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Hydrothermal carbonization of sewage sludge on industrial scale: energy efficiency, environmental effects and combustion

工业规模污水污泥的水热碳化：能源效率，环境影响和燃烧

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Abstract - **In an increasing number of countries sewage sludge must be disposed of using thermal treatment. Currently, the necessary drying of the sewage sludge, after mechanical dewatering, is often accomplished using thermal methods that need large amounts of heat energy.**

In this study we investigated hydrothermal carbonization (HTC) on industrial scale as an energy efficient alternative to thermal drying processes. An energy balance calculation and an assessment of the environmental effects of HTC compared to current sludge treatments were performed for a sewage treatment plant in Emmen, Switzerland. Furthermore HTC coal was burned in a sludge combustion plant, where fossil fuels could be temporarily substituted by HTC coal. Compared to the current sewage sludge drying process, it was possible to reduce the heat demand by up to 62 % and the electricity demand by up to 69 % by using HTC. A detailed life cycle assessment showed little differences of HTC compared to the thermal drying process using waste heat. However there are significant advantages of HTC compared to the thermal drying process using fossil fuels. HTC shows the most promise in terms of minimising environmental impact, provided optimization measures are applied, such as reducing phosphorus and nitrogen in the HTC process water, recycling phosphorus, using the waste heat or using renewable energy sources (e.g. sewage gas, wood chips or green electricity). Significant environmental benefits can be achieved if the HTC coal produced is used as a substitute for fossil fuels, for example in the cement industry, lignite power plants or sludge combustion plants.

Keywords – **Hydrothermal carbonization, sewage sludge, energy balance, life cycle assessment, combustion.**

I. INTRODUCTION

Every year, about 10 million tons of dry matter (DM) of sewage sludge is produced in the European Union, of which 37 % is recycled in agriculture [1]. However the application of sewage sludge to agricultural land is increasingly being restricted due to contamination with heavy metals, microorganisms, and a range of hazardous organic substances which can pose a threat to the soil, vegetation, animals, and humans. The thermal treatment of sewage sludge has emerged as an attractive disposal solution. Thermal treatment alternatives include mono-combustion and co-combustion in waste incineration plants and the use of dried sewage sludge matter as a surrogate fuel in cement kilns. Dewatering is a very important pretreatment step for sewage sludge before incineration. However, the established mechanical dewatering technologies for sewage sludge yield a maximum of 35% dry matter [2]. To further dry the sewage sludge by thermal methods, a large amount of energy is necessary, most of which is used to remove the moisture by evaporation [3].

The energetic benefit of mechanical expression coupled with the hydrothermal carbonization process (HTC) as compared to a conventional mechanical expression coupled with thermal drying of sewage sludge has been confirmed on laboratory scale [4]. HTC is a hydrothermal process where the solids are converted to a char-like product called HTC coal. The chemical reactions take place with the biomass fully surrounded by water. Under high temperature (180 – 220 °C) and a pressure of approximately 20 bar, water is separated from the organic biomass by dehydration, one of the main reactions in the entire process. After carbonization, the mechanical dewaterability of non-stabilized and stabilized sludge is increased significantly. During chemical dehydration hydroxyl groups are eliminated. The calculated energy consumption for drying non-stabilized sewage sludge was lowered by up to 62 % by HTC [4].

However, no such evidence has been collected on an industrial scale and it is not clear if the laboratory scale results can be extrapolated to industrial scale plants. Moreover, comprehensive investigations of the environmental impact related to this process are still scarce. While several studies assessed the environmental impact of different sewage sludge treatment options [5-9], the authors of these studies did not include a scenario using HTC. This study therefore compares the environmental impacts of HTC with those of conventional thermal treatment options. For this purpose, an energy balance was calculated for HTC and five conventional sewage sludge disposal options were compared to three alternatives including HTC using a life cycle approach.

There is currently no combustion plant exclusively designed for HTC-coal combustion. As an alternative, co-incineration experiments were carried out at a sludge incineration plant. The goal of these experiments was to investigate if the sewage sludge combustion plant could be operated with HTC-coal without harming the plant and if HTC coal could be a substitute for fossil fuel.

II. MATERIAL AND METHODS

Carbonization of sewage sludge

Kläusli 2011

Fig.1, AVA-CO2 Industrial hydrothermal carbonization pilot plant in Karlsruhe, Germany

The stabilized sewage sludge used in this study was collected from a wastewater treatment plant near Karlsruhe (Germany) with a dry matter content of 21 % and an original pH of 7.9. The pH was stabilized at 6.5 by the addition of sulphuric and acetic acid. The carbonization of the sewage sludge was performed in a 14 m^3 carbonization tank run by AVA-CO2 in Karlsruhe (Fig. 1). The process time was close to 5 hours at a median temperature of 210 °C and a pressure of 21 to 24 bar. The slurry produced was cooled to 20°C and then mechanically dewatered using a membrane filter press. A pressure of 7.5 bar was applied and HTC coal with 55% to 70% dry matter was produced. The upper heating values of the sewage sludge and the HTC coal (precision 120 kJ/kg) were analysed before the combustion experiments.

Life Cycle Assessment

The environmental impacts of the HTC of sewage sludge were analysed using life cycle assessment (LCA), following the ISO 14040-14044 guidelines [10, 11]. LCA modelling was performed using SimaPro 7.3.3 software [12] and background data from the ecoinvent Centre [13]. The goal of the LCA was to identify the most relevant factors contributing to the life cycle environmental impacts of the HTC process and to compare the HTC process with other sewage sludge treatment processes from an environmental perspective. The modelling was based on virtual and real installations at a sewage treatment plant (STP) in Emmen, Switzerland. The functional unit of the LCA was defined as "the disposal of one annual population equivalent sewage sludge from the catchment area of the Emmen sewage treatment plant", which is equal to a sewage amount of 27.5 kg dry matter. The alternatives analysed for the disposal of the sewage sludge are listed in Table 1. The non-HTC alternatives are based on [14].

TABLE 1, ALTERNATIVES ANALYSED FOR SEWAGE SLUDGE DISPOSAL

HTC	1A	HTC process, combustion in cement industry
	1B	HTC process, combustion in lignite power plant
	1C	HTC process, mono-combustion and phosphorus recovery
Non-HTC	2A	Digestion, on site mono-combustion and phosphorus recovery
	2B	No digestion, on site mono-combustion and phosphorus recovery
	2C	Digestion, sewage sludge disposal in municipal waste incinerator
	2D	Digestion, sewage sludge drying on site and combustion in cement industry
	2E	Digestion, sewage sludge drying and combustion in cement industry

Inventory data on the material and energy consumption in the HTC process as well as the composition of the process water were obtained from AVA-CO2 using a questionnaire. The steam required for the HTC process is produced by burning sewage gas. For the non-HTC systems, the included processes are inputs and emissions from the sewage sludge pre-treatment, the digestion, the combustion of sewage gas in a combined heating and power system, the purification of sewage gas for feeding into the natural gas grid, the gas flare, the sewage dewatering, the sludge drying (with waste heat), transportation processes, as well as the disposal of the sewage sludge through combustion in a sludge incinerator, a municipal waste incinerator, or a cement plant.

TABLE 2, CREDITS FOR RENEWABLE PRODUCTS

Renewable products	Credits in model
Heat fed into district heat grid	Heat from natural gas
Sewage gas fed into natural gas grid and burned in cars	Combustion of natural gas in cars
Application of recovered phosphorus for agriculture use	Application of conventional phosphorus fertilizer for agriculture use
Cement from cement plant using HTC coal	Cement from conventional cement plant
Electricity from burning HTC coal in lignite power plant	Electricity from conventional lignite power plant in Germany

In addition to the above mentioned processes, the HTC alternatives include the HTC process itself and the HTC process water treatment. HTC coal could be burned in a mono-combustion plant, a cement plant or a lignite power plant. For the renewable products from the different disposal routes, environmental credits were given using an avoided-burden approach (see Table 2).

In addition, an alternative scenario was considered in which natural gas is used for both the conventional thermal sludge drying and the HTC process. The selected life cycle impact assessment (LCIA) indicators and the methods used are presented in Table 3.

TABLE 3, LIFE CYCLE IMPACT ASSESSMENT (LCIA) INDICATORS

Criterion	Indicator	Unit	Source
Conservation of non-renewable energy sources	Cumulative energy demand of non-renewable energy source	MJ-eq.	[15]
Conservation of non-renewable materials	Cumulative energy demand of materials and minerals	MJ-eq.	[16]
Climate Change	Global warming potential	kg CO_2-eq.	[17]
Eutrophication	Eutrophication potential	kg PO_4-eq.	[18]
Human toxicity	Human toxicity potential	kg 1,4-DCB-eq.	[18]
Eco- toxicity	Aquatic and terrestrial eco-toxicity potentials	kg 1,4-DCB-eq.	[18]
Highly radioactive wastes	Volume of highly radioactive wastes	cm^3	Elementary flow

Combustion experiments

At the sewage sludge incineration plant (SVA) in Switzerland, approximately 2.7 tons of sewage sludge (approximately 30 %DM content) is usually burnt per hour.

Fig.2, Screw conveyor for transporting sewage sludge and HTC coal into the oven of the sewage sludge incineration plant (SVA)

Approximately 150 m^3 of natural gas was required per hour. On 17th September 2013, a dose of approximately 7.5kg HTC-coal per minute was added to the combustion process during three different time periods (from 12:55 to 13:02 h; from 13.15 to 14:03 h and from 15.10 to 17:02 h) (Fig. 2).

III. RESULTS

Life Cycle Assessment

The thermal energy balance of the hydrothermal carbonization of sewage sludge is compared to the conventional sludge drying process in Fig.3. The energy required by the conventional drying process to increase with a dry matter

(DM) content of the sewage sludge from 20 % to 92 % was 6.8 MJ heat and 0.26 kWh electricity per kilogram DM [14]. 92 % DM is the target value for sewage sludge in order for it to be burned in cement kilns.

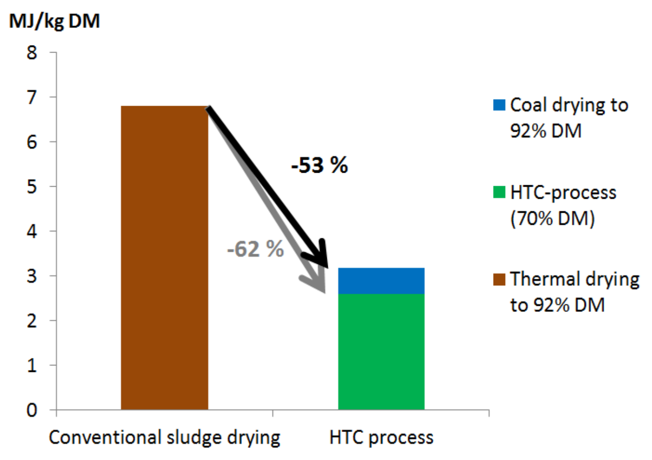

Fig.3, Comparison of the heat requirement for conventional sludge drying and hydrothermal carbonization for the drying of sewage sludge with a dry matter content of 21.3 % to a dry matter content of 92 %

The hydrothermal carbonization of sewage sludge produces HTC coal with a 70 % DM and requires 2.6 MJ heat and 0.08 kWh electricity per kilogram DM. In order to achieve a 92 % DM in the HTC coal, another 0.34 litre of water per kilogram DM must be evaporated, which requires an additional 0.6 MJ of heat and 0.02 kWh of electricity. In total, hydrothermal carbonization reduces the heat consumption for sludge drying by 53 %. Since there is sufficient waste heat from the HTC process to increase the DM content of the HTC coal from 70% DM to 92 % DM, the heat energy requirement to achieve a DM content equivalent to the convential process is reduced by an additional 9 % (62 % in total). These results confirm the laboratory results from [4], which reports a 61 % heat energy reduction potential for HTC of sewage sludge.

Similar to the reduction of heat energy, also electric energy can be reduced by up to 69 %, if HTC is applied instead of conventional drying.

The greenhouse gas (GHG) emissions resulting from the different methods of sewage sludge disposal and the GHG credits for the replacement of fossil fuels are presented in Fig. 4. The results show that the carbonization process (in black) makes only a small contribution to the overall global warming potential of the different disposal routes. In those cases where dried sewage sludge or HTC coal can be substituted for fossil fuels in cement kilns or power plants, the environmental credits outweigh the GHG emissions from the sewage sludge processing and disposal.

An overview of the life cycle impact assessment results for all impact indicators and sewage disposal routes is presented in Table 4. In several cases, the environmental credits exceed the environmental burdens.

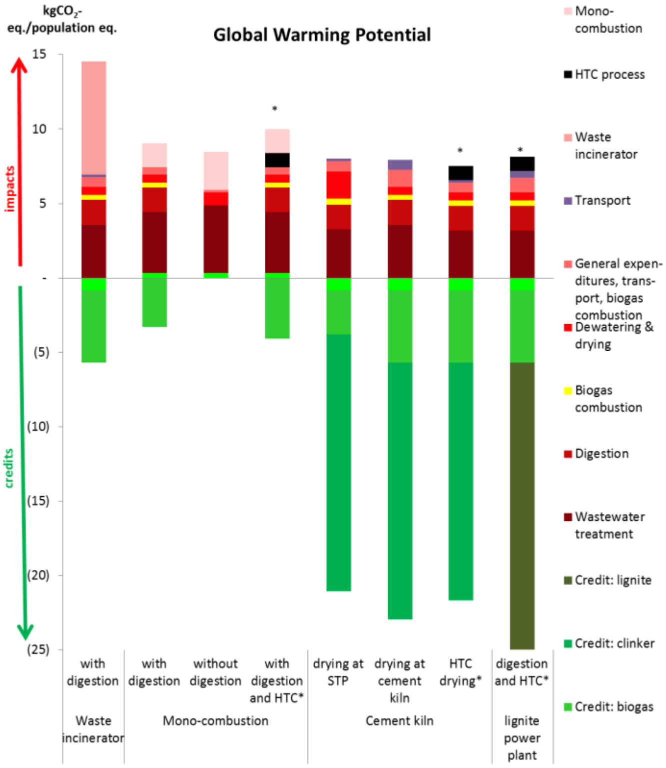

Fig.4, Comparison of greenhouse gas emissions of different ways of sewage sludge disposal. Environmental burdens (red colours) are juxtaposed with environmental credits (green colours). Alternatives with a HTC process are marked with a “*”.

Since the heat requirements for most processes are considered to be met by waste heat from burning dried sewage sludge, the main contribution to the non-renewable energy indicator comes from the share of nuclear power in the electricity used in the sewage treatment plant. The same share of nuclear power also determines the results for the radioactive waste indicator.

The mineral indicator value is heavily influenced by the precipitating agent used in the STP. High credits are awarded when phosphorus is recovered from the sewage and used as a substitute for conventional phosphorus fertilizer.

Eutrophication also receives high credit for phosphorus recovery due to the reduction in phosphorus emissions from conventional phosphorus production. For this indicator the alternatives with HTC show higher impacts than disposal routes without HTC because HTC process water has increased nitrate and ammonia concentrations.

The results for the different toxicity indicators are highly influenced by the dioxin and heavy metal emissions from the waste incinerators and the heavy metal input to the environment from using the recovered phosphorus in agriculture.

As shown in Fig. 4, there are only minor differences between the environmental impact of HTC and of conventional sludge disposal using recycled waste heat for the thermal drying step. However, if treatment plants use fossil fuels for thermal drying, HTC has significant environmental benefits (Fig.5).

TABLE 4, LCIA RESULTS (ENVIRONMENTAL IMPACT VERSUS ENVIRONMENTAL CREDITS) PER POPULATION EQUIVALENT

		Waste incinerator	**Mono-combustion**			**Cement kiln**			**Lignite power plant**
		with digestion	with digestion	without digestion	with digestion and HTC*	drying at STP	drying at cement kiln	HTC drying*	digestion and HTC*
Global warming potential ($kg\ CO_2$ eq)	Impact	14.0	9.5	9.3	10.5	7.4	6.9	7.0	7.3
	Credits	-5.7	-4.1	-0.8	-4.9	-21	-23	-22	-25
Non-renewable energy (MJ)	Impact	247	298	354	326	248	197	190	195
	Credits	-116	-83	-14	-99	-221	-261	-251	-321
Minerals (exergy) (MJ)	Impact	2.0	0.7	0.7	0.7	0.8	0.6	0.6	0.6
	Credits	-0.0	-3.6	-3.6	-3.6	-2.5	-2.5	-2.3	-0.0
Europhication ($g\ PO_4^{3-}$ eq)	Impact	14.2	4.0	4.3	10.5	3.2	3.3	9.0	9.2
	Credits	-0.7	-51	-51	-51	-3.0	-3.2	-3.1	-16
Human toxicity (kg 1,4-DB eq)	Impact	7.8	2.8	3.0	3.2	1.5	0.7	1.0	1.0
	Credits	-0.2	-0.1	-0.1	-0.1	-0.5	-0.6	-0.5	-0.2
Aquatic ecotoxicity (kg 1,4-DB eq)	Impact	0.29	2.77	2.78	2.77	0.05	0.04	0.04	0.04
	Credits	-	-	-	-	-	-	-	-
Terrestrial ecotoxicity (kg 1,4-DB eq)	Impact	0.07	0.30	0.30	0.30	0.15	0.14	0.13	0.06
	Credits	-	-	-	-	-	-	-	-
Highly radioactive wastes (cm^3)	Impact	104	161	187	174	136	99	94	95
	Credits	-2.4	-1.7	-0.1	-2.0	-4.6	-5.5	-5.2	-4.0

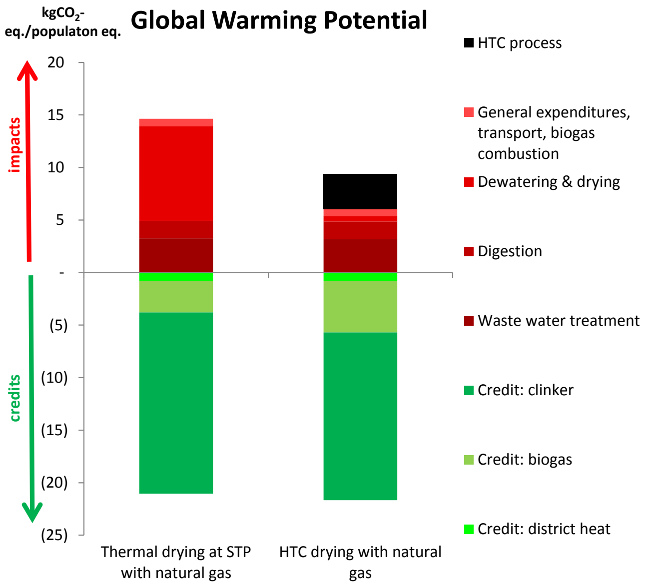

Fig.5, Global warming potential of sewage sludge disposal in a cement plant if the thermal drying and the HTC processes are fueled by natural gas. Environmental impacts (red colors) are juxtaposed with environmental credits (green colors).

Combustion experiments

The calorific value and the dry matter of the burned HTC-coal were significantly higher than the sewage sludge (Table 5). No negative effects on the sewage sludge incineration plant were observed after adding the HTC coal to the combustion process. Such effects would have been expressed by a massive increase in the oven quoin temperature to a critical value of approximately 920°C (red chart in fig. 6).

TABLE 5, CALORIFIC VALUES (INCLUDING DRY MATTER) OF THE MATERIALS USED FOR THE COMBUSTION EXPERIMENT

	Calorific value in MJ/kg (kWh/kg) at 85% DM for HTC-coal and 30 % DM for sewage sludge	**Calorific value in MJ/kg DM** (kWh/kg DM)
HTC-coal	12.5 (3.5)	14.7 (4.1)
Sewage Sludge	3.3 (0.9)	11 (3.1)

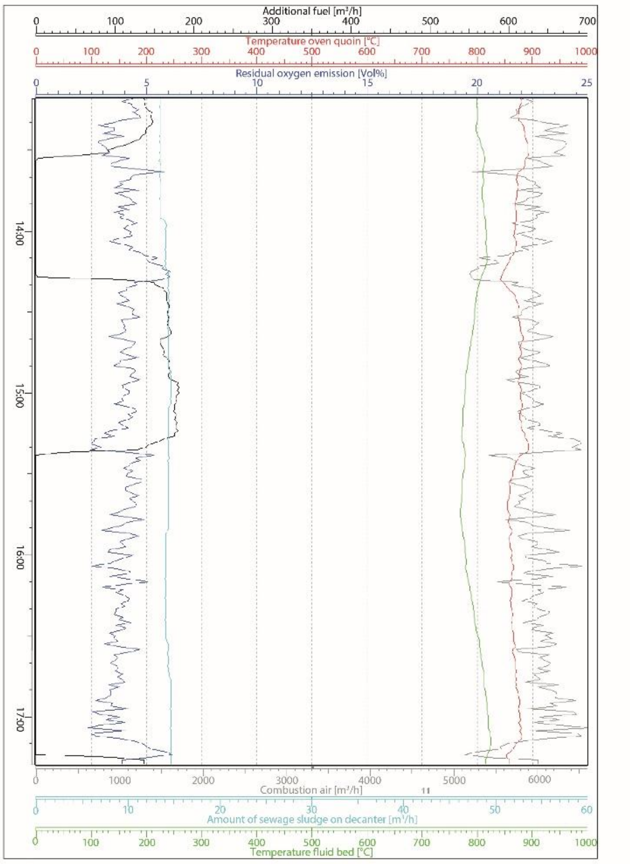

Fig.6, Change in different parameters during HTC coal addition to the sewage sludge combustion plant in Winterthur (17.10.2013); black: fossil fuel in m^3/h; red: oven quoin temperature, in °C; blue: residual oxygen emission in Vol%; grey: combustion air in m^3/h; blue-green: amount of sewage sludge on decanter in m^3/h; green: fluid bed temperature in °C. Approximately 7.5kg HTC-coal was added per minute to the combustion process from 12:55 to 13:02 h; from 13.15 to 14:03 h and from 15.10 to 17:02 h.

In this experiment the regular biogas was turned off entirely for a total of almost 2 hours during all three periods of HTC coal addition to the combustion process (black chart in figure 6) This is equivalent to an approximate saving of 300m^3 of biogas.

IV. CONCLUSION

Hydrothermal carbonization of sewage sludge reduced the energy requirement compared to conventional drying of sewage sludge by up to 62 %. These results correspond very well to results from laboratory experiments [4]. Under the following conditions, the hydrothermal carbonization of sewage sludge is particularly environmentally favourable:

- Waste heat, if available, or other local renewable energy sources, such as sewage gas, are used in the HTC process.
- Green electricity is used for HTC process, e.g. generated with sewage gas.
- Further reduction of the nitrogen and phosphorus freight in the process water.
- Phosphorous is recovered and recycled.
- HTC coal is used as a substitute for fossil fuels (e.g. in cement kiln or power plant).
- The HTC process is implemented in situations where the carbonization process can replace conventional sewage sludge drying with fossil fuels.

The use of HTC coal as a substitute for fossil fuels and the associated reduction in GHG emissions were also analysed by [19]. They identified a large potential for mitigating greenhouse gas emissions by substituting heating oil in auxiliary sewage sludge incineration firings with HTC coal. These findings support the results of the present study.

Under certain conditions, the HTC process can bring significant environmental advantages compared to conventional thermal sewage sludge drying. This paper shows that substituting fossil fuels in lignite power plants and cement kilns with HTC coal is particularly environmentally favourable.

Burning HTC coal in sewage sludge combustion plants is feasible and can it can be used as a substitute for natural gas for at least limited periods of time. In such plants, downstream phosphorous recovery from the combustion residues is also possible.

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