### Project acronyms
BIOFLEX

### Official project duration
January 2016-March 2019

### Coordinator institution
RISE Research Institute of Sweden

### Coordinator name
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### Partners
- BIOS BIOENERGIESYSTEME GmbH (BIOS)
- Technology and Support Centre of Renewable Raw Materials (TFZ)
- Umeå University, Department of Applied Physics and Electronics (UMU)
- Luleå University of Technology, Division of Energy Science (LTU)
- Chalmers University of Technology, Division of Fluid Dynamics (CTH)
- Saxlund (Opcon AB)
- AMANDUS KAHL GmbH & Co. KG
- Institute of Power Engineering (IEn)
- BTI – Biuro Techniczno Inżynierskie Jan Gumkowski (BTI - Office of Technology and Engineering)
- POLYTECHNIK Luft- und Feuerungstechnik GmbH (POLYTECHNIK)
- KWB Kraft und Wärme aus Biomasse GmbH

### Date
May 2019

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### 1. Status quo of the project

(achievement of milestones and objectives with regard to the work plan; Estimate the current degree of completion of the planned objectives; auto-evaluation of the internal cooperation and added value of international cooperation to the project)

The overall objective of BIOFLEX was to increase fuel flexibility and innovation potential for the use of more difficult solid biomass fuels that do not compete with food production, in the small to medium-scale heat and power production sector. Specific aims were:

- To further develop and implement fuel design and combustion system design related measures making the clean and efficient utilisation of bio-residues, by-products and other resource efficient energy crops, such as straw, grass, salix, horse manure beddings and sludges, possible in small-to-medium scale applications, at low emissions, high efficiencies and high availabilities, comparable to the Ecodesign and MCP directives.

- To develop guidelines for the design of appropriate low emission combustion technologies and for appropriate fuel design of the identified fuels.

- To perform testing of these measures in appropriately adapted testing plants in cooperation with furnace and boiler manufacturers.

To reach the objectives of the project the consortium has focus on three major R&D pathways:

- Fundamental ash transformation research for the chosen fuels
- Additives and fuel blending
- Further development of combustion technologies and process control systems by means of primary measures relevant for the selected fuels

The project work was divided into seven work packages with a couple of defined milestones. Below the achievement and the degree of completion of each milestone is presented.
Achievement of milestones

MS1.1: Information concerning the influence of process-, fuel- and additive parameters on pellet quality during pelleting

Fuels selected for this study included pellets of poplar, sunflower husk, wheat straw and grass. Furthermore, unpelletized poplar wood chips were used during combustion trials. All pellets were produced at TFZ using an Amandus Kahl press with exception of wood pellets, i.e. the reference fuel, that were purchased on the German market. To improve the ash chemistry regarding slagging behaviour and to reduce particle emissions by fixation of potassium into the ash (see section MS2.2), the clay mineral kaolin was used as an additive in all non-woody fuels. Kaolin was purchased from the company KAMIG (Perg, Austria) and consisted to 87 w-% of kaolinite. During production, kaolin was added to poplar fuels (1.5 w-%, d. b.) wheat straw (3.45 w-%, d. b.), sunflower husk (2.8 w-%, d. b.) and grass (8.1 w-% and 10.5 w-%, d. b., respectively). Mixing ratios derived from element analysis (see below) and from stoichiometric calculation (see section MS2.2).

Further trials were performed using poplar fuels that were additivated with kaolin (1.5 w-%, d. b.) after fuel production (pellets, wood chips). For these fuels, additivation was done by mixing pellets with kaolin manually in a barrel (pellets) or by adding kaolin directly into the screw feeder of the respective boiler (wood chips).

In addition to kaolin additivation, wheat straw was blended with 50 w-%, 75 w-% and 90 w-% of wood prior to the pelleting. This might also be done by mixing of already produced pure wheat and wood pellets. Thus, a 50/50 mixture of premanufactured pure wheat straw pellets and pure wood pellets was generated, as well.

All pure fuels were analysed for elemental composition including heavy metals and trace elements at BIOS Bioenergiesysteme GmbH. Physical fuel parameters of all fuels were determined at TFZ.

Table 1.1.1. Results from the stoichiometric calculations for the fixation of K in the ashes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Poplar</th>
<th>Wheat straw</th>
<th>Grass</th>
<th>Sunflower husk</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>mg/kg fuel d.b.</td>
<td>3.070</td>
<td>8.450</td>
<td>21.200</td>
<td>7.450</td>
</tr>
<tr>
<td>K</td>
<td>mole/kg</td>
<td>0.011</td>
<td>0.216</td>
<td>0.542</td>
<td>0.190</td>
</tr>
<tr>
<td>Stoichiometric</td>
<td>w-%</td>
<td>1.01</td>
<td>2.79</td>
<td>7.00</td>
<td>2.46</td>
</tr>
<tr>
<td>kaolin level*</td>
<td>d.b.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>3.12</td>
<td>7.84</td>
</tr>
<tr>
<td>Adjusted level I</td>
<td>w-%</td>
<td>n.a.</td>
<td>n.a.</td>
<td>10.50</td>
<td>n.a</td>
</tr>
<tr>
<td>(+12 %)*</td>
<td>d.b.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>10.50</td>
<td>n.a</td>
</tr>
<tr>
<td>Adjusted level II</td>
<td>w-%</td>
<td>1.52</td>
<td>n.a.</td>
<td>10.50</td>
<td>n.a</td>
</tr>
<tr>
<td>(+50 %)*</td>
<td>d.b.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>10.50</td>
<td>n.a</td>
</tr>
</tbody>
</table>

*The calculated levels are based considering that the kaolinite content in the kaolin used was 87 % as well as the moisture content of the fuels. The selected levels for the tests are marked up in boldface.

The pelleted fuels (Table 1.1.3) showed a high durability of 94.6 to 99.3 w-%. Fines were between 0.0 and 0.3 w-%. Thus, regarding these fuel parameters, pellets were on the same level as wood pellets fulfilling the requirements for ENplus certification. Sunflower husk with 2.8 w-% kaolin showed the lowest durability of 94.6 w-%, followed by pure sunflower husk and pure wheat straw.

For the pure fuels, bulk density was between 625 and 722 kg/m³ which is in the range stated for ENplus pellets. However, for the additivated or blended fuels, bulk density was higher. For example, for sunflower husk with 2.8 w-% kaolin, grass pellets with 8.1 w-% and 10.5 w-% kaolin and the 10 w-% wheat straw / 90 w-% wood blends, bulk density was above 750 kg/m³. This might be explained by the mean pellet length, which was shorter for the additivated fuels (data not shown). Therefore, it may be assumed that particle density does not vary significantly between pure and additivated fuels.

The ash content of the raw materials increased from conventional wood pellets (0.3 w-%) to poplar pellets (2.2 w-%), sunflower husk (2.9 w-%), wheat straw (4.3 w-%) and grass pellets (8.5 w-%, Table 1.1.2). By additivation with kaolin, the ash content was distinctly increased for each raw material. For example, for grass pellets with 10.5 w-% kaolin the ash content increased from 8.53 w-% to 15.96 w-%. Such high ash contents can lead to problems for the deashing system of a common biomass boiler.

The gross calorific value of the reference fuel wood pellets was approx. 20.080 kJ/kg (Table 1.1.3). Sunflower husk was slightly higher (20,200 kJ/kg) while poplar (19,600 kJ/kg), wheat straw (18,880 kJ/kg) and grass (18,350 kJ/kg) were characterised by a slightly lower gross calorific value. The addition of kaolin reduced this value.
when using kaolin as an additive additional wearing on the dies, rollers and bearings may occur. But for a more accurate quantification on the influence of additives on the service life of dies, rollers and bearings of a pellet plant more research is required.

A more detailed description of these findings can be found in the corresponding paper and conference contribution (MS 6.3).

It could be shown that all tested fuels with and without additive and also all blends could be pelletized with an adequate pellet quality compared to the mechanical parameters claimed by ENplus for example. During the pelletsisation process, heavy wear of the dies and rollers was observed which was probably caused by kaolin additives or by other operational parameters (e.g. start-ups and shut downs, die material etc.). This could lead to higher costs for fuel processing. But for a more accurate quantification on the influence of additives on the service life of dies, rollers and bearings of a pellet plant more research is required.
MS1.2: Novel fundamental knowledge of critical ash transformation issues, both operational and emission related

Combustion studies were performed in both a single-pellet reactor and in a small-scale pellet boiler, primarily with different kaolin additivated biomass fuels, but also with mixtures of biomass and sludge (only in the pellet boiler). In both set-ups, pelleted poplar and wheat straw were used, with and without kaolin addition. Poplar is a woody energy crop with low Si and P together with high Ca/K ratio, while wheat straw is an agro-residue with high ash content, excess of K together with relatively high Si, and some Ca and Cl, produced by TFZ. Kaolin was added to the poplar in the level of 1.5 wt-%, and for the wheat straw in the level of 3.1 wt-%. A specially designed macro-TGA set-up was used to study ash formation and transformation, including alkali release and slag formation, during the fuel conversion process. The experiments were performed at 950°C with air, and a semi-time-resolved approach was applied which included quenching of the conversion process at certain time points during the devolatilisation- and char conversion phases. Char and residual ash samples were characterized by SEM-EDS for morphology and elemental distribution, and P-XRD for the content and distribution of crystalline phases. For each case, 20 single pellets were combusted and the residues/ashes collected and pooled for subsequent analysis.

Distinct differences in ash formation and properties were seen caused by the differences between the K-silicate dominating ash in wheat straw and the Ca/K-oxide and carbonate dominating ash in poplar. For the first time, the time-resolved reactions between the kaolin and the fuel ash, could also be observed, and the ash transformation (release, melting etc.) during the fuel conversion can be discussed. For poplar, the ashes were in all cases composed mainly of Ca, K, P and Mg, suggesting different oxides, carbonates and phosphates. The increased Ca/K during the fuel conversion, clearly illustrate the release behaviour of K during the char combustion. Upon kaolin additivation, this effect was significantly reduced and the introduction of Al and Si to the system is seen, i.e. capture of K in high-temperature stable K/Al-silicates. For the wheat straw, the residual ash was dominated by K, Si, Ca and some Mg and P, indicating formation of K-silicates, as well as Ca-silicates and some additional Ca/K compounds (e.g. oxides, carbonates and phosphates). Upon kaolin addition, the Ca/K ratio was stable during the whole fuel conversion process, as well as the levels of the other elements.

Overall, the detailed laboratory single pellet studies have generated mechanistic understanding of the ash formation/ transformation processes during the fuel conversion and of influences of additives, thus proven a valuable complement to controlled burner experiments and full-scale tests.

The combustion experiments in a burner were performed in a boiler with an underfed pellet burner, designed as a cup with a rotating ring at the top. The gases were measured by FTIR and total particulate matter (PMtot) were measured by conventional dust sampling filters. The PM mass size distribution was determined by a 13-step (0.03-10 µm) low-pressure cascade impactor. The bottom ashes were quantified by size fractionation by gentle hand sieving, and the sintering degree for the different ash fractions was determined according to a classification procedure defined previously, based on visual inspection combined with a simple manual strength test. Fractionated bottom ash samples and fine PM, from the tests with kaolin additivation, were analysed for their elemental composition (milled) and for their morphology (non-milled) by SEM-EDS and for determination of crystalline phases by P-XRD. In addition, one combustion test was performed with pure poplar pellets with 1.5 wt-% kaolin added as powder, manual mixing with the pellets prior to adding them to the burner feeding system. Furthermore, the grass fuel was mixed with 50% of standard softwood pellets, to achieve a sufficient combustion performance and relevant combustion tests.

It was seen that the CO was significantly reduced upon kaolin addition, for both fuels. The NOx emissions were higher for grass than for poplar, and in principal not effected by the additivation. The emissions of SO2 was significantly increased for the grass fuel upon kaolin additivation and similar trend was seen for HCl, although the overall very low emissions of HCl. In contrast, the emissions of SO2 and HCl were not increased for the poplar fuels upon kaolin additivation, which were expected, but may be explained by the low sulphur content in the poplar. Relatively high emission factors of PMtot where determined for both poplar and grass, far above the emission limits defined in both the EcoDesign and MCP standards. The influences on the PM emissions studied here can be interpreted as influences on fine particles, formed from condensable alkali vapours. For both fuels, the addition of kaolin reduced the PM emissions considerably in the range of 60-75% (Figure 1.2.1). The largest effect were seen for poplar with co-pelletized kaolin. Indications of soot emissions was seen when the kaolin was added, although the CO was significantly reduced.
Bottom ashes were collected for size fractionation, assessment of sintering degree, and chemical and morphological characterisation. For pure poplar, around 80% was found as bottom ash with very low degree of sintering. This indicates that a significant fraction of the fuel ash (preferably kalium species) have been volatilized during combustion. When kaolin was added, this fraction was clearly reduced and a minor part of the ash was also found as loosely sintered. For grass, around 70-75% of the ingoing ash was found as bottom ash, both for the pure fuel and with kaolin added. However, significant slagging/sintering were seen for the pure grass fuel, illustrated by the elevated fraction of loosely and heavily sintered ash. With kaolin additivation, the fraction of heavily sintered ash was drastically reduced, almost totally depleted.

It was seen that the bottom ash from both the pure poplar as for poplar with kaolin was dominated by fine porous ash with some lumps, although with low sintering degree. When kaolin was added separately as powder, some larger grains were seen, which were shown to be composed of Al and Si, i.e. unreacted kaolin mineral. The SEM-EDS analysis showed that the poplar ash was dominated by Ca, K, Mg and P. Upon kaolin additivation, the major effect was the increased Al och Si contents. In addition, the ratio between Ca/K are significantly lower for the kaolin additivation case, implying that more K are captured in the bottom ash when kaolin was added with the fuel. This effect was somewhat more pronounced when kaolin was co-pelletized.

For the pure grass fuel it was seen that the bottom ash contained significant fraction of melted ash as larger lumps of crushed melted material. When kaolin was added the fraction as well as the size of melted ash was reduced, in line with the reduced sintering/slagging tendencies determined. The SEM-EDS analysis shows that the composition of the grass ash was dominated by K, Si and Ca, with significant contribution from Mg and P. A small trend of increased Si content in the larger ash fractions was also seen. Upon kaolin additivation, the major effect was also here the increased Al och Si contents. Also in this case, a trend was seen with higher Si content in the larger ash fractions, i.e. presumably composed of a higher fraction of melted K-silicates and similar. Similar results were seen between experiments from UmU as from TFZ.

From the XRD analysis, it is seen that the bottom ash from poplar combustion was dominated by oxides, carbonates and phosphates mainly of Ca and K. Upon addition of kaolin, the ash was composed mainly of K/Al-silicates and Ca/Mg/Al-silicates, as well as minor amounts of Ca oxides/carbonates/phosphates. The presence of K/Al-silicates confirm the successful use of kaolin. The presence of Ca/Al-silicates, highlights the potential reactions between the kaolin (kaolinite) and Ca in woody fuels like poplar. For the grass fuel, the crystalline part of the bottom ash is clearly a heterogeneous mixture of several different compounds, e.g. silicates, phosphates, carbonates and oxides. The ash from grass combustion contained significant amount of slag, i.e. melted ash, preferably K-silicates. Upon additivation with kaolin, the ash was more heterogeneous composed mainly of solid K/Al-silicates, and Ca/Mg-silicates, with also confirm the function of the kaolin in capturing alkali in the bottom ash. Furthermore, the SEM-EDS on the PM samples showed that the particles from combustion of poplar were dominated by K and S (K-sulphates, K-carbonates) with some minor amounts of Na, Cl and Zn. When kaolin was added, the relatively concentration of K decreased with higher share of S and Cl, thus more K-sulphates and –chlorides, and less K-carbonates. For the grass (grass-softwood), the fine PM was dominated by K, Cl and S (K-chloride and –sulphates), and with kaolin addition somewhat higher fraction of K-chlorides were seen.

For the burner tests with fuel blending of biomass and sewage sludge, wheat straw was used and mixed with municipal sewage sludge (MSS). The purpose of this fuel blending (co-pelletizing) approach was to study the effects on ash behaviour, slagging and emissions of admixing MSS (P-rich) into an ash-rich challenging agricultural biomass with high content of Si and K. The MSS was digested and coagulated with iron (II) sulfate and smaller amounts of aluminium chlorohydrate. In addition to the base fuels (pure wheat straw and pure MSS), two pellet assortments with
A fuel blend of 90/10 wt-% and 70/30 wt-% wheat straw/MSS were produced. It was decided to mix the sewage sludge with 67% of standard softwood pellets, to achieve a sufficient combustion performance and relevant combustion test.

Overall, no clear trend in CO emissions were seen, and the CO emissions was rather high for pure wheat straw as well as for the blend with 30% MSS, while significant lower for both pure MSS as well as for the blend with 10% MSS. NOx emissions increased with increasing share of MSS because of the higher nitrogen in MSS compared to wheat straw. The NOx emission factors of these fuel assortments were in the same range as those of the poplar and grass fuels. Also SO2 emissions increased significantly with pure MSS and fuel blends with MSS, because of their increasing sulphur content. HCl emissions showed a somewhat different trend, with comparable low emissions for pure wheat straw and pure MSS, but higher emissions for the blended fuels assortments. This is an interesting observation, and may be the result of an increased incorporation of potassium in bottom ash phases and/or melts with silicates and/or phosphates when admixing MSS with the wheat straw.

Furthermore, the particle emissions when using pure wheat straw was rather high, while combustion of pure MSS resulted in rather low particle emissions. This can presumable be explained by the differences in ash composition, where the straw fuel contains rather high amounts of alkali (especially K), Cl and Si, while the MSS ash is dominated by Ca, Fe, Al, Si and P, giving a more volatile ash where e.g. KCl can be volatized and forming fine PM. However, the PM emission trends for the two fuel blends did not show the expected decreasing trend, since the PM emissions instead showed higher for the blend with 30% MSS compared to the blend with 10% MSS. These variations may have been influenced by incomplete combustion conditions, as indicated by the CO emissions, with elevated of soot and organic PM.

Severe slagging tendencies were seen in the bottom ashes from both pure wheat straw and MSS. The total fraction of collected bottom ash for wheat straw was slightly above 60% which indicated a significant volatilization (release) of fine PM forming matter, in accordance with the high PM emissions of wheat straw. On the same basis, 20% of the in-going ashes of pure MSS formed fine PM. This result was not expected, in part due to the low content of alkali in MSS in part to the low fine alkali containing PM emissions. Compared to the pure fuels, the wheat straw with MSS blends showed medium slagging tendencies. In general, the mixture of wheat straw and MSS increased the amount of fuel ash captured in the bottom ash (up to around 90%), compared to the pure fuels. The SEM analysis showed that the bottom ash from pure wheat straw contained melted ash rather homogeneous in its structure, while the admixing of sludge resulted in a more heterogeneous ash with less clear melt fraction. The wheat straw ash is totally dominated by Si, K and Ca, while the contribution also from other elements, e.g. Fe, P and S, increased upon blending with MSS, although the effect was rather small here due to only 10% addition.

Figure 1.2.2. Elemental (relative molar) composition (by SEM-EDS) of bottom ash of wheat straw and wheat straw + MSS blend 90/10, showing bulk composition based on average of 5 images at x200-300, calculated on C- & O- free basis.

MS1.2: Novel fundamental knowledge of critical ash transformation issues, both operational and emission related, was fully achieved at the end of the project (some months delayed according to original plan).
MS1.3: Critical information concerning the fuel devolatilization and production of fuel gases and NOx precursors

BIOS performed lab-reactor tests with the fuel assortments poplar, sunflower husks, grass and wheat straw. The lab-scale reactor applied at BIOS is a purpose built device, which was development with the aim to achieve a design, which allows the simulation of the fuel behaviour in packed bed systems. The system has a reasonable sample intake (some 100 g) in order to simulate secondary reactions in the fuel bed appropriately. High heating rates of the fuel comparable with real-scale installations can be achieved. It consists of a ceramic (AlSint99.7) cylindrical retort (height about 42 cm, inner diameter about 12 cm) which is heated electrically by two separated PID-controllers. The fuel is put into a ceramic (AlSint99.7) cylindrical sample holder of 110 mm height and 95 mm in inner diameter. The mounting and vessel for the fuel bed are fixed on a plate, which is placed on a mass balance. Air is introduced through a porous plate at the bottom of the fuel bed. A liquid sealing filled with thermal oil is used to separate the mass balance and the reactor mechanically. Temperature measurements at different positions in the fuel bed (5 thermocouples in three different heights) and in the gas above the reactor as well as flue gas analyses (CO₂, CO, CH₄, OGC (C₅H₈), H₂O, NO, NH₃, HCN, NO₂, N₂O) are applied. The reactor is pre-heated to a defined temperature and then the fuel sample is introduced in the reactor and the release of gases as well as the reduction of mass are monitored over time till a complete combustion has taken place.

With this setup it is possible to measure the mass reduction of the sample during the combustion process continuously. Additionally important parameters such as the fuel behavior during the different conversion phases and the formation of NOₓ-precursors can be investigated. Moreover, the ashes remaining after charcoal burnout can be optically evaluated with respect to sintering and slagging behavior and analyzed concerning their chemical composition. Based on the results of the fuel and ash analysis, element balances for ash forming elements can be calculated and thus the release behavior of S, Cl as well as of volatile ash forming species (e.g. K, Na, Zn) can be evaluated which is of relevance regarding the aerosol formation and corrosion potential given.

As examples for such evaluations the conversion of the fuel nitrogen into different NOₓ-precursors as well as the expected fine PM emission potential and compositions derived from these test runs are presented in Figure 1.3.1.

![Figure 1.3.1](image)

**Figure 1.3.1.** Conversion of fuel nitrogen into NOₓ pre-cur-sors (left) and potential for fine particulate matter formation and fine particulate matter composition (right) derived from the release data gained from the lab-reactor test runs

Explanation: TFN … total fixed nitrogen = total of HCN, NH₃, NO, NOₓ and N₂O; the rest of the N in the fuel is assumed to be converted to N₂.

The work of BIOS regarding the performance and evaluation of the lab-scale reactor tests has proceeded as planned. The results have been presented to all partners and discussed at the first and second partner meeting. Moreover, the results have been forwarded to WP3 as a relevant basis for the CFD-aided adaptation and optimisation of combustion plants for the fuels of interest. MS1.3, *Critical information concerning the fuel devolatilization and production of fuel gases and NOₓ-precursors*, could thus be reached as initially scheduled in March 2017.

**MS1.4: Design concepts for applying fuel additives and fuel blending including information concerning suitable additive/fuel mixtures and levels for different fuel categories to target and reduce different ash related operational problems and fine particle emissions**

Fuel design is a general approach of using fuel based measures to increase the fuel quality and combustion performance in biomass combustion and gasification applications. In this context, fuel design was considered as a novel tool to design the ash and to reduce/avoid unfavourable ash chemical transformations and its related operational and emission effects in biomass combustion processes. Fuel design is applied by blending the primary fuel with a secondary fuel or an additive that has to be chosen explicitly to get the best and desired effect. In BioFlex, the work focused on the application of the clay mineral kaolin as fuel additive, and to define novel concepts with kaolin addition for different fuel categories. Furthermore, the concept of fuel blending was studied in BioFlex by mixing wheat straw with municipal sewage sludge.

A special objective within the project was to discuss some general aspects related to the use of kaolin as fuel...
additive and to develop a guideline with recommendations for kaolin additivation specifically. This guideline for kaolin additivation includes the following steps, to consider in its logical order:

1. Type of combustion system and problem definition.
2. Type of fuel(s) used/to be used.
3. Additive to use and quality aspects.
5. Additivation approach.
6. Implementation considerations.

MS1.4: Design concepts for applying fuel additives and fuel blending including information concerning suitable additive/fuel mixtures and levels for different fuel categories to target and reduce different ash related operational problems and fine particle emissions, was fully achieved at the end of the project, according to the plan.

MS2.1 Advanced fixed bed combustion model with first considerations of ash transformation phenomena

The objectives were to improve predictions of fixed-bed conversion of difficult biomass fuels and enable initial attempts to include ash transformation. The task was carried out by CTH with input from RISE and UMU.

A conceptual ash transformation model was implemented into a new mesh-based particle model developed at CTH. In this particle model, the thermochemical conversion of a biomass particle is essentially treated as a reactive variable-volume 1D transient heat conduction problem. Local particle properties are mass-weighted averages of the four basic constituents (moist fuel, dry fuel, char and ash), and the discretized partial differential equations are solved directly by LU factorization with a matrix solver (Meschach). This model has been implemented into a fixed-bed combustion CFD setup in a commercial solver (ANSYS Fluent). The ash transformation model describes the properties of the ash layer at the single-pellet level by varying the ash layer porosity due to ash transformations occurring in predefined temperature intervals.

The particle model has been validated against single-particle experiments performed at UMU with satisfactory results. The effects of ash transformations, if they occur, can be studied with the model. On the single-pellet level, ash transformations limit the peak temperature inside the combusting particle and prolong the time needed for char burnout, whereas devolatilization is largely unaffected. High reactor temperatures and high fuel ash contents amplify the effects of ash transformations – at low temperatures effects are insignificant. Ash transformations occurring during fixed-bed conversion are shown in simulations to extinguish the combustion by encapsulating the char and limiting the oxygen transport, if the temperatures are high enough to trigger the transformations in the first place. These computational explorations were made possible by the model despite the fact that no severe slagging (ash melt covering significant portions of unconverted fuel) was observed in the fixed-bed experiments. Numerical simulations could also illustrate how counter-current fixed-bed combustion is less sensitive to ash transformations induced by bed inhomogeneity than co-current operation.

Front propagation rates, temperature levels and gas phase compositions were in acceptable agreement for the pelletized fuels at low to medium air-flow rates. Close to the stoichiometric limit, the front propagation is overpredicted, which negatively affects the quality of the prediction for the gas phase composition. Front propagation rates are underpredicted for the highly porous wood chip bed. The transition from an oxygen-limited to a kinetically limited regime is captured by the model.

In conclusion, the milestone has thus been achieved. Two areas have been highlighted for continued development: the ability of the bed model to accurately describe wood chip combustion at the current conditions, and the accuracy of the predicted front propagation in the bed at high air-flow rates. Moreover, the ash transformation model uses four parameters (switching temperature, temperature transition interval and two limiting porosities at high/low temperature). It would be beneficial if these parameters could be linked to well-characterized fuel/ash properties. Experimental recordings of catastrophic ash transformations would therefore be very useful to further advance the ash transformation modelling in future work.

MS2.2 Validation of the model performed

In order to validate the model development of MS2.1, combustion experiments were performed in an insulated 60 L bench-scale stationary-bed reactor. Standard wood pellets were compared to poplar wood pellets and poplar wood chips. For each experiment, approximately 25 kg of pellets (or 6.5 kg of wood chips) were loaded in the reactor. The bed was ignited from the top while primary air was injected from below. Three different air-flow rates were used (0.1,
0.25 and 0.5 kg/m²/s) and repeated experiments were performed. The temperature in the reactor was measured with thermocouples in four different locations (at two heights inside the bed, above the bed and in the walls). The reactor was also placed on a scale to record the mass loss. Gas concentrations were measured with a micro-GC and an FTIR-instrument by extraction of gas samples from the fuel bed. Finally, the remaining ash was analysed by weighing and by assessing the degree of sintering and slagging after each run.

The vertical propagation speed of the front of fuel conversion, in opposite direction to the flow of air, was determined from the time between temperature gradients of vertically aligned thermocouples. The vertical propagation speed has been used to validate the model because it is a fundamental performance measure of fixed-bed combustion processes, which depends on the balance between the reaction rate and the heat transfer mechanisms in the bed. The position of the front is here defined as the position in the bed where the surface temperature of the fuel particles reaches 800 K. Measurements and model predictions of the front propagation speed for various fuels and air-flow rates are compared in Figure 2.2.1. Front propagation speed for experiments and simulations of pellet combustion in this project and in the previous ERA-NET project “MiniBioCHP”.

![Figure 2.2.1. Front propagation speed for experiments and simulations of pellet combustion in this project and in the previous ERA-NET project “MiniBioCHP”.

The predicted front propagation speeds are in acceptable agreement with the experiments. At larger air-flow rates, the simulations overpredict the front propagation rate. The shape of the curve in this region is sensitive to the particle size distribution. One possible explanation for the mismatch is that the uniform pellet size used in the simulations underestimates the effective size in the experiments. Experimental data on standard wood pellet combustion (from different batches and of different size) before and after reactor renovation are in good agreement. Front propagation rates were underpredicted for the highly porous wood chip bed, indicating that the heat and mass transfer correlations used need further revision for the chips.

No severe slagging (ash melt covering significant portions of unconverted fuel) was observed in the experiments. It was therefore not possible to tune the parameters of the ash transformation model to recreate such events. However, explorative simulations were performed in which ash transformations were triggered numerically to study the effect on combustion stability. At higher temperatures (i.e. higher air-flow rates), such an event causes ash melting to shut down char combustion relatively quickly. At temperatures lower than the ash melting temperature in the ash transformation model, no effects on the combustion process were observed.

The ash remaining in the reactor after the experiments with poplar pellets was characterized as partly sintered at all combustion conditions. The ash recovery was lower at the higher air-flow rates, which indicates non-negligible fly-ash entrainment.

MS2.2 Validation of the model performed, has been reached as planned.
MS3.1: Concepts for the adaptation of 2 fixed bed boiler technologies for new biomass fuels including process control available and ready for implementation by the industrial partners

Together with KWB, BIOS worked on the CFD-aided adaptation respectively optimisation of a small-scale (50 kWth) biomass boiler based on the KWB Multifire series to make it also suitable for the utilisation of ash, N, S and Cl-rich fuels such as wheat straw and sunflower husks. Results gained from the lab-reactor tests have thereby been taken as a relevant basis for an appropriate adaptation of the empirical packed bed model, which is applied to generate the release profiles of gas species and energy from the grate for subsequent gas phase CFD modelling. From comprehensive CFD simulations and discussions with KWB the following measures have been recommended for enhancing fuel flexibility:

- Improved insulation of the cooled section of the secondary combustion zone.
- Implementation of nozzles for re-circulated flue gas in the primary combustion zone.
- Modification of the shape and orientation of the secondary air nozzles.
- Operation of the plant at the air staging settings and flue gas recirculation ratios according to the CFD simulations (i.e. under extreme air staging conditions with low primary air ratios).

The respective adaptations of the hardware and the process control system have been implemented by KWB and an appropriately adapted boiler has been provided for the test runs within WP4.

Comparable work has been performed by BIOS in cooperation with Polytechnik regarding the medium-scale capacity range (<1 MWth), using sewage sludge and grass pellets as design fuels. Regarding this combustion plant the most relevant measures to enhance fuel flexibility were:

- In addition to flue gas recirculation above the fuel bed, flue gas recirculation below the grate should be installed.
- A reduction of the effective primary air ratio was recommended to reduce fuel bed temperatures.
- False air intake should be reduced by improvement of sealing especially regarding the fuel feeding, the de-ashing system and the flue gas recirculation pipes.
- The flue gas and furnace wall temperatures should be kept moderate by flue gas recirculation in order to reduce hard ash deposit formation on the furnace walls.
- The excess air ratio should be minimised via the amount of secondary air by a λ-sensor and simultaneous control of the gas temperature in the secondary combustion zone by flue gas recirculation should be realised in order to increase efficiency.

The respective adaptations of the hardware and the process control system have been implemented by Polytechnik and an appropriately modified combustion plant has been made available for the test runs within WP4.

Finally, BIOS used operation data gained from test runs performed within WP4 at the small (KWB) and medium-scale (Polytechnik) combustion plant as a basis to evaluate the CFD simulations and the models applied with test run data. The results of these CFD simulations proved the accuracy of the models developed. Moreover, they supported the evaluation of the test runs regarding the application of measures to further develop the plant technologies towards enhanced fuel flexibility.

The work at BIOS, KWB and Polytechnik has proceeded as planned. MS3.1, Concepts for the adaptation of 2 fixed bed boiler technologies for new biomass fuels including process control available and ready for implementation by the industrial partners, could thus be reached with a slight delay of two months in August 2017.

MS3.2: Concept for a pulverised fuel combustion system available for implementation in a testing plant.

The development of the concept of a new combustion system for difficult biomass fuels presupposes the use of dried sewage sludge and wheat straw for this purpose. The use of waste fuels limits the targeted production of energy crops and eliminates the onerous problem of biodegradable waste management. BTI as part of its task prepared the required amount of straw and delivered to the Institute of Power Engineering (IEn) in the form of ready dust. The dry sewage sludge, supplied by the municipal wastewater treatment plant, was micronized before the tests were carried out. In accordance with the procedure developed by IEn for the design of a new combustion system and the use of new fuels, IEn performed chemical and sieve analyzes of the particle distributions of the supplied dust fuels as well as ignition tests and ignition temperatures in a 1.5m drop tube reactor.

In the next stage of the task implementation, CFD simulations of the proposed concept of burners for the utilization of selected waste fuels were performed. During the project meetings, it was recognized that the most important from the economic point of view is primarily the utilization of dry sewage sludge. Three basic arguments give rise to such conclusions:
• disposal of hazardous waste (sewage sludge) whose agricultural use is already banned
• heat production with the possibility of conversion to electricity
• the possibility of recovering significant quantities of phosphorus from the ash obtained when burning sewage sludge.

At the same time, together with the construction of burners enabling the combustion of waste biomass fuels, combustion chamber designs have been proposed. The technology assumes the possibility of utilization of these fuels along with liquid or dry discharge of slag / ash from the combustion chamber. Both methods have many advantages under certain conditions. Liquid discharge of slag makes it possible to reduce the volume of ash produced in the combustion process, and the vitrified form of solidified slag prevents leaching of harmful elements, thus making it safe for further storage or use in construction for the production of aggregate or mineral wool in a special cooling process. However, dry slag removal can be beneficial in the case of sewage sludge combustion due to easier recovery of valuable phosphorus from ash than melted slag.

The following figures present the results of numerical simulations of sewage sludge and pulverized wheat straw combustion. The proposed combustion chamber is U-shaped (Fig.3.2.1) with a ceiling-mounted dust burner. In the lower part of the combustion chamber there is a drain hole for the liquid pathway.

Numerical simulations were performed for a typical high-stabilization design of the IEn swirl burner and a newly developed four-stage burner with divided outflow of secondary air. The high-stabilizing burner had two annular secondary air streams and an unswirled primary air stream with fuel. The power in the fuel is 1.3 MW.

However, in the case of a swirl burner, a very low, 10%, degree of ash uptake was obtained despite favorable temperature conditions on the walls of the combustion chamber (Fig.3.2.2 and Fig.3.2.4). About 75% of the surface of the walls has reached a temperature above the ash flow temperature (T > 1350 °C). However, the analysis of the simulation results showed that a relatively small percentage of the dust reaches the walls of the chamber. These results led to the development of a new burner design, largely devoid of these drawbacks. In the new burner concept, the secondary air flow was replaced by the outflow of 4 profiled tubes, circumferentially spaced in exchange for annular nozzles. In the new variant, the secondary air also had a circumferential angle because the tubes were bent in the tangential direction in the same way as in the vane burner blades. However, the discontinuity of the secondary air stream on the periphery caused dust particles to enter between the tubes. This effect is illustrated in Fig.3.2.3 and Fig.3.2.5 showing the trajectories of particles. The changes in the burner caused an increase in the degree of catching dust up to approx. 20%, mainly due to the increase in the amount of dust near the walls of the chamber, which significantly improved the pathway dripping conditions. The new burner did not cause deterioration of flame parameters and temperature conditions on the chamber walls.

In addition, the design of granulation grates improved the efficiency of ash catching, in combination with the new four-nozzles burner, to approx. 75%.

Fig.3.2.3 and Fig. 3.2.5 show the trajectories of particle movement in the combustion chamber for sewage sludge and wheat straw, both for the swirl burner and the four-nozzles burner. For both fuels, the conclusions are similar.

In the commercial design of the combustion chamber, the use of exhaust gas recirculation may also be considered, which in the case of dry ash removal should have beneficial effects on this phenomenon. Recirculation allows better control over maintaining the desired temperature inside the combustion chamber. However, the final decision regarding the choice of the type of ash discharging system (in liquid or dusty form) could only be made after performing experimental tests in task 4.4.
Fig. 3.2.1. Scheme of the proposed design of the combustion chamber

a) swirl burner  

b) four-nozzles burner  

Fig. 3.2.2. The temperature of the combustion chamber walls (°C), fuel - sewage sludge

a) swirl burner  

b) four-nozzles burner  

Fig. 3.2.3. Trajectories of particle motion - swirl burner (color - speed, m/s), fuel - sewage sludge
Finally the milestone has been fully achieved.

**MS3.3: Concept of the pulverized biomass fuel production and storage**

The first task involved developing the concept of a new method for pulverizing and storing of biomass fuels. In this task a concept of new technology was defined for pulverizing (grinding to dust) and storing biomass fuels. This technology takes into account the specificity of biomass fibrosity and vulnerability to explosion risks for powdered dry biomass. Therefore, the new technological concept is dominated and conditioned by the above aspects. The concept is based on the following assumptions:

1. The obtained biomass is initially crushed to make it uniform and then dried to the required moisture level, applying known and widely-used technologies.
2. The biomass prepared in this way is formed into pellets, which are transported and stored applying known and widely-used technologies.
3. Grinding of biomass pellets into dust directly in the burner system, where the burner is directly supplied with fuel-air mixture.

Where the first and second assumptions are implemented by known and widely-used technologies, the third assumption required detailed and original approach. The most important part of solving this problem was to design a shredder, which would be also able to co-operate with the burner in a series, dependent system.

BTI developed this solution and constructed a prototype of the grinder which allowed us to perform the tests with 1.2 MW burner. Effects of this solution include:

1. Low energy consumption of the grinding process due to the combined process of biomass cutting and grinding.
2. The system uses aerodynamic flow of air for transporting and cooling working elements of the grinder.
3. Easy and inexpensive method for the continuous feeding fuel (pellets) into the grinder and at the same time to the burner.
4. Easy and minimized range of explosion protection measures at the section of grinder-burner, ensured by HRD system.

The solution is based on a disk grinder, which has one fixed disk and one rotating disk. Moreover, the disks are fitted with a system of cutting blades and grinding rings that ensure low energy consumption of the grinding process.
To predict the slagging tendency of a fuel in a biomass boiler, the PASSA (Pellets ash and slag sieving assessing) method was used. The slag index is calculated according to the equation:

\[ \text{Slag index} = \sum \text{of particles} > 3.15\text{mm} / \text{total mass of ash} \]  

In a second step, the bottom ash, grate ash and fly ash from the heat exchanger were separately weighed on a balance with a resolution of 0.1 g (Mettler-Toledo GmbH, PG12001-S). The bottom ash and grate ash were analysed regarding slagging using a sieving machine (AS400 control by Retsch GmbH & Co. KG), operated at 200 rpm for one minute using mesh wire cloth sieve sets with opening widths of 0.5, 1.0, 2.0 and 3.15 mm. The slag index was then calculated according to equation 1.

Performance of the grinder is designed to meet the needs of the cooperating burner. The fuel is provided by adjusting the stream of material fed to the grinder.

The design of working parts of the grinder (disks) is a patent-pending solution submitted to the Polish Patent Office. After constructing the prototype and performing the tests, BTI proceeded to implement task No. 2 and prepared samples of pulverized biomass obtained from straw for IEn. The samples were provided to IEn in Warsaw.

Then within task No. 3, a comparative economic analysis was carried out, which revealed that the use of the new technology (compared to the process of grinding the biomass in a specialized plant and transporting liquid fuel for the burner system) is approximately 25%-35% cheaper in terms of investment costs and approximately 9%-14% cheaper in terms of operational costs.

**MS 4.1 – MS 4.4: Test and evaluations, as described in individual tasks, completed**

**MS4.1**

The boiler used for the combustion trials was a moving grate boiler (GUNTAMATIC Heiztechnik GmbH, Powerchip 20/30, constructed in 2010) with a lateral fuel insertion. The ash is removed via the moving grate to a screw conveyor which transports the ashes into the ash box. This boiler is suitable for wood chips (7–30 kW), wood pellets (7–30 kW), grain (7–25 kW) and miscanthus (7–25 kW) according to the user manual. To determine the fuel consumption during combustion, the storage tank was placed on a platform scale with a resolution of 0.005 kg. The heat consumption was permanently regulated to a nominal load of 30 kW (+ 8 %) following DIN EN 303-5. The gaseous components CO, CO₂, and O₂ were determined using a single component analyser (ABB Automation GmbH ABB AO2020), NOx by a chemiluminescence detector (Eco Physics GmbH CLD 822 Mhr Analysator) and for water vapour content, SO₂, HCl and CH₄ an FTIR-analyser (Ansyco GmbH FTIR DX4000N) was used. The recording interval for the continuous measurement was set to 10 seconds. The total particulate matter (TPM) was measured following VDI 2066-1 applying a filtration temperature during sampling and the filter pre- and post-treatment temperature of 180 °C. The boiler was operated at a constant flue gas draught of -15±2 Pa as it is suggested by the boiler manufacturer. The diameter of the flue gas duct and the connection pipe was 150 mm. The flue gas velocity was continuously measured using a vane anemometer (Höntzsch GmbH, ZS25/25-ZG4) positioned in a narrowed stretch of the measurement section with a diameter of 100 mm.

Prior to each trial, the combustion chamber, the heat exchanger and the fuel feeding system were completely cleaned using a vacuum cleaner, a brush and pressurized air. The storage tank was filled with sufficient amount of fuel and the boiler was started and heated up to steady state operation at nominal load (30 kW) within approx. 2 h. Then the measurement was performed over 8 h at nominal load operation. Within this time period, the gaseous emissions were continuously recorded but were evaluated only for the duration of the TPM measurements. Four TPM measurements were performed evenly spread over the whole 8 h (0–30 min, 150–180 min, 300–330 min and 450–480 min). All reported emissions refer to dry flue gas at 0 °C and 1.013 hPA and are based on 13 % O₂. After each test run ashes were completely removed from the boiler and analysed regarding slag formation. As a first step, visual classification according to Table 4.1.1 was done.

### Table 4.1.1. Description of sintering degree for slag collected from the residual ash

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Non sintered ash residue, i. e. no fused ash (clear grain structure)</td>
</tr>
<tr>
<td>2a</td>
<td>Partly sintered ash, i. e. particles contained clearly fused ash that breaks at a light touch (distinguishable grain structure).</td>
</tr>
<tr>
<td>2b</td>
<td>Partly sintered ash, i. e. particles contained clearly fused ash that holds together at a light touch but is easily broken apart by hand (distinguishable grain structure).</td>
</tr>
<tr>
<td>3</td>
<td>(Totally) sintered ash, i. e. the deposited ash was fused to smaller blocks that still are breakable by hand (slightly distinguishable grain structure).</td>
</tr>
<tr>
<td>4</td>
<td>Totally sintered ash, i. e. the deposited ash was totally fused to larger blocks that not are possible to break by hand (no distinguishable grain structure).</td>
</tr>
</tbody>
</table>

In a second step, the bottom ash, grate ash and fly ash from the heat exchanger were separately weighed on a balance with a resolution of 0.1 g (Mettler-Toledo GmbH, PG12001-S). The bottom ash and grate ash were analysed regarding slagging using a sieving machine (AS400 control by Retsch GmbH & Co. KG), operated at 200 rpm for one minute using mesh wire cloth sieve sets with opening widths of 0.5, 1.0, 2.0 and 3.15 mm. The slag index was then calculated according equation 1.

\[ \text{Slag index} = \sum \text{of particles} > 3.15\text{mm} / \text{total mass of ash} \]  

To predict the slagging tendency of a fuel in a biomass boiler, the PASSA (Pellets ash and slag sieving assessing) test was performed.
assessment) method has been developed in the EU project AshMelT and it was further elaborated at TFZ. For each pelletized fuel, the PASSA method was conducted twice. Therefore, 250 g of the respective pelletized fuel were placed in a pre-weighted crucible and thermally treated applying a temperature program as shown in Figure 4.1.1 (Nabertherm GmbH, muffle furnace LT15/13/P330). The maximal temperature was 1,000 °C.

![Figure 4.1.1. Temperature programme for the PASSA method.](image)

After the sample had cooled down in a desiccator, it was weighted together with the crucible on an analytic balance with a resolution of 0.001 g (Kern & Sohn GmbH, 572-35). Afterwards, the sample was carefully removed from the crucible using a brush and analysed granulometrically using the sieve set and the sieving machine mentioned in chapter 2.4.2. The empty crucible was weighted again after removing the loose ash fractions. If there was some amount of the sample left sticking to the crucible due to slagging or glazing it was added to the fraction > 3.15 mm. The slag index of the PASSA method was then also calculated applying equation 1.

All fuels were applied in the 30 kW boiler over an 8 h full load operation with exception of pure wheat straw. The pure wheat straw test had to be interrupted due to severe slagging which occurred after the second particle measurement (180 min). As a result, the boiler could not maintain steady state operation anymore. Therefore no direct comparison of the emissions from pure wheat straw (which is marked differently in the diagrams) and the additivated or blended fuels was possible.

The CO emissions from wood pellets as well as from the wood/wheat straw blends were on a very low level between 17 mg/Nm³ for pure wood and 5 mg/Nm³ for all blends (Figure 4.1.2, left). CO emissions even decreased with higher shares of wheat straw. The CO emissions of the blend with 50 w-% wood pellets mixed with 50 w-% pure wheat straw pellets (i.e. “Wood 50 Straw 50 mixed” in Figure 3 left) were 10 times higher than for the pelletized blends. Variation was also higher (see min and max values). However, results indicate that the combustion conditions were not so stable (high CO peaks spread over the whole trial) for the mixed compared to the pelletized blends. The highest CO emissions for this fuel group were measured for wheat straw with 3.45 mg/Nm³ for all blends (with a Lambda of 1.200), sunflower husk and grass fuels was possible. For poplar pellets the CO emissions were approx. 81 times higher and for poplar wood chips approx. 52 times higher than for wood pellets (Figure 4.1.2, middle). By additivation of poplar with 1.5 w-% kaolin, the CO emissions were largely reduced by approx. 92 %. When kaolin was added manually to fuels after pelleting in an additional trial (i.e. “poplar pure + 1.5 w-% kaolin”, Figure 4.1.4) the CO reduction was still high, i.e. at 74 %. By dosing the kaolin directly to (unpelletized) poplar chips into the screw feeder (“poplar chips +1.5 % kaolin”, Figure 4.1.2, middle) a reduction of 95 % was observed.

![Figure 4.1.2. CO emissions measured for all fuels containing wood and wheat straw (left), poplar fuels (middle) and sunflower husk and grass fuels (right).](image)

The same trends were observed for sunflower husk and grass pellets which showed even higher CO levels than poplar (Figure 4.1.2, right). The CO emissions of sunflower husk pellets were reduced by approx. 69 % by adding 2.8 w-% kaolin. For grass pellets, the reduction was 93 % (at 8.1 w-%) and 95 % (at 10.5 w-%).

The observed reduction of CO emissions was also indicated by several other researchers using underfeed cup burner, grain burner or moving grate burner. Only in one case, increased CO emissions had been measured (with a
cereal burner). One reason for CO reduction could be a catalytic effect of kaolin as it is used as a catalyst in other fields of application such as synthesis of 1,5-Benzodiazepines or for CO₂ photocatalytic reduction. On the other hand, the fire bed structure is expected to be improved by the embedment of K-silicates in the ash and. Therefore, it can be assumed that channelling and formation of CO layers is prevented in a more homogeneous fire bed.

Due to the better embedding of K in the bed ash (see chapter MS2.3), less reaction partners for Cl and S during aerosol formation were available and, consequently, HCl (Figure 4, left) and SO₂ (Figure 4.1.3, right) emissions were increased for the kaolin additivated fuels. For the fuel blends (wood / wheat straw), a dilution of the chlorine and sulphur content in the fuels was observed, resulting in lower HCl and SO₂ emissions compared to pure wheat straw.

For the organic gaseous carbon (OGC) emissions (data not shown) no clear trend was observed between pure and kaolin additivated fuels. The highest OGC emissions were detected for pure sunflower husk (18.8 mg/Nm³) and for sunflower husk additivated with 2.8 w-% kaolin (45.1 mg/Nm³).

The NOₓ emissions (Figure 4.1.4) increased with increasing nitrogen content in the fuels. For fuels with high nitrogen contents (e. g. in grass), the conversion rate from fuel nitrogen to NOₓ decreased. For the kaolin additivated fuels, the NOₓ emissions increased except for pure wheat straw. The deviation between the NOₓ emissions of the pure and additivated fuel is increasing with the nitrogen content of the fuel (by 5.5 to 26 %). The negative effect of kaolin on NOₓ emissions was also observed by other researchers and in a previous project at TFZ when kaolin additivated beech pellets were fired in a pellet boiler. The mechanism behind this is still unknown and further investigations are needed to get a detailed explanation about the negative impact of kaolin on NOₓ emissions.

Total particulate matter (TPM) emissions of wood pellets, wheat straw blends, pure wheat straw and additivated wheat straw are summarized in Figure 10. As expected, the lowest values were achieved for wood pellets emitting 24 mg/Nm³ of TPM during full load operation, which is close to the TPM emission threshold value of 20 mg/Nm³, i. e. the TPM emission limit of the 1. BImSchV (First ordinance of the German emission control act).
Blending of wheat straw with wood reduced TPM emissions compared to pure straw (Figure 4.1.5, left). A blend with 90 w-% pure wood caused nearly the same particle emissions as for pure wood pellets. Moreover, the process of fuel blending, i.e. whether fuel blending is performed before or after pelletization, was relevant. When already produced wheat straw and wood pellets were mixed at a ratio of 50:50 (i.e. “Wood 50 Straw 50 mixed” in Figure 4.1.5, left) TPM emissions of 57 mg/Nm³ were released. In contrast, lower emissions of only 42 mg/Nm³ were achieved, when the same fuel ratio was realized in the raw material before pelletization (i.e. “Wood 50 Straw 50” in Figure 4.1.5, left). Due to the above mentioned slagging related problems with pure wheat straw pellets, no direct comparison between this test run and the blended and additivated fuels was possible. Particle emissions of wheat straw with 3.45 w-% kaolin were 75 mg/Nm³ on average, which is clearly higher than for all straw/wood blends. However, with kaolin additivated straw pellets, the boiler could be operated over 8 h without any slag related problems indicating clear benefit of additivation or blending compared to pure fuels.

For pure poplar pellets, the particle emissions were on average 156 mg/Nm³ and therefore 6.5 times higher compared to wood pellets (Figure 6, middle). By additivation of 1.5 w-% kaolin, the particle emissions were reduced by approx. 71 % down to 46 mg/Nm³. By adding 1.5 w-% kaolin to poplar pellets after pelletizing (i.e. “Poplar pure + 1.5 % kaolin”), TPM was reduced down to 69 mg/Nm³. During the combustion of poplar wood chips, the particle emission was slightly higher compared to poplar pellets. By the direct additivation of kaolin to poplar wood chips via dosing to the screw feeder (i.e. “Poplar chips +1.5 % kaolin”), TPM could be reduced by 44 % compared to pure poplar chips.

Figure 4.1.5 (right) shows the particle emission measured for all sunflower husk and grass pellets. Compared to wood pellets, the particle emissions for pure sunflower husk pellets were 22 times and for pure grass pellets almost 36 times higher. By additivation with kaolin, the particle emissions for sunflower husk were reduced by 77 % (2.8 w-% kaolin) and for grass by 53 % (8.1 w-% kaolin) and 62 % (10.5 w-% kaolin), respectively. At this extremely high level of particle emissions, especially for pure sunflower husk and pure grass pellets, the additivation with kaolin alone cannot be the solution for low emission combustion in small scale biomass boilers as emission levels were still very high. However, kaolin might be an option to reduce dust pollution in the raw gas entered into a dust precipitator, which could then work more effectively.

Ash analyses and slagging behaviour of the pelletized fuels
All ash residues were collected from each combustion trial. The total amount of ash from an 8 hours full load operation plus approx. 2 h starting and preheating phase was between 0.2 kg for wood pellets and 16.6 kg for grass pellets with 10.5 % kaolin (Table 4.1.2). To cope with such high masses of ash, the ash box of the boiler had to be emptied after approx. 4 h of full load operation when grass containing fuels were applied. This means that for such fuels a boiler should be equipped with a large ash box or a powerful deashing system.

Table 4.1.2 shows the particle size distribution of the collected ashes. For the wood / straw blends, the fraction of particles larger than 3.15 mm increased gradually with higher shares of wheat straw, i.e. from 18.9 w-% for pure wood pellets up to 81.4 w-% for pure wheat straw. Additivation with kaolin reduced the fraction > 3.15 mm for pellets from wheat straw, poplar and sunflower husk. In contrast, for grass containing pellets this ash fraction increased with higher kaolin content.
A method.

Table 4.1.2. Results from the granulometric analysis of the boiler ashes (grate ash + fly ash)

<table>
<thead>
<tr>
<th></th>
<th>Total amount of ash</th>
<th>&gt; 3.15 mm</th>
<th>&gt; 2.0 mm</th>
<th>&gt; 1.0 mm</th>
<th>&gt; 0.5 mm</th>
<th>&lt; 0.5 mm w.b.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood pure</td>
<td>0.20</td>
<td>18.9</td>
<td>15.8</td>
<td>50.1</td>
<td>10.3</td>
<td>4.9</td>
</tr>
<tr>
<td>Wood90 straw10</td>
<td>0.52</td>
<td>43.3</td>
<td>9.2</td>
<td>38.8</td>
<td>6.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Wood75 straw25</td>
<td>0.98</td>
<td>71.4</td>
<td>5.7</td>
<td>16.0</td>
<td>5.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Wood50 straw50</td>
<td>1.85</td>
<td>78.8</td>
<td>5.5</td>
<td>11.2</td>
<td>3.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Wheat straw pure</td>
<td>2.42</td>
<td>81.4</td>
<td>8.8</td>
<td>7.6</td>
<td>1.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Wheat straw 3.1% kaolin</td>
<td>6.08</td>
<td>58.9</td>
<td>14.3</td>
<td>13.6</td>
<td>8.6</td>
<td>4.7</td>
</tr>
<tr>
<td>Poplar pure</td>
<td>1.42</td>
<td>72.6</td>
<td>7.4</td>
<td>12.6</td>
<td>4.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Poplar 1.5% kaolin</td>
<td>2.48</td>
<td>49.8</td>
<td>10.7</td>
<td>31.5</td>
<td>6.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Sunflower husk pure</td>
<td>1.70</td>
<td>70.9</td>
<td>8.7</td>
<td>10.2</td>
<td>6.4</td>
<td>3.8</td>
</tr>
<tr>
<td>Sunflower husk 2.8% kaolin</td>
<td>3.69</td>
<td>65.4</td>
<td>5.5</td>
<td>22.6</td>
<td>5.1</td>
<td>1.4</td>
</tr>
<tr>
<td>Grass pure</td>
<td>6.77</td>
<td>61.0</td>
<td>9.7</td>
<td>14.7</td>
<td>7.5</td>
<td>7.2</td>
</tr>
<tr>
<td>Grass 8.1 % kaolin</td>
<td>13.46</td>
<td>71.6</td>
<td>5.2</td>
<td>7.1</td>
<td>6.5</td>
<td>9.6</td>
</tr>
<tr>
<td>Grass 10.5 % kaolin</td>
<td>16.64</td>
<td>85.1</td>
<td>2.0</td>
<td>2.4</td>
<td>3.3</td>
<td>7.3</td>
</tr>
</tbody>
</table>

\(^{a}\) values are presented on as received basis; w.b.: wet basis

In direct comparison, the slag index calculated by the PASSA method and the slag index calculated by the boiler ashes (Table 4.1.3) are showing very similar results for wood pellets. For pure agricultural fuels, the wood / straw blends and the kaolin additivated fuels, the slag index calculated for the boiler ashes seems to distinguish more precisely between the different fuels than the slag index according to the PASSA method. This could be due to a lower bed temperature in the boiler due to cooling by the primary air through the grate. As a consequence, for some fuels, the PASSA method (in the current stage of development) is indicating contrary slagging tendencies compared to the slag index for the boiler ashes regarding the effect of kaolin.

The results of the visual classification of the ashes from the boiler tests (Table 4.1.3) are very subjective and depend largely on the person who performs the test. Nevertheless, these results are more in line with the slag index for the boiler ashes. Still, visual inspection did not allow for any differentiation between the wood / straw blends and the pure straw pellets. It also leads to contrary results regarding the additivation of poplar with kaolin.

One interesting aspect is the share of slag which remains sticking to the crucible after performing the PASSA method. While in case of pure wheat straw and pure grass pellet approx. 100 w-% of the sample remained sticking to the crucible (Figure 4.1.6), this share was drastically reduced to only 1 w-% (Figure 4.1.6) when additivation with kaolin was applied (Table 3). This was due to the fact that for wheat or grass fuels that were additivated with kaolin, the residues after the PASSA treatment in the crucibles did not turn into a small heap of loose particles but they rather retained their original cylindrical pellet shape while having been transferred into a very fluffy and soft mode with no particles sticking to the crucible (Figure 4.1.6). These sintered “ash pellets” were hard enough to not fall apart by a light touch (sintering degree 2a) but they were at the same time easily breakable by hand (sintering degree 2b–3, see definitions in Table 4.1.1).

Table 4.1.3. Sintering degree and slag index for boiler ashes and slag index and share of ash sticking to the crucible for the PASSA method

<table>
<thead>
<tr>
<th>Visual classification of boiler ash</th>
<th>Slag Index boiler</th>
<th>Slag index PASSA</th>
<th>PASSA: Slag share sticking to crucible</th>
<th>w-% w.b.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood pure</td>
<td>2</td>
<td>0.24</td>
<td>0.26</td>
<td>19</td>
</tr>
<tr>
<td>Wood90 straw10</td>
<td>4</td>
<td>0.43</td>
<td>1.00</td>
<td>100</td>
</tr>
<tr>
<td>Wood75 straw25</td>
<td>4</td>
<td>0.71</td>
<td>1.00</td>
<td>100</td>
</tr>
<tr>
<td>Wood50 straw50</td>
<td>4</td>
<td>0.79</td>
<td>1.00</td>
<td>100</td>
</tr>
<tr>
<td>Wheat straw pure</td>
<td>4</td>
<td>0.81</td>
<td>1.00</td>
<td>100</td>
</tr>
<tr>
<td>Wheat straw 3.1% kaolin</td>
<td>3</td>
<td>0.59</td>
<td>0.97</td>
<td>1</td>
</tr>
<tr>
<td>Poplar pure</td>
<td>2</td>
<td>0.73</td>
<td>0.49</td>
<td>24</td>
</tr>
<tr>
<td>Poplar 1.5% kaolin</td>
<td>2b</td>
<td>0.50</td>
<td>0.70</td>
<td>1</td>
</tr>
<tr>
<td>Sunflower husk pure</td>
<td>2b</td>
<td>0.71</td>
<td>0.41</td>
<td>26</td>
</tr>
<tr>
<td>Sunflower husk 2.8% kaolin</td>
<td>2a</td>
<td>0.65</td>
<td>0.69</td>
<td>1</td>
</tr>
<tr>
<td>Grass pure</td>
<td>2a</td>
<td>0.61</td>
<td>1.00</td>
<td>100</td>
</tr>
<tr>
<td>Grass 8.1% kaolin</td>
<td>3</td>
<td>0.72</td>
<td>0.99</td>
<td>1</td>
</tr>
</tbody>
</table>
Grass 10.5% kaolin  3  0.85  0.99  0

Figure 4.1.6. Pure wheat straw after performance of the PASSA test (left) and after cleaning the crucible by brush (middle-left), wheat straw with 3.15 % kaolin after performance of the PASSA test (middle-right) and after cleaning of the crucible by a brush (right)

For moving grate boilers or boilers with a comparable effective deashing system only a low risk of operational disturbance is to be expected even for fuels with such "severe" sintering classification into class 2b or 3. However, if such fuels are applied in cup burners or fixed grate burners, their performance could be limited, as those softly sintered ash pellets might be problematic for the deashing system, as they could lead to bridging or piling up in the burner or be blocking the air inlet nozzle. Therefore, the evaluation methods of slagging tendencies such as the PASSA method should be revised to distinguish between the complete melting of the sample (share of slag sticking to the crucible) which could cause trouble in all kinds of boilers (as seen for pure wheat straw) and the loose but sintered fraction > 3.15 mm which is not sticking to the crucible and should, thus, be uncritical for moving grate or comparable boilers. Slagging of fuel blends was also assessed (Table 4.1.3). Blending of wheat straw with wood pellets can slightly reduce slagging problems. However, only for a blend with high wood content (90 w-%) a distinct reduction of slagging was observed.

**MS 4.2**

Comprehensive test runs have been performed by KWB and BIOS at the modified small-scale 50 kW Multifire boiler (see MS3.2) and by Polytechnik and BIOS at the appropriately adapted 1 MWth medium-scale combustion plant. At the KWB plant, wheat straw and sunflower husk pellets were used as fuels while the Polytechnik plant was tested with sewage sludge and grass pellets.

During the test runs a comprehensive measurement program, as foreseen in the description of work in the project proposal, has been carried out. This involved the recording of relevant operation parameters, fuel, ash and fly ash sampling with subsequent chemical analyses of selected samples as well as the determination of gaseous (CO, OGC, NOx, SO2, HCl) and particulate emissions downstream the boiler. At the medium-scale combustion plant additionally deposit sampling with an air cooled deposit probe and subsequent SEM/EDX analyses of selected deposit samples took place. In addition to the measurements stated in the description of work, measurements with an on-line low temperature corrosion probe as well as discontinuous measurements of the SO2 and SO3 contents in the flue gas downstream the boiler have been performed to gain detailed insights into low-temperature corrosion related issues. Based on the process and analyses data mass, energy and element balances over the respective plant have been calculated and based on practical experiences made during the test runs, the results of these balances as well as of the emission measurements, the plant operation has been assessed. Moreover, CFD simulations based on the process data gained (see MS3.2) supported the evaluation of the test runs.

Regarding the small-scale KWB boiler it can be stated that during the test runs with sunflower husk and straw pellets, stable load conditions prevailed. The boiler efficiencies were with about 90.0% close to the values for wood chip combustion. The targeted air staging settings regarding the primary air ratio could be achieved. For wheat straw pellets a good gas phase burnout (CO emissions below 20 mg/Nm³ related to dry flue gas and 13 vol% O2) could be achieved while for sunflower husk pellets significant CO emissions lead to elevated average CO emissions (on average 417 mg/Nm³ related to dry flue gas and 13 Vol% O2). However, these emissions are still close to the respective emission limit. The NOx emissions were, as expected due to the high N content of the fuels comparatively high but still below the emission limit according to the 1. BlnSchV for NOx (500 mg/Nm³). The PM1 and TSP emissions exceeded, as expected, the current emission limits, however, this problem can be controlled by implementing an ESP, as it is currently already usual for wood chip combustion plants in this capacity range. Due to the measures implemented (extreme air staging concept and flue gas recirculation), no problems with slagging on the grate occurred.

Summing up, even though some further optimisations are still possible and in case of sunflower husk pellets regarding the CO emission also needed, the measures implemented have resulted in a combustion technology,
which is capable to utilise challenging biomass fuels such as wheat straw and sunflower husk pellets at high efficiencies, high availability and acceptably low emissions.

Regarding the medium-scale combustion plant, stable load conditions at around 870 kW could be achieved during the test runs with grass pellets. The targeted air staging and flue gas recirculation settings derived from the CFD simulations could almost be reproduced and formed the basis for a low-CO combustion without any problems with respect to ash melting on the grate and hard deposit formation in the combustion chamber. However, for a further improvement of air staging, a reduction of false air intake was recommended. The NO\textsubscript{x} emissions were, due to the high N content of the fuel, with 437 and 634 mg/Nm\textsuperscript{3} (NO\textsubscript{x} as NO\textsubscript{2}, related to dry flue gas and 6 vol% O\textsubscript{2}) high and in the range or even above the emission limits of the EU MCP directive (limit between 1 and 5 MW: 500 mg/Nm\textsuperscript{3}, limit > 5 MW: 300 mg/Nm\textsuperscript{3}). Therefore, the installation of an SNCR unit can be needed. Particulate emissions were with values of 866 to 1,028 mg/Nm\textsuperscript{3} (dry flue gas, 6% O\textsubscript{2}) at boiler outlet high and demand for an efficient dust precipitator. Appropriate ESPs or baghouse filters are state-of-the-art and commonly applied in medium-scale combustion plant.

Consequently, provided that appropriate measures for automated boiler cleaning, dust precipitation and NO\textsubscript{x} emission reduction are implemented, a combustion of grass pellets in the adapted Polytechnik furnace technology seems to be possible.

Due to its high ash content of typically more than 30 wt% (d.b.) and its unique ash composition (very high P contents), sewage sludge (SS) is an extremely challenging fuel. Even though it is not a preferred fuel for mono-combustion on a grate, it has been selected for test runs in order to represent an extreme cornerstone in the variation range of ash contents of challenging biomass fuels and to gain more information regarding the so far not well investigated P-chemistry during biomass combustion.

During the test runs with SS rather stable boiler load conditions prevailed at around 730 kW. The targeted air staging settings derived from the CFD simulations could not be reproduced due to slagging on the grate and the resulting pressure drop of the fuel bed. To reach the CFD values a fuel bed with a higher permeability is necessary. For further improvement of air staging, a reduction of false air intake and an adapted system for fuel feeding (screws instead of piston feeder) is required. Moreover, the grate size must be increased to reduce the bed height on the grate and increase the permeability of the fuel bed. However, very low CO and OGC emissions reveal a good burnout quality and indicate the fundamental usability of the fuel, even if the air staging conditions are not optimised. The NO\textsubscript{x} emissions were with 1,023 mg/Nm\textsuperscript{3} (dry flue gas, 6% O\textsubscript{2}) as expected, comparatively high due to the high N content of the fuel (5.48 wt% d.b.). In order to meet emission limits the installation of an SNCR unit is needed. Also for HCl and SO\textsubscript{2} emission reduction appropriate secondary measures need to be foreseen (dry sorption in combination with a baghouse filter). With the latter also the dust emission limits can be kept.

In general, the test runs have revealed that combustion of sewage sludge in a grate combustion plant is in principle possible, provided that the slagging related problems can be controlled. The related measures however, demand for a fuel specific design.

Summing up, the test runs performed have revealed that by implementing appropriate targeted adaptations the utilisation of challenging biomass fuels in small and medium-scale wood combustion plants is possible. However, as the extreme case of sewage sludge combustion shows, the applicable fuel potential for mono-combustion is limited to agricultural residues and excludes fuel assortments with outstandingly high ash contents and in parallel low ash melting temperatures such as sewage sludge. MS 4.2, Test and evaluations completed, has been reached with some delay at the end of the project. The delay was mainly due to higher efforts for the evaluation of the test runs and the interpretation of test run results. It had however, no impact on the work within other work packages.

**MS 4.3**

Combustion trials with a mix of wood chips and municipal sewage sludge have been performed in an existing commercially operated biomass grate boiler 2 x 8 MW + flue gas condensation 2 x 2 MW. The purpose of the trials was to add a level of sludge that would not affect the combustion in a negative way and where sludge more could act as a Sulphur additive. The sludge and chips mix consisted of 8% sludge and 92% wood chips in weight% wet raw material.

During the test runs the flue gases were analyzed with respect to SO\textsubscript{2}, HCl, NO\textsubscript{x}, CO, CO\textsubscript{2}, and O\textsubscript{2}. Sampling of dust particles was performed and HCl has been determined by wet chemical sampling. Fuel samples and ash samples were collected and analyzed according to standard methods at RISE accredited fuel laboratory and by Umeå University.

Fuel mixing of wood chips and sewage sludge worked similarly well. The Fuel composition was non-problematic from a combustion perspective (operation, slagging etc). SO\textsubscript{2}, HCl and NO\textsubscript{x} increased when adding sewage sludge and CO and dust emissions decreased. This was similar to the results from the laboratory experiments with added sewage sludge. Increased flue gas concentrations of HCl in combination with elevated SO2 concentrations could
show a reduction of chloride formation due to the Sulphur content in sludge. The ash analysis results didn’t show any big differences for the samples with added sewage sludge. A slightly increase in Cu, Al, Fe and P could be seen. MS 4.3. Test and evaluations completed, has been reached. In general, the test runs have revealed that combustion of wood chips in mix with small amounts of sewage sludge in a grate combustion plant is possible with small effects on the ash characteristics and emissions.

MS4.4

This task was performed to study the combustion of sewage sludge and wheat straw on equipment located at IEn with a capacity of approx. 0.3MW when the biomass supply. In the first stage, tests were carried out to assess the possibilities of sewage sludge combustion using typical technologies of pulverized fuel combustion. The tests used a highly stabilizing swirl burner of the IEn design. The layout of the test stand is shown in Fig.4.4.1. Preliminary tests were carried out without flue gas recirculation (FGR), which simulated typical conditions for biomass combustion. The tests showed a high slagging properties of sewage sludge. Fig.4.4.2a shows the interior views of the combustion chamber, showing the cleanliness of the combustion chamber using various techniques of sewage sludge burning in the form of dust.

Fig.4.4.1. Scheme of the test stand (max. 0.3 MW) with possible flue gas recirculation system

Preliminary studies have confirmed that in the case of incineration of sewage sludge is not possible to use conventional methods for biomass and construction of combustion chambers. After extensive analysis, it was decided that a key issue is the ease of recovery of phosphorus from the by-products of combustion of sewage sludge. Therefore, it is necessary to carry out the combustion process in such a way that the resulting ash has a dusty form. Therefore, it was decided to consider two variants - the use of recirculation of large quantities of fumes or the use of volumetric and flameless combustion technologies. Both methods allow to reduce the maximum combustion temperatures below the ash softening temperature from sewage sludge.

Fig.4.4.2. Interior views of the combustion chamber after tests carried out using various methods of organizing the combustion process

a) without FGR  b) with FGR  c) volumetric combustion

Therefore, additional numerical simulations of the swirl burner system and recirculation of significant amounts of flue gases were carried out. The simulation results are shown in Fig.4.4.3 and Fig.4.4.4.
The studies of micronised wheat straw and sewage sludge combustion were then carried out on a test stand at various FGR ratios.

Exhaust gas recirculation enabled reduction of the combustion temperature by about 100°C in the case of sewage sludge and even 150°C for wheat straw as compared to the case without exhaust gas recirculation. Lowering the maximum combustion temperature to approx. 1,090°C for sewage sludge has enabled the combustion chamber to operate below the ash melting point (around 1220°C).

The ultimate idea was to be able to carry out the combustion process bypassing the expensive exhaust gas recirculation system. Therefore, an attempt was made to apply volumetric combustion technology by dispersing the substrates and combustion products and simultaneously mixing them intensively in the whole volume of the...
combustion chamber. This was accomplished by means of six additional third-stage air streams arranged on the burner plate around the main swirl burner - Fig.4.4.6.

The numerical model was made and CFD calculations for a new burner for volumetric sewage sludge combustion were carried out.

Then a prototype of a new type of burner was made and laboratory tests of sewage sludge combustion in volume mode were carried out. This mode was characterized by the absence of a clearly visible flame front because the combustion process was dispersed.

The results of experimental investigations of temperature profiles in the combustion chamber are shown in Fig.4.4.8. At the same time, photographs of interior of the combustion chamber - Fig.4.4.2c - after testing with the use of a volumetric combustion system, indicate a significant reduction in the slagging process of the chamber walls. The view of the combustion chamber is comparable to the case of exhaust gas recirculation – Fig.4.4.2b. In all of the cases shown in Fig.4.4.2, the same amounts of sewage sludge were burned.
The volumetric combustion system enabled obtaining temperature profiles at a similar level as in the case of recirculation of significant quantities of exhaust gases, and even in most points of the combustion chamber below these values. Because the volumetric combustion system does not require an expensive system for exhaust gas recirculation, from the point of view of obtained experimental results it is the preferred method of utilization of municipal sewage sludge. The fly ash generated in this process has a convenient form for the recovery of significant amounts of phosphorus. The ash from the incineration of municipal sewage sludge contains about 23% P₂O₅.

Finally the milestone has been fully achieved.

**MS5.1: Common methodology for the techno-economic analyses defined**

Already in the second project year BIOS prepared a first structure and methodology for the techno-economic analyses, discussed it with the partners during the project meeting in September 2017 in Graz and then defined the final methodology to be applied. Within this methodology the framework conditions for the techno-economic analyses have been agreed which includes for instance the definition of reference regions, plant capacity ranges, fuels to be investigated as well as technology specific data needed as input from the project partners.

**MS5.1, Common methodology for the techno-economic analyses defined, has been achieved even ahead of schedule in January 2018.**

**MS5.2: Techno-economic analyses regarding design fuel utilisation as well as the specific combustion concepts for new biomass fuels finalised**

An economic evaluation of the production of the kaolin-additivated pelletised BIOFLEX!-fuels wheat straw, poplar, sunflower husks and grass in comparison to wood pellets and wood chips was performed. The main influencing cost factors considered in the calculations were the raw material, transport, additives, drying, pelleting and costs for increased wear and maintenance of the pelleting equipment, which are raising in close relation to the ash content of the specific fuel resp. fuel/additive-mixture. Sensitivity analyses concerning the increase respectively the reduction of the assumed lifetime of the pelleting equipment for the different fuels revealed only a minor impact on the total fuel costs.

In contrast, fluctuations in the price of the raw material and the transport have an important influence on the total fuel costs, since they have a dominant share of 62 to 67%. Due to the comparably low raw material costs for wheat straw and sunflower husks, respectively because of the fact that no drying is needed for pellet production from these feedstocks, the costs for additivated wheat straw pellets (WSP) and additivated sunflower husk pellets (SHP) in €/MWh are lower than for wood pellets (WSP: 24%; SHP: 34%). In case of SHP they are even lower than for wood chips (6%). The calculated price for additivated poplar pellets is in the same range as for wood pellets, whereas the production of additivated grass pellets seems not to be economically feasible due to the high raw material costs. In this context it has to be stated, that for grass currently only a market for high quality animal feed exists, resulting in comparably high prices. For fuel production, a cheaper raw material with lower quality requirements should be used to gain a competitive price for the additivated, pelletised fuel. However, the respective market has not developed yet. Consequently, according to the techno-economic analyses performed, additivation of challenging biomass fuels with kaolin seems to be feasible regarding both, technical issues as well as cost effectiveness for most fuels evaluated.

Moreover, the economic influences of the optimisation measures worked out within WP3 as well as realised and tested within WP4, have been investigated for both, the small-scale (KWB) and the medium-scale (Polytechnik) boiler technology in close cooperation of BIOS, KWB and Polytechnik. Based on the experiences made during the test runs within WP4 (see MS4.2), a technical assessment has been worked out.

For the economic evaluation only the additional (fuel flexibility related) costs and savings of the adapted boiler technologies in comparison to the costs of the basic boiler technologies (designed for wood fuels) have been considered. A cost calculation according VDI 2067 has been performed, containing the four cost groups capital and maintenance costs, consumption costs, operating costs and other costs. Austria has been chosen as reference region for the calculations. The fuels investigated for the adapted small-scale boiler technology were sunflower husk pellets (SHP) and wheat straw pellets (WSP), in case of the adapted medium-scale boiler technology, grass pellets (GP) and SHP were selected for the economic comparison, since sewage sludge has to be evaluated under the perspectives of the EU waste incineration guideline and can therefore not be compared with wood chips or wood pellet combustion.

**Results regarding the small-scale (50 kWₜ) boiler:** Taking 3,000 full load operation hours per year as a basis, the maximum fuel costs to compensate the additional costs for the adapted boiler technology and to achieve the same heat generation costs as for the basic boiler technology fired with wood pellets amount to 44.5 €/MWh for SHP and 41.3 €/MWh for WSP. The same calculation but in comparison to wood chips delivers 31.7 €/MWh for SHP and 28.6 €/MWh for WSP. As no market prices for SHP and WSP are available, the production costs of WSP and SHP without additivation have been calculated by BIOS in the same way as the production costs for the additivated BIOFLEX!-
fuels. According to these calculations the production costs of SHP (including a profit margin of 15%) amount to 30.8 €/MWh which is 31% lower than the maximum fuel costs compared to wood pellets and 3% lower than the maximum fuel costs compared to wood chips. The production costs of WSP (including a profit margin of 15%) of 35.5 €/MWh are 14% lower than the maximum fuel costs compared to wood pellets but 24% higher than the maximum fuel costs compared to wood chips. Consequently, the utilisation of SHP and WSP in an appropriately adapted boiler is competitive in comparison with wood pellet combustion and for SHP also in comparison with wood chip combustion.

Results regarding the medium-scale (1 MWth) combustion plant: Based on 6,000 full load operating hours per year, the maximum fuel costs of grass pellets (GP) to compensate the additional costs for the adapted boiler technology and to achieve the same heat generation costs as for the basic boiler technology amount to 33.9 €/MWh compared with wood pellets and 23.7 €/MWh compared with wood chips. For SHP these values amount to 36.1 respectively 25.7 €/MWh. Considering the calculated fuel production costs, SHP are with 30.1 €/MWh below the target costs for pellets but above those for wood chips while costs for GP exceed the target values in both cases due to the presently high raw material costs. Therefore, it can be concluded that for medium-scale systems the economic feasibility of the implementation of measure for enhanced fuel flexibility strongly depends on the fuel price and the development of a market for such fuels.

MS5.2, Techno-economic analyses regarding design fuel utilisation as well as the specific combustion concepts for new biomass fuels finalised, has been reached, as planned, at project end.

MS6.1: Project website
A website has been developed and completed within the BIOFLEX project, see https://bioflex-eranet.eu/

MS6.2: International workshop
An international workshop has been performed. The workshop was held at the European Pellet Conference February 28, 2019 during the World Sustainable Energy Days in Wels, Austria.

Eight presentations were held:
Technological solutions for the combustion of challenging biomass fuels
Ingwald Obernberger, Bios Bioenergiesysteme GmbH.

Fuel design concepts to reduce ash related problems and emissions – experiences from single pellet combustion tests
Christoffer Boman; Anders Rebbling; Markus Carlborg; Anna Strandberg, Umeå University.

Experiences from combustion tests with kaolin additivated fuels in residential boilers
Robert Mack & Hans Hartmann, TFZ; Christoffer Boman, Umeå University.

Modeling fixed-bed pellet combustion of fuels with varying ash contents
Henrik Ström, Chalmers

Application of non-wood pellets in appropriately adapted small-scale boilers – results and evaluation
Thomas Brunner, Bios Bioenergiesysteme GmbH; Georg Hofmeister.

Burner design for difficult pulverized biomass fuels
Pawel Bocian, Bartosz Swiatkowski, Institute of Power Engineering, Poland.

Guidelines for advanced furnace/boiler and fuel design
Thomas Brunner, Bios Bioenergiesysteme GmbH.

Guideline for fuel design – focus on kaolin additives
Christoffer Boman, Anders Rebbling, Robert Mack, Umeå University; Hans Hartmann, TFZ.

The presentations can be downloaded under publications at https://bioflex-eranet.eu/
MS6.3: Publication of the "Guidelines for advanced furnace/boiler and fuel design"

The guidelines for advanced furnace/boiler design have been prepared by BIOS and for fuel design by UmU and TFZ. The document summarizes the outcomes of the investigations regarding the design of appropriate low emission small and medium-scale combustion technologies and regarding appropriate fuel design strategies, i.e. the utilisation of fuel additives and the application of fuel blending in order to broaden the range of applicable biomass fuels. With its recommendations which have been derived based on scientific investigations as well as comprehensive test runs at small-scale and pilot-scale combustion plants it should support furnace and boiler manufacturers as well as biomass fuel producers and traders concerning the optimization of their products and the development and design of new products. Moreover, these guidelines shall provide information for plant operators regarding the risks and opportunities of the utilisation of so-called challenging biomass fuels. The main outcomes of the guidelines have been presented at the final workshop in Wels (see MS 6.2).

The guidelines are now in the final review process and will be published at the project website as soon as possible.

MS7.1: Kick-off meeting

A kick-off meeting was performed and hosted by RISE in Gothenburg, Sweden. February 3 and 4, 2016.

MS7.2: Signed consortium agreement

All partners have signed a consortium agreement.

MS7.3: Project coordination meetings

3 Project coordination meetings have been performed;
- Straubing, Germany September 28-29, 2017, hosted by TFZ.
- Graz, Austria, September 27-28, 2018, hosted by BIOS.
- Gothenburg, Sweden, December 4-5, 2018, hosted by CTH.

MS7.4: Final project report

An Era-net bioenergy final report was completed.

Internal cooperation and added value of international cooperation

The cooperation within the Bioflex project has strengthen existing networks between the involved senior researchers and PhD students. The cooperation within and between the different work packages has form a natural contact interface between the senior researchers, gaining deeper knowledge on the specific competence of the different partners. The project has introduced PhD students, working with specific task within the project, to new research environments and research areas. This will indirectly deepen their general competence on biomass related combustion issues.

2. If applicable, problems and changes in objectives (Describe the difficulties and problems that have hindered the achievement of the planned objectives, if any, and any alternative plan or change with respect to the former proposal)

In the BIOFLEX there were no difficulties or problems that have hindered the achievement of the planned objectives.

3. Collaboration within the consortium (Describe exchange of personnel, actual share of facilities etc. within the consortium)
Intensive exchange during frequent (semi-annual) meetings have created an atmosphere of strong interlinking of tasks and has established fruitful contacts which shall be continued after the project, too. The scientific group had the chance to learn about measuring practises of other scientific partners and to receive feedback on their existing practises in own laboratory and test stands. This exchange has also triggered some investments into laboratory infrastructure.

4. Collaboration with industry (Did you interact with industry partners during the project duration? Have you had possibilities to present your project to specific industry partner/platform, association etc.? Were there any difficulties/obstacles?)

The research and development (R&D) work has been performed in close cooperation with the industrial partners Opcon (SE), Kahl (DE), BTI (PL) as well as Polytechnik and KWB (AT) and thereby ensured that the R&D work performed is market oriented.

5. Project-derived exploitation, e.g. patents, publications

5.1 Publications of single partners (without involvement of other partners)


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5.2 Publications with the involvement of other partners of the consortium

5.3 Patents of single partners (without involvement of other partners)

5.4 Patents with the involvement of other partners of the consortium

5.5 Other exploitation
6. Suggestion for final seminar (Please indicate which international bioenergy conference you would find suitable for presentation of your project)

A final seminar/workshop was held at the European Pellet Conference February 28, 2019 during the World Sustainable Energy Days in Wels, Austria.

7. Follow-up activities – Implementation of the results (Please include any planned actions such as new proposals, scaling up proposals, collaboration with industry)

Input Austria

BIOS will use the know-how gained within the project to foster its reputation as a development partner for furnace and boiler manufacturers as well as utilities and its technology leadership as a R&D service provider in this field. Specifically BIOS wants to exploit the project results in cooperation with industrial partners in follow-up projects regarding the development of new plant technologies for challenging biomass fuels.

Polytechnik and KWB, as industrial partners, will use the new developments gained from the project to update respectively improve their products. Project results shall be partly implemented in existing product series and partly be applied to develop new furnace and boiler technologies. Especially Polytechnik expects from the knowledge gained a competitive edge in the design and construction of fuel flexible heating and CHP plants, as there is a generally high demand for such solutions in the medium-scale sector, which can presently not be satisfied by most of the competitors.

With the project an important step towards increased fuel flexibility of small and medium-scale biomass combustion systems has been made. However, in the near future additional R&D will be needed to accompany the market introduction of new fuel-flexible product series (in the small-scale) as well as demonstration projects regarding fuel flexible combustion (in the medium scale). In this respective a continuation of BIOS with KWB and Polytechnik is intended.

8. Other comments (on procedures or incl. feedback to the funding organisations, e.g. regarding the contract negotiation phase etc.)

9. Publishable executive summary of the project and its progress

The outcomes of your project will be disseminated via a call brochure e.g. http://www.eranetbioenergy.net/file/download/33751402). Please provide a summary of your project, that we can use to promote your project and the activities of the ERA-NET.

Please ensure the summary is suitable for public disclosure and please try to make it understandable for a non-technical audience as well.

Please add 3 high resolution pictures with an explanation when you return the report to the ERA-NET Bioenergy Secretariat Carina Lemke c.lemke@fnr.de

What are the results and the relevance of the project + impact on day-to-day life? (about 4000 characters or 800 words)
Please include any relevant information about your project partners as well. (Max. 1000 characters or 150 words)
In a future decentralised and sustainable European energy supply scenario, small to medium scale biomass combustion plants (< 50 WM) are destined to be important. At present, such plants burn mainly stem wood-based fuels in form of logs, wood chips, pellets and briquettes. A widened fuel base including new challenging biomass fuels would increase the growth potential for this sustainable biomass-based energy segment. To accomplish this, further comprehensive R&D work on primary design concepts on fuels and combustion technology is needed.

Possible new biomass fuels include assortments of forest residues, waste wood, short rotation forestry (SRF – e.g. poplar and willow), herbaceous fuels (e.g. straw) as well as residues from agriculture and industry (shells, kernels, sludges etc.). However, due to their chemical composition, these fuels are challenging in terms of combustion behaviour and emissions. Increased S, Cl and N contents lead to increased gaseous HCl, SOx and NOx emissions. Elevated ash contents with high levels of e.g. K, Si and P may cause problems with slagging, deposit formation and fine particulate emissions, of which especially the latter is growing in relevance with the EU-Ecodesign directive and the Medium Combustion Plant (MCP) directive.

While large-scale combustion plants may utilize relatively expensive secondary measures for emission reduction, it is generally not an economically feasible option for smaller plants. The rather limited knowledge of the problems associated with the new challenging biomass fuels has held back the development of fuel flexible combustion systems in small to medium scale. Therefore, the development of cost efficient and general primary concepts for increased fuel flexibility is urged to boost the innovation, enlarge market potential and deliver clean and efficient technology solutions.

The overall objective of the BIOFLEX-project has been to increase the fuel flexibility and the innovation potential for the use of challenging solid biomass fuels, that do not compete with food production, in the small to medium-scale heat and power production sector.

The project has increased the fundamental understanding of ash transformation issues in combustion, by ash transformation research. The application of additives and fuel blending have been investigated in order to make the new feedstock better applicable to small to medium-scale biomass combustion systems. The biomass fuels tested include wheat, wood, sunflower husk, grass and poplar. Measures to significantly decrease the alkali related fine PM emissions and slagging problems have been analysed. Relevant combustion experiments have been complemented by chemical analyses. Appropriate new concepts for fuel blending, additive selection as well as fuel/additive mixing ratios have resulted from the project. Within BIOFLEX a special focus has been given to the concept of using kaolin as additive in small- and medium scale grate-fired biomass systems and specific recommendations on how to estimate appropriate dosages have been presented.

Figure 1. Dosing of kaolin-additive into a mixer with milled fuel prior to palletisation.

Within the project, ash transformation concepts have been implemented in novel realistic, combustion-related modelling. The ash chemistry has been coupled to combustion processes, to enable predictions of slagging and other ash transformation-related events during combustion. Within the BIOFLEX project, the model has been improved and validated by comparing model results to combustion tests performed, both as single pellets and as fuel beds. The concept could serve as powerful tools in the prediction of the behaviour of the ash components in a fuel bed.
The ash chemistry has been coupled to combustion processes, to enable predictions of slagging.

The combustion technologies for small to medium sized grate fired boilers have been further developed by means of primary measures such as: advanced air staging concepts, improved control systems and CFD optimised design of the combustion chamber. The CFD simulations and the models applied have been evaluated by operational data from test runs in two different biomass fired grate boilers. The results proved the accuracy of the models developed. Moreover, they supported the evaluation of the measures applied to further develop the plant technologies towards enhanced fuel flexibility, maintaining low emissions, high efficiencies and high plant availabilities.

In addition, a prototype burner for pulverized straw and sewage sludge has been developed and evaluated by CFD-simulations and combustion experiments. The tests showed highly slagging properties of sewage sludge, for which a key issue is the recovery of phosphorus from the ash. To avoid molten ash, a new prototype burner was designed and consequently tested in a laboratory. The best results were obtained when the burner was operated in "volume mode", characterized by the absence of a clearly visible flame front. The fly ash thus generated had advantageous properties for the recovery of phosphorus. This work included developing methods to pulverize and store the biomass fuels, involving the construction of a prototype disk grinder. A patent application for a new design of the grinder has been submitted to the Polish Patent Office.

Based on accompanying techno-economic analyses it has also been shown that the resulting furnace concepts and proposed fuel additives are economically affordable and commercially competitive in comparison with conventional wood combustion systems as well as with fossil fuel fired systems.

Testing of proposed measures have been conducted has in appropriately adapted testing plants in cooperation with furnace and boiler manufacturers. The progress in BIOFLEX has been significant, solutions and technologies have been developed which make an application of these fuels in small to medium-scale plants possible.

Technologically and economically viable guidelines have been presented for the design of appropriate low emission combustion technologies and for appropriate fuel design by use of additives of new challenging biomass fuels.
Figure 3. On February 28 2019, the final workshop within the project was held in Wels, Austria.

The BIOFLEX! Consortium have consisted of 6 scientific partners and 6 company partners from Sweden, Austria, Germany, and Poland.

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How has the ERA-Net made a difference to your research or business?
("Quotation: about 80 à 100 words")

With the project an important step towards increased fuel flexibility of small and medium-scale biomass combustion systems has been made. Research partners will use the know-how gained within the project to foster its reputation as a development partner for furnace and boiler manufacturers as well as utilities and its technology leadership as a R&D service provider in this field. Industrial partners, will use the new developments gained from the project to update respectively improve their products. Project results shall be partly implemented in existing product series and partly be applied to develop new furnace and boiler technologies.