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THE USE OF LCA METHOD TO ASSESS ENVIRONMENTAL IMPACT OF SEWAGE SLUDGE INCINERATION PLANTS

ZASTOSOWANIE METODY LCA DO OCENY WPŁYWU NA ŚRODOWISKO SPALARNI OSADÓW ŚCIEKOWYCH

Abstract: Life Cycle Assessment (LCA) is one of the new, little more popular in Poland of elements of environmental management. In the world literature one can find many examples of the use of LCA but mainly for comparison purposes. The paper presents results of LCA analysis made on the basis of data from a running incineration of sewage sludge. Performing a thorough analysis of this process enables improved operational system, including through a better use of the resulting products of combustion, as well as determining the impact of the thermal treatment of sludge on the environment and compared the results with data from the literature. To date, in Poland has not been carried out environmental impact assessments and the process of thermal treatment of both sludge and waste, based on the assumptions of LCA.

Keywords: sewage sludge incineration, LCA analysis, environmental impact assessment

Introduction

Countries worldwide focus on methods that will advance the use of renewable energy (*e.g.*, hydropower, solar, wind, biomass), as well as achieve cleaner and more efficient energy consumption. This aim is the result of the increasing pressure brought on by initiatives, such as the call for energy savings, pollutant emission reduction, and sustainable economic development. This pressure has directed considerable attention toward sewage sludge, municipal refuse and other solid wastes processing. These waste derived from farming, housekeeping or operation of business contain large concentrations of various pollutants (*e.g.*, heavy metals, PAHs, pathogens) and are rich in organic matter. Given significant global population growth with rapid industrialization and urbanization, the volume of recently produced different classes of waste have dramatically increased. In the

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European Union and in China, more than 10 and 20 Tg (million Mg) of different classes of waste are respectively produced annually. That it is a significant biomass resource especially sewage sludge has been extensively used for energy generation [1].

Numerous waste-based energy production methods, such as incineration, melting, anaerobic digestion, carbonization, and co-incineration in coal-fired power plants, are employed across the globe. Unlike anaerobic digestion, waste incineration, melting, and co-incineration in coal-fired power plants presents serious environmental hazards related to dioxins, furans, and fly ash. Therefore, these materials should be properly disposed of to keep from harming the environment.

Incineration of sewage sludge becomes recently a popular method of its management both in Poland and Europe. Hence, a question arises what influence this method will have on the natural environment at present and in the future, which elements of the environment will be affected most, and consequently, how it can be optimized to minimize the potential impact of this process on the environment. In Poland in the years 2002-2013 the amount of sewage sludge produced increased from about 450 Gg per year to about 550 Gg per year and now stay at a nearly constant level. On the other hand, in this period a change in sewage sludge management was observed. There is a tendency to decrease the quantity of dumped sludge in favour of its incineration and also agricultural use (Fig. 1). However, the agricultural use of sewage sludge is strong limited due to the limited content of heavy metals and other organic pollutants. One of the methods to assess the real impact of the method of waste disposal on the environment is to use the method of life cycle assessment.

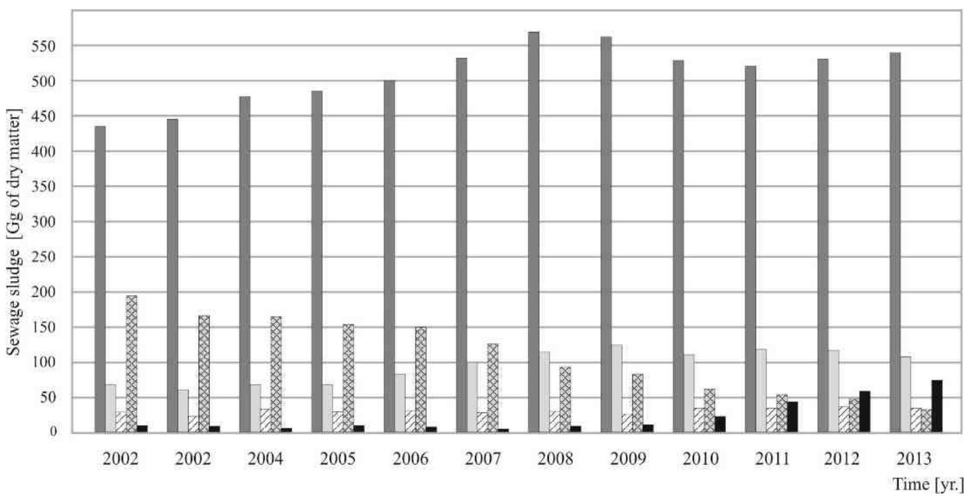

Fig. 1. Production and management of sewage sludge in Poland in the years 2002-2013 [2] (dark grey - total production, light grey - agricultural use, dashed - composting, checkered - dumping, black - incineration)

Life cycle assessment (LCA) is a relatively new methodological tool [3], based on a global vision of the production system, in which all of the processes and the operations that intervene, from the extraction of raw materials to the end of life, are analysed in terms of input and output, contemporarily encompassing the burdens associated with resource depletion and the releases on the environment. The integrated valuation of all environmental effects “from cradle to grave” is the foundation from taking a number of decisions aimed at achieving improved products and services.

The interest in LCA increased rapidly during the 1990s, also when the first scientific release occurred [4, 5]. At that time LCA was burdened with high expectations but its results were also a subject of frequent criticism [6]. Since then a strong development and harmonization has occurred resulting in an international standard [7, 8], complemented by a number of guidelines [9, 10] and textbooks [11, 12]. This has improved the maturity and methodological reliability of LCA. However this method is further developed. Several international initiatives to help build agreement and provide reference, including the Life Cycle Initiative of the United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry, the European Platform for LCA of the European Commission, and the emerging International Reference Life Cycle Data System (ILCD) are underway.

In the last years, life cycle assessment has been often used to assess the potential environmental impact of a product or of a system, including resources extraction, transportation, use and end-of-life treatments [13]. In addition, LCA has also been considered a tool to optimise process operating conditions [14], which can also support the decision making process in the field of waste management [15, 16], waste to energy applications [17] and for the development of future waste management scenarios [18-20]. LCA is also used to settle on treatment processes that are less polluting, to asses systems indicated by different collection methods and technologies [21] and to focus attention on substances that may be hazardous to human health and the ecosystem [22].

This comparatively new field of application of the LCA to integrated municipal solid waste (MSW) management shows great potential for development, especially in decision support of planners and companies that run waste collection, transport and recycling/disposal services. Although it generally represents a step of any product LCA, waste management can be taken into account as an separate system, with input streams firstly consisting of refuse from human and production activities and outputs as the final emissions into the environment (solid, liquid and gaseous) and creating the new useful products (recycled materials, energy, compost).

Life cycle assessment is a decision-support tool, that, thanks to its holistic approach in quantifying environmental impacts, has been indicated to give valuable inputs to identify proper solutions for managing solid waste.

The ability of LCA to be a decision-supporting tool to evaluating different waste treatment scenarios and highlighting environmental hot spots has been proven by many studies [13], even if the applicability of LCA for waste management planning is restricted by certain limitations, some of which are characteristics essential to LCA methodology as such, and some of which are direct specifically in the background of waste management. the last ten years, replete with publications referring to life cycle assessment [23]. Most of these papers focus on the environmental impact of the waste incinerators as a whole or compare waste incineration to other treatment options.

Life cycle analysis of the incineration of sludge from the operating sewage treatment plant made on the basis of data collected in the sewage sludge incineration plant is presented in the article. The aim of the study is an analysis of the components of the existing sewage sludge incineration system so that it could be improved through a more efficient use of the products of incineration and other by-products of this process, and also determination of its real environmental impact.

So far, in Poland no analysis of the environmental impact of thermal treatment of both sludge and wastes based on the life cycle assessment has been carried out. Although there is some controversy regarding the use of this method due to its ambiguous nature, it is increasingly applied both in designing, planning and improving a product. Thus, it becomes an element which determines the development strategy as well as competitiveness and market attractiveness of the tested product.

Materials and methods

LCA is a tool for assessing environmental burden associated with a product, process and service through the inventory of energy and mass flows and emissions to the environment. Additionally, this analysis can be used to determine the possibility of improving the environment [24].

The LCA method is an international standard and is considered to be one of the most effective tools to identify and assess environmental impacts associated with waste management options. In particular, a broad perspective of performing LCA facilitates an approach which brings significant benefits that can be obtained by various methods of waste management. For example, waste incineration with energy recovery reduces the need for other energy sources, recycled material replaces the original material and biological treatment may reduce the need to produce fertilizers and fuels for the transport sector [24].

There are several models which can be applied while performing the LCA analysis of waste management system. They allow analysts to determine, through the analyses of scenarios, the environmental impact of changes in the system analyzed [25].

Methodology

The methodology of life cycle assessment is based on guidelines according to standards EN ISO 14 040 : 2006, EN ISO 14 044 : 2006 [7, 8] with several indicators applied to examine the system efficiency from various points of view, such as the requirements concerning materials and energy, environmental impact and ecological footprint. This approach is used because the LCA of a product or service is made through the product taking into account its impact on the environment and human health and the necessity to seek a general ecological assessment. The LCA does not assume the assessment of the impact of a product or service in economic or social terms [24].

The scope of research and functional unit

The analyzed process comprises the following steps of system operation starting with digested dewatered sludge (Fig. 2):

- transport and storage
- drying
- incineration
- flue gas treatment

The analysis does not include the process of sewage sludge formation and dumping of ash and dust. The consumption of fuel, energy, reagents and water as well as generation of wastes such as dust and ash has been converted to 1 Mg of incinerated sludge per year.

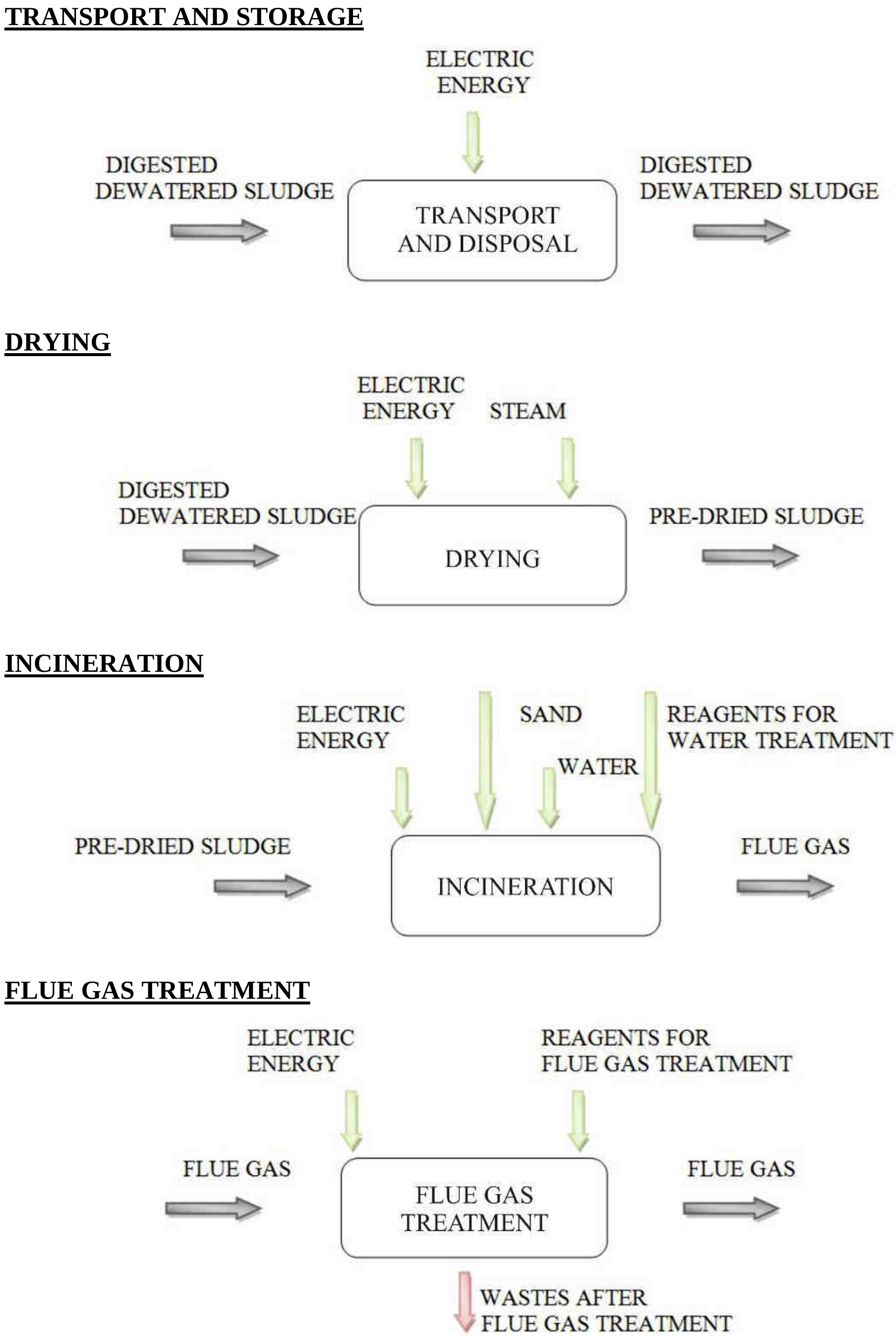

Fig. 2. Simplified scheme of subsequent steps of sewage sludge incineration

Definition of the functional unit of a quantitative cycle of a system or product as a reference unit in the LCA study provides a basis for evaluating the system efficiency. In this work the functional LCA unit of a product at the system output was assumed to be MWh of energy obtained. The functional unit for the performed analysis of waste management, at the system input, is the amount of waste, *i.e.* about 61 Gg of sewage sludge used per year. In reference to the scope of assessment, three different scenarios of waste management will be compared.

Scheme of sewage sludge incineration - boundary conditions

The installation for thermal processing of sewage sludge and screenings is located in the Combined Sewage Treatment Plant in Lodz. It consists of two separate process lines connected by common systems.

The dewatered sludge from settling tanks is transported on conveyors to the installation for thermal processing. The received sludge is pre-dried with steam in indirect disk dryers. After pre-drying the sludge is pumped to the incinerator by screw pumps. Also screenings are incinerated. A separate system of conveyors transports them to the incinerator.

The process of incineration of sludge and screenings is carried out in a fluidized bed incinerator. Fluidization, or the state of suspension of particles, is maintained due to blowing heated air underneath a sand bed. The bed consists of a mixture of quartz sand with different particle size distribution. The process temperature is 750-850°C. As a result of complex physicochemical reactions, liquids take the form of vapours and solid organic substances are gasified in a small amount of oxygen. The resulting energy is absorbed by sand. Gases emitted in the above processes are burnt in the secondary combustion chamber at a temperature of min. 850°C. The required residence time of flue gas in the incinerator is minimum 2 seconds. After leaving the fluidized bed incinerator the flue gases are directed to a multi-stage flue gas cleaning system.

The first step is to cool the flue gas which is implemented in a recuperator heating the air needed for the fluidization process. Air is taken from outside. With the help of blowers it flows in counter current through the recuperator taking heat from the exhaust gases. The next step in which further heat recovery occurs is steam generation. In the boiler water takes energy from the flue gas and the boiler drum generates steam used for sludge pre-drying.

The subsequent step of exhaust gas cleaning is dedusting in a cyclone. Dusty exhaust gas flows into the cyclone tangentially to its periphery. In this way, the heaviest impurities in the form of ash fall into the hopper of a pneumatic transport system. The ash is stored in a silo and periodically transported to the landfill.

In a further step, flue gas must have optimal conditions for cleaning in a bag filter. Chemical removal of acidic compounds and mercury proceeds with the use of a dry cleaning method. It consists in injecting sodium bicarbonate and activated carbon into the stream of gases. The mixture is stopped in the last element of the flue gas cleaning system which is the bag filter. The filter cleaning process produces dust which enters the pneumatic transport system. Next, as a hazardous waste, it is subjected to washing in order to reduce the quantity of salt compounds in it. The washed waste is disposed in a dumping site.

Impact categories

Impact categories analyzed in this paper are based on global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP). These are the indicators used in the LCA to evaluate possible damage to human health and ecosystem quality. GWP is the indicator referring to carbon dioxide emissions to the atmosphere quantified as kilograms of substance equivalent emissions calculated for the period of 100 years. EP is determined by the size of eutrophying substance emissions to air, water and soil, while AP indicates the impact of acidic substances emitted to the environment from the tested systems.

Results and discussion

All scenarios considered in the paper assume waste incineration with energy recovery. They are based both on the data collected during actual processes and on model assumptions:

Scenario 1: waste intended for thermal processing is transported directly to the incineration plant. This is the waste of undifferentiated calorific value 8.85 MJ/kg which generates 12.9 GJ of energy producing 967 MWh of electric energy. Energy recovery from the combustion process is 27%. For waste gases purification the following reagents are used: urea, activated carbon, calcium oxide and calcium hydroxide. Ash and dust from the process are disposed in a landfill [24].

Table 1

Comparison of mass and energy streams in individual scenarios

INPUT		Scenario 1	Unit	Scenario 2	Unit	Scenario 3	Unit
1	Oil	0.157	[kg/Mg]	0.0005	[m^3/Mg]	3.120	[kg/Mg]
2	Biogas	0.060	[m^3/Mg]	---		15.160	[m^3/Mg]
3	$NaHCO_3$	---		---		9.070	[kg/Mg]
4	Urea	3.000	[kg/Mg]	---		---	
5	Activated carbon	2.500	[kg/Mg]	---		0.180	[kg/Mg]
6	Water	---		---		0.320	[m^3/Mg]
7	NaOH	---		---		0.100	[kg/Mg]
8	$Ca(OH)_2$	3.200	[kg/Mg]	---		---	
9	NaCl	---		---		0.200	[kg/Mg]
10	H_2SO_4	---		---		0.020	[kg/Mg]
11	Electric energy	0.067	[MWh/Mg]	0.065	[MWh/Mg]	0.069	[MWh/Mg]
12	CaO	2.500	[kg/Mg]	---		---	
13	NH_3	---		2.000	[kg/Mg]	---	
14	$CaCO_3$	---		4.000	[kg/Mg]	---	
OUTPUT							
1	Energy	0.661	[MWh/Mg]	0.003	[MWh/Mg]	0.506	[MWh/Mg]
2	CO	0.389	[kg/Mg]	0.066	[kg/Mg]	0.003	[kg/Mg]
3	HCl	0.021	[kg/Mg]	0.030	[kg/Mg]	0.0008	[kg/Mg]
4	HF	data unavailable		0.00006	[kg/Mg]	0.00008	[kg/Mg]
5	NO_x	0.201	[kg/Mg]	1.300	[kg/Mg]	0.023	[kg/Mg]
6	SO_2	0.149	[kg/Mg]	0.017	[kg/Mg]	0.058	[kg/Mg]
7	CH_4	0.00004	[kg/Mg]	data unavailable		data unavailable	
8	Dust emission	0.005	[kg/Mg]	0.004	[kg/Mg]	0.003	[kg/Mg]
9	CO_2	265.8	[kg/Mg]	data unavailable		data unavailable	
10	NH_3	data unavailable		data unavailable		0.031	[kg/Mg]
DUMPING							
1	Ash	220.0	[kg/Mg]	data unavailable		44.0	[kg/Mg]

Table 1a

Comparison of mass and energy streams in individual scenarios (continued)

INPUT		Scenario 2A	Unit	Scenario 2B1	Unit	Scenario 2B2	Unit
1	Oil	0.0010	[kg/Mg]	---		---	
2	Biogas	---		3.00	[m^3/Mg]	3.00	[m^3/Mg]
3	$NaHCO_3$	---		4.48	[kg/Mg]	32.0	[kg/Mg]
4	Urea	---		---		7.0	[kg/Mg]
5	Activated carbon	0.014	[kg/Mg]	1.44	[kg/Mg]	0.80	[kg/Mg]
6	Water	---		0.44	[kg/Mg]	1.20	[m^3/Mg]
7	NaOH	0.0184	[kg/Mg]	---		0.40	[kg/Mg]
8	$Ca(OH)_2$	0.168	[kg/Mg]	17.6	[kg/Mg]	---	
9	NaCl	---		---		0.20	[kg/Mg]
10	H_2SO_4	---		---		---	
11	Electric energy	0.0003	[MWh/Mg]	0.15	[MWh/Mg]	0.15	[MWh/Mg]
12	CaO	---		---		---	
13	NH_3	0.014	[kg/Mg]	3.92	[kg/Mg	---	
14	$CaCO_3$	---		---		---	
OUTPUT							
1	Energy	0.002	[MWh/Mg]	0.444	[MWh/Mg]	0.444	[MWh/Mg]
2	CO	0.007	[kg/Mg]	0.205	[kg/Mg]	0.205	[kg/Mg]
3	HCl	0.001	[kg/Mg]	0.020	[kg/Mg]	0.020	[kg/Mg]
4	HF	data unavailable		0.001	[kg/Mg]	0.001	[kg/Mg]
5	NO_x	0.007	[kg/Mg]	0.478	[kg/Mg]	1.231	[kg/Mg]
6	SO_2	0.006	[kg/Mg]	0.020	[kg/Mg]	0.020	[kg/Mg]
7	CH_4	0.00009	[kg/Mg]	data unavailable		data unavailable	
8	Dust emission	0.003	[kg/Mg]	0.010	[kg/Mg]	0.014	[kg/Mg]
9	CO_2	9.08	[kg/Mg]	112800	[kg/Mg]	115850	[kg/Mg]
10	NH_3	0.014	[kg/Mg]	0.034	[kg/Mg]	0.068	[kg/Mg]
DUMPING							
1	Ash	2.48	[kg/Mg]	188.0	[kg/Mg]	241.0	[kg/Mg]

<u>Scenario 2</u>: processed waste incineration with energy recovery, with calorific value ranging from 13 to 22 MJ/kg, three incineration lines equipped with a grate furnace, two of them with semi-dry gas cleaning systems, one line with wet cleaning. It is assumed that the incineration plant requires 65 kWh of energy, 0.5 dm^3 of fuel per Mg of waste and reagents such as sodium hydroxide, calcium carbonate and ammonia necessary for flue gas purification (see Table 1) [17].

<u>Scenario 2A:</u> co-incineration of the coal and sludge. Water content, ash content and calorific value 7.5, 22.3% and 23.9 MJ/kg for coal and after carrying out processes thickening, dewatering and pressure filtration 57.5, 20.1% and 2.04 MJ/kg for sludge, respectively [25, 26]. In the first six months of 2012, they produced approximately 25.7 GWh of electricity and approximately $3.5 \cdot 10^5$ Mg of steam. Coal and sludge consumption levels were approximately $7.4 \cdot 10^4$ Mg of coal and $5.9 \cdot 10^4$ Mg of sludge, respectively.

<u>Scenario 2B:</u> The incinerator consisted of two working incineration lines, which were the subjects of a previous LCA study, and a third incineration line will be built next to them. The third line will be able to handle an amount of waste (300 Mg/d) which is twice the quantity currently treated by the existing plant. The type of waste sent to combustion will be the unrecyclable waste from separated collection, with a lower heat value of 12.558 kJ/kg. The expected energy recovery efficiency of the plant is 0.444 kWh per Mg of

MSW burned. This value is in line with the values reported in literature for electric energy production from MSW: about 0.5 MWh per Mg of waste burned [27], from 0.134 to 0.540 MWh/Mg [28], about 0.3-0.7 MWh/Mg [29]. The technological first solution considered is equipped with a dry flue gas cleaning (scenario 2B1) and the second solution is equipped with a wet flue gas cleaning (scenario 2B2).

Scenario 3: incineration of sludge and screenings with energy recovery in the form of heat used for drying the sludge and then to heat water and supply central heating throughout the plant. The analysis covered data for the period of one calendar year of sludge incinerator operation. A detailed description of the process has been presented earlier in the article. Figure 3 shows a block diagram of the process discussed.

For each scenario the flows of mass and energy indirectly or directly related to waste management were collected where published data were available.

Table 2

Comparison of mass streams at inputs converted with respect to chemical gram equivalents per unit of wastes and functional unit

Input		**Scenario 1**	**Scenario 2**	**Scenario 3**
Substance	**Gram equivalent**	[kg chem. equiv./Mg]	[kg chem. equiv./Mg]	[kg chem. equiv./Mg]
$NaHCO_3$	42.00	---	---	0.216
Urea	30.03	0.099	---	---
NaOH	40.00	---	---	0.0025
$Ca(OH)_2$	37.04	0.086	---	---
NaCl	58.50	---	---	0.0033
H_2SO_4	49.04	---	---	0.0004
CaO	28.04	0.089	---	---
NH_3	5.67	---	0.353	---
$CaCO_3$	50.04	---	0.079	---
Total emission		0.274	0.432	0.2222
Total emission per functional unit [kg chemical equivalent/MWh]		0.417	133.2	0.439

Table 2a

Comparison of mass streams at inputs … (continued)

Input		**Scenario 2A**	**Scenario 2B1**	**Scenario 2B2**
Substance	**Gram equivalent**	[kg chem. equiv./Mg]	[kg chem. equiv./Mg]	[kg chem. equiv./Mg]
$NaHCO_3$	42.00	---	0.107	0.762
Urea	30.03	---	---	0.233
NaOH	40.00	0.0005	---	0.010
$Ca(OH)_2$	37.04	0.0045	0.475	---
NaCl	58.50	---	---	---
H_2SO_4	49.04	---	---	---
CaO	28.04	---	---	---
NH_3	5.67	0.0024	0.691	---
$CaCO_3$	50.04	---	--	---
Total emission		0.0074	1.273	1.005
Total emission per functional unit [kg chemical equivalent/MWh]		0.018	0.565	0.446

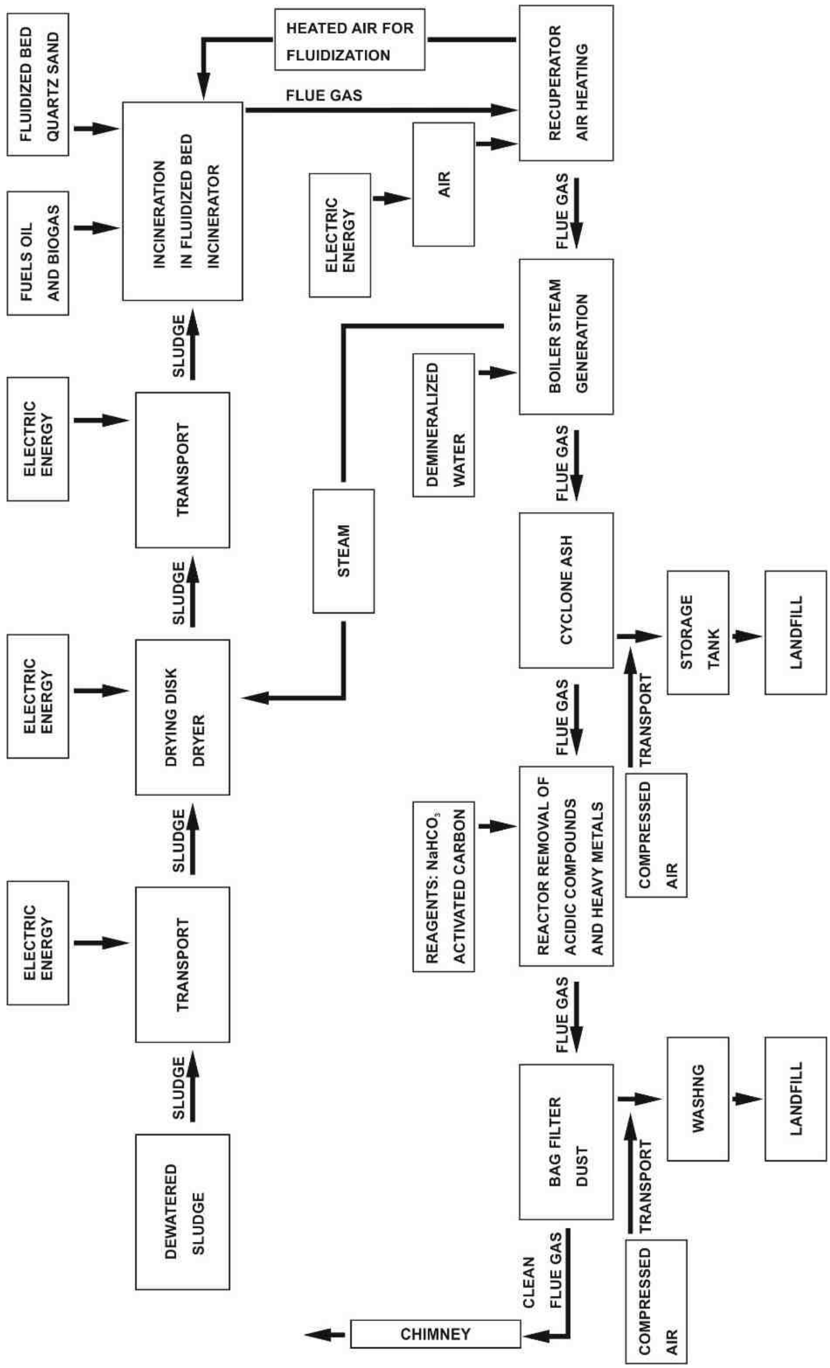

Fig. 3. Block diagram of the operation of the installation for thermal treatment of sewage sludge and screenings - scenario 3

Emissions of substances at both inputs and outputs, referring to earlier discussed impact categories, were converted into Mgs of incinerated wastes and functional units. Next, emissions related to each impact category were grouped and summed relating them to the scenarios discussed so as their comparison be possible. The results are shown in Tables 2-4.

Table 3

Comparison of mass streams at outputs converted into functional unit

OUTPUT		**Scenario 1**	**Scenario 2**	**Scenario 3**
Indicator	**Substance**	[kg/MWh]	[kg/MWh]	[kg/MWh]
AP	HCl	0.032	9.231	0.0017
	HF	data unavailable	0.018	0.0002
	NO_x	0.304	400.0	0.0454
	SO_2	0.226	5.231	0.1139
	Total	**0.562**	**414.48**	**0.1612**
GWP	CH_4	0.00006	data unavailable	data unavailable
	CO	0.589	20.308	0.0069
	Total	**0.589**	**20.308**	**0.0069**
OUTPUT		**Scenario 2A**	**Scenario 2B1**	**Scenario 2B2**
Indicator	**Substance**	[kg/MWh]	[kg/MWh]	[kg/MWh]
AP	HCl	0.0033	0.0091	0.0091
	HF	data unavailable	0.0006	0.0006
	NO_x	0.018	0.2122	0.5466
	SO_2	0.016	0.0091	0.0091
	Total	**0.0373**	**0.2310**	**0.5654**
GWP	CH_4	0.0022	data unavailable	data unavailable
	CO	0.0167	0.0911	0.0911
	Total	**0.0169**	**0.0911**	**0.0911**

Table 4

Comparison of scenarios by indicators of impact categories

Comparison of scenarios	**Ratio of indicators**		
	GWP **[-]**	**AP** **[-]**	**EP** **[-]**
Scenario 2 to 1	34.5	736.3	319.6
Scenario 2 to 3	2 954	2 570	303
Scenario 1 to 3	85.7	3.5	0.95
Scenario 1 to 2A	34.83	15.33	23.19
Scenario 2 to 2A	1 200	11 287	7 407
Scenario 3 to 2A	0.406	4.39	24.41
Scenario 1 to 2B2	6.46	0.995	0.935
Scenario 2 to 2B2	223	733	298
Scenario 3 to 2B2	0.075	0.285	0.984
Scenario 2A to 2B2	0.185	0.065	0.040
Scenario 2B1 to 2B2	1.000	0.408	1.267
Scenario 1 to 2B1	6.46	2.44	0.738
Scenario 2 to 2B1	222	1794	235
Scenario 3 to 2B1	0.075	0.698	0.777
Scenario 2A to 2B1	0.186	0.159	0.032

Conclusions

According to the literature data, sewage sludge incineration as compared to the other option of sludge treatment such as: landfilling or land application after composting or digestion, is not the most environmentally friendly method of treatment, especially that landfilling of dust and ash were not taken into consideration in any option mentioned. Comparing possible methods of sewage sludge management, incineration as well as agricultural use has high heavy metal emission to the environment, but in different impact categories [30].

The LCA does not facilitate direct comparison of all analyzed scenarios. Rather, it indicates which of the technologies is environmentally preferable for each specific type of waste. Further research in this topic should provide an economic assessment. Examples in literature show, that economic methods can also be very useful tools to evaluate waste management systems. It is complicated to conduct both types of analysis: environmental and economic, but it is possible to achieve with sufficient data available [31].

The LCA method may be burdened with a high uncertainties, although its methodology. The uncertainty is defined as "the discrepancy between a measured or calculated quantity and the true value of that quantity". Those uncertainties may be classified differently, but the sources of them are the same: data, choices and relations between elements of the system described. Dealing with the uncertainties depends on the aim of the provided analysis and the influence which uncertainties may have on the usage of its results [13]. Because analysis in the paper is theoretical, the uncertainty will not have influence on any decision making process in the considered installation. Still from the available data we can clearly conclude that in relation to the incineration of municipal waste the sewage sludge incineration is much less detrimental to the environment.

Only a comparison of thermal treatment of the same type of sewage sludge would offer a possibility to indicate the need for changes in management methods and also in treatment technology of such waste [32, 33].

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