technologies in Electrical Engineering 1-6 April 2018
7. Tomaszewski R., What will Poland do without lignite?, 13.07.2017, https://www.politykainsight.pl/gospodarka/pienergy/1712204,1,co-polska-zrobi-bez-wegla-brunatnego.read [access: 31.07.2018]
8. Polish Geological Institute, Origin, occurrence, resources and deposits of hard coal in Poland and in the world https://www.pgi.gov.pl/psg-1/psg-2/informacja-i-szkolenia/wiadomosci-surowcowe/10416-geneza-wystepowanie-zasoby-i-zloza-wegla-kamiennego-w-polsce.html [access: 31.07.2018]
9. wnp.pl, Siemens has broken the world efficiency rekord of Power unit, http://energetyka.wnp.pl/siemens-pobil-rekord-swiata-sprawnosci-bloku-energetycznego,266794_1_0_0.html [access: 31.07.2018]
10. Polish Geological Institute, Coal mining in Poland, https://www.pgi.gov.pl/psg-1/psg-2/informacja-i-szkolenia/wiadomosci-surowcowe/10418-wydobycie-wegla-kamiennego-w-polsce.html [access: 31.07.2018]
11. Szuflicki M., Malon A., Tymiński M. (red): Balance sheet of mineral resources in Poland untill December 31, 2016, Polish Geological Institute - National Research Institute, Warsaw, 2017
12. Central Statistical Office, Ministry of Energy, Department of Energy: Fuel and Energy Economy in 2015 and 2016, 27.10.2017,https://stat.gov.pl/obszarytematyczne/srodowiskoenergia/energia/gospodarka-paliwowo-energetyczna-w-latach-2015-i-2016,4,12.html [access: 31.07.2018]
13. Kassenberg A., Wilczyński M., Poland. It's not easy to identify resources, 20.06.2016, https://pl.boell.org/pl/2016/06/20/polska-nie-tak-latwo-okreslic zasoby [access: 31.07.2018]
14. Cholewiński M.: The reduction of atmospheric emissions after the implementation of first Polish nuclear power plant, EPJ Web Conf., Vol 177, 2018
15. Cholewiński M., Estimation of mercury from solid fuel combustion processes, Zeszyty Energetyczne, Vol. 4, p. 74-87, Wroclaw, 2017
16. Central Statistical Office, Ministry of Energy, Department of Energy: Fuel and Energy Economy in 2015 and 2016, Zakład Wydawnictw Statystycznych, Warsaw, 2017.
17. Wierzbowski M., Filipiak I., Łyżwa W., Polish Energy Policy 2050 - an instrument to system. Renewable and Sustainable Energy Reviews 74, p. 51-70 June 2017
18. Pawlik M., High-tech power units in the national power system. Archiwum energetyki, XLIII, No.1-2, p. 75-85 (2013)
19. Information from the President of the Energy Regulatory Office No. 153/2014 regarding the average price of electricity sales on the competitive market for the year 2013. 31.03.2014, Warsaw
20. Information from the President of the Energy Regulatory Office No. 12/2015 regarding the average price of electricity sales on the competitive market for the year 2014. 30.03.2015, Warsaw
21. Information from the President of the Energy Regulatory Office No. 13/2016 regarding the average price of electricity sales on the competitive market for the year 2015. 25.03.2016, Warsaw
22. Information from the President of the Energy Regulatory Office No. 17/2017 regarding the average price of electricity sales on the competitive market for the year 2016. 28.03.2017, Warsaw
23. Information from the President of the Energy Regulatory Office No. 28/2018 regarding the average price of electricity sales on the competitive market for the year. 30.03.2018, Warsaw
24. Information from the President of the Energy Regulatory Office No. 45/2018 regarding the average price of electricity sales on the competitive market for the first quarter of 2018. 20.06.2018, Warsaw
25. Czaplicki A., The evolution of the EU greenhouse gas emission allowance trading system (EU ETS), Energy Policy, 2017, 20 (2), p. 5-24.
26. European Commission, ETS Market Stability Reserve will start by reducing auction volume by almost 265 million allowances over the first 8 months of 2019, 15.05.2018https://ec.europa.eu/clima/news/ets-market-stability-reserve-will-start-reducing-auction-volume-almost-265-million-allowances_en [access: 31.07.2018]

27. gramwzielone.pl, Polish power industry under pressure. The costs of CO2 emissions are expected to increase rapidly, 4.05.2018, http://gramwzielone.pl/trendy/30979/polska-energetyka-pod-presja-koszty-emisji-co-2-maja-szybko-wzrosnac [access: 31.07.2018]
28. wnp.pl, Winter package with Poland's support. Support for coal-fired power plants only until 2030, 19.12.2017, http://energetyka.wnp.pl/pakiet-zimowy-z-poparciem-polski-wsparcie-dla-elektrowni-weglowych-tylko-do-2030-roku,313503_1_0_2.html [access: 31.07.2018]
29. Commission Implementing Decision (EU) 2017/1442 of 31 July 2017 establishing the Best Available Techniques (BAT) Conclusions for large combustion plants under the Directive of the European Parliament and of the Council 2010/75 / EU (notified as dokument C (2017) 5225), https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017D1442&from=PL [access: 31.07.2018]
30. Piotr Kocoł, New BAT conclusions for LCP accepted, 18.05.2017, https://www.cire.pl/item,145879,14,0,0,0,0,0,nowe-konkluzje-bat-dla-lcp-przyjete.html [access: 31.07.2018]
31. wszystkooemisjach.pl, BAT conclusions for large LCP combustion plants, http://wszystkooemisjach.pl/342/konkluzje-bat-dla-duzych-obiektow-energetycznego-spalania-lcp [access: 31.07.2018]
32. Regulation of the Council of Ministers of 22 December 2017 on unit fees for the use of the environment, 29/12/2017, http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20170002490/O/D20172490.pdf //prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20170002490/O/D20172490.pdf [access: 31.07.2018]
33. Thierry Lecomte, José Félix Ferrería de la Fuente, FrederikNeuwahl, Michele Canova, Antoine Pinasseau, Ivan Jankov, Thomas Brinkmann, Serge Roudier, Luis Delgado Sancho,Best Available Techniques (BAT) Reference Document for Large Combustion Plants, 2017,http://eippcb.jrc.ec.europa.eu/reference/BREF/LCP/JRC107769_LCPBref_2017.pdf [access: 31.07.2018]
34. Piotr W. Saługa, Jacek Kamiński, Power market in Poland - a single-price auction versus discriminatory one, Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk, 2017, No. 98, p. 167-176.

Wojciech Pospolita, MSc, Eng.
ORCID 0000-0001-6592-4413

MSc Eng Wojciech Pospolita is a PhD student at Wroclaw University of Science and Technology in a field of energetic systems and energy storage. His professional and scientific interests include new technologies of energy storage, energy generation improvements and waste energy utilisation. He is the author of more than 20 publications in many fields of power engineering.

Maciej Cholewinski, MSc, Eng.
ORCID: 0000-0002-1831-9760

MSc Eng Maciej Cholewinski is a PhD student at Wroclaw University of Science and Technology in a field of coal combustion and environment protection issues. Moreover, he works as a scientific assistant at the Department of Cryogenic, Aeronautic and Process Engineering. His professional and scientific interests include clean coal technologies, new-generation power technologies, aircraft propulsions, waste energy utilisation, and air protection issues associated with power engineering. He is the author of more than scientific 50 publications in many fields of power engineering.

Reviewers 2017:

Borkowski Paweł, DSc, Associate Professor - Institute of European Studies, University of Warsaw

Fiala Roman, PhD, Eng. - Department of Economy, College of Polytechnics Jihlava

Gędek Stanisław, DSc, Eng., Associate Professor – Rzeszów University of Technology

Głogowski Aleksander, DSc, Associate Professor - Institute of Political Sciences and International Relations, Jagiellonian University

Ludera-Ruszel Agata, PhD - Department of Law and Administration of University of Rzeszow

Marszałek Marcin, PhD - University of Law and Public Administration in Rzeszow

Narayanan G. Badri, PhD., Assistant Professor, University of Louisville

Szurlej Adam, DSc, Eng., Associate Professor - Department of Gas Engineering, AGH University of Science and Technology

ISSN: **2545-0859**