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SELECTED THERMAL WASTE TREATMENT PLANTS IN EUROPE, CASE STUDY

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Abstract

The functioning of societies involves the generation of large amounts of municipal waste. This study analyses the amounts of pollutants emitted during waste incineration at selected waste incineration plants in 2022. Four plants were analyzed, including three with the highest waste processing efficiency (Copenhagen, Poznan and Kraków) and one with the lowest efficiency (Konin). The choice of the factory in Copenhagen was also dictated by its strategic location in the city center. Analysing the emissions from the selected plants it can be concluded that environmental safety was maintained and none of the plants exceeded the permissible emissions value.

Keywords: thermal waste treatment plant, incineration, permissible value, pollutant emission

1. INTRODUCTION

The history of municipal waste treatment by thermal conversion dates to the late 19th century. Threatening epidemics at the time that could be traced back to improper waste management led to the development of waste incineration activities. In 1870, waste heat and electricity were first obtained from incinerated waste in the UK in Paddington near London. Subsequently, at the turn of the 20th century, incineration plants were established in cities such as Hamburg, Cologne, Frankfurt, and Zurich [1].

In Poland, the first thermal waste incineration plant (with a capacity of about 10 000 Mg/y) was built in Warsaw in 1912. Unfortunately, it was destroyed during the Warsaw Uprising. Another plant was put into operation in Poznan in 1927, but it only lasted until 1942. It was partially destroyed in 1945, rebuilt in 1955 and finally closed in 1957. It was the first and most modern plant of its kind in Central Europe [2]. The capacity of the Warsaw incineration plant was too low compared to the waste production of the society of the time. The technology of the incineration plant was based on Freyer's designs from 1874, where the heat generated during the waste incineration process at 600-900 ºC was

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transferred to elements of the water heaters to produce process steam and, via an exchange station, hot water for the baths and laundry.

Between 1876 and 1908, more than 210 waste incineration plants were built and put into operation in Europe, in England, Denmark, Belgium, Sweden, Switzerland and Germany, while more than 180 plants were put into operation in the USA [3]. In the middle of the 20th century, in addition to waste reduction, attention also began to be paid to the cleanliness of flue gases and reaction products, which had been increasing in number during energy production in the past. In the following years of the last century, the automatic operation of incineration plants was considered, and plants were modernised with this in mind. Strict environmental regulations in European countries forced many countries to modernise and upgrade waste incineration plants and to use efficient solutions for flue gas cleaning nodes. In the late 1970s, electrostatic precipitators, cyclones, and systems for adsorption of sulphur dioxide and hydrogen chloride from outgoing flue gases began to appear. In the 1980s, the issue of dioxins emitted from the emitters of incineration plants was discovered, so the development of thermal waste treatment plants was halted at that time. Advances in the development of flue gas cleaning systems contributed to the development of modern materials used in filtration techniques. The development of waste incineration plants involved the graded supply of air to the boiler and divided it into primary and secondary air, which translated into the efficiency of the incineration process and subsequent flue gas cleaning. The greatest changes in the technology of the process itself occurred at the beginning of the 21st century, when boilers with moving grates began to be used more and more frequently, allowing waste of different calorific values to be incinerated, thanks to the reciprocating motion of the moving grate [3]. The first modern and environmentally effective municipal waste incineration plant in Poland was built in Warsaw in the 1990s, which was commissioned at the beginning of 2000, despite many social protests and administrative decisions. The designers intended the facility to be used for waste separation with secondary recovery and thermal processing and composting. In addition, it was also assumed that the slag and ash produced during the incineration process would be turned into granulate [3]. The next incineration plants to appear in Poland were financially supported by the Infrastructure and Environment Operational Programme. It was intended that 12 thermal waste incineration plants would be built, but only six were constructed.

Problems associated with dioxin and furan emissions contributed to the development of technologies with similar themes, but other than waste incineration, namely pyrolysis and waste gasification. Europe, the United States and Asian countries have attempted to implement this type of technology, but these have not resulted in significant achievements in the development of waste treatment facilities. The first of the six plants were the municipal waste incineration plant in Konin, commissioned in 2015. It has a total capacity of approximately 94,000 Mg/y, with a thermal capacity of 15.5 MWt and an electrical capacity of 4.4 MWe. The next incineration plant to be built in Poland was the 2016 commissioning. Municipal Waste Neutralisation Plant in Bialystok. The plant has a capacity of approximately 120 000 Mg/y. The thermal capacity of this incineration plant is 17.5MWt and the electrical capacity is 6.1 MWe. Another incineration plant commissioned was the Thermal Waste Conversion Plant in Bydgoszcz, commissioned in the first quarter of 2016. The plant has a thermal power of 27.7 MWt, an electrical power of 9.2 MWe and a waste treatment capacity of approximately 180 000 Mg/y. The fourth incineration plant developed was the Municipal Waste Thermal Conversion Plant in Krakow, which has been in operation since 2016 with a capacity of approximately 220 000 Mg/y. The achievable thermal power of the incineration plant is approximately 35 MWt, and the electrical power is approximately 10.7 MWe. Another of the plants that processes waste for incineration is the Municipal Waste Thermal Conversion Facility in Poznan, commissioned in the second half of 2016. The capacity of the plant is estimated to be around 210 000 Mg/y, while the thermal power is 34 MWt and the electrical power is 15 MWe. The last incineration plant built under the Operational

Programme Infrastructure and Environment was the Waste Disposal Plant in Szczecin, commissioned in 2017, with a capacity of 150 000 Mg/y, a thermal power of 32 MWt and an electrical power of 10.4 MWe [2].

An installation developed outside the Infrastructure and Environment Operational Programme, was the 2018-built Thermal Waste Conversion Facility in Rzeszów with a capacity of 100 000 Mg/y, thermal power of 16.5 MWt electrical power of 4.6 MWe. The plant is owned by the Polish Energy Group. The list of operating municipal waste incineration plants (both mixed and RDF) is supplemented by an RDF-fired multi-fuel boiler at the FORTUM CHP plant in Zabrze, in which up to 250 000 Mg/y of RDF can be thermally converted. Installations to be built soon will be thermal waste conversion plants in Gdansk, Olsztyn, Lodz, and the expanded plant in Warsaw [2].

One European country that transformed its waste management was Finland. There, cooperation between municipalities on waste management started in the 1980s. The law that accelerated separate waste collection in the 1990s was the 1997 Landfill Decision and the 1999 European Union Landfill Directive. Since 2000, the Finnish waste-to-energy field has been gradually expanded and modernised. In 2010, the network of waste incineration plants and biological treatment plants was expanded. Today, the transition to a closed-loop economy is one of the main priorities in the waste sector in Finland [4]. Another of the countries in Europe operating waste incineration plants is Denmark, where rotary kiln-based waste incineration plants were established in Frederiksberg and Aarhus in 1934. The reason for the establishment of waste incineration plants in Denmark was that the waste collected at landfills was often incinerated at the end of the day, so the decision was taken to build a waste incineration plant. Copenhagen, on the other hand, was running out of places to dispose of waste, which is precisely what led to the construction of the first waste incineration plant in Frederiksberg. The next town to decide to build a waste incineration plant was Gentofte, where the landfill sites were also beyond the town's capacity. Unfortunately, during the Second World War, some of the incinerators were destroyed. In 1982, Denmark started to develop the subject of incinerators again and 48 incineration plants were put into operation. By 2005, the number of thermal waste incineration plants had decreased to 29 plants. Denmark was the first country in Europe to ban the storage of incinerable waste and this was enacted by the Environmental Protection Act and the Waste Ordinance issued by the Danish Ministry of the Environment [5].

2. THERMAL WASTE TREATMENT METHODS

The thermal treatment of waste consists mainly in its incineration; the pyrolysis and gasification methods are much less frequently used. Waste incineration is a thermal process to produce energy and decreases environmental impacts. The term incineration describes a violent oxidation reaction in which the primary substance involved is waste as fuel. At the same time, in order to burn the waste, it is necessary to supply the required amount of oxygen. Waste and air are the substrates, while flue gases and other solid products are the by-products of combustion [6, 7].

In the combustion chamber, in addition to the complete products and complete combustion, substances harmful to the environment are also produced, e.g., carbon oxides, sulfur dioxides, nitrogen oxides, polycyclic aromatic hydrocarbons and metal compounds. To comply with environmental requirements, flue gases containing dust must be treated as effectively as possible. An individual balance sheet of substances, including harmful emissions, is prepared for each waste incineration plant. According to the Regulation of the Minister of Development of 21 January 2016 [8] "on the requirements for carrying out the process of thermal treatment of waste and ways of handling the resulting waste", the incineration process is carried out as follows:

- the temperature of the gases resulting from the combustion process, measured close to the inner wall or elsewhere in the combustion chamber resulting from the technology of the solution used, has been raised in a controlled and homogeneous manner and has been maintained for at least 2 seconds at a level not lower than: 1100 ºC for hazardous waste containing more than 1% halogenated compounds and 850 ºC for other waste,
- the process in the incineration chamber should be operated in such a way that the overall organic carbon content in slag and ash is less than 3% or the loss on ignition of slag and ash post-combustion products is less than 5% of dry matter,
- waste incineration plants shall be equipped with an automatic waste handling system which makes it possible to stop feeding waste at start-up until the required temperature is reached. The feeding of waste to the boiler shall be stopped when the required combustion temperature is not reached and if continuous measurements show that the emission limit value is exceeded due to a breakdown,
- technical devices for flue gas discharge guarantee that the emission standards set out in separate regulations are met,
- installations shall be equipped with technical devices designed to protect the soil, surface water and groundwater from contamination, with a sealed and impermeable bottom with a system to collect any leachate,
- incineration plants shall be equipped with technical facilities for the storage of waste resulting from the process.

Waste-to Energy (WtE) recovery system consisting of boiler, turbine, condensers, and heat exchangers. The main device in the energy recovery system is a drum-type heat recovery boiler with natural flue gas recirculation, where the heat exchange takes place.

There are currently more than 2,600 WtE plants in operation around the world [9], with more than 500 thermal waste treatment plants in operation in Europe [10]. It should also be noted that in Europe, about 50% of WtE operate as Combined Heat and Powe plants [11, 12] and cover up to 15% of existing district heating demand and the trend is still increasing. In countries with cool climatic conditions, such as Denmark and Sweden, it has become common practice to use heat from WtE plants for public heating purposes. In eastern and central Europe, WtE plants with District Heating systems also exist and are attracting more interest due to the relatively high system efficiency and low CO_2 emissions when compared with power only plants. [13]

There are currently 9 municipal solid waste incineration plants in Poland with a total capacity of 1,374,000 Mg/year [14]. Incineration takes place on a mechanical grate. In addition, all installations are equipped with facilities to recover waste and produce electricity and heat from it. Installations may accept mixed municipal solid waste for incineration and a selected fraction – RDF fuel, whose average share is 40%. The share of incineration is currently nearly 15–16% of the total mass of municipal waste generated [14, 15]

Most installations in Europe (about 64%) use grate technology [16], the alternative is fluidised bed technology, based on a fluidised bed. While in the Far East and the United States, residual technologies such as gasification, pyrolysis or plasma technology are often used [2]. In grate furnaces, an inclined, reciprocating grate is most used to ensure transport and mixing of the waste in the combustion zone, thus reducing unburnt contained in the waste substances. In the 1960s, the minimum operating conditions for a grate furnace were estimated and it was established that the calorific value of the waste must be at 5 MJ/kg. Today, grate technology already exists to burn waste with a calorific value of around 4MJ/kg.

3. WASTE AS FUEL

Waste management is a method that plays a major role in the closed waste cycle process. According to Directive 2008/9/EC of the European Parliament and of the Council of 19 November 2008 on waste [17], Member States should conduct their waste policies in such a way as to exploit the waste hierarchy [18].

Waste as fuel is defined as an alternative fuel, i.e. combustible waste with a suitable degree of granulation and homogeneous mixing, which may be produced by mixing non-hazardous waste with or without solid or liquid fuel, the thermal treatment of which does not result in exceeding the emission levels set out in the Regulation of the Minister of Climate and Environment on emission standards from installations relating to the waste incineration process [2].

In 2003, the European Union embraced two alternative fuel types derived from waste, known as RDF (Refuse Derived Fuel) and SRF (Solid Recovered Fuels). According to a document [19] from the European Commission, RDF fuel may consist of specific municipal waste, including paper, plastics, wood, textiles, and post-industrial waste, as well as sewage sludge. The wide variety of waste materials that can be integrated into alternative fuel production has generated substantial debate, leading to the standardization of this fuel under the name SRF [18]. Three perspectives - economic, technological, and environmental - are used to evaluate the use of waste as a fuel substitute. The fuel's calorific value, that is, the quantity of heat generated during the fuel oxidation process, is an economic factor. The waste's chlorine content directly impacts the process temperature, and therefore affects technology. The presence of mercury in the fuel is an environmental concern. However, it is important to consider not only mercury but also other factors when operating a thermal waste conversion plant, such as cadmium, lead, chromium, cobalt, manganese, vanadium, and other metal compounds [18].

The yield of a particular fraction depends on the morphological composition of the waste, on the substrate of its origin and on the unit processes of the entire process node. All waste-to-energy (SRF) technologies must meet stringent requirements for the preparation of the waste fuel itself, and these are the type of comminution, its homogeneity, and its formation [6]. Currently, there is a high demand for SRF fuel in Poland, and among its primary consumers are cement factories. Additionally, several heating plants and combined heat and power plants are intending to either construct or update a technological system capable of combusting waste fuel. It is crucial to construct new fuel preparation plants as waste treatment facilities advance to efficiently isolate the combustible components from the waste stream and customise the waste to the recipients' technology.

Increasing the amount of waste ready for energy conversion could reduce the cost of electricity and heat, thereby improving the separation, collection, and management of waste in accordance with existing legislation.

3.1. The source and characteristics of waste.

At present, only the high-energy fraction of municipal waste is utilised in waste management. The composition of waste is primarily influenced by the area's economic growth and the type of agglomeration (urban or rural) [15]. Wastes intended to be used as RDF need to meet relevant environmental, technical, and physicochemical criteria. The physico-chemical properties, calorific value, moisture content and ash content of the fuel are closely related to the physical structure of the waste. The physico-chemical data for a selection of waste examples are given in Table 1.

Tabel 1. Selected waste parameters, own studies

Types of waste	Heat of combustion, kJ/kg	Humidity, %	Ash, %
Paper and cardboard	15 300	19.00	12.00
Plastics	35 100	9.00	8.00
Rubber/Leather	23 300	9.00	20.00
Wood	16 300	19.00	5.00
Textiles	15 900	22.00	7.00
Organic waste	4300	65.00	11.00
Kitchen waste	10 700	40.00	9.00
Garden waste	9500	50.00	5.00
Fraction <10mm	5000	20.00	50.00
Metals	0	5.00	93.00
Inert waste	0	2.00	98.00
Other waste	6700	30.00	30.00

From Table 1 it can be seen that plastic and rubber wastes have the highest calorific value. Organic and garden waste attains the highest moisture content, whereas inert waste, which is impervious to chemical reactions, has the highest ash content. Depending on the source of the waste, it may contain, among other things, trace metals, fluorine, sulphur, and chlorine. Some components in classified waste are found in much higher concentrations than in mixed waste. Mixed waste has better properties in terms of harmful substances per unit of energy compared to sorted waste [20].

4. MATERIALS AND METHODS

The paper discusses the operation of selected thermal waste treatment facilities. The aim of the analysis is to evaluate the operation of the thermal waste treatment plant in terms of the amount of waste incinerated and the emissions of pollutants emitted during incineration. This study examines two of the most efficient waste processing installations in Poland (Poznan and Krakow) and one with the lowest efficiency (Konin). The Copenhagen (Denmark) installation was selected for its strategic positioning in the heart of the city. A SWOT analysis was also conducted, examining the strengths, weaknesses, opportunities, and threats in relation to four key factors: technical, economic, social, and environmental.

4.1 Waste Thermal Treatment Installations in Poznan

The installation, located in Poznan at 5 Energetyczna Street, is managed by the company PreZero Zielona Energia S.A. The City of Poznan entered into a public-private partnership agreement with PreZero Zielona Energia S.A. in 2013. The investment, in the form of a waste incineration plant, was financed with EU funds from the Operational Programme "Infrastructure and Environment" [21]. The main objectives of the project were to meet the applicable legal requirements, to achieve the highest ecological regimes and for the economic development of the City of Poznan and neighbouring cities, so that the waste management system could not develop significantly. The area of the thermal waste conversion plant is located in the neighbourhood of the Karolin CHP Plant, which is the only CHP Plant in Poznan. The area in the vicinity of the investment is characterised by low natural, landscape and recreational value, therefore this area was selected for safe and efficient operation of the installation.

Fig. 1. Waste Thermal Treatment Installations in Poznan [21]

The most important features of the solution operated in Poznan are the technology using a backward-sloping grate, the design of which has also proved successful in other European cities. Energy recovery from waste is carried out by a combined cycle turbine-condensing unit, which produces electricity and heat using the cogeneration method. Flue gas treatment is carried out using an efficient SNCR non-catalytic reduction system to reduce nitrogen oxides, while dust is removed on an electrostatic precipitator and bag filters. The plant is made up of the following nodes, which, linked together, form the entirety of the thermal waste conversion plant together with the slag valorisation and metal recovery plant.

These nodes can be divided into, respectively:

- waste reception and storage node,
- incineration and heat recovery node,
- energy recovery unit,
- flue gas cleaning unit,
- post-processing waste treatment unit [22].

The detailed technical parameters of the installation are shown in Table 4. The waste management system comprises different nodes equipped with essential machinery. Specifically, the waste reception and storage node consist of entry and exit scales, an unloading hall containing a waste bunker, overhead cranes affixed with grabs, and a deodorisation plant. The combustion and heat recovery node involves a hopper, waste feeder, mechanical grate, four-pass boiler, and burners, all facilitating the waste combustion process. For the energy recovery system, the primary element is a turbine set which includes a turbine and generator, an air-cooled condenser, and heat exchangers used to heat water for the district heating system. The flue gas treatment facility includes nitrogen oxide reduction facilities, a semi-dry reactor, bag filters, flue gas draft fans, and an emitter chimney. The final waste node for post-processing comprises a slagging installation, a system for transporting boiler ash, and a unit for transporting dust from flue gas cleaning within reactor.

4.2. Waste Thermal Treatment Installations in Konin

The Thermal Waste Treatment Plant in Konin is located at 13 Sulańska Street and is part of the Municipal Waste Management Plant, which includes facilities such as a sorting plant, a composting plant, a landfill, and a selective waste collection point. The facility was built between 2013 and 2015 with funding from the European Union's Cohesion Fund. Figure 2 shows the view of the Thermal Treatment Plant for Municipal Waste.

The Municipal Waste Management Plant is 100% owned by the City of Konin. Its main objective is to solve the problem of waste dumping in the Konin sub-region and to provide alternative sites for technological development. Its core mission is the resolution of the growing waste problem, with energy production from waste as a profitable by-product. The installation system guarantees the retrieval of heat from waste incineration, which is subsequently converted to generate electricity and heat. Table 4 provides primary information concerning the installation. The nominal operating time for the system is roughly 7800 hours, incorporating maintenance shutdowns necessary for the power systems. The waste incineration plant also includes a slag valorisation plant, which is an essential element for the operation of the overall plant [23].

The plant is divided into individual technological nodes such as:

- waste import and unloading node,
- waste loading center for incineration,
- waste incineration plant,
- energy conversion node,
- post-process flue gas treatment plant,
- node for removing exhaust gases from the boiler,
- speedway valorization and seasoning hall node,
- a center for the disposal of fly ash and solid flue gas purification products.

Fig. 2. Waste Thermal Treatment Installations in Konin [23]

4.3. Waste Thermal Treatment Installations in Krakow

The facility managed by Krakowski Holding Komunalny S.A. is located on Jerzy Giedroycia Street in Krakow. It was built as a part of Krakow's Municipal Waste Management Program to address the city's environmental requirements. The construction was initiated in November 2013 and was finished in June 2016 after a duration of two years. The European Union heavily financed almost 56% of the total cost of the installation. The project was funded by Krakowski Holding Komunalny and a loan from the National Fund for Environmental Protection and Water Management. Its main goal was to fulfil the European and environmental waste management standards. By employing thermal waste processing, the mass and volume of waste sent to landfills is reduced. This leads to the elimination of unprocessed waste storage and a more rational recovery of raw materials. The environmental policy of Krakowski Holding Komunalny S.A. focuses on the thermal conversion of municipal waste and energy generation. In addition, the main objectives of the environmental policy in this area include maintaining permissible levels of dust and ash emissions, adhering to the guidelines of the integrated waste management permit, reducing water consumption in the production process, and ensuring compliance with emission permits. The location of the Thermal Waste Transformation Plant in Kraków has a favourable impact on the logistics of the waste management system due to its proximity to a nearby expressway junction.

Surrounding the incineration plant to the north is the steelworks, to the east is the Vistula River water canal, which supplies water to cool the smelter, to the south is the active slag and ash dump from the Krakow thermal power plant, and to the west is the Krakow city bypass. Figure 3 shows a view of the Krakow thermal waste conversion plant.

Fig. 3. Waste Thermal Treatment Installations in Krakow [24]

The thermal waste treatment installation consists of individual process nodes which, during the operation phase, are combined into the entire installation to guarantee highly effective processing of the waste stream and, after the energy production process, purification of exhaust gases and slag waste. These nodes can be divided into:
•waste collection and storage center,
•combustion and heat recovery node,
•energy recovery node,
•exhaust gas treatment plant,
• post-process residue management node.
Table 2 presents individual technical parameters of the installation and energy data.

4.4. Waste Thermal Treatment Installations in Copenhagen

The waste incineration plant in Copenhagen, Denmark, is one of the most remarkable thermal waste treatment facilities in the world. The facility, known as "Amager Bakke" or "Copenhill", commenced operations in 2017 after being designed and constructed at a cost of around £670 million. The implementation of a thermal waste processing plant, with its distinct architecture, provides a victorious demonstration of assimilating such establishments into metropolitan regions while pursuing the cooperation of nearby inhabitants to achieve social approval. Copenhill is seamlessly integrated into the daily lives of Copenhagen's citizens, thanks to its innovative architectural design. The installation boasts a rooftop area for relaxation and leisure, complete with a climbing wall and ski slope [25]. Figure 4 illustrates a Danish waste treatment plant.

Fig. 4. Waste Thermal Treatment Installations in Copenhagen [26]

The thermal waste conversion plant in Copenhagen operates on similar principles to Polish plants of this type. Waste is initially transported by truck to a bunker and then transported to the combustion chamber by means of a grab crane connected to a boiler. Thermodynamic transformations take place in the boiler, generating superheated dry steam that drives the turbine blades. The transfer of energy to the rotor sets in motion an AC generator connected to it. The result is the generation of electricity, which is transmitted through a system of block transformers to a high-voltage substation. The flue gas treatment system for grate combustion includes an electrostatic precipitator to capture ash from the gases, an SCR catalyst to eliminate nitrogen oxides from the flue gases.

5. RESULTS AND DISSCUSION

When analysing the selected installations, the technical rating data, the plant technology, the volume of waste received and treated, and the emission data were considered. Based on the reference literature, the technical parameters of all installations were listed and are thus presented in Table 2.

Table 2. Technical data of the analysed installations, own studies [22-25]

Technical data	Poznan	Konin	Krakow	Copenhagen
Capacity, Mg/year	210 000	94 000	245 000	560 000
The number of thermal transformation lines	2	1	2	2
Nominal efficiency of one thermal transformation line, Mg/h	13.5	12.05	14.1	30
Nominal operating time per line, h/year	7800	7800	7800	7800
The nominal calorific value of waste, kJ/kg	8400	8500	8800	11 500
Type of waste to be incinerated	Mixed municipal waste	Mixed municipal waste	Mixed municipal waste	Mixed municipal waste
Pressure of superheated steam, bar	40	40	40	70
Superheated steam temperaturę, ^{0}C	400	400	400	440
Electric power, MW_e	15	15.5	10.7	63
Thermal power, MW_t	34	6.75	35	200

According to table 2, it is evident that the Copenhagen installation in Denmark boasts the highest installation capacity, while Konin has the lowest. Amager Bakke ranks first in terms of process line efficiency, with the Poznan and Krakow installations performing similarly, while Konin ranks the lowest. In terms of fuel calorific value, the polish installations ensure waste with a nominal value at a comparable level, whereas the Copenhagen installation necessitates fuel with higher calorific value due to its operating parameters for the boiler and turbine being higher.

Table 3. Average 30-minute pollutant emissions in Polish waste incineration plants in 2022 (data received from waste incineration plant operators)

Parameter, mg/m_u^3	Poznan Line 1	Poznan Line 2	Konin Line 1	Emission standards, mg/m_u^3 [27]
Particulate	0.5	0.6	1.43	30
SO_2	5.4	6.3	21.5	200
NO_x	166.8	148.2	157.52	400
TOC	0.44	0.47	0.32	20
HF	0.16	0.13	0.02	4
HCL	4.31	4.71	3.08	60
CO	4.1	3.0	2.94	100

Comparing the results presented in Table 3 and Table 4 it can be stated that none of the waste incineration plants exceeds the limit value of pollutant emission, in the Regulation of the Minister of Climate on emission standards for certain types of installations, fuel combustion sources and appliances for waste incineration or co-incineration [27]. The highest concentrations for each installation are for NOx emissions, the other pollutants are at very low levels. Similar results were observed for average pollutant emissions in Polish waste incineration plants in 2018 and 2019 [7, 28].

Table 4. Average daily pollutant emissions in Polish waste incineration plants in 2022 (data received from waste incineration plant operators)

Parameter, mg/m_u^3	Krakow Line 1	Krakow Line 2	Emission standards, mg/m_u^3 [27]
Particulate	0.2	0.1	10
SO_2	13.9	15.2	50
NO_x	138.9	142.9	200
TOC	0.30	0.20	10
HF	0.00	0.00	1
HCL	3.10	2.40	10
CO	9.7	8.1	50

The emission figures for all the compounds emitted from the facilities at Amager Bakke in Copenhagen are shown in detail in Table 5. Throughout the year 2018, it was observed that none of the compounds were more than the regulatory limits of the European Union directive. The emissions of certain compounds were in several cases tens of times lower than the maximum permitted level. The annual assessment of emissions shows that the site is functioning properly, thus ensuring environmental safety.

Table 5. Comparison of different limit values for emissions into the air from WtE plants typical measured emissions emission values based on the first year of operation. [25]

Parameter, mg/m_u^3	EU Directive	Environmental approval	BREF	Copenhill facility
Particulate	10	5	2 - 5	0.82
HCL	10	5	2 - 8	0.58
SO_2	50	30	5 - 40	1.16
NO_x	400	1000	50 - 150	14.65
Hg	0.05	0.025	0.005 - 0.02	0.0004
Sum of 9 metals (Hg, Cd, TI, As, Pb, Cr, Cu, Ni, Zn)	0.5	0.25	0.01 - 0.3	0.009
Dioxins	0.1	0.08	0.01 - 0.08	0.0015

6. THE FUTURE OF THE THERMAL WASTE TREATMENT PLANTS IN POLAND - SWOT ANALYSIS

In the near future, more than a dozen new energy-efficient thermal waste processing facilities are to be built in Poland. There was a high level of interest in the subject of energy-based waste processing in the 'Rational Waste Management' programme implemented by the National Fund for Environmental Protection and Water Management, under which entities could apply for funding to build waste incineration plants. The call for applications ran from December 2021 to the end of 2022. Applications for the construction of investments concerned as many as 39 plants located all over Poland. The realisation of all incineration plants may enable the capacity of waste to be processed in installations at the level of 2.9 million Mg/year and obtain approximately 600 MW of additional capacity of cogeneration units. According to the draft National Waste Management Plan 2028, by 2034 the capacity of the installations is to be approximately 4.2 million Mg/year. The largest planned and under-construction installations in terms of capacity and waste throughput are the ITPOs in Olsztyn, Gdansk and Lodz. The installation in Warsaw will be expanded and modernised. Unfortunately, investment planning often fails due to objective difficulties, NIMBY conflicts, etc. Therefore, before investing in new WtE, it is advisable to conduct a SWOT analysis and evaluate their strengths, weaknesses, opportunities, and threats based on four key factors: technical, economic, social, and environmental.

Table 6. SWOT analysis

TECHNICAL FACTORS	
STRENGTHS	**WEAKNESSES**
Modern technology for efficient waste incineration to produce electricity and heat. The ability to hold waste in the bunker for several days. Automated process High efficiency of flue gas cleaning The possibility of recycling the by-products (slag, ash, ferrous and non-ferrous metals).	The irregularity of the waste delivered due to the introduction of additional fuel. Equipment breakdowns and malfunctions that shut down the entire plant. Low calorific value of the fuel, resulting in lower energy efficiency of the combustion process. In case of exceeding the permissible values of emissions into the atmosphere, the plant is shut down until the stable operation of the equipment is restored.
OPPORTUNITIES	**THREATS**
Improving the energy recovery rate from waste, Achieving low outgoing emissions from the installation, Accepting and treating increasing waste streams, Obtaining more slag and ash for reuse by customers.	Corrosion and fouling of the boiler heating surfaces. Occurrence of grate burnout due to high temperature in the combustion chamber Low calorific value of the supplied waste fuel Inappropriate waste being fed into the system, which may cause equipment failure or defects.
ECONOMIC FACTORS	
STRENGTHS	**WEAKNESSES**
Reduction of the area occupied by waste in landfills. The waste is supplied to the plant by the local communities. Low operating costs due to low number of staff needed to operate the installation. Reduction of the number of wastes landfilled or inappropriately treated	The high investment costs associated with designing and constructing the installation. The continuity of substrate supplies necessary for energy production. High costs associated with maintaining equipment in full working order. Costs associated with repairing and inspecting installations.

OPPORTUNITIES	THREATS
The National Fund for Environmental Protection and Water Management provides grants for the establishment of facilities. Increased number of customers connecting to the district heating network Increased company profit due to increased production of energy in cogeneration. Profit from the sale of white certificates, due to the combustion of alternative fuels	The costs associated with the recruitment of adequate technical staff. To provide the installation with the necessary technical infrastructure. If the waste does not meet the required calorific value, additional fuel will be required, increasing the cost of the installation process.
SOCIAL FACTORS	
STRENGTHS	**WEAKNESSES**
Subsidies for waste collection for residents of municipalities and cities, Increased public satisfaction by reducing landfill, Reduction of heat and electricity prices. Making towns and cities more attractive.	Residents' fears for their health and lives due to pollution emitted from the incinerator, Public protests blocking investment, Negative public attitudes through inadequate knowledge of the incinerator, Relocation of residents to other areas due to the construction of infrastructure and the waste incinerator itself.
OPPORTUNITIES	**THREATS**
Reduction in the number of illegal landfills, Open days of waste incineration plants, Educational activities about thermal waste disposal, Public consultation.	Reducing the attractiveness of land located close to the installation, NIMBY conflicts. The community is unwilling to accept the establishment and operation of incinerators near the residences of citizens residing in towns or municipalities, The construction of the facility has been accomplished via legal measures and notifications. Attempts to damage incinerator property.
ENVIRONMENTAL FACTORS	
STRENGTHS	**WEAKNESSES**
Compliance with emission limit values, Implementing both primary and secondary flue gas cleaning techniques Significantly decreasing carbon dioxide emissions in comparison to the operation of coal-fired thermal power plants are imperative.	The potential risks associated with the temporary exceedance of emission limits, the possible failure or malfunction of the equipment resulting in increased resulting in the higher emission of pollutants into the environment. he infiltration of rodents into the facility due to food waste in municipal rubbish.

OPPORTUNITIES	THREATS
Compliance with BAT conclusions, No odour or methane gas formation unlike landfills, Reuse of post-process waste (slag, ash, post-reaction product of flue gas cleaning) in a closed loop economy.	Heterogeneous waste structure, which may affect the operation of flue gas cleaning equipment, The need to clean the loading bunkers, due to leachate formation, Increased amounts of flue gases or pollutants due to heterogeneous mixing of waste or waste of unknown origin.

7. CONCLUSIONS

1. After analysing the 30-minute or 24-hour average emissions (depending on the data providing by the operators of waste incineration plants), it can be concluded that environmental safety has been maintained, none of the installations exceeding the permissible emission limits.
2. The highest concentrations for each installation relate to NOx emissions, the other pollutants are at very low levels, in several cases tens of times lower than the maximum permitted level.
3. It is essential for a thermal waste treatment plant to receive fuel with the correct structure, calorific value, and moisture content for optimum operation. Proper maintenance of the equipment and installations involved in the generation of electricity and heat from waste is also essential, as poor maintenance can lead to malfunctions.
4. Failures occurring at installations treating waste thermally concerned pressure equipment, i.e., boilers, water tanks or pumps. Due to their specific nature, installations exceeding the permissible emissions of pollutants are taken out of operation as soon as an exceedance of a particular compound is detected. The waste incineration process is restored to operation when emissions stabilise.
5. In the history of the operation of the thermal waste treatment installations, no emergency cases with potential environmental impact have been recorded.

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