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Techno-Economic Analysis of Fluidized Bed Combustion of a Mixed Fuel from Sewage and Paper Mill Sludge

Milan Carsky [1,2], Olga Solcova [1,*], Karel Soukup [1], Tomas Kralik [3], Kamila Vavrova [4], Lukas Janota [3], Miroslav Vitek [3], Stanislav Honus [2], Marek Jadlovec [2] and Lenka Wimmerova [5]

[1] Institute of Chemical Process Fundamentals of the CAS, 165 00 Praha, Czech Republic
[2] Faculty of Mechanical Engineering, Department of Energy, VSB-Technical University of Ostrava, 708 33 Ostrava, Czech Republic
[3] Faculty of Electrical Engineering, CTU Prague, 166 27 Prague, Czech Republic
[4] Silva Tarouca Research Institute for Landscape and Ornamental Gardening, 252 43 Průhonice, Czech Republic
[5] Faculty of Environmental Sciences, Czech University of Life Sciences Prague, 165 00 Prague, Czech Republic
* Correspondence: solcova@icpf.cas.cz; Tel.: +420-220-390-279

Abstract: The treatment and disposal of sewage sludge is one of the most important and critical issues of wastewater treatment plants. One option for sludge liquidation is the production of fuel in the form of pellets from mixed sewage and paper mill sludge. This study presents the results of the combustion of pelletized fuels, namely sewage and paper mill sludge, and their 2:1 and 4:1 blends in a fluidized bed combustor. The flue gas was analysed after reaching a steady state at bed temperatures of 700–800 °C. Commonly used flue gas cleaning is still necessary, especially for SO_2; therefore, it is worth mentioning that the addition of paper mill sludge reduced the mercury concentration in the flue gas to limits acceptable in most EU countries. The analysis of ash after combustion showed that magnesium, potassium, calcium, chromium, copper, zinc, arsenic, and lead remained mostly in the ash after combustion, while all cadmium from all fuels used was transferred into the flue gas together with a substantial part of chlorine and mercury. The pellets containing both sewage and paper mill sludge can be used as an environmentally friendly alternative fuel for fluidised bed combustion. The levelized cost of this alternative fuel is at the same current price level as lignite.

Keywords: pelletizing; sewage sludge; paper mill sludge; combustion; fluidized bed; environmental assessment; economic evaluation

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1. Introduction

The treatment and disposal of sewage sludge from wastewater treatment plants is one of the most essential wastewater treatment and management issues. World volumes of sewage sludge and paper mill waste grow every year. Countries of the European Union produce about 10 million tonnes of dry matter of sewage sludge annually [1,2]. In 2021, paper production reached 90.1 million tonnes in the EU [3], and 4.3–40 kg of dry matter of paper mill sludge is generated for every tonne of paper production [4]. Sewage sludge often contains pollutants harmful to human health (heavy metals, toxic substances, drug residues, harmful metabolites, hormones, pathogenic organisms) [5]. However, regarding sewage sludge, the main concern in the European Union is the content of heavy metals (Cd, Cu, Hg, Ni, Pb, and Zn). The major use of sewage sludge is associated with agriculture, and to less extent, with power and thermal generation. A promising and frequently tested method of the liquidation of sewage sludge is its combustion and co-combustion with other fuels. Sewage sludge calorific values range from approximately 6 MJ/kg to 16 MJ/kg, depending on the water content and the level of fermentation [6]. Sewage sludge combustion and co-combustion with other fuels is a topic widely elaborated on in the literature, contrary to the combustion or co-combustion of paper mill sludge [7–12]. Raw sewage sludge can be burned with other fuel, usually coal [13–24], or it can be dried to improve its calorific value for mono-combustion [16,25–28]. However, some of the works used thermogravimetric analysis (TGA) only [7–9,20,29].

On average, sewage sludge contains 26 g of phosphorus/kg dry matter, which can be recovered from the ash after sludge combustion. Thermochemical modification by alkaline carbonate with the doping of magnesia minerals is a possible way to fix and recover phosphorous in the ash [30]. As expected, the combustion temperature, steam, and oxygen concentration affected the retention of Zn, Mn, and Cr in the ash after sewage sludge combustion [31]. The migration behaviours of As, Se, and Pb during the co-combustion of sewage sludge with coal was investigated in circulating fluidized-bed (CFB) boiler units with a capacity between 150–350 MW and two pulverized coal boiler (PC) units with a capacity of 350 MW and 600 MW. In the wet flue gas desulphurisation unit, the proportions of As, Se, and Pb in gypsum are higher than those of fly ash and bottom slag [32]. Karasek [33] investigated the behaviour of heavy metals and their compounds during the sewage sludge incineration process. A comprehensive analysis of heavy metals in all products of a standard flue gas treatment and in the flue gas itself from sewage sludge combustion was presented in the study. Leckner et al. [18] used laboratory and pilot plant circulating fluidized bed boilers for the co-combustion of sewage sludge together with coal or wood. Their results from a CFB plant showed that neither EU nor German emission limits were exceeded for the sludge fraction of less than 25%, except for the chlorine emission. However, that could be reduced by a flue gas treatment. Moreover, a considerable reduction of nitrogen oxide was achieved despite large quantities of nitrogen in the sewage sludge with only a few percent of the nitrogen converted to NO or N_2O. Sulphur dioxide that formed during the combustion of sulphur, which may also be present in sewage sludge, can be captured by the conventional method of limestone addition.

Combustion experiments of sewage sludge with rice husk briquettes were conducted with a Fenton (a solution of hydrogen peroxide with ferrous iron) CaO conditioner [34]. The results showed that the NO_x emissions of conditioned sludge combustion were reduced approximately 1.3 times compared to that of the sludge alone with a rice husk mixing ratio of 43.8%, the Fenton/CaO conditioner dosage of 220 mg/g, and the temperature of 829 °C.

Complete combustion using fluidized bed technology can be achieved with 20–50% excess air. This is about half the amount of air used for multiple hearth furnaces. The fluidized bed technology is therefore a promising way to combust fuels with a low heating value because of the maximized thermal efficiency, minimized char, and emissions control. A relatively low and uniform process temperature together with low excess air within the bed reduces the formation of NO_x. The emissions of CO in flue gas are low. Additions of limestone into the bed and/or ammonia into the freeboard initiate desulphurization and denitrification processes [35–38]. However, fluidized bed combustion emerged as an advantageous method for the treatment of other hazardous wastes as well [39–41].

Caputo et al. [12] estimated savings of EUR 15–20 million for the combustion of paper mill sludge during an estimated plant life of 15 years, with a pay-back period of about four years. This was based on their feasibility analysis and significant savings; compared to the landfill option, the waste-to-energy plant was built in 1999. Folguearas et al. [17] investigated the fluidized bed combustion of five different fuels (sewage sludge samples, bituminous coal, and sludge–coal blends). They found that the addition of sludge up to 10 wt% did not affect coal reactivity. For the 50 wt% blends, the reactivity depended on the temperature of combustion. At a temperature of combustion below 350 °C, the blend reactivity was close to that of sludge, whereas for the combustion temperature above 350 °C, it was close to that of coal. The kinetic process was successfully explained by the first order reaction mechanism related to Arrhenius law. Otero et al. [13] investigated the fluidized bed combustion of three different sludge samples and sludge–coal blends. The combustion parameters were measured by thermogravimetry. Some additives, e.g., coal or various forms of biomass, improved both parameters of the pelletizing (dewatering, pressure, temperature) [6] and combustion processes [42], respectively. In general, biomass of various origins [43–45] may be either incinerated as waste or used as alternative fuel.

In the former case, the waste biomass must usually be co-combusted with other fuels. The critical emissions from the combustion of waste biomass are heavy metals, organic pollutants, chlorinated and fluorinated compounds, SO_2, NO_x, and CO (see, e.g., [46]). The combustion of sewage sludge is well elaborated on in the literature, and studies on the combustion of a paper mill sludge can be found there as well; however, no research has been conducted on the fluidized bed combustion of paper mill–sewage sludge mixtures and a flue gas analysis.

This paper presents the results of a pilot plant fluidized bed combustion of pellets of sewage sludge, mixed paper mill sludge, and mixtures of 2:1 and 4:1 of sewage and mixed paper mill sludge to judge the potential use as an alternative fuel to coal.

2. Materials and Methods

Fuel pellets of sewage sludge, mixed paper mill sludge, and 2:1 and 4:1 blends of sewage and mixed paper mill sludge, delivered by ENVISAN-GEM, Czech Republic, were used for a pilot plant fluidized bed combustion. Both sewage sludge and paper mill sludge of 80% moisture content were sun dried. The product obtained was free of pathogens. Unlike the sewage sludge, it was necessary to crush the fibrous paper mill sludge after drying. Material densities were determined as a ratio of masses of ten pellets and a sum of their calculated volumes, and the bulk density was determined from a mass of pellets in a one-litre beaker. The higher and lower heating values and the moisture content were obtained from the Engineering Test Institute, Public Enterprise, Brno, Czech Republic [47,48]. For the properties of fuel pellets, see Table 1.

Table 1. Fuel properties (as delivered by ENVISAN-GEM).

Fuel	Material Density [kg/m^3]	Bulk Density [kg/m^3]	Higher Heating Value [47] [MJ/kg]	Lower Heating Value [47] [MJ/kg]	Moisture Content [48] [wt.%]
Sewage sludge	1439 ± 7	716 ± 16	9.83	8.10	19.3 ± 2.5
SPB 4:1			10.87	9.32	
SPB 2:1			11.13	9.49	
Paper mill sludge			14.0	12.6	

Notes: SPB = blend of sewage and paper mill sludge. Shape of particles: pellets, mean length = 12.5 mm, mean diameter = 6 mm.

Sand (size 0.9–2 mm, 1.44 mm mean size, density 2600 kg/m^3) was chosen as a bed inert material. The minimum fluidization velocity of 0.764 m/s at ambient temperature was determined experimentally by a standard method of plotting a superficial velocity vs. bed pressure drop. The minimum fluidization velocities of 10, 15, and 20 wt.% mixture of sand and fuel pellets were determined in the same way to be 0.88–1.04 m/s. It has been observed that, at too-low fluidization velocities or with no replacement of bed particles, the bed may agglomerate.

The pilot plant fluidized bed combustor used for the tests is shown in Figure 1. The combustor had a circular cross-sectional area of an inner diameter of 140 mm. A fan equipped with a frequency controller (SIEMENS 6SL3210-1NE21-0UG1 Germany) delivered the air, for which the flowrate was measured by a mass flowmeter. The duration of all tests was 60 min after reaching a steady state. The fluidizing air was preheated to the temperature T_0 equal, on average, to 390 °C, and its flowrate was kept constant at 31.67 Nm^3/h. The fluidized bed material was heated to temperatures of 700–800 °C with 12 kW electrical heaters. Once the required temperature of the bed was reached, the electrical heaters were switched off.

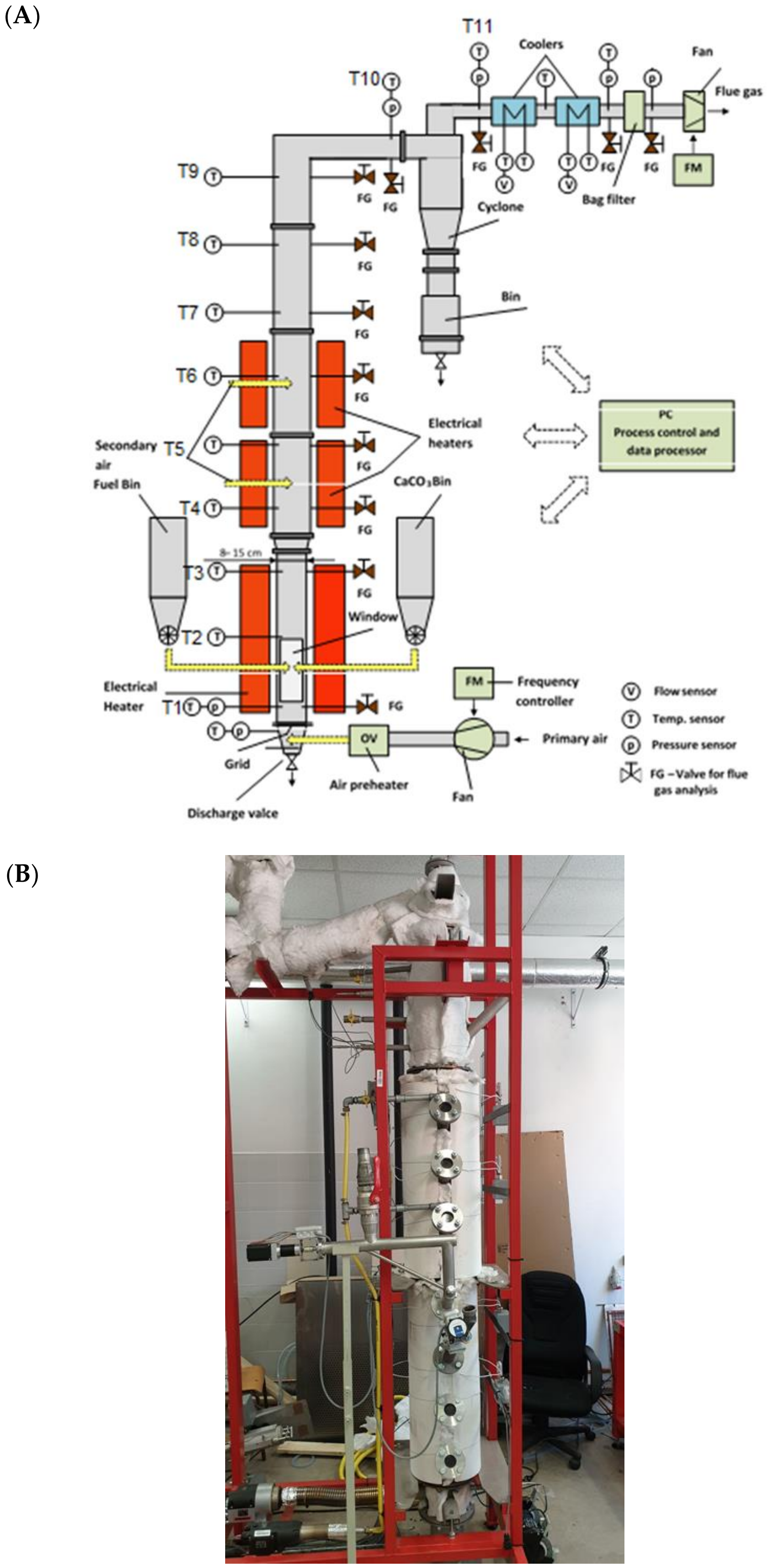

Figure 1. Scheme (**A**) and photo (**B**) of the experimental unit. Distance of temperature sensors from the grid: T1 120 mm, T2 320 mm, T3 520 mm, T4 720 mm, T5 920 mm, T6 1120 mm, T7 1320 mm, T8 1520 mm, T9 1720 mm, T10 1920mm, and T11 2120 mm.

The fuel was introduced into the fluidized bed by a screw feeder from the fuel bin at a rate of 2–6 kg/h. The flue gas was cooled down in two water coolers, passed through a bag filter, and the discharge fanned to a chimney. There was a provision for continuous measurement and storage of data of temperature by thermocouples delivered by Testo SE & Co. KGaA, Germany, pressure by sensors delivered by Farnell, Germany, and flowrates in different points of the plant. A Gasmet DX4000 portable FTIR gas analyser was used for the analysis of CO_2, CO, NO_x, SO_2, NH_3, HCl, CH_4, and O_2 in the flue gas, and the CVAAS (Cold Vapor Atomic Absorption Spectroscopy) HM-1400 TRX analyser was used for the analysis of all gaseous mercury compounds in the flue gas. The emissions were recorded at a steady state temperature of 700–800 °C. The chemical composition of the ash samples was determined by X-ray Fluorescence with an XEPOS (Spectro, Germany) energy dispersion spectrometer.

3. Economic Evaluation

To conduct a correct economic evaluation, it is primarily essential to establish the boundaries of the model under evaluation. Therefore, to be able to directly compare the alternative fuel with its substitutes (in particular lignite), the model boundary was set at the level of the produced alternative fuel, not including transport costs to the final point of use. The start of the evaluation was determined at the primary feedstock output at the point of production. The boundaries of the model respect all costs associated with the production of alternative fuel, i.e., all input costs for the acquisition and commissioning of the required technologies, as well as all fixed and variable costs associated with fuel production. This corresponds to the classical approach in setting LCOE boundaries, as discussed by the authors in [43]. It was also assumed that the feedstock (waste cellulose and waste sludge) had zero cost. This reflects the current situation where there are costs associated with the disposal of these wastes. Thus, both producers are currently willing to give up this material for free (saving their costs).

This is summarised in detail in Figure 2. The processing and utilization of sludges produced by municipal wastewater treatment or other biomass waste treatment comprises a series of processes and can be divided into the following basic stages in terms of economic assessment:

- Wastewater treatment, sludge production, and primary sludge dewatering (before the transportation to the processing site or input into the next process), currently implemented at wastewater treatment facilities.
- Transportation of dewatered (condensed) sludge.
- Sludge drying.
- Sludge processing into final fuel (pellets or granules).

The economic evaluation was based on the calculation of the levelized costs of energy (LCOE). The LCOE is a well-known standard method for calculating the cost of energy production. The principle of the LCOE calculation is the quantification of all discounted costs over the lifetime of the project per unit of production. In other words, the LCOE represents the cost of production that guarantees the investor a required financial return over the life of the project equal to the specified discount rate. A detailed explanation including all relevant equations is provided by Raikar and Adamson [49]. Table 2 summarizes the input data used to calculate the LCOE of the alternative fuel.

The economic lifetime of the project was derived from the lifetime of the solar dryer, which is 20 years [43]. This means a complete renewal of the pelletizing line in the 10th year of operation. The electricity price was taken from long-term contracts and does not reflect the current turbulent times in the electricity markets. Indeed, it can be assumed that the price will stabilise at this level concerning the following few years (as the current panic and nervousness on the commodity markets will be calmed).

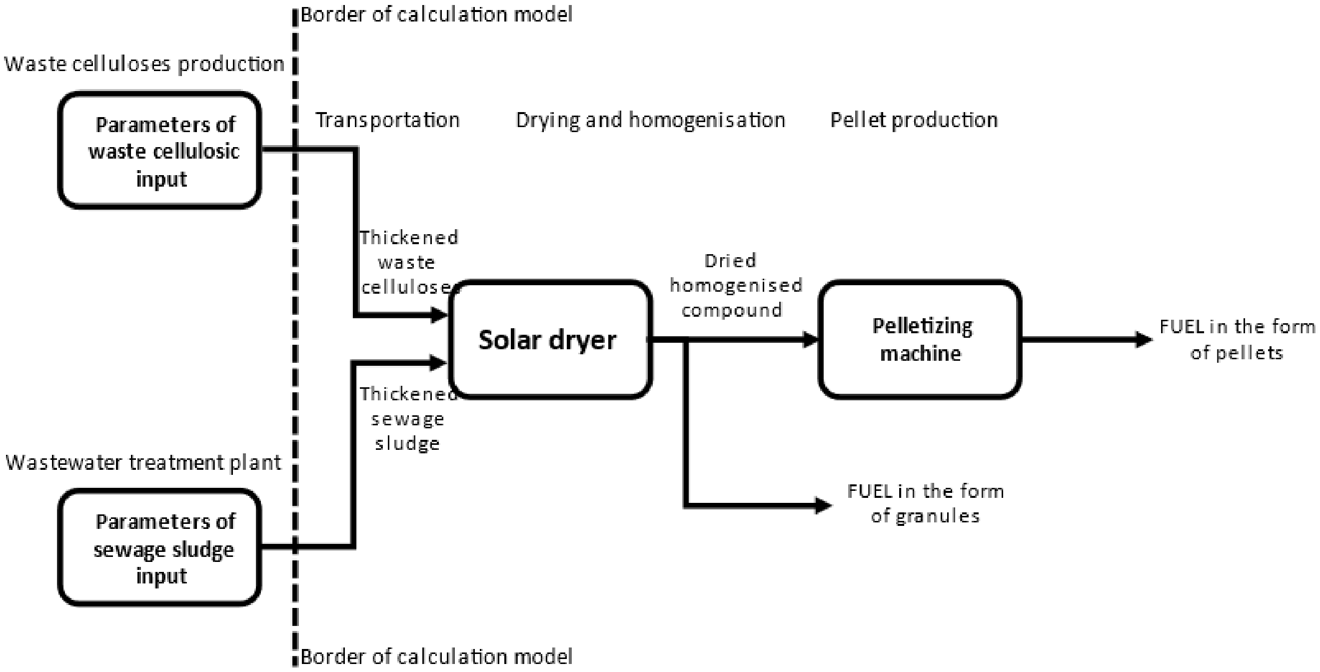

Figure 2. Boundaries for the economic evaluation.

Table 2. Economic inputs [43,44].

Sludge Drying		
Total volume of imported sludge (sewage + paper)	5410	t/year
Cost of sludge import (sewage + paper), producer′s own transport	0.45	EUR/t·km
Sludge transport distance	5	km
Specific power consumption per kg of evaporated water	0.04	kWh_{el}/kg
Total annual electricity consumption	118,335	kWh/year
Operator requirement	1	person/year
Pellet production		
Number of shifts per day	1	
Number of working days	250	days/year
Hours in operation	8	per 1 shift
Hourly production capacity of pelletizing line	1015	kg/h
Total hourly electricity consumption	99	kWh/year
Economic inputs		
Investment costs of solar dryer	3533	10^3 EUR
Investment costs of pelletizing line	261	10^3 EUR
Repairs and maintenance	38	10^3 EUR/year
Personnel costs (employees)	33	10^3 EUR/year
Energy and other material costs	129	10^3 EUR/year
Electricity price	0.4	EUR/kWh
Discount rate	7	%
Long term inflation	2.0	%

4. Results and Discussion

A typical temperature profile alongside the fluidised bed column is shown in Figure 3.

The values of concentration in the following figures and tables were expressed for a dry flue gas at the pressure of 101,325 Pa, at the temperature of 273.15 K, and at the concentration of oxygen of 11%. The concentration of mercury in the flue gas for the combustion of all fuels used in the study is given in Table 3.

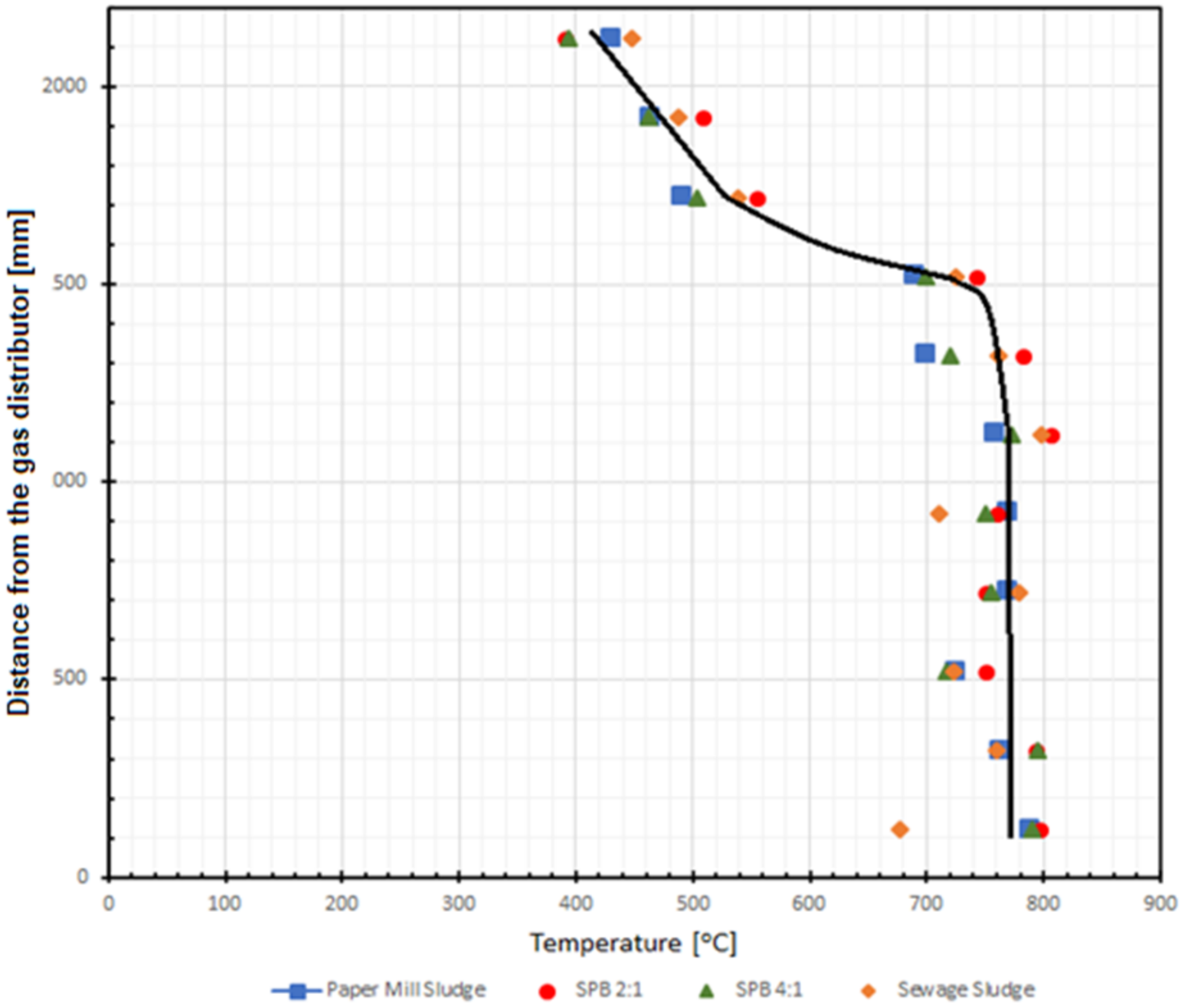

Figure 3. Steady state temperature profile in the fluidized bed reactor at various fuel combustions.

Table 3. Average concentration of mercury in the flue gas.

Material (Pellets)	Average Concentration (μg/m^3)
Sewage sludge	106.59 ± 16.32
SPB 4:1	59.62 ± 11.80
SPB 2:1	48.59 ± 4.26
Paper mill sludge	≈0

The mercury concentration in the flue gas decreased substantially with the addition of paper mill sludge to the sewage sludge. Such alternative fuel complies with the limits of a flue gas mercury concentration acceptable in most EU countries [50].

The steady concentration of carbon dioxide, carbon monoxide, and sulphur dioxide in the flue gas for the combustion of all fuels used in the study are given in Table 4.

The carbon dioxide concentration in the flue gas was not affected by the addition of paper mill sludge. The average concentrations of carbon monoxide in the flue gas of all fuels used in the study were in the range of 34.5–229.3 mg/m^3, complying with usual worldwide norms, e.g., [50]. The sulphur content of paper mill sludge was low; therefore, the concentration of SO_2 in the flue gas was negligible. The sulphur content in the sewage sludge may be significant (and fluctuating). Therefore, the SO_2 flue gas concentration of the other three fuels was high. However, the addition of limestone into the bed initiates the desulphurization process [18,35–38].

Table 4. Average concentrations of carbon dioxide, carbon monoxide, and sulphur dioxide in the flue gas.

Material (Pellets)	CO_2 Average Concentration (%)	SO_2 Average Concentration (mg/m^3) and (ppm)	CO Average Concentration (mg/m^3) and (ppm)
Sewage sludge	5.3 ± 0.5	3307 ± 848 1156.9	34.5 ± 26.7 27.6
SPB 4:1	5.7 ± 0.2	1775 ± 220 621.2	106.3 ± 49.2 85.1
SPB 2:1	5.0 ± 0.1	1608 ± 74 562.7	86 ± 65.5 68.8
Paper mill sludge	5.4 ± 0.6	64.2 ± 9.5 22.5	229.3 ± 195.2 183.5

Table 5 shows the average concentrations of NO_x, NH_3, HCl, and CH_4 in the flue gas for the combustion of the four materials mentioned in Table 1. The concentration of NO_x in the flue gas decreased substantially with the addition of paper mill sludge to the sewage sludge to acceptable levels [50]. However, the addition of ammonia into the freeboard initiates further denitrification [35–38]. The ammonia and methane flue gas concentrations were negligible for all four fuels. The hydrogen chloride concentration in the fumes for the sewage sludge pellets exceeded the acceptable level of 50 mg/m^3 [51], similarly to the work of Leckner et al. [18]. The addition of paper mill sludge to the sewage sludge showed a decrease of HCl concentration to acceptable levels.

Table 5. Average concentrations in the flue gas.

Material (Pellets)	NO_x (mg/m^3) and (ppm)	NH_3 (mg/m^3) and (ppm)	HCl (mg/m^3) and (ppm)	CH_4 (mg/m^3) and (ppm)
Sewage sludge	576.2 280.8	1.9 2.5	181.4 111.5	5.43 7.6
SPB 4:1	153.7 74.9	0.83 1.1	14.9 9.1	0
SPB 2:1	64.9 31.6	1.74 2.3	60.1 37	0
Paper mill sludge	184.0 89.7	1.2 1.58	19.6 12.1	0

The superficial velocity of fluidization at the combustion of all fuels in the study was about twice the minimum fluidization velocity. Although it was not observed particularly, it might be expected that the possibility of bed agglomeration under identical or similar conditions exists if the process is operated for long enough periods. Therefore, it is recommended to run the process at higher fluidization velocities and to replace the bed, either continuously or periodically.

The chemical composition of the ash samples was determined by X-ray fluorescence on the energy dispersion spectrometer XEPOS (Spectro, Germany). The analysis of ash samples compared to the composition of corresponding species in the sewage sludge, SPB 2:1, SPB 4:1, is shown in Table 6.

The analysis of the paper mill sludge did not detect any elements shown in Table 6. Furthermore, the combustion of paper mill sludge produced no measurable quantity of ash. The data in Table 6 suggest that magnesium, potassium, calcium, chromium, copper, zinc, arsenic, and lead remained mostly in the ash after combustion, while all cadmium from all fuels used was transferred into the flue gas together with a substantial part of chlorine and mercury. These results are in accord with previously published works [31–33].

In addition to the technological tests, a basic analysis of environmental impacts of the prepared alternative fuels was carried out. The assessment was conducted as a simplified environmental input-output based life cycle assessment (EIO-LCA) [52] of the selected, but limited, input and output streams. During this short study, material and fuel balances were considered in terms of the input waste used and oxygen consumption needed for the fluidized bed process, together with the output parameters representing the amount of energy produced, the character of the flue gases, and the post-combustion ashes. Concerning the environmental aspect, the data presented above in Tables 1 and 3–6 were used together with the material balance of the process. The study was prepared in the open LCA software v1.10.3 (GreenDelta, Berlin, Germany, 2020) using the ecoinvent v.3.8 database and the APOS unit model (Ecoinvent, Curich, Switzerland, 2021). The resulting impacts were assessed by the most common method of the life cycle impact assessment (LCIA), the CML baseline created by the Institute of Environmental Sciences, University of Leiden (the Netherlands) in 2001 [53], which includes a core group of midpoint impact categories such as climate change, the depletion of abiotic sources, human toxicity, and ecotoxicity [54]. The CML-IA baseline v.4.4 of January 2015 used was provided within the openLCA LCIA methods as the package v2.1.2 (GreenDelta, Berlin, Germany, 2021) and was compatible with the used ecoinvent v3.8. The functional unit (FU) was set on processing 1 kg of the alternative fuels. The final comparison was converted to the production of 1 MJ heat.

Table 6. Analysis of sewage sludge, SPB 2:1, SPB 4:1, and their ash after combustion.

Element	Sewage Sludge mg/kg	Ash (Sewage Sludge) mg/kg	SPB 4:1 mg/kg	Ash (SPB 4:1) mg/kg	SPB 2:1 mg/kg	Ash (SPB 2:1) mg/kg
Magnesium	4499	7210	4498.8	7980	3131.5	7650
Chlorine	261.63	260	227.1	30	204.7	60
Potassium	2972.5	9570	2554	10,880	2282	9690
Calcium	20,388	82,560	26,340	85,780	30,290	84,110
Chromium	355.85	400	285.46	430	239.71	410
Nickel	142.77	200	115.22	220	97.31	210
Copper	892.44	1390	716.05	1490	601.4	1380
Zinc	1499.4	2990	1202.1	3310	1008.9	2880
Arsenic	7.525	20	6.22	30	5.37	20
Cadmium	4.975	0	4	0	3.37	0
Mercury	1.965	10	1.636	0	1.422	0
Lead	153.23	170	122.73	190	102.91	140

Table 7 shows the LCIA results of the assessed fuels. Each selected LCIA category is displayed in the rows, and the project variants are in the columns. The unit is the unit of the LCIA category, as defined in the selected LCIA method.

Table 7. LCIA results (CML-IA baseline, v.4.4, 2015) of the pelletized fuels for the production of 1 MJ heat.

Indicator	Unit	Paper Mill Sludge	SPB 2:1	SPB 4:1	Sewage Sludge
Abiotic depletion (elements)	kg Sb eq.	1.61×10^{-8}	4.61×10^{-8}	5.22×10^{-8}	6.75×10^{-8}
Abiotic depletion (fossil fuels)	MJ	1.88×10^{-1}	5.37×10^{-1}	6.08×10^{-1}	7.87×10^{-1}
Acidification	kg SO_2 eq.	3.26×10^{-5}	9.41×10^{-5}	1.07×10^{-4}	1.38×10^{-4}
Eutrophication	kg $PO_4{}^{3-}$ eq.	4.68×10^{-6}	1.34×10^{-5}	1.52×10^{-5}	1.96×10^{-5}
Freshwater aquatic ecotoxicity	kg 1,4-DB eq.	2.31×10^{-3}	3.14×10^{-2}	3.79×10^{-2}	4.61×10^{-2}
Global warming (GWP100a)	kg CO_2 eq.	8.54×10^{-2}	1.42×10^{-1}	1.51×10^{-1}	1.81×10^{-1}
Human toxicity	kg 1,4-DB eq.	1.67×10^{-3}	6.32×10^{-3}	7.56×10^{-3}	9.84×10^{-3}
Marine aquatic ecotoxicity	kg 1,4-DB eq.	2.54×10^{0}	1.54×10^{1}	1.81×10^{1}	2.24×10^{1}
Ozone layer depletion (ODP)	kg CFC-11 eq.	2.45×10^{-9}	7.02×10^{-9}	7.95×10^{-9}	1.03×10^{-8}
Photochemical oxidation	kg C_2H_4 eq.	1.28×10^{-6}	3.69×10^{-6}	4.18×10^{-6}	5.40×10^{-6}
Terrestrial ecotoxicity	kg 1,4-DB eq.	8.84×10^{-4}	2.86×10^{-3}	3.61×10^{-3}	2.30×10^{-2}

The performed basic input-output analysis showed that only the alternative fuel produced from sewage sludge has the most significant impacts on the environment regarding all assessed categories. In the case of both SPB tested, these impacts were generally reduced by 20–30% in average, with lower environmental impacts for the SPB 2:1 fuel, mainly due to its higher paper sludge content. The highest impacts were calculated for the categories of ecotoxicity, global warming, and fossil fuel depletion due to the character of the fluidized bed combustion process, the emissions produced, and the composition of the ash after combustion.

Figure 4 gives the relative indicator results of the tested pelletized fuels. For each indicator, the maximum result was set to 100%, and the results of the other fuels are displayed in relation to this result.

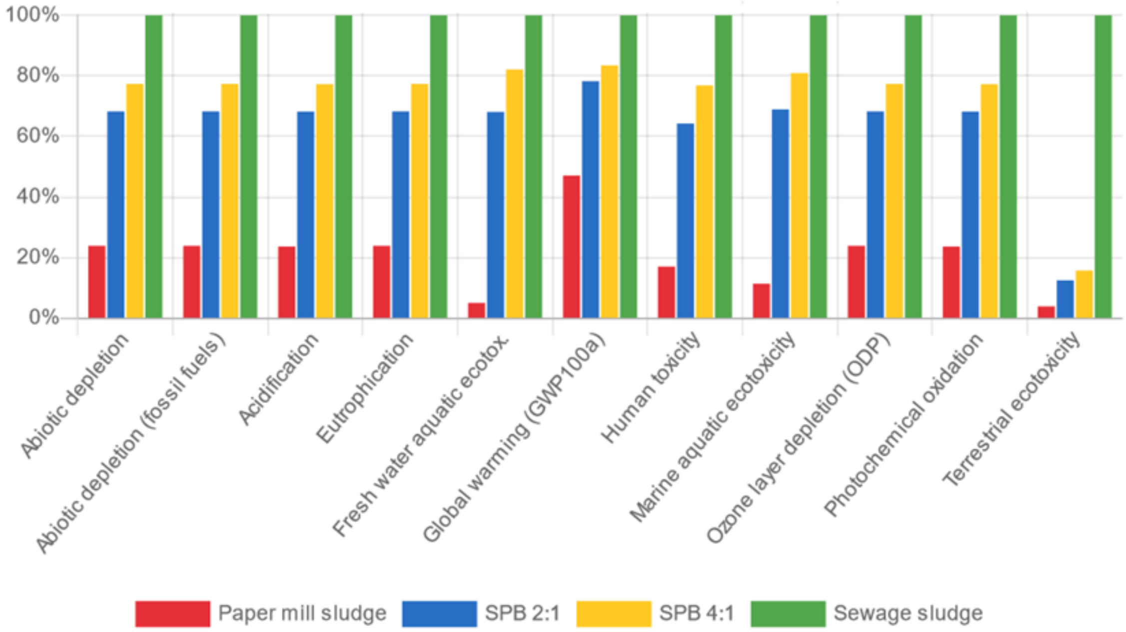

Figure 4. Relative indicator results of the pelletized fuels for the production of 1 MJ heat (drawn in the openLCA software, Berlin, Germany, v1.10.3).

From the graph above, it is obvious that the combination of sewage sludge and paper sludge into an alternative fuel can bring positive aspects related to the reduction of most categories of their environmental impacts. However, a full LCA analysis, as defined in the latest version of the ISO 14040 and 14044 standards [55,56], should be performed for a final conclusion on the environmental impacts of the tested alternative fuels.

The LCOE for a 2:1 blend ratio is 25 EUR/GJ in alternative fuel at the point of pelletization (excluding transport to the point of final consumption). To better understand the result obtained, this price per 1 GJ can be compared with a close substitute—lignite. However, lignite is not traded on an open commodity market—the price is subject to bilateral negotiations between a producer and a buyer (very often these companies are vertically integrated, which can have a significant impact on pricing). However, Bejbl et al. [57] proposed a solution to determine this price from available hard coal price data. This approach assumes a lower price per GJ of energy in the fuel due to the poorer quality of lignite compared to hard coal. For this reason, the ARA (Rotterdam) price of hard coal multiplied by the ratio 0.8 is used as a benchmark for the European market. When applied to current prices (for pricing in this way, price averages over a longer period are used), we currently obtained the price of EUR 10 per GJ in lignite. However, it would be a mistake to compare this price with LCOE directly. First of all, it should be noted that the fuel sources utilizing lignite are also using a corresponding emission allowance; in our case, the allowance price is 81 EUR/tCO_2, which corresponds to 6 EUR/GJ in fuel of cost savings. Another important point is the ongoing discussion on the (even negative) price of sewage sludge. Producers are forced to sanitise all sludge or have this performed by an external company. Thus, it can be assumed that wastewater treatment companies might be willing to pay for sludge removal. The current discussion indicates the disposal price of approximately 40 EUR per tonne of thickened sludge. Considering this as an income for the alternative fuel producing company, we obtain an additional 6 EUR/GJ, compared to lignite. Taking these two additional items into account, the final difference is only EUR 3/GJ. The possible use of an alternative fuel in the form of granulate (this is the output from the solar dryer without further pelletizing) might represent a significant cost saving. This fuel can be used in larger combustion plants, and from the price point of view (including the price adjustments mentioned above), the price is already below the current price of lignite with the price of the emission allowance included.

5. Conclusions

Four pelletized wastes, sewage sludge, paper sludge, and their mixtures in a 2:1 and 4:1 ratio, were tested as alternative fuels in a pilot plant fluidized combustion plant. It was verified that alternative fuels can be used for fluidized bed combustion using a conventional flue gas treatment technology. Moreover, the addition of paper mill sludge into the pellets from sewage sludge not only increased the heating value of pellets but also significantly decreased the Mercury concentration in the flue gas, as well as NOx and hydrogen chloride. The average CO concentration complied with usual worldwide norms, similarly to SO_2 after the desulphurisation of flue gas. Ammonia and methane flue gas concentrations were negligible for all four fuels.

The superficial velocity of fluidization during the combustion of all fuels in the study was about twice the minimum fluidization velocity; nevertheless, the possibility of bed agglomeration under identical or similar conditions exists if the process is operated for long enough periods.

The simplified input-output assessment of the pelletized fuels originating from sewage sludge and paper mill sludge showed that this could be a way to produce an environmentally better material and, consequently, an energy alternative for their processing, considering the current need for the circulation of such waste materials. From an economic perspective, the alternative fuel price, based on sewage sludge, is currently competitive with the price of lignite (including the price of the emission allowance) derived from the ARA price on the Rotterdam Commodity Exchange. It seems that the incineration of sewage sludge, especially together with paper sludge, can be one of the best alternatives for its use. In the future, it will also be necessary to test the possibilities of its co-combustion with both coal and other alternative fuels.

The future study should focus on other operating factors of fluidized bed combustion of fuels, e.g., a ratio of primary and secondary air, in order to decrease concentrations of CO and NO_x, the co-combustion of this type of fuel with coal or pelletized straw in different weight ratios, and measurements of organic micropollutants in the flue gas.

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