Thermal Treatment of Sewage Sludge
– State of the Art and Evaluation of the Variants –

Jörn Franck, Josef Lux, Guomin Zhang and Ralf Wittstock

1. Introduction 641

2. Sewage sludge and its treatment in Germany and Europe 642

3. Process technologies for thermal treatment of sludge and their evaluation 644

3.1. Steps of the conventional thermal sludge treatment 644

3.2. Combustion technologies for mono-combustion of sewage sludge 644
3.2.1. Fluidized Bed Incineration 644
3.2.2. Grate Incineration 645
3.2.3. Pyrolysis 646
3.2.4. Technology Comparison combustion/pyrolysis 646

3.3. Heat recovery systems 648
3.3.1. Water-steam-Cycle 648
3.3.2. Thermal oil system 648
3.3.3. Technology Comparison of the heat recovery system 649

3.4. Sewage Sludge Drying 649
3.4.1. Drying process (direct vs. indirect drying) 649
3.4.2. Direct Drying 649
3.4.3. Indirect Drying 650
3.4.4. Technology Comparison drying plant 650

3.5. Flue gas cleaning systems 650

4. Summary and conclusions 653

5. Literature 653

1. Introduction

Due to pending legal changes (landfill ban) and foreseeable limitations on agricultural use, the disposal of sewage sludge in the future will increasingly be done by thermal treatment.

With around 17 MJ kg/TR (raw sludge around. 70 % GM) sewage sludge has a high energy potential, which can be used to satisfy the energy demand (electrical and thermal) of a wastewater treatment plant with sludge digestion and incineration and provide surplus energy available to the grid. Wastewater treatment plants without sludge digestion and incineration have to completely cover their need by external energy.

The European Commission recommends the fluidized bed technology due to high combustion efficiencies and low exhaust gas volumes as state of the art (IPPC – Reference Document on the Best Available Techniques for Waste Incineration, 2006). In addition, pre-treatment of the sludge by drying is recommended in order to avoid the use of supplementary fuels.

The present paper deals with sewage sludge as fuel and its thermal utilization. Different thermal process technologies as well as the associated flue gas cleaning processes are considered to describe the current status of the thermal treatment of sewage sludge.

2. Sewage sludge and its treatment in Germany and Europe

The resulting sludge from wastewater treatment is a mixture of solids contained within the water (primary sludge) and the mass of bacteria from any biological treatment stage (secondary sludge). The daily specific sludge production is about 1.5 l/P×d to 2 l/P×d (about 80 g DM/P×d). The sludge has a high water content of between about 97 and 98 % (2 – 3 % DM). Table 1 shows the main parameters of raw and digested sludge.

Table 1: Essential parameters raw and digested sludge

	Dry Matter % DM	**Carbon Loss** % GV	**Ash Content** % DM	**Water Content** % Water	**CV** MJ/kg DM
Raw-Sludge	0.70 – 4	60 – 90	40 – 10	96 – 99	13 – 20
Digested Sludge	4 – 8	45 – 55	55 – 45	92 – 96	10 – 13

Source: Thomé-Kozmiensky, K. J.: Klärschlammentsorgung. Neuruppin: TK Verlag Karl Thomé-Kozmiensky, 1998

The disposal of fresh, untreated sewage sludge is not possible due to legal constraints and requires therefore adapted systems. The historical development of sludge disposal in Germany is shown in figure 1 from 1987 to 2009.

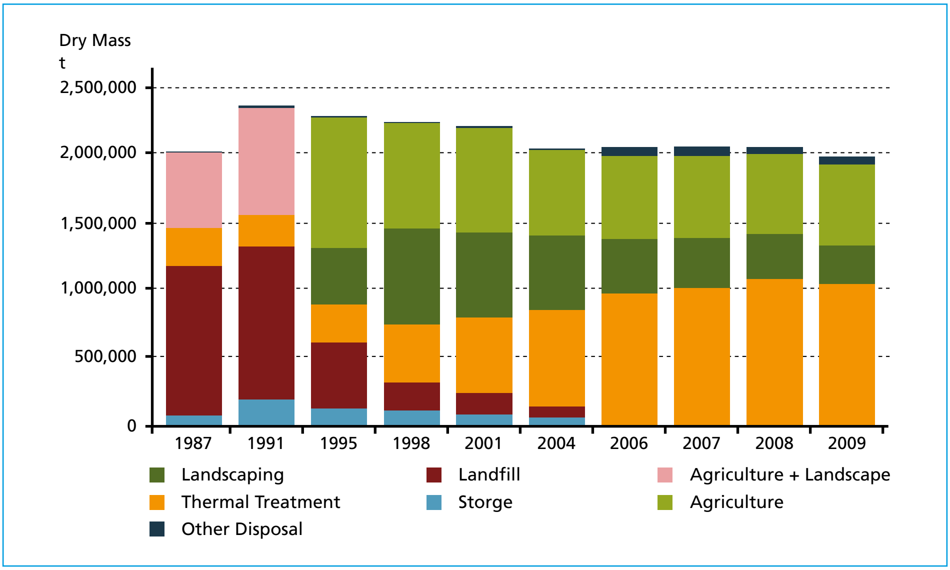


Figure 1: Development of sludge disposal in Germany

Quelle: Lehrmann, F.: Klärschlammentsorgung in Europa, DWA – Tagung (ENERGIE-/BIOGASTAGE), Kassel, 2011

Figure 1 clearly shows that the thermal disposal of sewage sludge in Germany has grown in importance in the last twenty years. The amount of sewage sludge, which was a brought to agricultural remained approximately constant in the years 2006 through 2009.

In 2009, the thermal treatment of sludge accounted for 53 % of the total sludge disposal whereby mono- and co-combustion in power plants covered 23 % each as shown in figure 2.

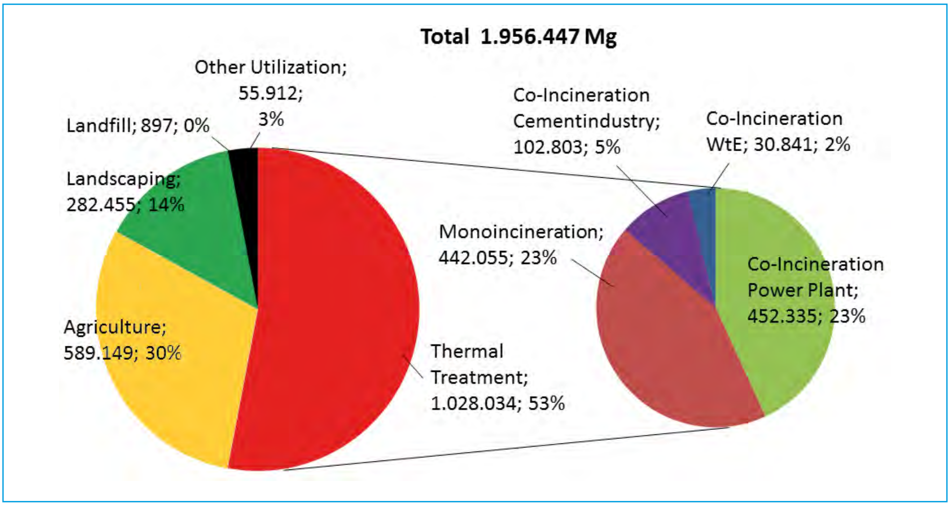


Figure 2: Sewage sludge disposal in Germany (2009)

Quelle: Lehrmann, F.: Klärschlammentsorgung in Europa, DWA – Tagung (ENERGIE-/BIOGASTAGE), Kassel, 2011

A comparative look at the European situation is shown in table 2 with approximately 1 million tons/year of sewage sludge incineration in Germany (52 % of total) as compared to about 3 million tons/year in Europe (26 % of the total). The difference is due to the still strong use of sewage sludge in agriculture as well as its storage in landfills, which account for approximately 57 % of the total.

Table 2: Sludge disposal in Germany (2009) and Europe (2010)

	Germany 2009		**Europe 2010**	
	Mg	%	Mg	%
Other uses	55,912	3	1,413,700	12
Agriculture	589,149	30	5,312,200	45
Landscaping	282,455	14		
Disposal site	897	0	1,367,780	12
Incineration	1,028,034	53	3,054,520	26
Statistical loss			626,800	5
Total	**1,956,447**	**100**	**11,775,000**	**100**

Source: Lehrmann, F.: Klärschlammentsorgung in Europa, DWA – Tagung (Energie-/Biogastage), Kassel, 2011

If the agricultural use and disposal in Europe would have to be terminated permanently, thermal treatment capacities would have to be increased significantly by approximately 6.5 million tons/year over the next years.

3. Process technologies for thermal treatment of sludge and their evaluation

3.1. Steps of the conventional thermal sludge treatment

For the classical thermal sludge treatment, the process can be divided into

- drying
- combustion
- energy recovery
- flue gas cleaning

shown in figure 3.

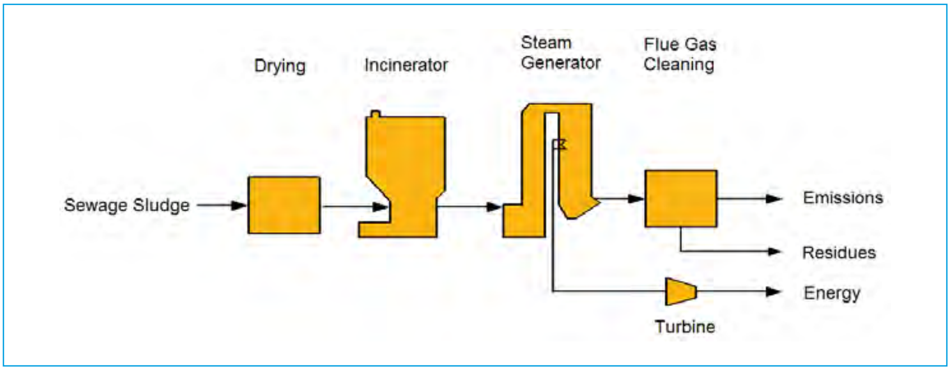


Figure 3: Simplified flow diagram for thermal treatment plant

For the mono-incineration of sewage sludge grate incinerators, fluidized bed incinerators and pyrolysis have been developed over the years. In addition, methods of co-combustion in fossil-fired power plants and/or cement kilns are known. However, the focus of this article focuses on the different methods for mono-combustion of sewage sludge only.

3.2. Combustion technologies for mono-combustion of sewage sludge

General

For mono-combustion of sewage sludge different combustion technologies are used. The various systems differ fundamentally in their process technology, their design and the way they are operated and have specific advantages and disadvantages, as shown below.

3.2.1. Fluidized Bed Incineration

For the fluidized bed technology both, the stationary fluidized bed and the circulating fluidized bed have been established over the past years. For sewage sludge combustion, the stationary fluidized bed is being preferred due to good fuel adaptation (high mass-transition promotes the ignition of the sewage sludge) and low discharge of fine dust particles.

The combustion chamber is designed as a brick furnace and provided with a closed nozzle floor or in an open design with a nozzle beam. The required combustion air is blown into the combustion chamber at the bottom of the furnace via nozzles. For the reduction of harmful gas emissions which are originated from the combustion process secondary air is inserted above the fluidized bed into the combustion chamber.

The fluidized bed is kept in the vertical, generally cylindrical combustion chamber. It consists of a layer of inert material such as sand, which is kept in a liquid-like state (fluidization) due to the air injection at the bottom. The combustion temperature is between 800 and 900 °C. To start up, the combustion chamber is heated by an external burner.

The sewage sludge, which is inserted into the combustion chamber onto the fluidized bed from above, undergoes a drying and, due to the fluid-dynamic properties of the fluidized bed, a disintegration into smaller pieces before it is ignited and burned. The fine ash particles are held back almost entirely from the flue gases by cyclones and/or electrical or bag house filters. Coarse ash particles are discharged through the bottom of the bed via natural separation process.

The energy-rich flue gas from the combustion chamber can be cooled using a recovery system (boiler/steam generator) to provide energy. The flue gas is cleaned in a subsequent purification process of pollutants before it is released into the environment. Figure 4 shows a simplified schematic of the fluidized bed combustion process.

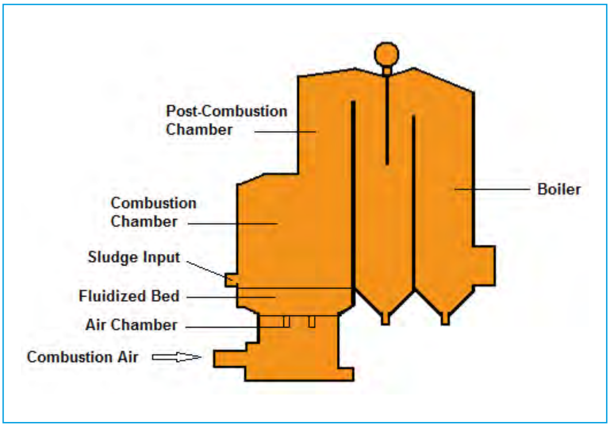


Figure 4:

Principle of fluidized bed with recovery boiler

3.2.2. Grate Incineration

The grate incineration technology is probably the most advanced combustion process, which has been adapted over the years to a variety of solid fuels. Today, most applications of grate systems are in the field of waste incineration. However, grate systems are also applied to the combustion of sewage sludge (eg Denmark, Sweden) with the possibility of energy recovery.

As opposed to the fluidized bed system sewage sludge is fed into the combustion chamber onto a moving grate. After an initial drying phase due to the prevailing temperature in the combustion chamber, ignition and combustion of the sewage sludge takes place on the grate. By the movement of the grate, the sludge is *fueled* and transported during its burnout. The required air for combustion is fed as primary air from below through the grate and as secondary air in a second stage above the grate.

The furnace above the grate is brick lined. Depending on the energy content of the sludge, the combustion chamber may also be designed as a steam generator, ie the walls are membrane tubes.

At the end of the grate the bottom ash (slag) is discharged. An ash removal system below the combustion grate collects the riddling ash from the grate and provides the primary air to control combustion performance. Figure 5 shows the principal for a grate system including heat recovery unit.

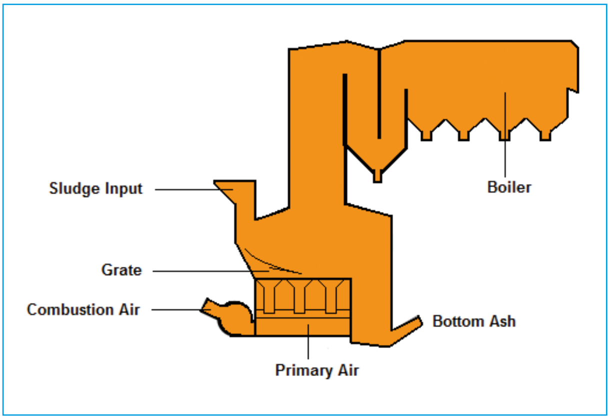


Figure 5:

Grate incinerator with heat recovery unit

3.2.3. Pyrolysis

In the pyrolysis process, the sludge is heated without the presence of oxygen up to 500 to 700 °C and disintegrates into a pyrolysis gas and a pyrolysis coke. The pyrolysis gas is a mixture of carbon monoxide (CO), hydrogen (H_2), possibly small amounts of carbon dioxide (CO_2), methane (CH_4) and a number of impurities. The solid coke contains carbon and the ash of the sewage sludge. The energy content in the products (gas and coke) is maintained during the pyrolysis and can be utilized for downstream equipment such as gas purification for engines, gas turbines, etc..

Different technical reactors (fixed bed gasifier, fluidized bed gasifier and entrained flow gasifier) have been developed over the years. They differ mainly by the type of contact between sludge and gasification agent (air, oxygen or hydrogen). Figure 6 provides an overview of a selected pyrolysis process (*Kopf* process) and its major aggregates.

3.2.4. Technology Comparison combustion/pyrolysis

Table 3 shows selected performance and key data of the aforementioned methods for the thermal treatment of sewage sludge.

Table 3 shows that for mono-combustion, the grate technology is applied for low power levels and power generation is not common. In addition, an increased cost for the pre-treatment of the sludge (water content and grain size) can be expected.

The pyrolysis process is still under development for sludge treatment and has not achieved sufficient large scale applications. The system requires enhanced effort for the pre-treatment of the sludge (water content and grain size).

For the mono-combustion of sewage sludge, the stationary fluidized bed technology has been established, which has the lowest pre-treatment requirements in terms of grain size and water content of the sludge.

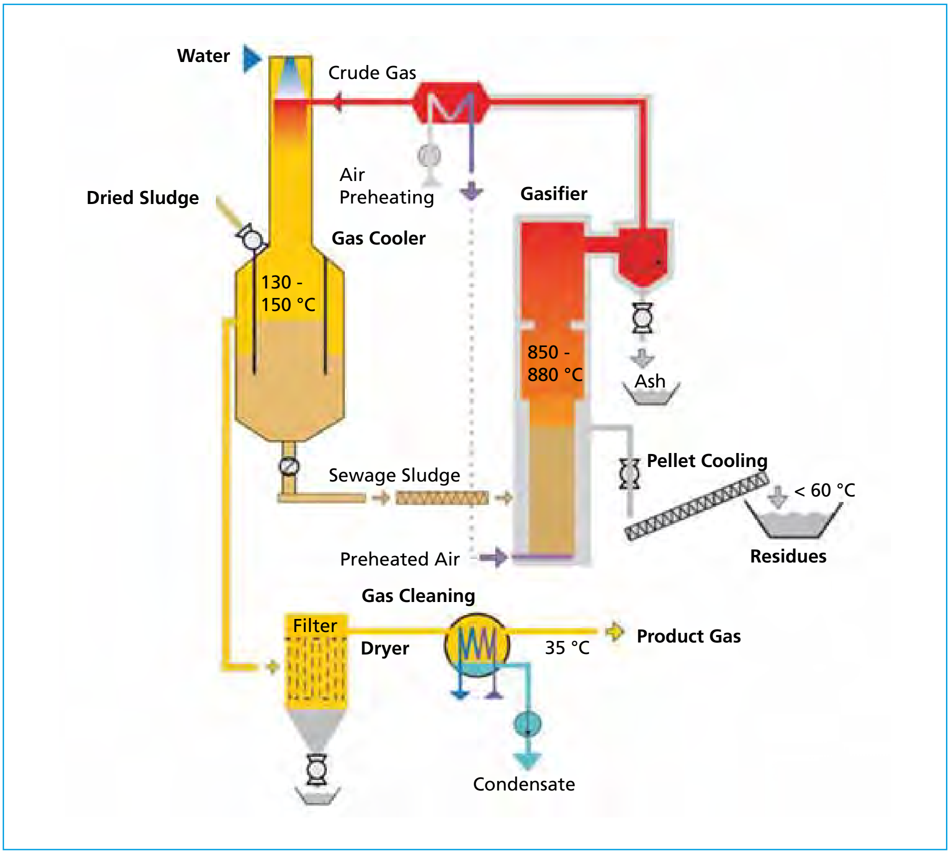


Figure 6: Pyrolysis Process (*Kopf* Process)

Table 3: Comparison of different thermal technologies

	Grate system	Fluidized bed	Pyrolysis
State of the art technology	Yes	Yes	No
Realised plants	Yes	Yes	Pilot/Yes
Load range	2 – 10 MW	4 – 80 MW	2 MW
Reliability	+	+	–
Approvability	+	+	+
Integrated Drying	No	No	No
Electrical power production	Yes	Yes	Limited
Drying requirement	> 80 % TS	> 40 % TS	> 85 % TS
Particle size of input	< 10 mm	No limitation	Pelletized < 3 mm
Economy	Proven, few plants	Proven, significant number of plants	Not proven
References	Few plants	Significant number of plants	Very few plants

+ = positive/good; – = Negative/bad

3.3. Heat recovery systems

Heat recovery systems differ substantially in their carrier medium (water or thermal oil), the working pressure and have specific advantages and disadvantages. The flue gas from combustion of the sludge leaves the combustion chamber commonly with temperatures between 850 – 1,000 °C. The objective of the heat recovery unit is to utilize the energy contained in the flue gas for the production of steam or to heat up thermal oil. Therefore, the flue gas is cooled to temperatures of approximately 160 – 200 °C heat exchangers. The heat transfer can be realized via a water-steam cycle (temperatures > 450 °C), a hot water system (maximum temperatures of 180 °C) or a thermal oil boiler (maximum temperature to 350 °C).

3.3.1. Water-steam-Cycle

Figure 7 shows a simplified flow diagram of a water-steam system for heat recovery. The main technical component of the system is the heat recovery steam generator with its heat exchangers. The heat exchangers (boiler tubes) transfer the thermal energy of the flue gas to the carrier medium which is water under increased pressure by evaporation. The high pressure steam can be used in a steam turbine to produce electricity or in a drying aggregate to pre-treat the sludge.

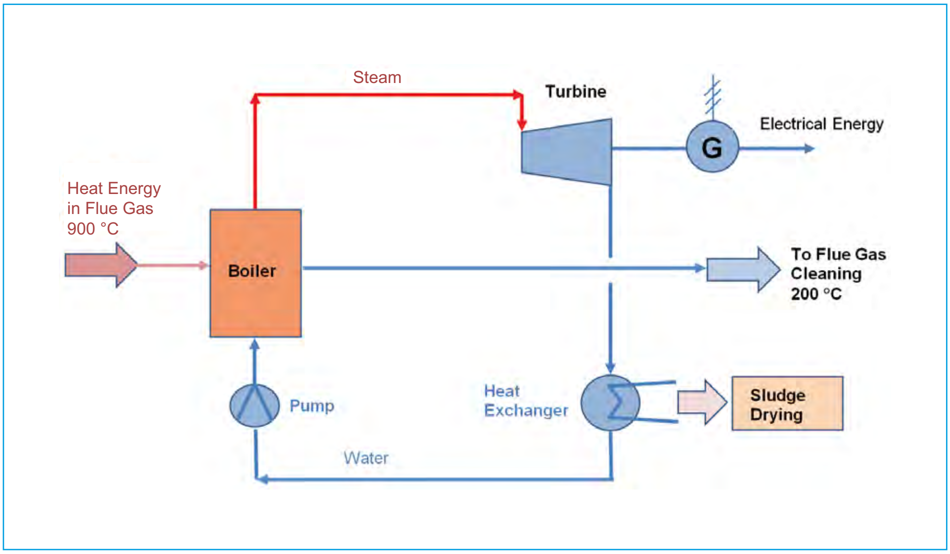


Figure 7: Principle of water steam cycle

3.3.2. Thermal oil system

Figure 8 shows a simplified flow diagram for a thermal oil system for heat recovery. The thermal oil boiler works on a similar principle as the water-steam process with the difference that thermal oil will be used instead of water and this is not evaporated despite elevated temperatures. The heat contained in flue gas is released into the hot oil and can be used to dry the sewage sludge or an ORC process (Organic Rankine Cycle) power generation.

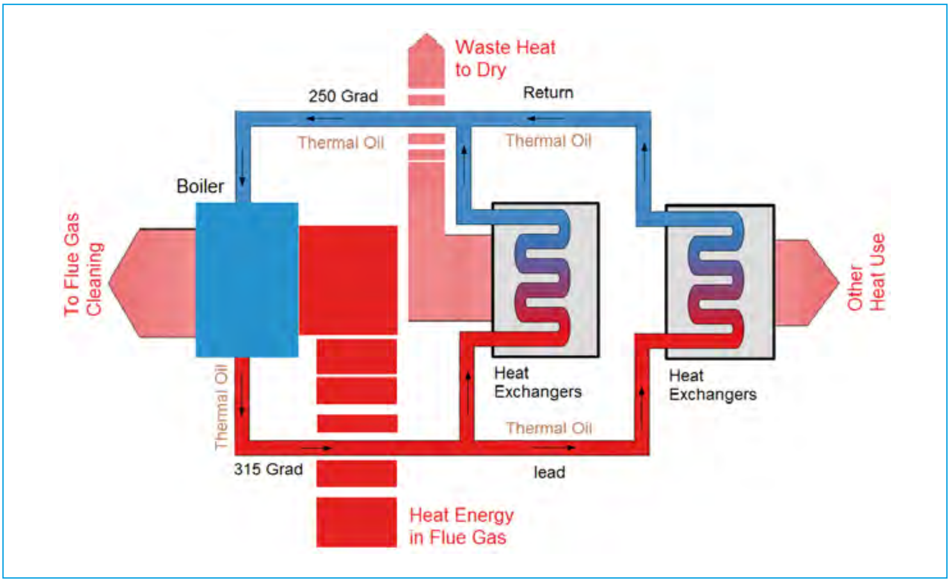


Figure 8: Principle Thermal oil system

3.3.3. Technology Comparison of the heat recovery system

The thermal oil cycle with downstream ORC system is mostly applied for smaller units (< 8 MW) due to reduced safety requirements at low operating pressures as compared to steam cycles. The electrical efficiency of the ORC process is, however, with about 15 % relatively low compared to water-steam cycle with steam turbine (26 %).

3.4. Sewage Sludge Drying

3.4.1. Drying process (direct vs. indirect drying)

Mechanical sludge dewatering achieves commonly a drying efficiency of 25 to 30 % TS. Using a thermal drying process, it is possible to adjust the water content of the sludge to the requirement of the thermal treatment plant. Part- or full-drying can be used and a volume reduction of sewage sludge is achieved by evaporating the water within the sludge. Two methods of drying sewage sludge are commonly applied:

- Direct drying (convection drying)
- Indirect drying (contact drying)

3.4.2. Direct Drying

Using convection drying the heating medium (air, inert gases, fumes, gas or superheated steam) is in contact to the sludge. The drying by convection uses the water-holding capacity of the heating medium (strong temperature dependence). The evaporated water (vapor) together with the heating medium leaves the dryer. The saturated steam vapor contains impurities and must be purified and odors may be removed. The vapor condensate is loaded with organics and has a relatively high ammonium-N content, which requires further treatment (if necessary treatment in the digester). Figure 9 shows the principle of convection.

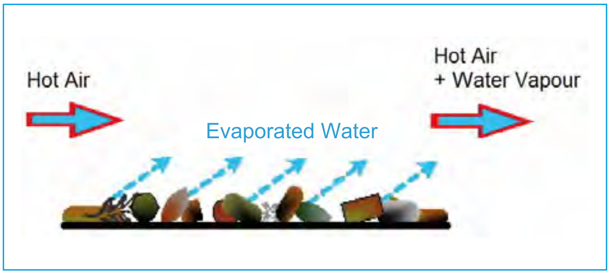


Figure 9:

Principle of convection drying

3.4.3. Indirect Drying

Applying contact drying heated surfaces are used for the drying of the sludge. The heating medium is thus not in direct contact with the sludge, but is provided via a separate closed cycle heating system. The energy of the sludge vapor can be recovered by condensation. Since the vapors are not mixed with the heating medium, the vapor condensation can be performed more easily than in the convection dryers. Figure 10 shows the principle of contact drying.

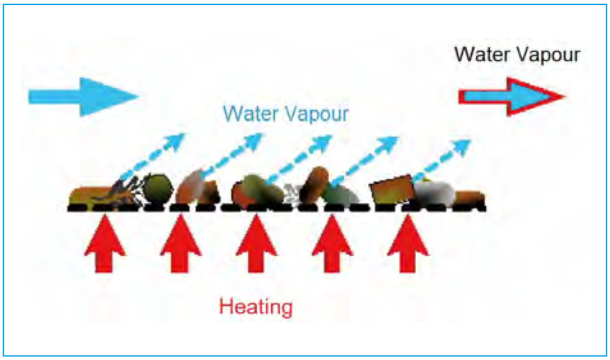


Figure 10:

Principle of contact drying

3.4.4. Technology Comparison drying plant

Table 4 shows an evaluation of different drying methods for the drying technologies for sewage sludge. Although direct dryers are more commonly used for larger throughputs, they tend to have high specific energy consumption.

Indirect drying systems are characterized by a smaller size. For odour free operation contact dryers such as disc-dryers, thin film dryer or screw-dryer offer preferred solutions. Screw-dryers are in favour due to small foot prints and the possibility of full and partial drying as well as relatively low energy consumption.

3.5. Flue gas cleaning systems

In order to reduce environmentally harmful emissions primary and secondary measures are used. Pollutants which are originated in the combustions process such as carbon monoxide and nitric oxide can be encountered effectively by primary measures during firing while fuel-related pollutants, such as dust, heavy metals and acidic components flue gas cleaning systems (secondary measures) have to be applied.

Table 4: Essential criteria for sludge drying technology

Process	**Belt dryer**	**Drum dryer**	**Fluidized bed dryer**	**Thin film/Disc dryer**	**Screw dryer**
Drying Technique	**Direct**	**Direct**	**Direct**	**Indirect**	**Indirect**
State of the art	Yes	Yes	Yes	Yes	Yes
Realised plants	Yes	Yes	Yes	Yes	Yes
Load range (max. t_{H2O}/h)	5	5	12	4	1.50
Reliability	–	–	+	+	+
Operate ability	+	–	–	+	+
Approve ability	+	+	+	+	+
Foot print	–	–	–	+	+
Electrical demand kWhel/t_{H2O}	90	100	140	80	40
Thermal demand kWhth/t_{H2O}	850 – 950	850 – 950	850 – 950	760 – 850	760 – 850
Part drying	+	–	–	+	+
Full drying	+	+	+	– (+)	+
Input size/form	Small rods	Granulate	Fine granulate	Fine granulate	Granulate
Vapour energy recovery	–	–	–	++	++
Odour	–	–	+	+	+

+ = positive/good; – = Negative/bad

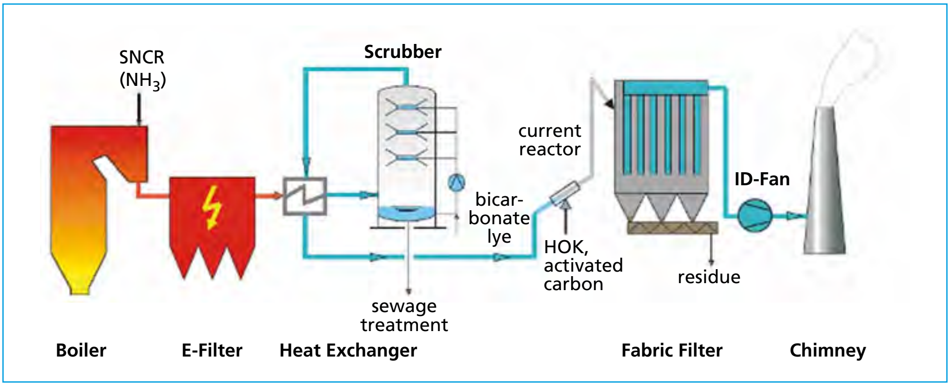


Figure 11: Wet scrubbing system

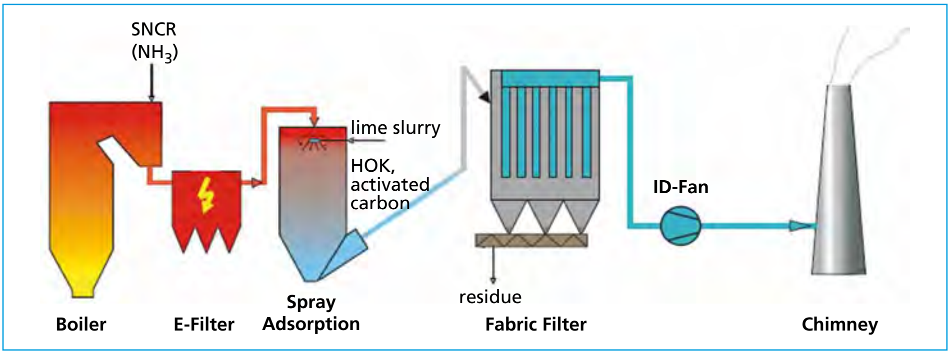


Figure 12: Semi-dry system

For the removal of solid gas particles cyclones, electrostatic precipitators or fabric filters are used. For the deposition of organic compounds and heavy metals, dry, semi-dry or wet adsorption methods can be used. For reducing oxides of nitrogen catalytic or non-catalytic methods are used. Flue gas cleaning systems are designed with respect to the expected pollutants from the sludge and to meet the legal emission standards. Figures 11-14 show an overview of different flue gas cleaning systems and their possible arrangement.

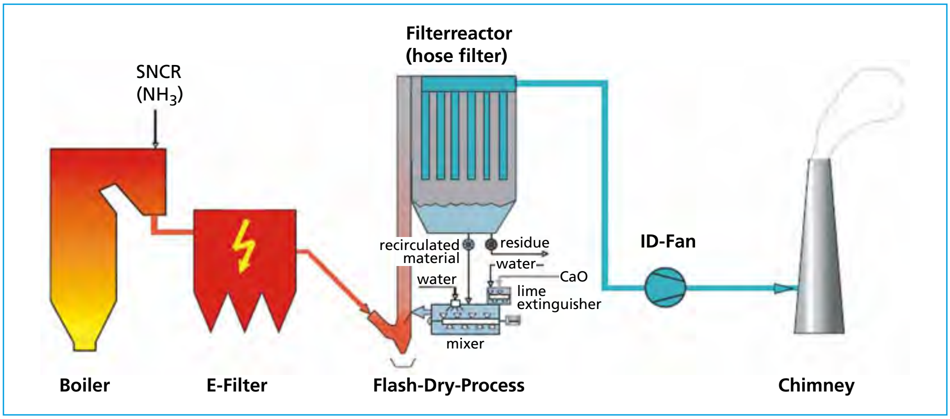


Figure 13: Flash-Dry-System

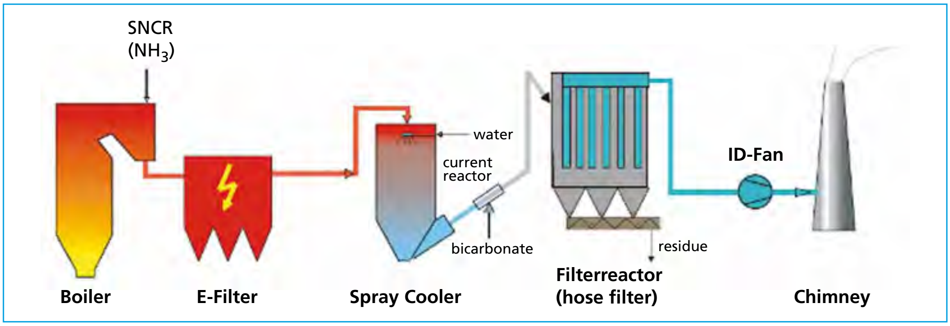


Figure 14: Dry system

Technology comparison flue gas cleaning systems

An evaluation of flue gas cleaning systems is shown in the following Table 5.

Table 5:

Essential criteria flue gas cleaning systems

	Wet Scrubbing	Semi-dry	Flash Dry	Dry
Pollutant removal	++	+	+	+
Mercury removal	–	+	+	+
Residues	+	0	0	0
Water demand	–	0	+	+
Waste water	–	+	+	+
Energy demand	–	0	0	0
Chemicals demand	+	0	0	0
Plume at chimney	–	0	+	+
Process complexity	–	0	+	+

+ = positive/good; – = Negative/bad

The comparison shows that wet methods provide a fundamentally better pollutant removal capacity. However, dry/flash dray and semi-dry flue gas cleaning systems also meet the strict requirements on emissions safely but they can be operated without any waste water and lower chemical consumption. In addition, the dry methods are less technically complex compared with the wet process.

4. Summary and conclusions

The future disposal of sewage sludge in agriculture or on landfills will no longer prevail due to environmental impacts which will enforce legal restrictions. Therefore, sustainable and environmentally friendly alternatives are required. The thermal treatment of sewage sludge has been established successfully in Central Europe and offers such an alternative.

In an evaluation of different process variants which are offered today, it has been shown, that the most preferred system for large scale mono-combustion of sewage sludge is the incineration in stationary fluidized bed system. An effective means of sludge pre-treatment and energy recovery from the drying process can increases the energy benefits of the procedure significantly.

The assessment carried out showed that a combination of stationary fluidized bed combustion with water-steam-cycle, a thin film or disc drying and a dry flue gas cleaning is currently the preferred solution for industrial size plants (e.g. Ulm and Hong Kong).

Other thermal processes such as pyrolysis or the grate combustion are currently of minor importance to the market but can be development further.

5. Literature

[1] European Commission; Integrated Pollution Prevention and Control, Refernece Document on the Best Available Techniques for Waste Incinertion, 2006

[2] Baumann, A.; Lopp, M.: Möglichkeiten zur Energieeinsparung in der Abwassertechnik, DWA – Landesverbandstagung, LV Nord-Ost, Merseburg, 2008

[3] Lehrmann, F.: Klärschlammentsorgung in Europa, DWA – Tagung (ENERGIE-/BIOGASTAGE), Kassel, 2011

[4] Lux, J.; Wittstock, R.; Schröder, L.; Schaum, C.: Möglichkeiten und Grenzen einer Klärschlammbehandlung: Eine Übersicht zum Stand der Technik, 85. Darmstädter Seminar – Abwassertechnik, Klärschlammfaulung und -verbrennung: Das Behandlungskonzept der Zukunft? Ergebnisse einer Grundsatzstudie der Städte Augsburg, Frankfurt am Main, Karlsruhe, Mannheim, München, Stuttgart und Zürich, WAR Schriftenreihe Band 204, Darmstadt, 2010

[5] Schaum, C.; Lux, J.: Bewertung von Varianten zur Klärschlammbehandlung aus technischer, ökonomischer und ökologischer Sicht, 85. Darmstädter Seminar – Abwassertechnik, Klärschlammfaulung und –verbrennung: Das Behandlungskonzept der Zukunft? Ergebnisse einer Grundsatzstudie der Städte Augsburg, Frankfurt am Main, Karlsruhe, Mannheim, München, Stuttgart und Zürich, WAR Schriftenreihe Band 204, Darmstadt, 2010

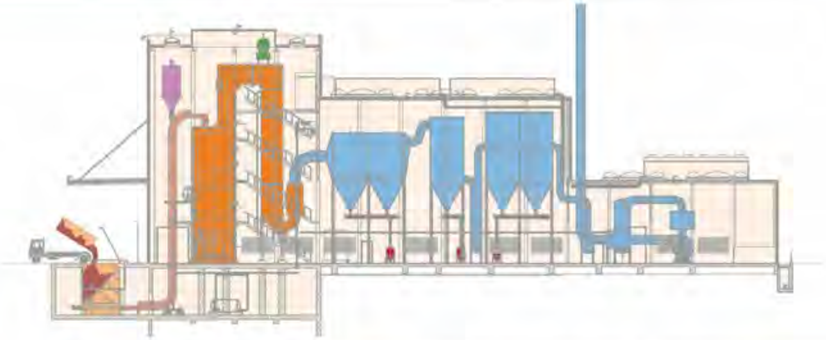
[6] Thomé-Kozmiensky, K. J.: Klärschlammentsorgung. Neuruppin: TK Verlag Karl Thomé-Kozmiensky, 1998

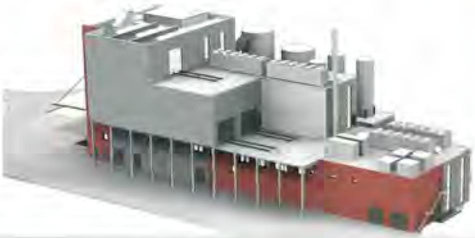
[7] UBA: Integrierte Vermeidung und Verminderung der Umweltverschmutzung (IVU), BVT-Merkblatt über best verfügbare Techniken der Abfallverbrennung, Umweltbundesamt, Dessau, 2005

hanse.ing®
Hamburger Ingenieure

wandschneider + gutjahr
ingenieurgesellschaft mbh

fbi Fiedler Beck Ingenieure AG





Extra experience.
Extra ambition.
Extra know-how.

When experience, ambition and know-how unite, the result is simply the better product.

Focus:
thermal treatment of refuse, sludge and biomass.

We provide solutions for any kind of task in the field of combustion, power and heat generation or flue gas treatment - from feasibility studies to designing an entire plant in detail.

Contact us if you want to extend or upgrade your plant, or if you are thinking about a new one.

This is what you can expect:

- Innovative ideas and fast, flexible response time.
- Quality, punctuality, cost certainty.
- Services from one source that cover process technology, civil engineering, electrical and control technology as well as accessories.
- Fixed lump sum prices based on a detailed and project specific definition of our tasks.

Civil and process engineering, plant design

» www.hanse-ing.de

wandschneider + gutjahr
ingenieurgesellschaft mbh
Burchardstraße 17
D-20095 Hamburg
Telefon +49 (0)40 - 70 70 80 900
Telefax +49 (0)40 - 70 70 80 903

» www.wg-ing.de

Fiedler Beck Ingenieure AG
Burchardstraße 17
D-20095 Hamburg
Telefon +49 (0)40 - 6 88 60 790
Telefax +49 (0)40 - 6 88 60 79 97

» www.fbi-ing.de