DE GRUYTER
OPEN

DOI: 10.1515/eces-2015-0027 ECOL CHEM ENG S. 2015;22(3):459-469

Sebastian WERLE[1]

SEWAGE SLUDGE-TO-ENERGY MANAGEMENT IN EASTERN EUROPE: A POLISH PERSPECTIVE

ENERGETYCZNE ZAGOSPODAROWANIE OSADÓW ŚCIEKOWYCH W EUROPIE WSCHODNIEJ: POLSKIE SPOJRZENIE NA PROBLEM

Abstract: The Sewage Sludge Directive 86/278/EEC was adopted about 30 years ago with a view to encourage sewage sludge reuse in agriculture and to regulate its use. Meanwhile, some EU Member States have adopted stricter standards and management practices than those specified in the Directive. In particular, the majority of Member States has introduced more stringent standards for sludge quality, including stricter limits for most potentially toxic elements, organic contaminants and other elements. In general, untreated sludge is no longer applied and in several Member States it is prohibited. In some cases, stringent standards have resulted in an effective ban on use of sludge in agriculture. Moreover, the implementation of the Urban Wastewater Treatment Directive 91/271/EC should increase EU production of sewage sludge, thus enhancing problems related to sustainable sewage sludge management. Additionally, European legislation prohibits the landfill and water deposits of sewage sludge. The latest trends in the field of sludge management, *ie* combustion, pyrolysis, gasification and co-combustion, have generated significant scientific interest. This trend is specially strong visible in "new" EU Members countries which have to introduce strong EU Directive in their low system. Here the review the state of knowledge and technology in thermal methods for the utilization of municipal sewage sludge to obtain useful forms of energy such as pyrolysis, gasification, combustion, and co-combustion taking into consideration Poland situation is presented.

Keywords: sewage sludge, waste-to-energy, drying, combustion, pyrolysis, gasification, co-combustion

Introduction

The management of sewage sludge, which is the sludge originating from the process of treatment of wastewater, is a problem of great concern in Europe. In fact, about 10 million tons, dry matter (d.m.) of sewage sludge is estimated as produced in Europe every year [1]. This value refers to the period 2003-2006 and quantifies an annual production of 8.7 million Mg d.m. in the old Member States (EU-15) and an additional 1.2 million Mg d.m. for the 12 new Member States (EU-12). A difference in per capita sewage sludge production may exist between old and new Member States since a different level of implementation of the Urban Wastewater Treatment Directive (UWWTD) [2] can be observed. The UWWTD, which regulates the treatment to be dispensed to the wastewater

[1] Institute of Thermal Technology, Silesian University of Technology, Konarskiego 22, 44-100 Gliwice, Poland, phone +48 32 237 29 83, fax +48 32 237 28 72, email: sebastian.werle@polsl.pl

from municipal and industrial origins, obliged all EU Member States to connect all the agglomerations of more than 2,000 person equivalent to systems for the collection and treatment of municipal wastewater [2]. The deadline for the implementation of the directive in old EU-15 was 2005, while for the new EU-12 some of the transitional periods that were granted on the basis of the size of agglomerations and the nature of the discharge area are still in force. As a result, EU-15 has achieved a 97% compliance rate of the directive, while EU-12 is still far from reaching the final objective, being at 72% of the compliance rate [3]. In particular, 9 countries have achieved the maximum compliance rate so far, 18 countries have levels of collection beyond 95% of compliance, while only 5 countries (all EU-12) collect less than 50% of the load that should be collected.

Since the improvement of collecting and treatment systems for wastewater in a country leads to the increase of annual sludge production [4], a further increase of the total sludge production in Europe is expected in the upcoming years, because of the increasing compliance with the requirements of the UWWTD (1991), in particular in EU-12, while in EU-15 the implementation of this directive has already led to a 50% increase of annual sewage sludge production from 1992 to 2005 [5]. It is therefore urgent to find a solution to the problem of sewage sludge disposal, which has faced increasing issue in the EU Member States in the last years.

Sewage sludge disposal routes should be designed coherently with the waste hierarchy introduced by the Waste Framework Directive [6], which indicates an order of preference for action to reduce and manage waste, *ie* prevention, minimisation, reuse, recycling, energy recovery and, as a final and undesired option, landfilling. The amount of sewage sludge disposed of in landfills is intended to rapidly decrease in upcoming years, since the Landfill Directive [7] obliges the Member States to reduce the amounts of biodegradable waste (and, so, of sewage sludge, which a biodegradable waste) sent to landfill to 35% of 1995 levels by 2016. This implies that landfilling of sewage sludge will be excluded from the possible disposal solutions in the long term and no significant amounts of sewage sludge are expected to go regularly to landfill in the EU-27 by 2020 [1].

Sewage sludge contains harmful substances such as heavy metals, poorly biodegradable organic compounds, bacteria, viruses [8], pharmaceuticals and hormones [9], dioxins, which make its disposal management difficult. The sewage sludge could be considered, in its dry form, to be a special type of biomass due to the high quantity of organics and the sufficiently high calorific value [10] of the sludge. In this context, thermal conversion of sewage sludge (combustion, co-combustion, gasification and pyrolysis) appears to be most promising alternative for the management of this waste that will be produced in the future according to a sustainable route.

The present paper is written to review the state of the art in thermal technologies for sewage-sludge utilization taking into account the existing facilities and Polish perspective.

Sewage sludge production in Poland

Poland is inhabited by 38.2 million people with an average population density of 122 persons per square kilometer, and has a territory of 322,577 km^2, of which 311,904 km^2 is occupied by land. In the year 2013, in 4,296 (both municipal and industrial) Polish sewage-treatment plants more than 1,100 thousand tons of municipal and industrial sewage sludge (d.m.) was produced. In Poland, 98% of municipal wastewater treatment plants use a biological treatment, and, among them, 36% with enhanced biogenic removal. In the EU, 50% of sewage-treatment plants have anaerobic digestion, 18% incorporate aerobic digestion and 4% lime stabilization, whereas 24% of the plants undertake no sludge stabilization; the same tendencies are observed in Poland [11]. In 2008, wastewater-treatment plants serviced only 70.3% of the population (93.3% in urban areas and 35.3% in rural areas, where about 39% of the population lives) [12]; by comparison, in the countries of Western Europe, more than 78% of the population is serviced by waste treatment plants. In Poland, only 388 from 794 cities possessed a modern waste-treatment plant with enhanced nitrogen and phosphorus removal. In these plants, 918 hm^3 of waste was treated, which accounts for 73% of the waste discharged through urban and rural sewerage systems. This ratio fluctuates around 70% in most countries. The average unit index of sewage sludge generated in Polish municipal wastewater-treatment plants amounts to 0.25 kg d.m./m^3 of treated wastewater. Table 1 presents the quantities of municipal sewage sludge produced in Poland in the years 2005-2013 along with the anticipated amount in the future [12].

Table 1

The amount of municipal sewage sludge produced in Poland in the period 2005-2013 [12] (and the anticipated amount in the future)

Year	Amount of sludge produced [thousands Mg (d.m.)]
1999	354.0
2000	359.8
2002	435.0
2004	476.0
2005	486.1
2006	501.3
2007	533.4
2010	526.7
2012	533.3
2013	540.3
2018	706.6

According to the objectives of the National Waste Management Plan 2014 (NWMP) [13] as well as the National Urban Wastewater Treatment Program (NUWTP) [14], the quantity of sewage treated in Poland is systematically increasing. A measurable effect of this is, first of all, the increasing proportion of the population being served by sewage treatment, but also the growth of the amount of produced sewage sludge (and sewage). On the basis of demographic projections, it is estimated that the quantity of sludge which will be produced in Poland between the years 2013 and 2018 will increase from 540.3 thousands Mg (d.m.) to 706.6 thousands Mg (d.m.) [12].

Currently, the predominant method for the disposal of sewage sludge is its storage and agricultural application. Nevertheless, thermal methods are going to be also an important rout in sludge management. Table 2 presents the current structure of the municipal sewage-sludge management system [12].

In terms of the commitments derived from the introduction of European Union (EU) Directives, this structure of sewage-sludge utilization in Poland is still quite unfavorable. The main problems are the high percentage of stored sewage sludge and a lack of installations for its thermal utilization. Thermal processes can be used for the conversion of large quantities of sewage sludge (*eg* in large urban areas) into useful energy. Processes for thermal utilization of sludge can be developed at existing installations (*eg* heating plants, power plants, or cement plants) or in newly built facilities. Thermal methods of sewage-sludge utilization should be preceded by dehydration and drying of sludge.

Table 2

Structure of the municipal sewage-sludge disposal system in Poland, 2000-2013

Specification [thousands Mg of d.m.]	**2000**	**2005**	**2010**	**2012**	**2013**
Total sewage sludge generated in municipal wastewater treatment plants during the year	359.8	486.1	526.7	533.3	540.3
Of which:					
Applied in agriculture	**-**	**66.0**	**109.3**	**115.0**	**105.4**
Applied in land reclamation including reclamation of land for agricultural purposes	-	120.6	54.3	50.3	29.4
Applied in cultivation of plants intended for compost production	**25.5**	**27.4**	**30.9**	**33.3**	**32.6**
Thermally transformed	5.9	6.2	19.8	56.6	72.9
Landfilled	**151.6**	**150.7**	**58.9**	**46.8**	**31.4**
Total:	183.0	370.9	273.2	302.0	271.7

Characteristics of sewage sludge

To determine the usefulness of sewage sludge for thermal transformation it is necessary to know its basic physical and chemical characteristics. The elementary composition of sewage sludge and the contents of trace elements and inorganic compounds depend on many factors, but it may play a central role for the country or region of the world.

Table 3

Properties of the biomass in comparison to dried sewage sludge

Parameter		**Wood waste**			**Agricultural waste**		**Dried sewage sludge**		
		Pine sawdust	**Willow sawdust**	**Oak sawdust**	**Rape straw**	**Wheat straw**	**World, average**	**SS1**	**Turkey, average**
mass fraction	C	0.46	0.44	0.47	0.43	0.42	0.406	0.32	0.395
	H	0.058	0.054	0.0563	0.0547	0.0526	0.054	0.0436	0.062
	N	0.0001	0.0031	0.0004	0.006	0.0095	0.045	0.0488	0.039
	O	0.39	0.37	0.41	0.37	0.37	0.235	0.15	0.255
	S	0.0002	0.0004	0.0003	0.0015	0.0013	0.012	0.0167	0.0145
	F	0.00001	0.00001	0.00004	0.00003	0.00004	0.00013	0.00013	0.0002
	Cl	0.00003	0.00004	0.00004	0.00042	0.00124	0.004	0.00217	0.001
	Moisture	0.09	0.111	0.059	0.106	0.09	0.07	0.053	0.09
	Ash	0.004	0.021	0.002	0.037	0.055	0.2483	0.365	0.235
	Volatile matter content	0.77	0.71	0.77	0.70	0.68	0.508	0.51	0.49
Lower heating value [MJ/kg]		16.8	15.8	17.1	15.4	15.5	15.1	13.0	12.0

Table 3 shows an average sample of elementary stabilized and dried sewage sludge [15] in comparison to conventional biomass. Analyses this table it can be concluded that dried sewage sludge are characterized by lower content of carbon, oxygen and volatile matter in comparison to biomass. The lower heating value of sewage sludge is also lower in comparison to biomass. Nevertheless, sulphur and ash content in sewage sludge are much higher in comparison to analyzed examples of agriculture and wood waste biomass.

Drying

Drying is relatively simple technological operation of delivering energy to the system to evaporate the water resulting its densification. In Poland there are 29 installations for sewage sludge drying (including 12 solar drying installations) [16]. Figure 1 presents the location of the mechanical and drying installation of sewage sludge. Additionally, in Table 4 main characteristic of these installations is presented. Analyzing the data presented in this table, it can be concluded that among the mechanical dryers, the most popular systems are based on the belt dryer. Nevertheless, two the biggest mechanical installations (Poznan and Wroclaw) are based on drum and vertical tray dryer system.

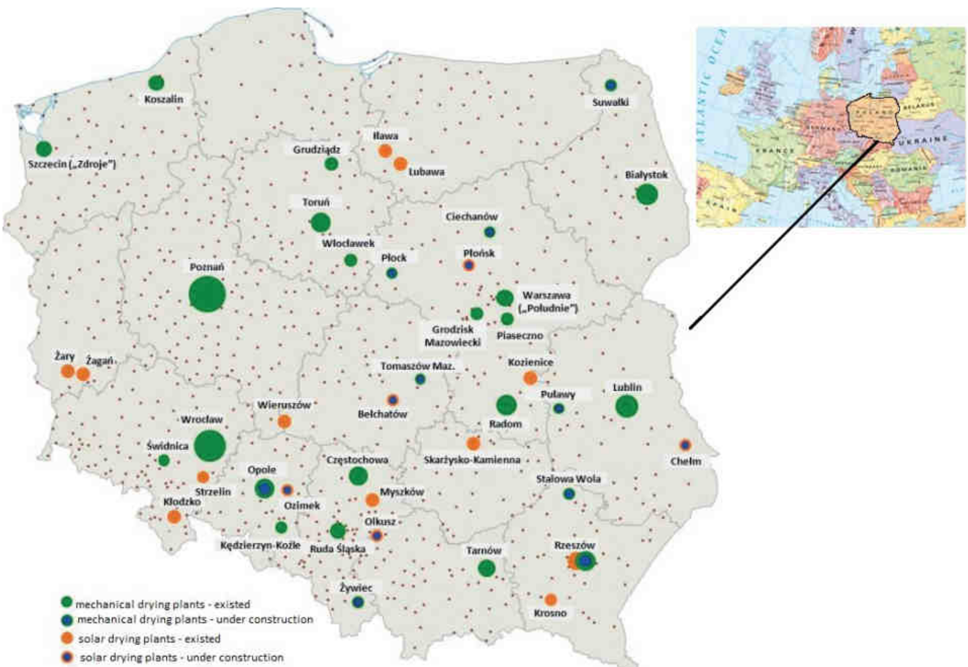

Fig. 1. Location of the mechanical and drying installation of sewage sludge in Poland [16]

Another way of the sewage sludge drying is solar drying process. Solar sludge drying has acquired significant interest over the last years. This way of sewage sludge drying in greenhouses, in particular, is a low maintenance system, where the demand for thermal energy is entirely covered by the sun. However, data concerning process performance under typical Polish conditions, which are characterized by low annual solar radiation and temperature, is not very optimistic.

Table 4

Main characteristic of Polish sewage sludge drying installations [16]

Wastewater treatment plant	**Capacity [Mg d.m./year]**	**Characteristic**	**Additional information**
Warszawa	4,800	Two stages: disk and belt dryer	Existed from 2006
Poznan	30,000	Vertical tray dryer	Existed from 2008
Radom	7,000	Belt dryer	Existed from 2009
Ruda Slaska	4,000	Belt dryer	Existed from 2009
Bialystok	8,000	Vertical tray dryer	Existed from 2010
Wloclawek	3,000	Belt dryer	Existed from 2009
Czestochowa	6,000	Vertical tray dryer	Existed from 2009
Grudziadz	1,600	Belt dryer	Existed from 2011
Lublin	9,000	Fluidized dryer	Existed from 2008
Tarnow	6,400	Belt dryer	Existed from 2008
Szczecin	4,000	Belt dryer	Existed from 2011
Grodzisk Mazowiecki	1,500	Thin layer dryer	Commissioning
Wroclaw	22,000	Drum dryer, 4 lines	Commissioning
Torun	7,650	Belt dryer	Commissioning
Koszalin	5,000	Belt dryer	Commissioning
Piaseczno, Swidnica		Mechanical dryer with problems	
Opole, Suwalki, Rzeszow, Zywiec, Siedlce, Plock, Ciechanow, Tomaszow Mazowiecki, Pulawy		Mechanical dryer - under construction	
Rzeszow, Ilawa, Kozienice, Myszkow, Zary, Klodzko, Zagan, Lubawa, Krosno, Strzelin, Wieruszow, Skarzysko-Kamienna		Solar dryers	
Belchatow, Plonsk, Chelm, Olkusz, Konskie, Ozimek		Solar dryers - under construction	

Combustion and co-combustion with fossil fuels and waste

Combustion is the most popular way used for the processing and management of sewage sludge. This process significantly reduces volume of disposed sewage sludge. Conventional combustion usually must be preceded by pre-drying of sewage sludge to 18-35% d.m. content [17], usually about 25% [18]. In recent years, in Poland 12 sewage sludge combustion installations were built. In Figure 2 localization of these installations is presented.

Most of these examples are based on the fluidized bed technology (*eg* Pyrofluid™, Thermylis®). This tendency is also visible in other countries all over the world. The papers [19-21] presented the results of the combustion of sewage sludge in a bubbling-fluidized-bed combustor. The emission of nitrogen oxides and ash comminution were analyzed with the aid of different and complementary experimental protocols. In bubbling-fluidized-bed combustors, granular sewage sludge is rapidly mixed due to the turbulence of the bed. As a result of the mechanical action of the grains, the ash agglomerates formed during combustion are fragmented. Rapid equalization of the temperature and the high heat-transfer coefficient result in an intense and even combustion process, ensuring low emissions of NO_x. Shimizu and Toyono presented a study of a process for combustion of sewage sludge in a circulating fluidized bed [22]. In this type of bed, the gas from the reactor passes through the combustion chamber with a significantly higher velocity than in the bubbling fluidized bed; thus, a very high degree of mixing and uniform combustion are achieved. Sometimes, when prepared for combustion material has a low LHV, it is necessary to design co-combustion process with other fuel (coal, waste, etc.).

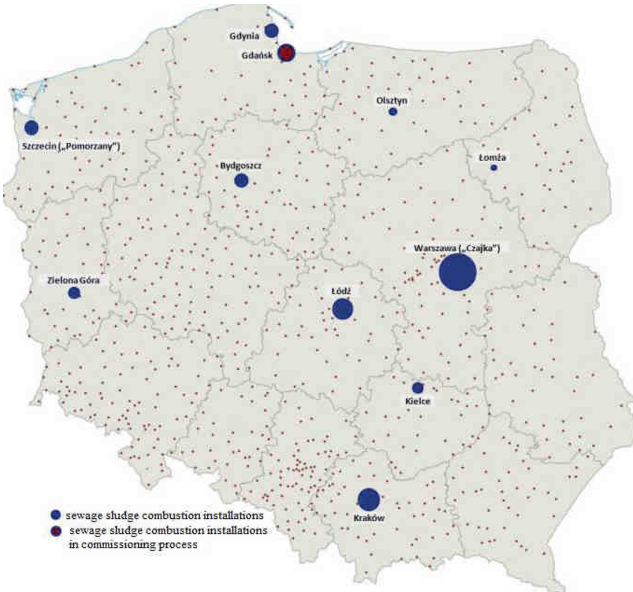

Fig. 2. Location of the combustion of sewage sludge in Poland

Taking into consideration Polish situation, the most promising solution is co-combustion in coal fired dust boilers. Stelmach and Wasilewski reported a Polish experimental co-firing of sewage sludge with coal in a type OP-230 dust boiler in a thermal-electric power station in Gdansk [23]. They concluded that co-combustion, with the addition of sludge at 1% of the total mass of fuel, does not require structural changes to the boiler. Moreover, the process did not significantly affect the efficiency of the boiler. The authors drew the overall conclusion that the thermal utilization of sewage sludge is highly promising. Another Polish example of sewage-sludge co-combustion with coal was in a thermal-electric power station in Rzeszow. Tests with co-combustion of sewage sludge in a WR-25 stoker boiler were conducted [24]. Kotlicki presents properties of sludge originating from Polish sewage treatment plants [25]. The purpose of an analysis is consideration of sewage sludge co-firing in power plant. The influence of sludge drying on its heat value is presented in simulation as well as possibilities to produce a renewable energy in power plant. There is concluded that sewage sludge may be in small quantities (a few percent) successfully burned in boilers without any negative consequences. In [26] environmental aspects of sludge from sewage-treatment plant treatment during co-combustion in energetic boilers are presented. Detailed study on thermal treatment of sludge during co-combustion in energetic boilers is given. The analysis of costs and benefits of application of those technologies are presented. On the basis of data obtained form heating plant Gliwice the possible quantity of sludge for utilization was calculated. The mass and energy flows during co-combustion were analyzed as well as economic aspects of the process. The results showed that the use of sewage sludge did not result in exceeding emission standards and operation costs of installation.

Sewage sludge can also be co-combusted with lignite [27], wood [28], or municipal waste [29]. Municipal waste is an especially good material for co-combustion with sewage sludge [30]. There exist a whole range of technologies for the co-combustion of sewage sludge with municipal wastes: wood boilers, fluidized-bed boilers, furnaces for kilning bricks, cement furnaces or rotary furnaces [31]. One example is the Siemens Schwell-Brenna Technology, in which crushed wastes are mixed with sewage sludge [31]. In this method, a rotary kiln is used and the pyrolysis process is run at a temperature of 450ºC. Post-process residues, consisting of about 30% of carbon, are supplied to the boiler, where they are burned together with the gas at a temperature of around 1,300ºC. The recovered heat is used, *eg*, for the heating of the charge.

An important method for the utilization of sewage sludge is by co-firing in rotary kilns for the processing of cement. Zabaniotou and Theofilou presented the results of studies on sewage-sludge combustion in this type of furnace [32]. Wet sludge was utilized, and the analysis was focused on the emission of heavy metals, especially mercury. The results showed that the use of sewage sludge did not result in exceeding emission standards. This was mainly due to the high temperature (up to 1,800ºC), providing for a total decomposition of organic matter [32]. Additionally, in this type of furnace, the gas-residence time is much longer than in the conventional equipment for the combustion of sewage sludge. Moreover, the combustion is affected in a highly alkaline environment so that the acidic components of the exhaust gases are chemically bound.

Pyrolysis and gasification

Generally it can be assumed that pyrolysis is a process of degradation (breakdown) of chemical molecules under the influence of a sufficiently high temperature (300-900ºC [33]) in an anaerobic environment [34]. The main groups of products arising from the pyrolysis of sewage sludge are as follows [33, 35]:

- A gas fraction, mainly consisting of hydrogen, methane, carbon dioxide, and carbon monoxide, along with a few minor gases; the calorific value of the pyrolytic gas is approximately 15 MJ/m^3 [36].
- A solid fraction (pyrolytic coke); this also includes inert substances and dust with a significant content of heavy metals.
- A liquid fraction, consisting mainly of tars and oils, water, and organic compounds.

The relative proportions among the various pyrolytic components depend mainly on the temperature and pressure of process and also on the turbulence in the reactor and many other factors. The *oil-from-sludge* technology is based on pyrolysis [37]. The essence of this process is to submit sewage sludge containing 95% dry matter to pyrolysis at 450ºC for more than 30 minutes at atmospheric pressure. As a result, solid hydrocarbons and carbonization products (*eg* pyrolytic coke) are formed. Liquid hydrocarbons are also generated. The product can be used a raw material for use in many industries (*eg* petrochemical). A crucial process for the pyrolysis of sewage sludge is the Carver-Greenfield technology (C-R) leading to a refuse-derived fuel (RDF) [11]. This process provides for the possibility of simultaneously drying the sewage sludge before its combustion or gasification. The essence of the process is the mixing of raw sewage sludge with oil waste (*eg* used motor oil). The prepared mixture is passed through an evaporating system to remove all the water. After drying, the sludge is passed to a centrifuge to separate the liquid phase from the particles. The result is a solid waste and the liquid phase is returned to the installation for use as fuel.

Gasification is the process of converting a solid fuel into a gas by treating the solid fuel in a generator with oxygen, air, and steam, or by other gasification methods [34]. As shown in Marrero et al, gasification of sewage sludge leads to a high-quality flammable gas that can be used for the generation of electricity or support such processes as the drying of sewage sludge [38]. The lower heating value of the gas after gasification varies around a value of 4 MJ/m^3. The gas obtained can be used to generate electricity or to produce heat for the drying of sewage sludge [39]. An important aspect of the process of the gasification of sewage sludge is the production of hydrogen. Mathieu and Dubuisson presented a possibility for producing hydrogen by means of a high-temperature gasification process [40]. There are many applications of the gasification process. Bien quotes a number of sewage-sludge gasification technologies [36]. The Krupp Uhde PreCon technology is one example. Here dry sewage sludge is gasified in a fluidized-bed reactor. After the removal of the metallic and inorganic components, the crushed material is dried to a moisture content of 10% and put into a reactor at a temperature of 700-1,000ºC.

In Poland, gasification of sewage sludge is still largely a prospective technology. It is associated with the extensive experience in biomass gasification; therefore, there it is natural to build on this experience. The installation by Zamer of an EKOD gasifier for the gasification and pyrolysis of sewage sludge is a good example. This fluidized-bed reactor is able to utilize 1.7 Mg/h of sewage sludge [41]. The solid fraction from the gasification goes to pyrolysis and the gas from gasification can be burned in the power-stoker boilers popular in Poland or, after purification, used in combined heating-and-power (CHP) systems.

The installation by Institute of Thermal Technology [42] is another example of sewage sludge gasification facility. This fixed bed reactor is able to utilize 5.0 kg/h of dried sewage sludge. The gas is used as a reburning fuel in small capacity of coal-fired boiler [43]. Additionally, properties of the gasification gas, like laminar flame speed, is determined [44].

Conculsions

1. According to the prognosis, the stream of produced water-treatment and sewage sludge in Poland will grow; this follows foremost from the lifestyle changes of our society, but is also due to the increased percentage of the population connected to the sewerage network.
2. The legislated limits will determine the choices for sewage-sludge utilization; the disposal of sewage sludge in places other than hazardous-waste landfills, and even agricultural use will have to be replaced in the next few years by other methods. This is strong incentive to develop thermal methods of sewage-sludge utilization.
3. The National Urban Wastewater Treatment Program is the largest with regard to investment and the most expensive from among all the tasks resulting from the implementation of the EU directives in the field of environmental protection.
4. Thermal methods are a promising alternative, which must (and will) prevail for several years.

5. Classic combustion of sewage sludge is well-known and controllable, but because of the emissions of nitrogen oxides, heavy metals, and other harmful compounds, it raises many questions and social objections and requires large investments for the purification of flue gases.
6. Co-combustion of sewage sludge with other natural resources (coal, lignite, or wood) or municipal waste has a good outlook and appears to be a satisfactory method for the management of sewage sludge. In adding only small quantities of sewage sludge in relation to the total mass of burned fuel, these methods do not require any additional investment. In Poland, circumstances would appear to indicate particular interest in the co-combustion of sewage sludge in dust and stoker boilers. To date, there are few Polish examples, but it is still a developing area of sewage-sludge utilization.
7. Alternative methods for the thermal utilization of sewage sludge (pyrolysis, gasification, or combined processes) are an important element in the wider problem of sludge disposal. There are many technologies that use gasification or pyrolysis (or a combination of these two). Their undoubted advantage, in addition to the disposal of sludge, is that it becomes possible to obtain a product that can be effectively used for the generation of energy. Polish conditions also appear to present a good opportunity to utilize this group of waste-disposal technologies.

Acknowledgments

The paper has been prepared within the frame of the Grant no RGH-6/RIE6/2014.

References

[l] Milieu Ltd. Final report for the European Commission, Milieu Ltd, WRc, RPA, DG Environment 2008. www.ec.europa.eu/environment/archives/waste/sludge/pdf/part_ii_report.pdf.
[2] UWWTD, Council Directive 91/271/EEC concerning urban waste water treatment, 1991, L 135, 40-52.
[3] Umweltbundesamt GmbH, Final report for the European Commission, DG Environment, 2012. www.ec.europa.eu/environment/waste/pdf/final_report_10042012.pdf.
[4] Kelessidis A, Stasinakis AS. Waste Manage. 2012;32:1186-1195. DOI: 10.1016/j.wasman.2012.01.012.
[5] LeBlanc RJ, Matthews P, Richard RP. United Nations Human Settlements Programme (UN-HABITAT), ISBN: 978-92-1-132009-1, 2008.
[6] EC Directive, Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste, 1999, L 182, 1-18. www.eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:31999L0031.
[7] EC Directive, Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, 2008, L312, 3-30. www.eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:0030:en:PDF.
[8] Seggiani M, Vitolo S, Puccini M, Bellini A. Fuel. 2012;93:486-91. DOI: 10.1016/j.fuel.2011.08.054.
[9] Bodzek M, Dudziak M. Desalination. 2006;198:24-32. DOI: 10.1016/j.desal.2006.09.005.
[10] Manara P, Zabaniotou A. Renew Sust Energy Rev. 2012;16:2566-2582. DOI: 10.1016/j.rser.2012.01.074.
[11] Werther J, Ogada T. Prog Energ Combust. 1999;25:55-116. DOI: 10.1016/S0360-1285(98)00020-3.
[12] Statistical Yearbook of the Republic of Poland, 2014. www.stat.gov.pl/en/topics/statistical-yearbooks/.
[13] Resolution no. 217 of the Council of Ministers of 24 December 2010 on the "National Waste Management Plan 2014" (Monitor Polski of 31 December 2010). www.mos.gov.pl/artykul/3340_krajowy_plan_gospodarki_odpadami_2014/21693_national_waste_management_plan_2014.html.
[14] The National Urban Wastewater Treatment Program, Regulation of the Ministry of Environment, Republic of Poland, Warszawa 2003. www.kzgw.gov.pl/en/Krajowy-program-oczyszczania-sciekow-komunalnych.html.
[15] Werle S, Dudziak M. Energies. 2012;19:137-144. DOI: 10.3390/en7010462.
[16] Niesler J, Nadziakiewicz J. Industrial Furnaces & Boilers. 2013;9-10:29-41. www.infona.pl/resource/bwmeta1.element.baztech-6a7a3ed7-7f79-460c-afb3-78beced5cf68.

[17] Donatello S, Cheeseman CR. Waste Manage. 2013;33:2328-2340. DOI: 10.1016/j.wasman.2013.05.024.
[18] Houillon G, Jolliet O. J Clean Prod. 2005;13:287-299. DOI: 10.1016/j.jclepro.2004.02.022.
[19] Shimizu T, Toyono M, Ohsawa H. Fuel. 2007;86:957-964. DOI: 10.1016/j.fuel.2006.10.001.
[20] Murakami T, Suzuki Y, Nagasawa H, Yamamoto T, Koseki T, Hiroshi et al. Fuel Process Technol. 2009;90:778-783. DOI: 10.1016/j.fuproc.2009.03.003.
[21] Łobos-Moysa E, Dudziak M, Zoń Z. Desalination. 2009;31:43-48. DOI: 10.1016/j.desal.2008.02.029.
[22] Shimizu M, Toyono M. Fuel. 2007;86:2308-2315. DOI: 10.1016/j.fuel.2007.01.033.
[23] Stelmach S, Wasilewski R. J Mater Cycles Waste. 2008;10:110-115. DOI: 10.1007/s10163-007-0206-9.
[24] Wilk J, Wolańczyk F. Energy Policy. 2008;11:139-149.
[25] Kotlicki T. Archives of Waste Manage Environ Protection. 2008;9:11-18.
[26] Pikoń K, Kokot K. Archives Waste Manage Environ Protect. 2009;11:43-62.
[27] Wolski N. Fuel Process Technol. 2004;85:673-686. DOI: 10.1016/j.fuproc.2003.11.024.
[28] Pettersson A, Amand LE, Steenari BM. Biomass Bioenerg. 2008;32:224-235. DOI: 10.1016/j.biombioe.2007.09.016.
[29] Freitag G. Fuel and Energy Abstracts. 1996;37:284.
[30] Lin H, Ma X. Waste Manage. 2012;32:561-567. DOI: 10.1016/j.wasman.2011.10.032.
[31] Shen L, Zhang DK. Fuel. 2003;82:465:472. DOI: 10.1016/S0016-2361(02)00294-6.
[32] Zabaniotou A, Theofilou C. Renew Sust Energy Rev. 2008;12:531-541. DOI: 10.1016/j.rser.2006.07.017.
[33] Fytili D, Zabaniotou A. Renew Sust Energy Rev. 2008;12:116-140. DOI: 10.1016/j.rser.2006.05.014.
[34] Magdziarz A, Wilk M. J Therm Anal Calorim. 2013;114:519-529. DOI: 10.1007/s10973-012-2933-y.
[35] Magdziarz A, Wilk M, Kosturkiewicz B. Chem Proc Eng. 2011;32:299-309. DOI: 10.2478/v10176-011-0024-4.
[36] Werle S. Chem Proc Eng. 2011;32:411-421. DOI: 10.2478/v10176-011-0033-3.
[37] Australia secures first oil from sludge. Water Quality Internat. 1997;1-2:4.
[38] Marrero TW, McAuley BP, Sutterlin WR, Morris JS, Manahan SE. Waste Manage. 2004;24:193-198. DOI: 10.1016/S0956-053X(03)00127-2.
[39] Hamilton CJ. Water Environ Manage. 2000;14:89-93.
[40] Mathieu P, Dubuisson R. Energ Convers Manage. 2002;43:1291-1299. DOI: 10.1016/S0196-8904(02)00015-8.
[41] Babko R, Łagód G, Jaromin-Gleń K.M. Annual Set Environ Protect. 2012;14:56-68, www.old.ros.edu.pl/text/pp_2012_002.pdf.
[42] Patent no P-397225 based on the application from 2.12.2011, Biomass gasification installation, mainly for sewage sludge.
[43] Werle S. Ecol Chem Eng S. 2015;22(1):83-94. DOI: 10.1515/eces-2015-0005.
[44] Magdziarz A, Werle S. Waste Manage. 2014;34:174-179. DOI: 10.1016/j.wasman.2013.10.033.

ENERGETYCZNE ZAGOSPODAROWANIE OSADÓW ŚCIEKOWYCH W EUROPIE WSCHODNIEJ: POLSKIE SPOJRZENIE NA PROBLEM

Wydział Inżynierii Środowiska i Energetyki, Politechnika Śląska, Gliwice

Abstrakt: Dyrektywa 86/278/EWG, która została przyjęta około 30 lat temu, definiowała możliwości ponownego wykorzystania osadów ściekowych w rolnictwie oraz regulowała ich wykorzystanie. Tymczasem niektóre państwa członkowskie UE przyjęły bardziej rygorystyczne normy i praktyki zarządzania osadami ściekowymi niż te określone w Dyrektywie. W szczególności, większość państw członkowskich wprowadziła bardziej rygorystyczne normy dotyczące jakości osadów ściekowych, w tym surowsze limity dla potencjalnie najbardziej toksycznych pierwiastków, zanieczyszczeń organicznych i innych składników. W niektórych przypadkach rygorystyczne normy doprowadziły do skutecznego zakazu stosowania osadów ściekowych w rolnictwie. Niemniej jednak, wdrożenie dyrektywy 91/271/WE powinno zwiększyć produkcję w UE osadów ściekowych, zwiększając w ten sposób problemy związane ze zrównoważoną gospodarką osadami ściekowymi. Najnowsze trendy w dziedzinie gospodarki osadowej, czyli spalanie, piroliza, zgazowanie i współspalanie, stanowią obiekt zainteresowań naukowców od wielu lat. Tendencja ta jest szczególnie widoczna w „nowych" państwach członkowskich. W pracy przedstawiono przegląd technologii w zakresie termicznych metod wykorzystania komunalnych osadów ściekowych do uzyskania użytecznych form energii, biorąc pod uwagę sytuację Polsce.

Słowa kluczowe: osady ściekowe, energia z odpadów, suszenie, spalanie, piroliza, zgazowanie, współspalanie