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Thermal sewage sludge utilization in Poland in the context of circular economy

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ABSTRACT

Adopting the idea of the circular economy, European Commission on 4 March 2019, delivered 54 actions in a form of a comprehensive report on the implementation of the Circular Economy Action Plan. These actions would lead to resource-efficient and environmentally friendly outcomes. In general, biological materials should be returned to the natural metabolic cycles after necessary pre-treatment while waste that cannot be prevented or recycled is to be used for energy recovery. Sewage sludge is a large-tonnage waste produced at wastewater treatment plants (WWTPs). Its utilization causes some problems. Among many different ways of sludge utilization, its thermal treatment has to be taken into account. During thermal treatment some hazardous substances in sewage sludge can be destroyed or removed, energy can be recovered and some nutrients can be obtained from ash or other by-products. According to the information from the Polish Central Statistical Office (GUS), in 2017 in Poland, 584.5 thousand tonnes of sewage sludge dry mass was produced at municipal WWTPs. More than 100 thousand tonnes of was subject to thermal processing. The paper presents the situation within Polish wastewater treatment plants in which thermal treatment has been activated in terms of preparation for the implementation of the rules resulting from the Circular Economy Action Plan.

Keywords: Sewage sludge; Thermal utilization; Circular economy; Poland

1. Introduction

Sewage sludge is a large-tonnage waste produced at wastewater treatment plants (WWTPs) and it generally should be disposed of outside facilities. However, the high water content in sludge impedes its final disposal. Also, many contaminants such as heavy metals as well as organic toxins and pathogens limit some potential methods of sludge utilization although sewage sludge contains valuable nutrients such as nitrogen and phosphorus [1,2]. Not so long ago the most common way of sewage sludge disposal in Europe was deposition in landfills, but due to the new European Union (EU) conceptual approach regarding waste as a resource this method is eliminated or limited in several EU countries. According to an integrated waste management hierarchy presented in the Directive 2008/98/EC on waste, landfilling is the least preferable option of waste treatment. Also, the Directive 99/31/EC on the landfill of waste intends to prevent and reduce the adverse effect of waste landfilling on the environment. Disposal of sludge in landfills causes many significant drawbacks including the necessity for sizeable lands, environmental pollution and the loss of valuable nutrients. Hence, different methods in sludge management schemes are more favorable. These options generally include a tendency for using sludge in agriculture as a fertilizer, either pre-dried or composted [3]. However, this approach needs careful evaluation because problems associated with environmental pollution by harmful substances contained in sludge are not removed [4]. The idea of common biowaste transformation into compost under Directive 2008/98/EC, where such compost has considerably fewer probabilities to

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contain hazardous substances compared to sewage sludge is interesting but must be under particular care. Hence, energy-based alternatives such as thermal methods of sludge utilization or usage pre-dried sludge as a supplementary fuel in industry are interesting options [5–7]. However, at present, this pathway of sludge final disposal is practiced only in a few countries around the world. The reason for such a situation is mostly due to high capital and running costs [8]. The situation in Poland in sludge management routes has changed significantly in recent years. In 2003 only 1% of sewage sludge was incinerated while in 2017 nearly 20% of produced sludge is thermally treated.

This paper provides a summary overview of thermal sewage sludge utilization in Poland in the context of a circular economy approach and presents the actual status of installations in the preparation of circular economy challenges.

2. Concept of circular economy

The concept of the circular economy is one of the priority concepts of economic development underlying the current EU policy in the field of environmental protection. Of course, the idea of the circular economy is not new. Practical applications and thoughts behind this idea are known since the late 1970s when a small group of academics and visionaries have considered all materials involved in industrial and commercial processes as nutrients, of which there are two main categories: technical and biological. Technical nutrients include highly stable materials that are designed to be retrieved and reused within the closed-loop cycle of sustainable manufacturing. Coherent biological and technical metabolisms ensure the availability of raw materials for industrial processes [9]. Adopting this idea in 2015 European Commission has announced an Action Plan for the Circular Economy, and after three years after adoption, on 4 March 2019, 54 actions have been already delivered in a form of a comprehensive report on the implementation of the Circular Economy Action Plan (CEAP) [10]. These actions include a balanced mix of initiatives and regulatory actions along with four key action areas: production, consumption, waste management and secondary raw materials. In the case of sewage sludge, only the last two key areas should be taken into account. According to the Directive 2008/98/EC on waste following the integrated waste management hierarchy will lead to resource-efficient and environmentally friendly outcomes. Biological materials should be returned to the natural metabolic cycles after necessary pre-treatment while waste that cannot be prevented or recycled is to be used for energy recovery. The EU communication "The role of waste-to-energy in the circular economy", adopted on 26 January 2017, clarifies the position of different waste-to-energy processes in the waste hierarchy as well as identifies the technology and processes which currently hold the greatest potential to optimize energy and material outputs, taking into account expected changes in the feedstock for waste-to-energy processes. Using waste energy potential is preferable to landfilling. However, the introduction of secondary raw materials is crucial to ensure the transition to a circular economy. Nutrients are indicated as an important element of the secondary raw materials obtained from waste [11]. Considering this key action the European Parliament and the Council reached on 12 December 2018 a political agreement on new regulation on fertilizers [12]. The new regulation grants a level playing field to organic fertilizing products that would now have the Circular Economy mark, which signifies that product sold in the single market in the European Economic Area (EEA) meets safety, health, and environmental protection requirements. This boosts the European market for innovative organic fertilizers manufactured from by-products and recovered bio-waste. In the case of sewage sludge, this helps recovery of nutrients, such as nitrogen and phosphorus, which are essential substances needed to supply growing population food demand, but does not solve the problem of environmental pollution. There is a risk associated with possible negative impacts of pathogens, organic toxins, and the accumulation of heavy metals in organisms. Some of these concerns can be removed using thermal treatment methods.

2.1. Thermal facilities of sewage sludge utilization in Poland

According to the information from the Polish Central Statistical Office (GUS), in 2017 584.5 thousand Mg of dry matter (DM) of sewage sludge was produced at municipal sewage treatment plants. Poland is the fifth largest country within the EU countries in terms of sewage sludge production [13]. More than 100 thousand Mg DM of sewage sludge was subject to thermal processing in 2017. Thermal waste treatment methods commonly include incineration, gasification, and pyrolysis. All of the thermal methods reduce the volume of sewage sludge [8,14]. Incineration is an exothermic oxidation process of combustible material resulting in a certain amount of energy (heat), ash and flue gases. The recovered heat can be used for drying of sewage sludge or electricity production [15,16]. During the gasification process, the organic substances are converted into gas, known as syngas (mainly composed of H_2, CH_4, C_nH_m, CO and CO_2). The process is carried out under partial oxidation at a temperature range of 700°C–1,000°C [17]. The calorific value of syngas varies from 4 to 6 MJ/Nm^3 [18,19], and after treatment is used to run a gas engine. Pyrolysis is a thermal conversion in an oxygen-deficient environment at elevated temperatures of 350°C–900°C. Depending on the process conditions including operating temperature, reaction time as well as sludge characteristics the quantity and quality of liquid, gas and solid by-products vary in a wide range [20]. Compared to the highly exothermic character of the incineration process, pyrolytic reactions are endothermic, consuming energy, so pyrolysis of sewage sludge is in most cases connected to the final combustion of pyrolysis gas or char. In Europe, only a small number of plants for sewage sludge gasification and pyrolysis are in operation. There is no such commercial installation in Poland. Currently, there are 11 municipal mono-incineration plants for sewage sludge in Poland. Seven of them are using the fluidized bed technology, and in four plants, sewage sludge is incinerated on a grate. These are both small- and large-scale facilities. The smallest mono-incinerator is located in Lomza and has a capacity of 1.5 thousand Mg DM/y, whereas the one in Warsaw is a real giant with a capacity of 62 thousand Mg DM/y. The most popular technology applied in four installations, that is, in Warsaw, Kielce, Lodz, and Cracow, is Pyrofluid™ [14]. The summary of parameters is given in Table 1, and the location of facilities is presented in Fig. 1.

There are also several facilities for sewage sludge drying, both solar and conventional hot-air. Using the greenhouse effect in solar driers for sewage sludge drying is the cheapest option. About thirty such facilities are in operation in Poland. The first was a solar drying facility in Bien [21]. This facility was commissioned in 2004. In general, solar dryers differ in size, efficiency, and technological solutions. The main differences concern the ventilation system and turner which is used for sludge overflowing. In terms of size, there are facilities with a single hall with an area of about 700–800 m^2 as well as facilities consisting of four halls with a total area of over 5.700 m^2. The vast majority of solar facilities runs the drying process in a continuous system, sludge is introduced into the dryer from one side and collected from the other. The main source of heat is solar radiation. However, in some objects, there is also the other heat source.

Table 1
Mono-incineration plants of sewage sludge in Poland [20]

Parameter	Value
Total number of mono-incinerators	11
Total capacity of all mono-incinerators, Mg DM/a	160,000
The scope of the incinerator's efficiency, Mg DM/h	0.2 ÷ 7.9
Sludge water content, % DM	33 ÷ 90

Based on today's observations, it can certainly be said that the use of heat pumps is a completely unsuccessful experiment, which usually cost a lot, and the operating cost of sludge drying is not low due to the significant consumption of electricity [22]. It also does not cause a significant increase in the efficiency of water evaporation. As a result, such a solution has no technical or economic justification. Solar drying using solar radiation is a reasonable choice for small and medium wastewater treatment plants. The location of the

Fig. 1. Location of sludge mono-incineration plants [21]

solar drying plant is shown in Fig. 2. As it could be seen solar dryers are located mainly in the southern part of Poland.

The high-temperature sludge drying process is usually more expensive and technically more complex than drying using solar radiation. This solution finds its application mostly at large wastewater treatment plants, particularly where there are not enough funds to build an incineration facility. There are about thirty such facilities in Poland with a total capacity of about 100 thousand tonnes of dry matter per year. The water evaporation efficiency during drying is within a wide range of 1–9.15 Mg H_2O/h for these facilities. The main energy carrier in the drying process is natural gas. The biogas, usually generated at a wastewater treatment plant in a digestion process, is used in an insignificant share for drying purposes as well as waste heat from the drying process is used rarely. This requires some actions for process optimization to reduce high operational costs. The sludge is mostly dried till 90% of dry mass, the starting point is a dry matter in sludge after mechanical dewatering. Some general characteristics of sewage sludge drying plants are given in Table 2. Their location is presented in Fig. 3.

2.2. Sewage sludge in EU action plan for the circular economy

In 2015, the European Commission has adopted an ambitious CEAP, which includes measures that would help stimulate Europe's transition towards a circular economy. Recycling and the recovery of secondary raw materials is a precondition for a circular economy – resources and materials can be

Table 2
General characteristics of sewage sludge drying facilities

Parameter	Value
Total	30
Combined capacity, Mg DM/a	100,000
Water evaporation efficiency, Mg_{H_2O}/h	1 ÷ 9.15
Drying range, % DM	18 ÷ 95
Temperature of drying agent, °C	90 ÷ 180
Heat consumption index, kWh_{th}/kg_{H_2O}	0.75 ÷ 1.3
Electricity consumption index, kWh/kg_{H_2O}	0.06 ÷ 0.085

Fig. 2. Location of sludge solar driers [21]

Fig. 3. Location of conventional hot-air sludge driers [21].

recycled, returned to the economy and used again. In general, four key action areas have been defined: production, consumption, waste management and secondary raw materials.

Sewage sludge can be simply defined as an inevitably waste from municipal or industrial wastewater treatment processes. The rise in population, industrialization as well as high requirements for sewage treatment enhanced the production of sewage sludge. Statistical data shows that the production per person per year is more or less at the level of 25 kg of dry matter [23]. Sewage sludge is generated mainly via mechanical treatment (primary sludge) and biological and chemical treatment at the secondary stage at wastewater treatment plants. The composition of sludge depends on the composition of the treated wastewater. The typical composition of sludge includes about 59%–88% biodegradable organic matter. The organic portion contains 50%–55% carbon, 25%–30% oxygen, 10%–15% nitrogen, 6%–10% hydrogen, 1%–3% phosphorus and 0.5%–1.5% sulfur [24].

The next area of CEAP, a consumption, is not, of course, applicable to sewage sludge. Sewage sludge needs to be treated. The first step in sludge treatment is its stabilization. Then sludge can be categorized as aerobic or anaerobic stabilized sludge. The physical and chemical properties of sludge are the functions of stabilization techniques and pollution load from the treated wastewater. As a result, sludge can contain many pollutants such as heavy metals, pathogenic organisms, toxic organic substances, but also considerable amounts of valuable ingredients such as nitrogen, phosphorus, macroelements. Stabilized sludge is then thickened and mechanically dewatered. Sewage sludge has high water content. After stabilization sludge contains 1%–3% of dry solid content. The thickening process gives this value at a level of about 3%–5%. After mechanical dewatering sludge contains about 20%–30% of dry matter, it means that sludge still contains 70%–80% of water [25]. The further treatment of sludge is required. Fortunately, diverse treatment technologies are available just for safe disposal, resource utilization, and energy generation. Deposition in landfills was one of the primary methods of sludge disposal not so long ago. However, due to some limits introduced by the Directive 99/31/EC of

26 April 1999 on sludge storage and by Directive 2008/98/EC on waste, landfilling is the least preferable means of sludge treatment. In Poland, landfilling as a method of sludge disposal is not possible in practice. As regards the issue of reducing the mass of waste sent to landfill the Minister of Economy introduced a regulation dated 16 July 2015 (Journal of Laws of 2015, No. 1277) where set the criteria for allowing waste, other than hazardous or inert waste, to be landfilled. In accordance with the regulation, as of 1 January 2016, it is not possible to landfill waste with the total organic carbon content higher than 5% of dry matter, and the gross calorific value higher than 6 MJ/kg of dry matter. It requires looking for other options for sludge management. The EU legislation concerning the disposal of sewage sludge, when it is used in agriculture is included in the Council Directive 86/278/EEC on environmental protection of 12 June 1986. Sewage sludge needs to be pre-dried or composted. A significant number of wastewater treatment plants (WWTPs) compost dewatered sludge under aerobic conditions with green wastes or other bulking materials for use as fertilizer. Pre-dried sludge can be also used as fuel. Commonly used technologies for energy recovery include incineration, gasification, pyrolysis, hence Directive 2010/75/EC of 24 November 2010 on industrial emission specifies norms and rules for incineration of waste and emission standards. There are also some other pathways such as wet air oxidation or hydrothermal carbonization, however, they have a limited application [6].

With the new conceptual approach regarding waste as a resource, the recovery of secondary raw materials plays a crucial role. In this context, the wastewater treatment plant is not anymore considered as a pollution removal system but as a nutrients and energy recovery plant [26]. Nutrients are indicated as an especially important category of secondary raw materials. Nitrogen and phosphorus are essential elements for life and quite large amounts of them, mainly in the form of ammonium and phosphate, are needed for fertilizer production. Sewage sludge is a rich source of nitrogen (2.4%–5.0% TS, total solids) and phosphorus (0.5–0.7% TS), but it also a source of hazardous substances so it's necessary to prevent harmful effects on environment by limiting the possible transfer of heavy metals, organic toxins, and pathogens into soil and living organisms [27,28]. Generally, the Directive 86/278/EEC on environmental protection prohibits the sludge from WWTPs from being used in agriculture unless specified requirements are fulfilled, including the testing of the sludge and the soil. However, the European Parliament and the Council reached on 12 December 2018 a political agreement on a new regulation on fertilizers [29]. The new regulation should boost the European market for innovative organic fertilizers manufactured from by-products and recovered bio-waste. The idea is to make European farming much less dependent on imported mined and fossil raw materials, especially phosphate rock. Nutrients from sewage sludge can be achieved also by alternative options. One of them is a precipitation of phosphate and nitrogen as struvite (magnesium ammonium phosphate) [30]. Becker et al. [31] found that the combination of hydrothermal carbonization and acidic leaching with struvite precipitation showed very good performance with a total phosphate reclamation of about 80% related to the native sludge. Another interesting option is a recovery of phosphorus from sludge ashes. The P-recovery from ashes after sludge incineration is under wide investigation nowadays [32,33]. A two-step thermal treatment is suggested. In a first step, organic pollutants are destroyed by mono-incineration of sludge, and the incineration results in ash with high phosphorus contents of approximately 20% P_2O_5. Generally, the phosphorus content in ashes varies from 5% to 11% [34]. Phosphorus released from sludge is deposited mainly in bottom ash (89.29%) rather than in fly ash (5.61%) [32]. Cieslik et al. [35] stated that phosphorus recovery from ashes could be 5–10 times higher in comparison to that achieved from sludge directly. However, phosphorus in the ashes shows a low bioavailability, a disadvantage in farming. Therefore, usually, the second step is necessary, where phosphorus is transferred into mineral phases available for plants as well as heavy metals can be removed [36]. Some authors indicate the possibility of using biochar, which is a carbonaceous product from sludge pyrolysis [37]. The incorporation of the biochar can influence the structure, texture, porosity, particle size distribution and density of the soil, and in this way, it alters the air oxygen content, water storage capacity and microbial and nutritional status of the soil [38]. However, the condition of the pyrolysis process plays an important role in achieving nutrients in biochar. Yuan et al. [37] found as the pyrolysis temperature was increasing, the nitrogen content of the resulting sewage sludge biochar decreased, phosphorus content increased. A similar trend has also been reported in biochar produced from sewage sludge in [39]. The positive information is that there is a big difference between the sewage sludge biochar and the biochar derived from other biomass. Biochar from sewage sludge is rich in nutrients, and the nutrients may be released easily in soil incubation and leaching experiment [37]. As it was already noticed, the range of organic (including flammable) compounds content in sewage sludge is quite broad, with the mean of approx. 60%. Thus, the calorific value of dried sewage sludge is mostly between 14–18 MJ/kg, so the recovery of sludge energy potential should be considered [40,41]. Sludge is the subject of thermal treatment in different technologies such as incineration, gasification, pyrolysis or a combination of them. Even the effectiveness of obtaining energy from sewage sludge may be further improved as a result of co-combustion with fossil or renewable fuels. Fluidized bed boilers are particularly well-suited for this purpose a wide range of fuel blends including difficult, low-quality fuels can be incinerated, and heat and electricity are generated.

An overview of the highlighted important aspects of the circular economy concept in relation to sewage sludge management is presented in Table 3.

3. Survey results: preparation of Polish sewage sludge combustion installations for circular economy challenges

A survey was prepared and sent to all Polish WTTPs, where the incineration of sewage sludge is conducted. The questions concerned aspects of potential energy and nutrients recovery. The response was from nine WTTPs. In general, the heat from sludge incineration is mainly used for WTTP's needs, especially for the drying of the sewage sludge and for preheating air before incineration. It was mentioned in three cases that the heat could be used for central heating

Table 3
Areas of circular economy in relation to sewage sludge management [8]

Key areas of the action plan	Features		Limitations & possibilities		Risks
Production	Limiting the sludge production	→	Sludge volume reduction at WWTPs	←	High costs of chemical reagents
Consumption	Not applicable				
Waste management	Pretreatment	→	Wide range of methods at WWTPs	←	Inappropriate sludge preparation for final utilization
	Landfilling	→	Landfill practice is forbidden	←	Considered less costly than others methods
	Agriculture	→	New regulation on fertilizers	←	Harmful substances
	Thermal methods	→	Emission standards	←	High investment and operational costs
Secondary raw materials	Nutrients recovery		Precipitation of P in form of struvite		Environmental pollution through high organic pollutants, pathogens and
		→	Direct use in agricultural land	←	parasites
			Incinerated ashes	←	Environmental pollution through heavy metals
	Energy recovery	→	Reduced consumption of fossil fuels	←	Environmental pollution through emissions
			Heat and energy generation		
			Using by-products after sludge thermal treatment (char, coke, oil, gas)	←	No market for the by-products, insufficient quality of the by-products
			Destruction of organic hazard substances	←	Accumulation of heavy metals in solid by-products

at WWTPs and in one case for heating of the digestion tank. There is only one case where electricity is produced from steam in Polish installations. It's known that in bigger fluidized bed boilers nearly 80% of energy can be recovered, where around 20% of the energy is lost via off-gas, discharge of the ashes and losses by radiation, convection, and heat conduction. The efficiency of electricity production is low, up to 20% [42]. So in many cases, the generation of steam and the production of electricity is not realized of economical reason. The energy balance of the thermal treatment plant in Gdańsk is shown in Fig. 4 [43]. As can be seen, a heat loss by flue gas is almost 50% of the total heat generated from sludge incineration.

Due to high inorganic matter in sludge, the high amount of ash is generated during sludge incineration. In fluidized bed boilers, there are bottom ash and fly ash. The content of phosphorus in ash is up to 8.6% by mass, and therefore it is much higher than in sludge [33,36]. Based on these data, it is worth to make a potential analysis of phosphorus recovery from ash at each incineration plants. Such analysis has been prepared almost at all polish installations where incineration of sewage sludge is conducted. The conclusion is that the cost of potential phosphorus recovery from ash is too high currently. None of the installation is recovering phosphorus itself. Only in one case ash is transferred to a company that produces fertilizers. Until the recovery of phosphorus out of fly ash is more expensive than the production of phosphorus out of phosphorus ore there will be no interest from WWTPs.

4. Conclusions

According to the communication of the Committee to the European Parliament of December 2015 on the EU CEAP, the key issue is action aimed at recycling, which in terms of sewage sludge means agricultural or natural use by returning nutrients contained in sludge to natural metabolic cycles. However, it does not solve the problem of environmental pollution by harmful substances contained in the sludge. The problem can be partly eliminated by a sludge thermal treatment, and at the same time, raw materials or energy can be obtained. This causes that for sewage sludge management two options are mainly considered now: the use in agriculture and thermal utilization.

During the thermal sludge utilization, the recovered heat can cover the needs for sludge drying as well as other heat needs of the wastewater treatment plant. A plant with a high capacity of sludge incineration there is a possibility to generate electricity from the produced steam. This is a case in Poland, where only in one installation the electricity is produced from the generated steam. Other plants use heat mostly for sludge drying and preheating air before incineration. This allows savings on primary energy resources. Much worse situation is with phosphorus recovery. Its recovery from ash is considered in polish installations quite inefficient in terms of economic value. During the combustion process, the phosphorus is transferred into a low-solubility mineral phase with low availability for plants. And still,

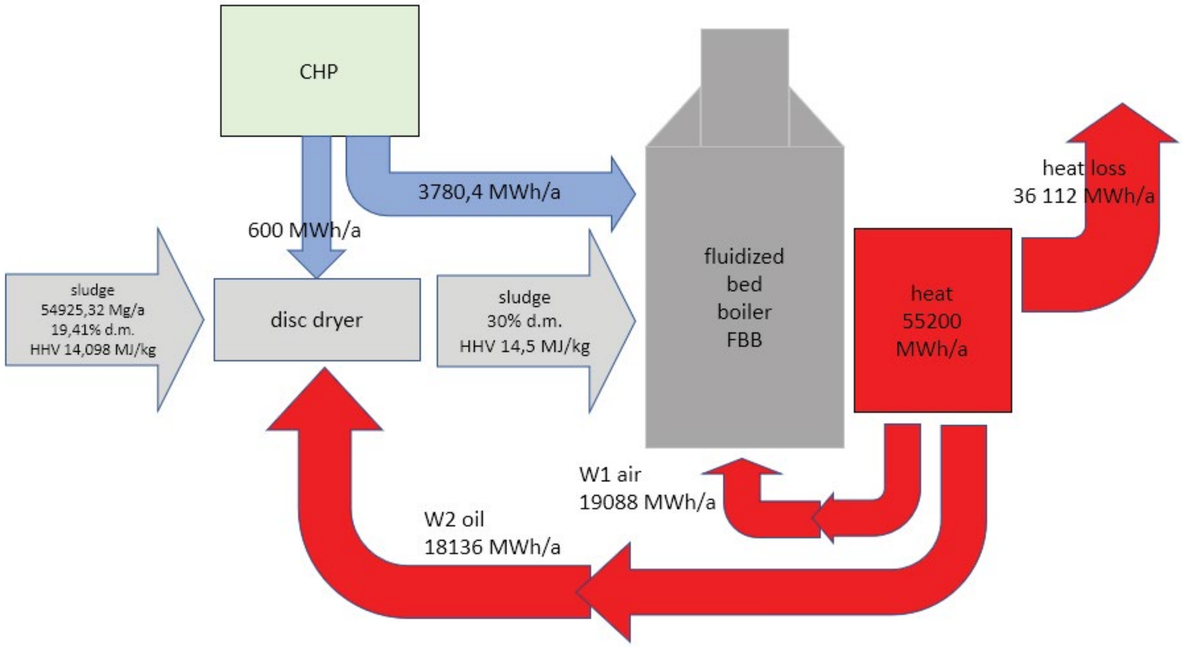

Fig. 4. Electricity and heat balance of the thermal treatment plant in Gdańsk [41].

there is a risk associated with possible negative impacts of the accumulation of heavy metals in organisms. The results of this study show that the first steps were undertaken in the implementation of circular economy ideas in sewage sludge thermal management. However, still, appropriate technologies are required in terms of cost of treatment, energy efficiency and nutrients recovery.

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