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SLUDGE THERMAL UTILIZATION, AND THE CIRCULAR ECONOMY

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Abstract

In 2015, the European Commission has adopted an ambitious Circular Economy Action Plan (CEAP), which includes measures that would help stimulate Europe's transition towards a circular economy. In general four key action areas have been defined: production, consumption, waste management and secondary raw materials. Actions will lead to the resource-efficient and environmentally friendly outcomes. Biological materials should be returned to the natural metabolic cycles after necessary pre-treatment while waste that can not be prevented or recycled is to be used for the energy recovery. Sewage sludge is a large-tonnage waste produced at wastewater treatments plants (WWTPs). Its utilization causes some problems. High water content in sludge, hazardous substances as heavy metals, organic toxins and pathogens limit some potential methods of sludge utilization. Thermal treatment methods offer a solution, some hazardous substances can be destroyed or removed, energy can be recovered and some nutrients can be obtained from ash or other by-products.

Keywords: circular economy, recovery of heat and nutrients, sewage sludge, thermal methods

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1. INTRODUCTION

The concept of circular economy is actually one of the priority concepts of economic development underlying the current EU policy in the field of environmental protection. However, the idea of circular economy is not new. The notion of circularity has deep historical and philosophical origins. Practical applications and thoughts behind this idea are known since the late 1970s, when a small group of visioners have considered all material involved in industrial and commercial processes to be nutrients. Coherent biological and technical metabolisms ensure the availability of raw materials for industrial processes [1]. 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 [2]. These actions include a balanced mix of initiatives and regulatory actions along four key action areas: production, consumption, waste management and secondary raw materials.

According to the Directive 2008/98/EC on waste following the integrated waste management hierarchy will lead to the resource-efficient and environmentally friendly outcomes. Biological materials should be returned to the natural metabolic cycles after necessary pre-treatment while waste that can not be prevented or recycled is to be used for the energy recovery. On 26 January 2017, the Commission introduced the communication on the role of waste-to-energy in the circular economy [3]. It focuses on energy recovery from waste and its place in the circular economy. Waste incineration with a high level of energy recovery is regarded as other recovery. On the other hand, waste incineration with limited energy recovery is regarded as disposal. In general, the communication 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 optimise energy and material outputs, taking into account expected changes in the feedstock for waste-to-energy processes.

Sewage sludge is a large-tonnage waste produced at wastewater treatments plants (WWTPs) and it generally should be disposed outside. However some physical and chemical properties of sludge impedes its final disposal. High water content in sludge, hazardous substances as heavy metals, organic toxins and pathogens limit some potential methods of sludge utilization although sewage sludge contains also valuable nutrients such as nitrogen and phosphorus [4,5]. One of the most commonly way of sewage sludge disposal in Europe was deposition in landfills, but due to new EU conceptual approach regarding waste as a resource this method is prohibited or limited in several EU countries. According to integrated waste management hierarchy presented in the Directive 2008/98/EC on waste landfilling is the least preferable means 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. So, it is clear that using the sludge energy potential is more preferable to landfilling. There is also an option to use pre-dried or composted sludge in agriculture as a fertilizer, or for reclamation. However, this approach needs careful evaluation because problems associated with environmental pollution by harmful substances contained in sludge is not removed in that way [6]. Heavy metals, non-biodegradable harmful chemicals and potentially pathogenic microorganisms, all likely to create serious health concerns [7]. However the introduction of secondary raw materials in an Action Plan for the Circular Economy is crucial to ensure the transition to a circular economy. Nutrients are indicated as an important elements of the secondary raw materials obtained from waste [8]. In such context thermal sewage sludge methods are regarded as one of the best methods to address sewage sludge management problems because they can reduce the volume and toxicity of sludge, obtain an energy as well concentrate nutrients (phosphorus) in ash [9].

This paper provides a summary overview of the role of thermal sewage sludge utilization in the context of circular economy approach.

2. SEWAGE SLUDGE IN EU ACTION PLAN FOR THE CIRCULAR ECONOMY

The first basic area of concern in CEAP is production. 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 [10]. Sewage sludge is generated mainly via mechanical treatment (primary sludge) and via biological and chemical treatment at secondary stage at wastewater treatment plants. The composition of sludge depends on the composition of the treated wastewater. 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 [11]. There is no possibilities to eliminate the production of sludge. The amount of sludge can be limited by means of technical operations at WWTPs.

A consumption, the second area of CEAP, is not applicable to sewage sludge.

Sludge management. 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. In 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 mechanical dewatered. Sewage sludge has high water content. After stabilization sludge contains 1-3% of dry solid content. Thickening process gives this value at level of about 3-5%. After mechanical dewatering sludge contains of about 20-30% of dry matter, it means that sludge still contains 70-80% of water. The further treatment of sludge is required. Fortunately a diverse treatment technologies are available just for the 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. The European Union 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 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 a 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.

Secondary raw materials. With the new conceptual approach regarding waste as a resource the recovery of secondary raw materials plays a crucial role. In this context wastewater treatment plant is not any more considered as pollution removal system but as nutrients and energy recovery plant [12]. Nutrients are indicated as an especially important category of the 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% total solids) and phosphorus (0.5 - 0.7% total solids), 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 [13, 14]. 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 [15]. The new regulation should boost the European market for innovative organic fertilisers 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 the precipitation of phosphate and nitrogen as struvite (magnesium ammonium phosphate)[16]. Becker et al [17] 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 ash. The P-recovery from ash after sludge incineration is under wide investigation nowadays [18, 19]. A two-step thermal treatment is suggested. In a first step organic pollutants are completely destroyed by mono-incineration of sludge, and the incineration results in ash with high phosphorus contents of approximately 20% P2O5. Generally, the phosphorus content in ash varies from 5 to 11% [20]. Phosphorus released from sludge are deposited mainly in bottom ash (89,29%) rather than in fly ash (5.61%) [17]. Cieslik et al [21] stated that phosphorus recovery from ash could be 5-10 times higher in comparison to that achieved from sludge directly. However, phosphorus in the ash 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 [22]. Some authors indicate the possibility of using biochar, which is a carbonaceous product from sludge pyrolysis [23]. 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 [24]. The condition of pyrolysis process plays an important role in achieving nutrients in biochar. Yuan et al [24] found as the pyrolysis temperature was increasing, the nitrogen content of the resulting sewage sludge biochar decreased, phosphorus content increased. The positive information is that there is a quite 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 [25]. 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 is considered [26, 27]. Sludge is the subject of thermal treatment in different technologies such as incineration, gasification, pyrolysis or a combination of them. The effectiveness of obtaining energy from sewage sludge may be further improved as a result of co-combustion with fossil or renewable fuels. There are also some other possibilities. Some authors indicate the potential recovery of enzymes, bio-plastics, bio-pesticides or proteins [14, 28 – 32]. It was found that ultrasonication is an appropriate method for an effective recovery of the hydrolytic enzymes (e.g. lipase and protease) from sludge. Moreover, this method could be scaled up for industrial application. It was also observed that several microorganisms in sludge have the ability to accumulate polyhydroxyalkanoates (PHAs) [33]. However, the process costs of PHAs production from sludge are likely to be reduced before potential widespread uses. Tyagi et al [34] stated that sludge appears to be highly nutritional and cost-effective medium for bio-pesticide (Bacillus thuringiensis - Bt) production, which will substantially reduce the Bt production cost and will contribute to sustainable sludge utilization and management according to concern of circular economy.

An overview of the highlighted important aspects of circular economy concept in relation to sewage sludge utilisation and management is presented in Table 1.

Table 1. Areas of circular economy in relation to sewage sludge management

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 parasites
		→	direct use in agricultural land	←	
			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
	products recovery (enzymes, bio-plastics, bio-pesticides, proteins)	→	potential as an animal feed	←	high production costs, more studies on parametric optimization are required

3. THERMAL METHODS OF SLUDGE UTILIZATION IN CIRCULAR ECONOMY

Thermal waste treatment methods commonly include incineration, gasification and pyrolysis. All of thermal methods reduce a volume of sewage sludge. Incineration is an exothermic oxidation process of combustible material resulting in a certain amount of energy (heat), ash and flue gases. Incineration reduces 90% of sludge volume and destroys pathogens. The ash can be disposed into the landfills or be utilized for production of building material [35]. The recovered heat can be used for drying of the sewage sludge or producing steam for electricity production [36,37]. The fluidized bed boilers have been considered as a best solution for sludge incineration according to high combustion efficiency and low pollutants generation [38]. 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 700-1000°C [39]. Calorific value of syngas varies from 4.5 to 5.6 MJ/Nm^3 [40], and after treatment is used to run a gas engine. The end-products of sludge gasification depends on sludge properties (i.e. moisture, volatile matter, inorganic matter), experimental conditions (i.e. temperature, heating rate, gasifying agent, catalysts) and the gasifier design (i.e. downdraft or updraft fixed gasifier, fluidized gasifier). However, the gasification of sewage sludge meets some problems. High water content and low heating value of sludge result in lower gasification efficiency. Moreover, high tar production from sludge gasification requires additional attention because it can probably impede the proper operation of gasifier, make the process complex and costly. To improve the process sludge co-gasification with other carbonaceous substances is the subject of research [41,42]. In particular woody biomass is an appropriate material for co-gasification due to high volatile matters, low ash and moisture content. Peng et al. [41] investigated the co-gasification of wet sludge (76% dry basis moisture content) and woody biomass (8.6% dry basis moisture content). He noticed that addition of woody biomass to sludge compensated the moisture content and improved the volatile matter content in the blend. Pyrolysis is a thermal conversion in an oxygen deficient environment at elevated temperatures of 350-900°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 [43]. Compared to the highly exothermic incineration, pyrolytic reactions are endothermic consuming energy, so pyrolysis of sewage sludge is in most cases connected with a combustion of pyrolysis gas or char. It's stated that products from sludge pyrolysis such as oil, gas or char can be utilized for various application, even pyrolysis was identified as a zero waste technology [44]. However only a few plants of sewage sludge gasification or pyrolysis are in operation in Europe. The most popular technology among thermal methods of sludge utilization is its incineration, especially in fluidized bed reactors [45].

3.1. Recovery of heat and energy

In general, in bigger fluidized bed boilers nearly 80% of energy can be recovered. Around 20% of the energy is lost via off-gas, discharge of the ashes and losses by radiation, convection, and heat conduction. Efficiency for electricity production is however low, up to 20% [46]. In many cases the generation of steam and the production of electricity is not realized of economical reason, so only heat is recovered from flue gas for drying sludge and preheating air before incineration. If there is a such possibility heat could be used for district heating. For reaching an auto-thermal combustion sludge should have a minimum heating value of 3 – 4 MJ/kg. However, for better efficiency of incineration process in fluidized bed unit sludge has to be thermally dried to at least 33% dry matter. This thermal drying is achieved by the energy recovered out the combustion process. An example of heat and electricity balance from sludge incineration plant is given in Fig 1. As it could be seen from the figure most of the heat is recovered for sludge drying and for boiler air preheating. However, still there is a quite large amount of energy (heat) that can be used. In this case it is released into the air and is lost.

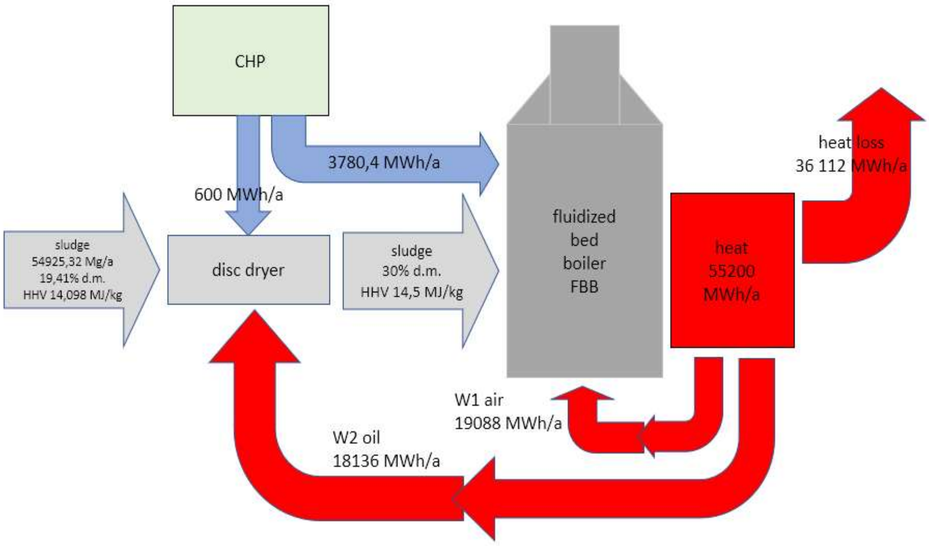

Fig. 1. Electricity and heat balance of the sludge thermal treatment plant in Gdansk (Poland) [47]

There are only three commercial sludge gasification plants in Europe, all located in Germany. The smaller one has a capacity of 1955 Mg ds/a and is located in Balingen, the middle in size has a capacity of 4000 Mg ds/a, and is located in Koblenz, the bigger one has a capacity of nearly 5000 Mg ds/a and is located in Mannheim. All plants are based on a two stage gasification process [48]. From the silo, sewage sludge with a dry content of 85% – 95% is transported together with limestone to a thermolysis screw – the first stage of gasification. The products produced in thermolysis, such as thermolysis gas, carbon and ash are next conveyed into a fluidized bed gasifier – the second stage of gasification (Fig. 2).
The gasification takes place at temperature of 850-900°C, what completely destroys all toxic substances in the sewage sludge. The synthesis gas produced in the fluidized bed gasifier is treated before used in CHP unit. However, there are no precise information about heat and energy generation. Operators inform that with the recovered energy, the plant's own consumption is almost covered. This means that no surplus energy is exported from the process [49]. Although gasification is common in many industries, gasification of sewage sludge is still considered innovative.

Pyrolysis is also an established technology used in the chemical industry to produce charcoal, activated carbon and methanol, but pyrolysis of sewage sludge is also considered as an innovative technology. Similar to gasification, pyrolysis can generate a combustible gas, a pyrolysis gas, with a low heating value but also can be used to generate char and oil. There are only a few plants in Europe where pyrolysis process is applied to sewage sludge, with two different configurations.

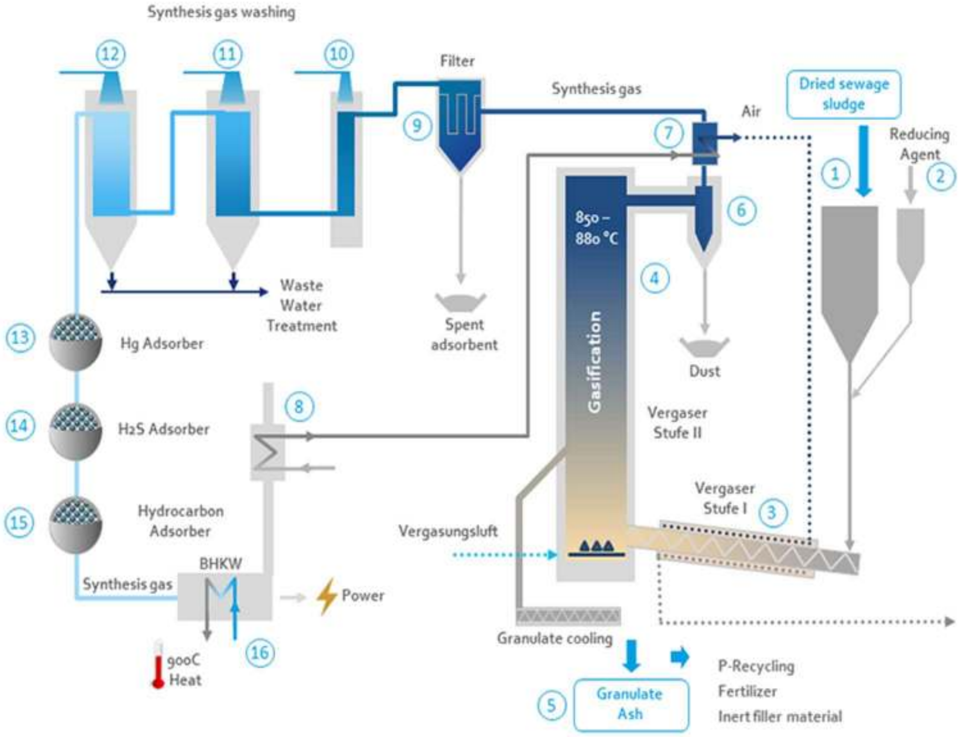

Fig. 2. Gasification process by Sulzle Kopf [48]

The first one is known as Eisenmann Pyrobuster technology (Fig. 3) [50]. The process is organized in two sequential steps. First, sludge of 90% dry solids is fed in the pyrolysis chamber at 300-350°C, where it is pyrolyzed. The process produces char, which is transferred to the Pyrobustor's oxidation zone, where the char is incinerated. The hot flue gas generated by this process is fed past the pyrolysis chamber via a ring gap, providing the energy required for pyrolysis by indirect heat input. The energy of flue gases is transferred for sludge drying by a thermal oil heat exchanger. Two facilities are in operation, at Stadtwerke Crailsheim, Germany (capacity of approx. 650 kg/h of 90% ds sludge) and in South Tyrol, Italy (capacity of approx. 550 kg/h of 90% ds sludge) [51].

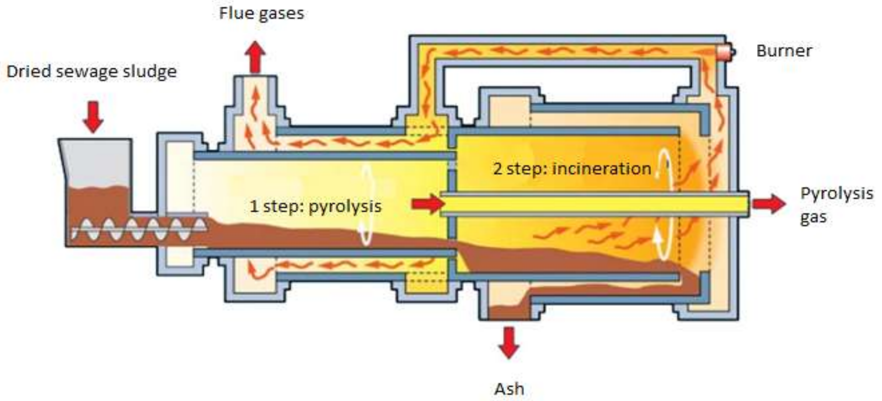

Fig. 3. Pyrolysis process by Eisenmann Pyrobuster [50]

In Greenlife pyrolysis process the sludge of about 65% ds is conveyed through the reactor for 30 minutes and heated to 600°C (Fig. 4).

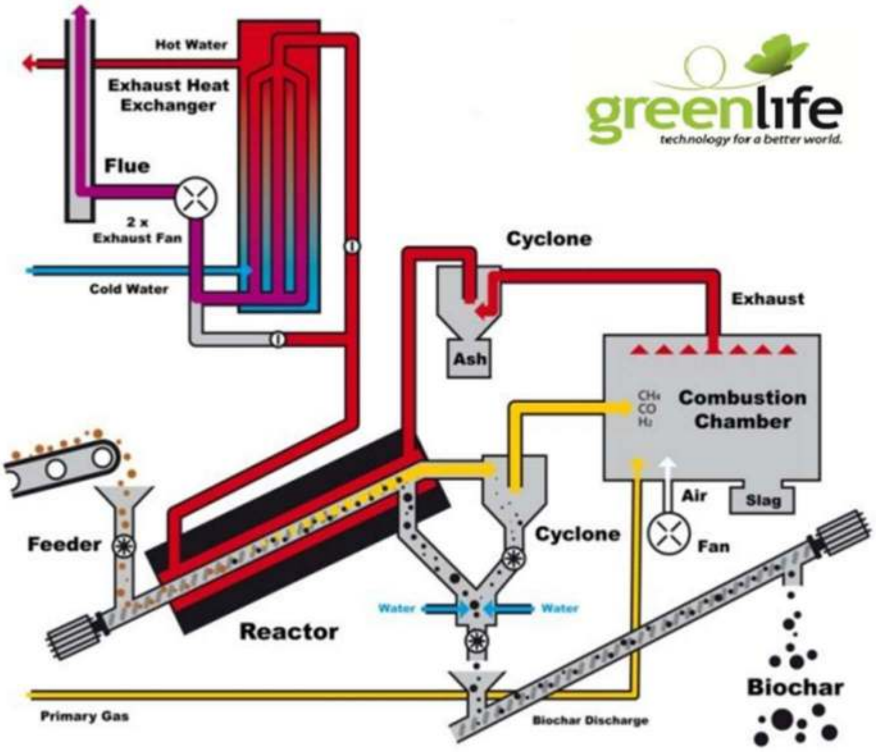

Fig. 4. Pyrolysis process by Greenlife [52]

The gas formed in the carbonization process is extracted and fed into the combustion chamber. The produced char is conveyed after passing a water spraying system via a rotary feeder and a discharge screw in the biochar bunker. The resulting gases are burned in the combustion chamber at 1100°C, and the flue gases are cleaned by a cyclone. Subsequently, the gases pass through the reactor and heat a new portion of sludge that is introduced in the reactor. The whole system is closed in a 20-feet-container. From 500 kW sludge input the heat of about 150 kW is achieved and provided for drying of the sewage sludge.

In general, the energy balance in pyrolysis processes is negative. Heat produced in the process is completely used, even more input energy is required to maintain the overall process. During gasification there is also no extra energy in the process. Operators from plants in operation informed that the plant's own energy consumption is almost covered by the recovered energy. A certain amount of extra energy is only possible when sludge is incinerated.

3.2. Recovery of phosphorus

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. Ash after sludge incineration is rich in nutrients. The phosphorus content in ash is up to 11% by mass, and therefore it is much higher than in sludge [53]. Nowadays there is much interest in the recovery of phosphorus from ashes either as phosphoric acid or as a fertilizer [53, 54]. It is believed that phosphorus recovery from waste will be a partial solution to the limited supplies of rock phosphate. To achieve this certain technologies were already developed, and theoretically in BIOCON, SEPHOS, ASHDEC, RECOPHOS, PASCH almost 70-85% of phosphorus in ash after sludge incineration can be recovered [55]. Much less information is available on phosphorus recovery from pyrolyzed sludge char. A review made by Fonts et al [56] confirms that phosphorus recovery from ash has been explored but the recovery from char has been overlooked. However, some experiments show that phosphorus recovery from char could be more attractive. Recent study indicates pyrolysis can strongly immobilize heavy metals into the biochar matrix, then heavy metals can hardly be leaching out reducing the potential risk to soil and living organisms. Moreover, Kleemann at al [57] found that pyrolysis is more affective than incineration in converting inherent phosphorus into bioavailable phosphorus. Thus, biochar can be used in soil condition. Ash from sludge incineration is usually unsuitable for use as fertilizers due to low phosphorus bioavailability. In addition, heavy metals content in sludge ash also hampers its direct use as a phosphorus source [58]. A line of Greenlife facility with a capacity of 4000 Mg/a of dewatered sewage sludge (25% ds) can produce up to 500 Mg/a of biochar [53]. Potentially the phosphorus can be also recovered from ash after gasification. Gorazda et al [59] stated that efficient phosphorus recovery from the solid gasification residue can be obtained with the investigated PolFerAsh technology within the range of 73–82%. Phosphorus can be selectively leached, as most of the iron and heavy metals stay in the solid phase. At Kopf gasification plant it is reported that phosphorus can be recovered from produced slag [60].

4. CONCLUSIONS

In 2010, some 42% of Europe's municipal sewage sludge was treated and used on farmland, 27% was incinerated, 14% was disposed of by landfilling and about 17% was disposed of in other ways, according to Eurostat [61]. Almost all sludge is incinerated in Netherlands (99%), in Germany (58%), Austria (52%), Denmark (29%), Finland (23%), Poland (18,2%). Thermal sludge utilization is attractive due to full destruction of non-readily biodegradable organic substances and pathogens as well as sewage sludge volume and mass reduction. However, due to the concept of circular economy and waste hierarchy announced in the Directive 2008/98/EC on waste there are much more preferred environmental option of waste utilization than thermal treatment. The ultimate goal is to deliver the best environmental outcome. Biological materials should be returned to the natural metabolic cycles after necessary pre-treatment while waste that can not be prevented or recycled should be used for the energy recovery. Nowadays, for sewage sludge these two options are mainly considered in Europe: the use in agriculture and thermal utilization. Thermal sewage sludge treatment methods commonly include incineration, gasification and pyrolysis. In the paper, in the context of circular economy context, a comparative analysis of these three thermal methods for sludge utilization has been performed. The analysis shows that at this stage of knowledge and technical development the best option is sewage sludge incineration. The recovered heat can cover needs for sludge drying as well as other heat needs of WTTP plant. In plants with high capacity there is a possibility to generate electricity from the produced steam. The process of gasification or pyrolysis do not create such possibilities. The energy balance is usually negative. Phosphorus is the most valuable substance contained in sewage sludge. Therefore, in this case also mono-incineration is preferred for sewage sludge since its ash has higher phosphorus content and already there are technologies developed for phosphorus recovery from ash. However, it has to be taken into account that ash from sludge incineration is usually unsuitable for use as fertilizers due to low phosphorus bioavailability, thus the further treatment is necessary. In result the process needs an optimization from the economic point of view. The char after pyrolysis is more attractive due to phosphorus bioavailability. Ultimately, thermal methods of sewage sludge utilization are fully part of a new conceptual approach regarding waste as a resource.

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