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ScienceDirect

Energy Procedia 120 (2017) 286–293

Energy Procedia

www.elsevier.com/locate/procedia

INFUB - 11th European Conference on Industrial Furnaces and Boilers, INFUB-11

Use of Low-quality Biogenic Fuels in a Decentralized Biomass Boiler for Thermal Energy Generation

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Abstract

The KIT generate heat with three hot water tube boilers and a combined heat and power unit. Their operation is based on natural gas. Alternatively, light fuel oil can be used in the hot water tube boilers. For the future the KIT has to achieve climate protection goals and for that to consider about alternative heat generation. This could be the operation of a biomass boiler, which is operated with wood chips or wood pellets. The Institute of Technical Chemistry (ITC) and Facility Management (FM) of KIT in cooperation with medium-sized enterprises now plans to integrate a decentralized biomass boiler into the existing heat supply network of KIT Campus North. The goal for the decentralized biomass boiler is to operate with low-quality biogenic fuel. Within the framework of preliminary studies, the biogenic fuels shall be characterized according to their combustion properties. To enhance sustainability, reduce the consumption of resources and increase economic efficiency, the studies are to focus on the use of waste materials. In addition, the waste flows at KIT and the suited waste shall be identified. The considered materials are lop, sieve residues or other previous identified waste.

When planning such a project, legal and licensing-relevant aspects and their consequenses have to be considered. Then, the requirements to be met by the selected fuels will be listed and experimental tests at the "KLEAA" test facility of ITC will be reported. This test facility is a fixed bed reactor used for the characterization of burnout of solid fuels. Studies are aimed at identifying and assessing alternative fuels for future use in biomass boilers. Furthermore side effects such as corrosion, slagging, and emissions shall be taken into account. Depending on the achieved intermediate data the insert of additives to reduce the side effects will be tested. The project findings will be verified in an experimental facility later on.

In the proposed paper first results of the preliminary investigations shall be presented.

Peer-review under responsibility of the organizing committee of INFUB-11

Keywords: low-quality biogenic fuels; waste; biomass boiler

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Peer-review under responsibility of the organizing committee of INFUB-11
10.1016/j.egypro.2017.07.211

1. Introduction

Usage of renewable energy sources to replace fossil fuels, such as crude oil, natural gas and lignite, is an important issue of our society, science, and politics.

Renewable energy sources are of great potential not only in e-mobility, but especially in the field of heat and electricity generation. Technologies for using solar heat, photovoltaics, or wind power are well advanced. In addition to volatile generation capacities, flexibly controllable capacities, such as heat and power generation by biogas plants and biomass power plants, are required to secure energy supply in Germany. In the sector of energy utilization by biomass combustion, analysis focuses on the fuels that might be used in an economic way. Besides combustion of specially produced wood chips and wood pellets, co-incineration of low-quality biogenic fuels is gaining importance. One potential source of low-quality biogenic fuel is biogenic waste.

To reach future climate protection goals, Karlsruhe Institute of Technology (KIT) evaluates various alternative heat generation concepts. One option is the operation of a biomass boiler with low-quality biogenic fuel. To enhance sustainability, reduce the consumption of resources, and increase economic efficiency, use of waste materials is considered. The requirements to be met by selected fuels will be listed and experimental tests at the “KLEAA” test facility of KIT’s Institute for Technical Chemistry (ITC) will be reported below.

2. Description of Biogenic Fuels

In this chapter, the considered biogenic fuels are described.

2.1. Biogenic Fuels Tested

The series of experiments focused on the combustion of low-quality biogenic fuels, especially from waste management. First, the waste streams of KIT Campus North were analyzed in order to determine potential fuels. When selecting the fuels, legal boundary conditions for plant operation were not taken into account. Classes of waste available for tests in the KLEAA test facility and their applicabilities are listed in the following table:

Tab. 1: Classes of waste at the KIT [1]

No.	Classes of waste	Description	Amount
1	Root wood	Root wood results from construction and excavation work and is separated from the soil by sieves. As the amount of soil is extremely high, the amount of root wood can be neglected.	10.2 Mg/a
2	Sewage waste	Mixture of street sweepings and green waste that mainly originates from cleaning sewers. Due to its high amount of stones, it is not suitable for the experiments either.	13.0 Mg/a
3	Sludge	Sludge that comes from the biological wastewater treatment plant. Due to its high humidity (30% dry matter), it is not suitable for the tests.	110.5 Mg/a
4	Green waste	Material produced by landscaping work on the whole KIT campus. Although it contains certain impurities, the material can be used for experiments.	193.2 Mg/a

In addition, wastes from disposal plants were considered. Residues from paper production as well as sieve overflow from a composting plant were selected. The high humidity content and the limited availability of the paper production residues, however, caused them to be excluded. The sieve overflow was made available by

RETERRA GmbH, part of the Remondis SE & Co. KG group. This material is a sieved residue arising when preparing green wood for composting or as a material for soil improvement.

2.2. Description and Physical Properties of the Biogenic Fuels

The hackled green waste (Figure 1a) was made available by the company Mineralix GmbH which also utilizes waste from KIT, such as rubble and excavated material. The green waste was sieved by a starscreen to a size of >8 mm and <70 mm. Due to the special characteristics of green waste, shorter and longer pieces may still be present after sieving. The fraction of <1 mm in diameter essentially consisted of soil.

The green waste mainly consisted of cut branches. Leaves and grass were hardly found in this fraction. Among the impurities contained were stones, plastics, and styrofoam. However, they made up less than 5 % of the total mass.

The sieve overflow (Figure 1b) is produced by crushing and sieving green waste in the region of Erftstadt. These green wastes are collected among others at municipal collection centers and are transferred to the composting plant of RETERRA GmbH for further processing and utilization. Sieving results in three fractions. The medium-sized grain fraction represents the so-called sieve overflow. No direct utilization path exists for this fraction. It mainly consists of branches, but also contains leaves.

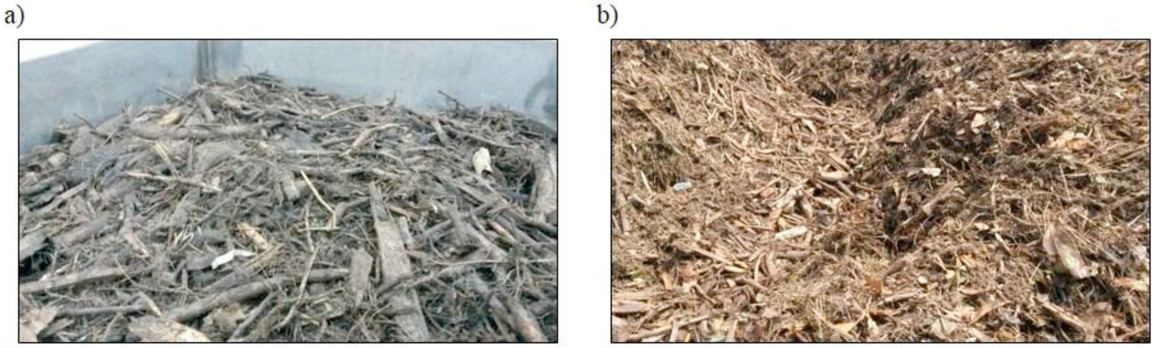

Fig. 1: a) The appearance of the green waste; b) The appearance of the sieve overflow

To assess the fine and coarse material fractions, sieve analyses were made. The largest mesh width of the five sieves available was 31.5 mm. The proportion of green waste larger than 31.5 mm was 30.0 %, the sieve overflow share was 40.0 %. The fraction of <1 mm of both fuels mainly consisted of soil. The results of sieve analysis are shown in Figure 2. As it is envisaged to use fuel without previous treatment stages, the materials were not subjected to sieving prior to the tests and no impurities were removed.

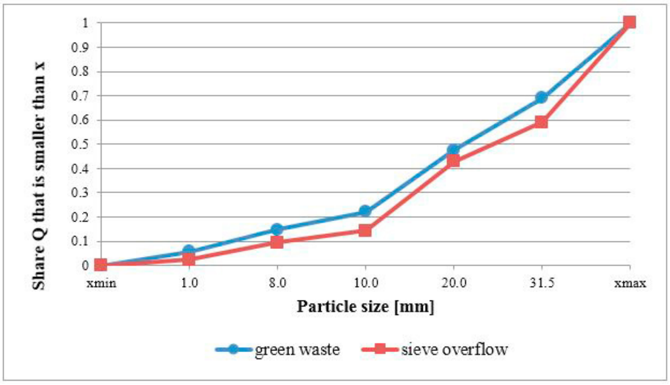

Fig. 2: Result of sieve analysis

2.3. Laboratory Analysis of Biogenic Fuels

To determine the chemical and caloric properties, proximate and elementary analyses were carried out. In addition, the ash was analyzed with regard to the limits given in the German Landfill Ordinance and German Fertilizer Ordinance.

2.3.1 Chemical Properties

Table 2 (ar = as received, wf = water-free) lists the results of proximate analysis, Table 3 the results of elementary analysis of green waste and sieve overflow in comparison to wood chips (industrial wood chips).

Apart from the higher water content, green waste also has a much higher content of ash. This results in a high char concentration, which is composed of ash and carbon C_{fix}. The large ash fraction is caused by unburnable secondary impurities, such as soil and other mineral constituents. Moreover, the relatively high proportion of bark and the coniferous wood fraction make the ash fraction exceed that of wood chips. [2] The sieve overflow has the highest water content of all fractions. The ash fraction, by contrast, only amounts to 7.66 m-%. The char concentration corresponds to that of wood chips.

Tab. 2: Proximate analysis

	Green waste (GW)		**Sieve overflow (SO)**		**Wood chips (WS)**	
	m-% ar	**m-% wf**	**m-% ar**	**m-% wf**	**m-% ar**	**m-% wf**
Water content	20.40	0.00	34.00	0.00	11.20	0.00
Volatiles	39.80	50.00	50.77	76.90	73.52	82.80
Char	39.80	50.00	15.23	23.10	15.28	17.20
C_{fix}	7.65	9.60	7.57	11.50	14.59	16.40
Ash	32.15	40.40	7.66	11.60	0.69	0.80

The lower carbon value of the green waste is attributed to the fact that the green waste mainly consists of short-lived branches rather than trees that have been growing for many years, thus enriching carbons. The nitrogen contents of green waste and sieve overflow exceed that of wood chips. Whether this leads to increased NO_X values in the offgas has to be checked. The green waste's and sieve overflow's chlorine and sulfur concentrations are higher than those of wood chips, as a result of which use of green waste and sieve overflow is expected to lead to increased corrosion. [2]

Tab. 3: Elementary analysis

	Green waste (GW)		**Sieve overflow (SO)**		**Wood chips (WS)**	
	m-% ar	**m-% wf**	**m-% ar**	**m-% wf**	**m-% ar**	**m-% wf**
Water content	20.40	0.00	34.00	0.00	11.20	0.00
Carbon	25.98	32.60	31.66	47.90	44.45	50.10
Hydrogen	3.14	3.90	3.69	5.60	5.22	5.90
Nitrogen	0.30	0.38	0.58	0.88	0.23	0.25
Oxygen$_{diff}$	17.97	22.64	22.29	33.83	38.21	42.98
Sulfur	0.03	0.04	0.05	0.08	0.01	0.01
Chlorine	0.03	0.04	0.07	0.11	0.01	0.01
Ash	32.15	40.40	7.66	11.60	0.67	0.75

2.3.2 Caloric Properties

The gross calorific value of the water-free green waste was determined in the laboratory and amounted to 12.9 MJ/kg. When the water content is 20.4 %, a net calorific value of 9.1 MJ/kg results for the fuel used. The gross calorific value of the water-free sieve overflow amounted to 18.9 MJ/kg. With the water content of 34 %, a net calorific value of 10.8 MJ/kg results. In comparison, the net calorific value of wood chips with a water content of 11.2 % amounts to 16.2 MJ/kg, while that of lignite with a water content of 55 % is 8 MJ/kg. This low net calorific value compared to wood chips is also due to the high ash fraction. [3]

3. Plant Design and Characteristics of the Experiment

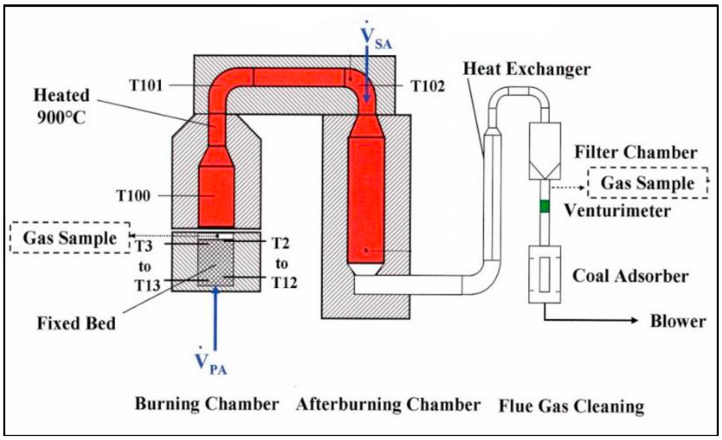

Fig. 3: Setup of the KLEAA system [4]

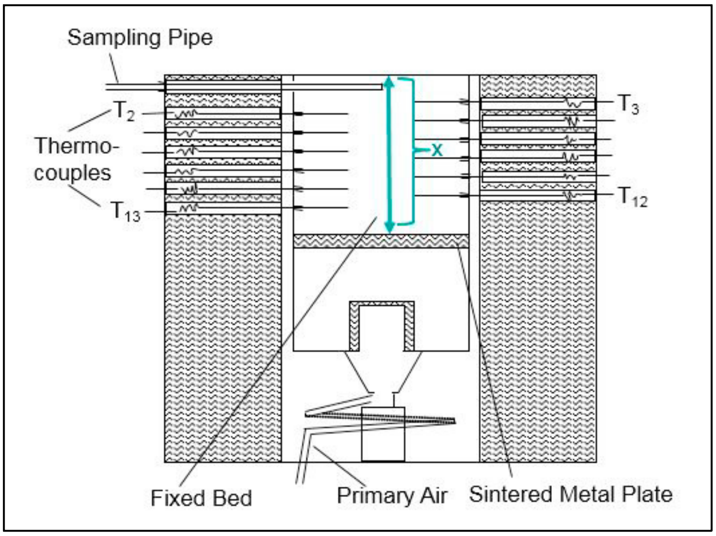

Fig. 4: The sampling pipe and the thermocouples in the fuel bed

Experimental studies for characterizing the combustion properties of green waste fuel were carried out in the KLEAA reactor. KLEAA is a fixed-bed batch reactor at the Institute for Technical Chemistry of KIT. Figure 3 shows the setup of the system. The main components of KLEAA are the combustion chamber with a fixed bed and a heated furnace, the afterburning chamber, and the flue gas cleaning system consisting of a heat exchanger, filter chamber, and coal adsorber. The fuel bed has a volume of 10 l and the maximum filling level is 250 mm. The furnace and afterburning chamber can be heated electrically up to a maximum temperature of 1100 °C. [4]

Primary air is supplied from below through a sintered metal plate and can be pre-heated up to a maximum temperature of 300 °C. [4, 5] For the test, the movable combustion chamber with the solid fuel is connected to the burning chamber in an airtight manner. The solid fuel is ignited by radiant heat from the furnace and burns down in opposite direction to the primary air flow. Gas samples are taken at two different locations (s. Figure 3). The concentrations of CO_2, CO, organic carbon, H_2O, and O_2 are determined above the fuel bed. At the second gas sampling point located at the outlet of the filter chamber, the concentrations of the flue gas components CO_2, CO, H_2O, and O_2 as well as of the pollutant gases NO, NO_X, N_2O, and SO_2 are determined.

The temperatures are recorded at several points in the fuel bed and along the gas path. Figure 4 shows the arrangement of the sampling pipe and of the thirteen thermocouples (T2 – T13) in the fuel bed. [4, 6]

Characteristics are used for evaluating the individual experiments. These are the ignition time IT, the reaction front velocity RFV, the ignition rate IR, and the mass conversion rate MCR.

The IT is defined as the time required for ignition of the upper layer of the fuel after primary air flow is turned on. [4]

$$IT = t_1 = t_{ignition} - t_{primary\ air}\,[min] \tag{1}$$

The RFV results from the temperature profiles measured in the fuel bed and it is a characteristic to quantitatively describe the combustion behavior of a solid fuel and the position of the reaction front at any point in time. [4]

$$RFV = \frac{dx}{dt}\left[\frac{mm}{min}\right] \tag{2}$$

The IR is defined as the product of the RFV and bulk density ρ of the feedstock. It describes the fuel mass ignited per grate area. [4]

$$IR = RFV * \rho\ \left[\frac{kg}{s*m^2}\right] \tag{3}$$

The MCR describes the fuel mass loss per area A_{GRATE} and time. It is determined from the mass loss signal $\dot{m}_F$ of the fuel bed scales. For an easy comparison of the IR and MCR, the latter is corrected by the ash content $\xi_{ASH,F}$ of the fuel. [4]

$$MCR = \frac{\dot{m}_F}{A_{GRATE}(1-\xi_{ASH,F})}\left[\frac{kg}{s*m^2}\right] \quad \text{and F. 5:} \dot{m}_F = \frac{dm_F}{dt}\left[\frac{kg}{s}\right] \tag{4}$$

The MCR I describes the change of mass until the ignition front arrives at the bottom of the burning chamber. MCR II stands for the change after this moment.

4. . Experimental Results

Several combustion tests were carried out in the KLEAA test facility to study the burnout behavior. Apart from tests with green waste (GW) that will be described below, tests with sieve overflow (SO) were made. In addition, sieve overflows mixed with wood chips (SO/WC) were combusted to improve certain combustion parameters.

Now, the combustion test with green waste shall be described in more detail.

For the experiment, 1.35 kg of green waste were fed into the combustion chamber, which corresponded to a bulk density of about 132 kg/m³. The amount of primary air was 10 Nm³/h, it was not pre-heated. Ignition time of the green waste was 80 seconds. Compared to wood chips which ignited after 45 seconds, ignition was delayed slightly, but still comparable. In Figure 5 ignition time is reflected by the rapid increase in T2. After about 12 minutes, the ignition front arrived at the bottom of the burning chamber. Also T13 reached its ignition temperature. The main burning phase is the time between ignition and the flame reaching the bottom of the burning chamber. During this phase, the material burns down nearly homogeneously from the top to the bottom. The water content of the fuel also influences combustion temperature. Maximum temperature in the main burning phase was 851 °C, it was measured at T6 and lower than that of the wood chips. For the latter, a

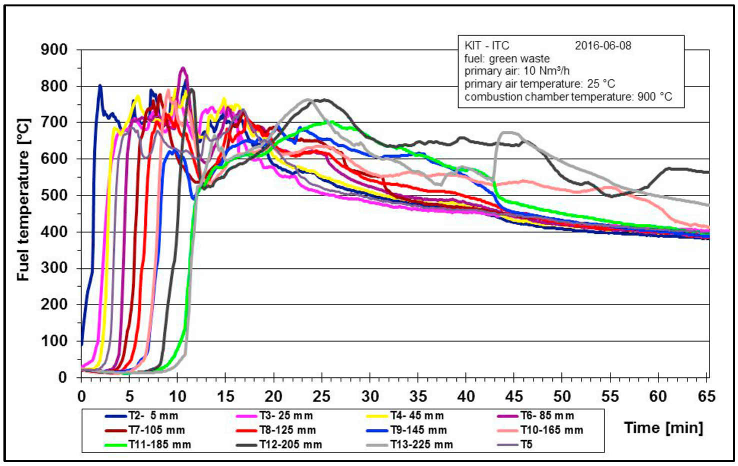

Fig. 5: Temperature of the fuel bed

maximum temperature of 924 °C was measured for a short term. After the twelfth minute, the char burnout phase started, during which occasional temperature increases were observed when the fuel or ash heaps collapsed and primary air supply of still unburnt material was improved. As a result, this material started to burn. The large ash fraction, the higher water content, and the smaller content of volatile substances compared to wood chips (cf. Tab. 2) resulted in a smaller RFV of green waste and, hence, a longer duration of the experiment. The experiment with the wood chips ended after 45 minutes, whereas the experiment with green waste took 65 minutes.

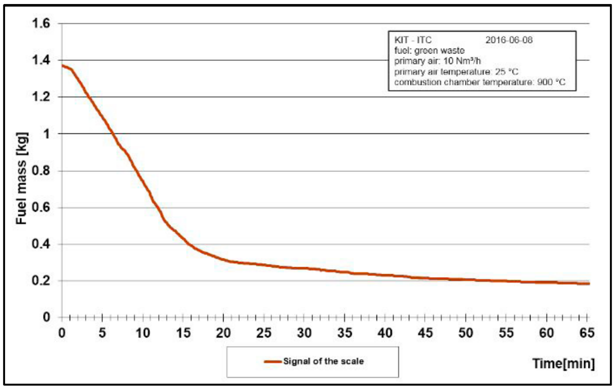

Fig. 6: Fuel mass loss

In the green waste experiment, the RFV amounted to 19.8 mm/min and, hence, was below that of wood chips by 1/3. For the wood chips, an RFV of 30.0 mm/min was measured at a bulk density of the material of 155 kg/m³. At a similar bulk density, an increased water content of the material was found to lead to a smaller RFV.

The MCR I and IR of green waste were comparable with 0.042 kg/m²*s and 0.043 kg/m²*s, respectively. Compared to wood chips (IR = 0.077 kg/m²*s and MCR I = 0.056 kg/m²*s), both values are smaller, which can be explained by the different RFV value. Quicker burning of the wood chips results in a quicker mass reduction and, hence, in a higher MCR I. This relationship also holds for MCR II (MCR $II_{green waste}$=0.0067 kg/m²*s and MCR $II_{wood chips}$=0.0085 kg/m²*s).

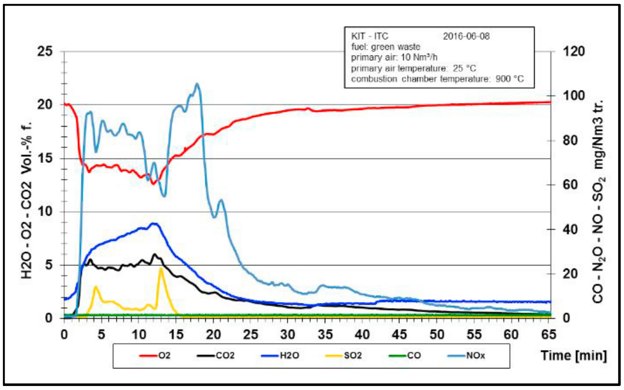

Fig. 7: Gas concentration in the afterburning chamber

When burning green waste, gas concentrations normalized to 11 % O_2 exhibit smaller NO_X and SO_2 values downstream of the fabric filter than in case of the combustion of wood chips ($NO_{X\ total}$ of green waste = 128,51 mg/m³ and wood chips = 160,54 mg/m³; $SO_{2\ total}$ of green waste = 9.43 mg/m³ and wood chips = 81.78 mg/m³). The lower temperature during combustion led to a lower NO_X value of the offgas.

As the SO_2 concentration in the offgas produced by green waste combustion is much smaller than for wood chips and the concentrations in the feedstocks are about comparable, a large amount of SO_2 can be assumed to be bound by the char. Hence, it is located in the ash. The CO_2 fraction of the offgas also is below that of wood chips. This is due to the lower carbon concentration of the feedstock.

Moreover, the ash produced by the experiments was analyzed to consider the slagging potential and disposal and utilization options. In all experiments, the ash softening temperature was analyzed with respect to slagging. Laboratory analyses yielded an ash softening temperature of about 1170 °C. In the combustion tests, this temperature was never reached. Also when studying the ashes, no indication of slagging was found.

Utilization or disposal options were checked on the basis of the limits given in the German Fertilizer Ordinance and German Landfill Ordinance. The results of the analysis of green waste according to the Fertilizer Ordinance were inconspicuous and found to be below the valid limit values except for chromium VI. The results for sieve overflow and the mixture of sieve overflow and wood chips also revealed that the limit value of nickel was exceeded. For this reason, the ash cannot be used for fertilization or soil improvement.

The results of the laboratory analyzes according to the Landfill Ordinance revealed the following: It would be permitted to dispose of the green waste on landfills of class I only. As the ashes of the sieve overflow have too high DOC and free cyanide values, this waste has to be disposed of on landfills of class III.

5. Conclusion

To find out whether green waste or sieve overflow might be applied as alternative fuels, several aspects have to be considered. As a result of the low calorific values, also combustion temperatures of these materials are lower than those of wood chips. Apart from the positive effect that the ash of green waste protects the boiler against rust, the high fraction of ashes and the high concentrations of chlorine and sulfur increase the potential of boiler contamination and corrosion. This leads to increased maintenance and repair expenditures. Apart from contamination, an increased amount of fly ash may be produced, causing higher offgas cleaning efforts. When using sieve overflow, corrosion tendency is higher than when using wood chips. Comparison of the offgases reveals NO_X values for sieve overflow (NO_X normalized to 11 % O_2 = 264.99 mg/m^3) which are far above those of green waste and wood chips. Hence, use of sieve overflow would be associated with more complex offgas cleaning. In addition, the costs of these alternative fuels, such as transportation costs and disposal costs, have to be taken into account. Fuel costs, including transportation, for wood chips per generated MWh amount to EUR 35, for green waste to EUR 21, and for sieve overflow to EUR -7. The latter value results from the fact that the sieve overflow is paid for by the disposal companies. As the limits given in the Fertilizer Ordinance are exceeded, all ashes have to be disposed of. Laboratory analyses yield different values, corresponding to different landfill classes. The legal limit values are also exceeded for wood chips, with disposal on landfills of class III being required. Only green waste might be disposed of on a landfill of class I. Taking into consideration the landfill classes and the ash fraction, the costs per Mg used fuel amount to EUR 0.69 for wood chips, EUR 14 for green waste, and EUR 8 for sieve overflow.

Taking into account all results mentioned above, combustion of sieve overflow can be recommended. The somewhat higher disposal costs would be compensated by payment for purchases. For compliance with the offgas limits, however, mixing with wood chips is recommended. Due to the high costs of green waste and the large ash fraction that is associated with increasing operation costs, use of green waste cannot be recommended.

Acknowledgements

The authors would like to thank Mineralix GmbH and RETERRA GmbH, part of the Remondis SE & Co. KG group, for the supply of the fuels for the experiments.

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