GA no 282826

Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction

Deliverable No. D7.3 “Combustion behaviour of torrefied pellets in pellet boilers and corrosion load on chimneys”

Deliverable No. D7.4 “Combustion screening of three pellet boiler technologies and fuel assessment trials”

Executive Summary

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Nature		
R	Report	X

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1 Introduction

Torrefaction is considered worldwide as a promising key technology for boosting large-scale implementation of bioenergy. It involves heating biomass in the absence of oxygen to a temperature of 200 to 320 °C. As a result, the biomass looses all its moisture, a minor share of volatiles and becomes easy to grind and water resistant, which reduces the risk of spontaneous ignition and biological degradation. By combining torrefaction with pelletisation or briquetting, biomass is converted into a high-energy-density commodity solid fuel or bioenergy carrier with superior properties in view of (long-distance) transport, handling and storage, and also in many major end-use applications (e.g. co-firing in pulverised-coal fired power plants, (co-)gasification in entrained-flow gasifiers and combustion in all size classes. Moreover, torrefaction-based bioenergy carriers may form a good starting point for biorefinery routes.

The SECTOR project is focussed on the further development of torrefaction-based technologies for the production of solid bioenergy carriers up to pilot-plant scale and beyond and on supporting market introduction of torrefaction-based bioenergy carriers as a commodity renewable solid fuel. The core of the project concerns the further development of torrefaction and densification technologies for a broad biomass feedstock range including clean woody biomass, forestry residues, agro-residues and imported biomass. Production recipes will be optimised on the basis of extensive logistics and end-use testing. Much attention is given to the development, quality assurance and standardisation of dedicated analysis and test methods. The experimental work is accompanied by extensive desk studies to define major biomass-to-end-use value chains, design deployment strategies and scenarios, and conduct a full sustainability assessment. The results will be fed into CEN/ISO working groups and international sustainability forums.

2 Objectives

The objectives of work package 7 are to evaluate the end-use applications of torrefied biomass in three principal application areas, namely

- medium-to-large scale firing and co-firing in pulverized-fuel boilers,
- medium-large-scale gasification and co-gasification in entrained-flow gasifiers, and
- small-scale combustion in commercial pellet boilers.

BIOS is the leader of Task 7.4 “Small-to-medium scale pellet boilers” and partner B2020 and TFZ contribute to this task. Within the scope of this task, lab-reactor and TGA tests with torrefied pellets were foreseen to evaluate their combustion and volatiles release behaviour as well as to adapt a special particle layer model for CFD simulations to torrefied pellet combustion. Moreover, fuel assessment was performed with several torrefied fuels in state-of-the-art small-scale heating systems (understoker, grate, overfed boilers up to 50 kW_{th}), covering tests at full and partial load, load cycle tests as well as longer term test runs. A special focus was also put on condensation and corrosion. CFD simulations of selected test runs supported the evaluation and the identification of probably needed modifications of small-scale pellet boilers and the related process control settings for the utilization of torrefied pellets. The results of the CFD simulations performed are described in Deliverable No. D 7.7 “Modified particle layer model and CFD-simulations of selected combustion trials”.

In this report the work performed by the partners BIOS, BE2020 and TFZ within the scope of the deliverables No. D7.3 “Combustion behaviour of torrefied pellets in pellet boilers and corrosion load on chimneys” and No. D7.4 “Combustion screening of three pellet boiler technologies and fuel assessment trials” is summarized.

Within the scope of Task 7.4 BIOS performed TGA tests with 3 different kinds of torrefied pellets to evaluate the decomposition behaviour in comparison to conventional softwood pellets, lab-scale reactor tests with one selected torrefied fuel to evaluate the combustion and volatiles release in comparison to conventional softwood pellets and test runs with one selected torrefied biomass fuel in a 21 kW overfed pellet boiler.

BE2020 performed combustion experiments at the BE2020 testing facilities. Fuel assessment was performed with several torrefied fuels in state-of-the-art heating systems. A special focus was also put on additional issues as condensation and corrosion, i.e. the determination of the corrosion load on chimneys. Combustion technology screening was carried out by tests with 3 different small-scale combustion technologies namely grate, overfeed and understoker appliances with capacities of up to 50 kW. In addition, a prototype boiler was investigated by BE2020. For the fuel assessment trials, test runs were conducted in one boiler with 5 different fuels with particular focus on start-up procedures and start-up emissions.

TFZ assessed within the scope of task 7.4 the behaviour and direct applicability of torrefied fuels in several state-of-the-art combustion systems (underfeed stoker, grate, overfed boilers) for the residential sector. This assessement was done by applying standard test procedures (e. g. type testing routines at full and partial load operation), practise related load cycle tests and long-term test runs for durability assessment. All tests should reflect the direct applicability of the new fuels in modern small-scale state-of-the-art boiler systems. The combustion tests at TFZ were also aiming to contribute to practice related fuel assessment by applying several torrefied fuels and comparing them to the usual standard reference fuels (i. e. wood pellets) for which the boilers are usually designed. Therefore, a selection of small-scale testing boilers (capacities up to 50 kW) was made (underfeed stoker, top feed and grate boiler types as they are usually prevailing in practise). Due to the fact that fuel applicability and fuel based differences sometimes do not become visible under steady state operating onditions it was necessary to perform further tests under repeatable load changes (i. e. variable power output conditions of a standard load cycle test) as such a test reflects the usual practise of a real-life field operation. Furthermore, the torrefied pellets were examined concerning their behaviour under permanent high load operation over several days, which can have an effect on boiler availability and ash related problems. Continuous emission monitoring was therefore required for a non-stop operation over several days (72 hours).

3 Summary

3.1 Work performed by Partner BIOS

In total 3 torrefied fuels (TOPELL_spruce, CENER_beech-270, CENER_pine-300) were analysed regarding their elemental composition. As expected the C content of the torrefied materials is higher and the H content slightly lower than for softwood pellets. However, the C content of CENER_beech-270 is with 51.5 wt% d.b. considerably lower than for the other torrefied materials. The N content is the highest for CENER_beech-270 (0.12 wt% d.b.) and lower for CENER_pine-300 (0.09 wt% d.b.) as well as for TOPELL_spruce (0.07 wt% d.b.). The lowest N content was detected in softwood pellets (0.05 wt%). In general the ash content and the concentrations of ash forming elements should be slightly higher in torrefied material compared to the untreated original biomass fuel due to the loss of volatiles during torrefaction process. The ash content of torrefied beech is with 1.1 wt% d.b. the highest and for all analysed torrefied materials higher compared to softwood pellets.

The results of the TGA tests performed show that the volatiles content of the torrefied materials is lower than for softwood pellets (62 – 65.8 wt% d.b. compared to 73 wt% d.b.) and the fixed carbon content is with 32.6 to 37.6 wt% d.b. higher than for softwood pellets (26.7 wt% d.b.). The volatile content of CENER_beech-270 is the highest for all torrefied materials tested and the carbon content is the lowest. Since hemicellulose is released during the torrefaction process usually no or only a small amount of hemicellulose is detected in torrefied materials, which is the case for TOPELL_spruce and CENER_pine-300. In the CENER_beech-270 a considerable amount of hemicellulose is detected ((14 wt% d.b.). This indicates that the torrefaction rate was considerably lower for the CENER_beech-270 sample compared to the other torrefied materials.

Lab-scale reactor tests have been performed with torrefied softwood pellets (TOPELL_spruce) and conventional softwood pellets. The test run duration was about 2,500 seconds for both fuels investigated. The drying phase took longer for softwood pellets. The main decomposition phase (release of volatiles and charcoal gasification) took longer for TOPELL_spruce compared to softwood pellets and the respective degradation rate was smaller. The degradation rate of charcoal combustion related to the input weight is similar for both fuels. However, the degradation rate related to the air supplied is for TOPELL_spruce somewhat higher than for softwood pellets. The results of the lab-scale reactor tests indicate that the overall combustion process for TOPELL_spruce is slower than for softwood pellets. The total conversion rate of N to TFN (related to N content in the fuel) is for both fuels approx. 95 to 100% which is a normal conversion rate under consideration of the low N content in both fuels. The calculated maximum potential for aerosol emissions is approx. two times higher for TOPELL_spruce pellets compared to softwood pellets, which is due to the higher K content in the fuel and the higher release rate for K measured.

Furthermore, combustion tests with a modern pellet boiler have been performed with torrefied softwood pellets (TOPELL_spruce) and conventional softwood pellets at full load and partial load. For TOPELL_spruce two different control settings have been tested (same settings as for conventional softwood pellets (furnace settings 1) and an operation with increased the primary air ratio (furnace settings 2). For all test runs stable conditions could be obtained at nearly full load conditions and at partial load (approx. 30% of the nominal boiler capacity). The results show that the CO emissions increase at full load from conventional softwood pellets (10 mg/Nm^3 related to 13 vol% O_2, dry flue gas) to TOPELL_spruce pellets with furnace settings 1 (22 mg/Nm^3) and to TOPELL_spruce pellets with furnace settings 2 (47 mg/Nm^3). The CO emissions are generally higher at partial load than at full load. For conventional softwood pellets CO emissions amount to approx. 100 mg/Nm^3 related to 13 vol% O_2, dry flue gas. For TOPELL_spruce pellets the CO emissions are approx. 3 times higher which shows that further modifications and optimizations of the control settings are required in order to guarantee a complete burnout of the flue gases with torrefied pellets in the pellets boiler used. The NO_x emissions amount to approx. 160 mg/Nm^3 (related to 13 vol% O_2, dry flue gas) at full load for conventional and TOPELL_spruce pellets.

The PM_1 emissions at full load were for conventional softwood pellets on a very low level (5.7 mg/Nm^3 related to 13 vol% O_2, dry flue gas). For TOPELL_spruce pellets they were somewhat higher (6.6 to 8.2 mg/Nm^3) but also on a low level. At partial load the PM_1 emissions for conventional softwood pellets were slightly higher than at full load (7.5 mg/Nm^3). However, PM_1 emissions increased considerably for TOPELL_spruce pellets at partial load (20.3 – 25.1 mg/Nm^3). TSP emissions are generally higher than PM_1 emissions for all test runs performed (by a factor 1.4 to 2.4) which shows that a certain amount of coarse fly ash particles is entrained from the fuel bed. The fly ashes of conventional softwood pellets contain primarily K_2SO_4 and KCl whereas the fly ashes of TOPELL_spruce pellets contain in addition K carbonates (in particular at partial load). The K transfer coefficients from the fuel to the fly ash are at full load for softwood pellets slightly higher than for TOPELL_spruce. However, they are 2.8 to 3.5 times higher at partial load than at full load for TOPELL_spruce. The reason for the higher transfer coefficients for K at partial load for TOPELL_spruce pellets is not fully understood yet. However, it is most likely that the air ratio in the PCC for TOPELL_spruce was not favorable at partial load and that the bed temperatures were higher (according to CFD simulations performed) which leads to a higher K release from the fuel bed. The subsequent carbonate formation is due to the low S and Cl contents in the fuel. The results are repeatable and only slightly affected by the furnace settings applied.

The TOC content of the grate ash of conventional softwood pellets at full load is the lowest (37 wt% d.b.) and at partial load approx. 1.6 times higher (60 wt% d.b.). The TOC content in grate ashes of the TOPELL_spruce pellets is considerably higher (78 – 85 wt%) and the results show that the increase of primary air (furnace settings 2) did not improve the burnout quality of the grate ashes. However, it has to be mentioned that the burnout quality of the pellets boiler used for the test runs performed is not sufficient even though standard de-ashing intervals and burnout periods defined by the boiler manufacturer have been applied. Since the boiler used has a retort burner which is discontinuously de-ashed it is probable that by increasing the burnout period before de-ashing the burnout quality can be considerably improved in general by a comparably easy adaptation of the control settings.

3.2 Work performed by Partner BE2020

The results derived from the work performed by BE2020 show that torrefaction changes the properties of the fuels. The content of moisture and volatile compounds is reduced. The combustion behaviour of torrefied fuels differs with regard to the steps of a combustion process, since drying does not require a long time, however the gasification as well as the burn out of combustion char takes much longer in comparison to the utilisation of the small scale appliances with wood fuels. A too short residence time leads to a high amount of unburnt material in the bottom ash and therefore, to a decreased energy efficiency. Furthermore the end-customer is disturbed by having unburnt residues in the ash box, which might cause warranty claims.

The volatile compounds affect the combustion behaviour especially during the ignition and start-up phase. The char burnout of the fuel takes longer and the required residence time on the grate may increase. Additionally, the changed content of VOC changes also the elemental composition (particularly the CHO-ratio) of the fuel. Therefore, the air demand for a stoichiometric combustion changes as well. The oxygen supply depends on the control strategy of the boiler. Since most of the combustion appliances are controlled by a lambda-probe, excess oxygen and heat output are not optimised during the operation of the boiler with torrefied fuels. The respective requirements of primary and secondary air supply change. Due to the higher content of carbon and the increased residence time due to the combustion char, a higher share of primary air might be necessary. Furthermore, higher emissions are possible due to the non-optimal distribution of primary to secondary air.

In general, it is possible to operate the combustion of torrefied material in standard pellet boilers. The combustion behaviour however depends strongly on the raw material which is torrefied and on the combustion technology. Mainly the control strategy, but also the ash removal solution, influences the combustion behaviour of the modified raw material.

Depending on the combustion appliance, torrefied pellets can be combusted without or only with minor adjustments or modifications when they are made of biomass with a low content of ash. Torrefied pellets from an ash richer material require an adjustment of the ash removal settings. The emission release (CO, NO_x and PM) depends on the raw material as well.

The temperature on the grate area is slightly increased in comparison to the combustion of wood pellets. Depending on the combustion technology, the high temperature can lead to agglomerations on the grate or slagging.

In order to investigate the corrosion load on chimneys, a standard testing method developed by BE2020 was applied. The corrosion risk of torrefied fuel combustion was found to be very similar to the combustion of wood fuels. The main influencing parameter is still the fuel composition and therefore the quality of the raw material.

According to the “description of work” of the SECTOR project, the tasks of BE2020 were the operation of three different small-scale combustion technologies with conventional and torrefied softwood pellets. In addition, a prototype boiler was investigated. The investigated technologies differ also in terms of the control strategy, so it is possible to make evaluations of the combustion behaviour of torrefied fuels in appliances which vary regarding feeding and ash removal systems, air supply, control strategy as well as the material used and the area of the grate and the volume of the combustion chamber. The results show, that as expected, the combustion appliances tested produce a higher heat output due to the higher NCV of the torrefied pellets compared to conventional pellets. CO emissions are on the same level or slightly increased with torrefied pellets and the NO_x and PM emissions are almost on the same level. The grate temperatures are usually increased with torrefied pellets while the temperatures inside the combustion chamber are usually almost comparable with the values during the operation with conventional pellets.

The second task was to run fuel assessment trials with five different fuels with particular focus on start-up procedures and start-up emissions (Spruce_raw, Forest_residues, Spruce_260, Pine_270 and Poplar_270). In addition, the burn-out behaviour was investigated and differences were discovered. The results show that during stable conditions spruce_raw showed the lowest CO release in comparison to the other fuels. Forest_residues showed significantly higher emissions of CO. For the other three torrefied fuels only a slight increase of the CO emissions has been measured. The NO_x emissions depend on the N content in the fuel and vary accordingly. The PM emissions of spruce_260 and pine_270 were comparable to spruce_raw. For Poplar_270 the PM emissions were four times higher.

The combustion experiments were performed in small-scale appliances which are authorised for the application of standardized wood pellets only. Although the application of torrefied fuels turned out to be possible, it is not permitted to operate the heating systems with fuels which are not certified according to the instruction manuals of the boiler manufacturers.

3.3 Work performed by Partner TFZ

It was the objective of TFZ to assess the behaviour and direct applicability of new torrefied fuels in several state-of-the-art combustion systems for the residential heating sector. Two types of torrefied wood pellets were tested and compared to standard wood pellets in several combustion trials. Torrefied pellet 1 (Topell_spruce) was produced as 6 mm pellets from similar wood resources as they are normally applied in small-scale pellet boilers, it had a low ash content of 0.4 %. The other torrefied fuel was an 8 mm pellet from wood residues with high ash content of 3.2 % (Torrefied pellet 2 - Topell_wood residues). Three boilers were applied: Boiler 1 was an understoker feed boiler (15 kW), Boiler 2 was a top feed boiler (12 kW) and Boiler 3 was a moving grate boiler (30 kW). Only Boiler 1 and Boiler 2 enabled a stable operation which allowed to perform the full test program with all three fuels. Combustion trials were performed at partial load and full load operation as well as by using a standard 8 h test sequence with a continuously changing load (standard load cycle test). Furthermore, both boilers were used with Torrefied pellet 1 to perform a long-term test over 72 hours at almost full load (90 %); this was done to identify any ash related problems.

With Torrefied pellets 1 the operation at full and partial load operation was non-problematic. Carbon monoxide (CO), organic gaseous carbon (OGC), NO_x and particulate matter (PM) emissions were on the same level as for reference wood pellets at full load. At partial load even some advantages were observed regarding PM emissions. This was however, not the case for Torrefied pellets 2, which mostly caused largely higher PM and NO_x emissions in both boilers. This can be attributed to differences in fuel composition. These unfavourable fuel properties and the higher pellet diameter (8 mm instead of 6 mm) was also responsible for severe operational problems encountered with Boiler 2 (top feed boiler), where the CO and OGC emissions were beyond acceptable limits for Torrefied pellets 2.

The torrefied wood pellets showed the potential to provide at least the same combustion efficiency as achievable with wood pellets when tested at full or partial load, where the efficiency level was mostly in the order of 95 % (i.e. indirect efficiency, excluding the boiler loss). Under variable load operation (i. e. load cycle) the boiler efficiency was directly assessed (instead of indirect efficiency), it reflects the expected annual efficiency. Here even some advantages were observed for the Torrefied pellets 1 compared to wood pellets. The efficiency gain (direct measuring method) was between 4 to 7 percentage points, with highest levels of 87.6 % for the top feed boiler using Torrefied pellets 1.

The load cycle tests also proved that concerning emissions the torrefied pellets can generally be compatible with wood pellets, at least this was demonstrated for pellets produced from similar resource quality (Torrefied pellets 1). But equally to wood pellets, also for torrefied wood fuels the risk of causing higher pollutant emissions is increasing with the use of unsuitable raw materials before torrefaction. This is shown by the results with Torrefied pellets 2, where again excessive PM and CO emissions were observed in Boiler 2.

But the flue gas composition as determined during short term operation cannot easily be extrapolated for longer periods. This was shown by the increasing fluctuation of flue gas parameters, as mainly observed for CO, which also followed a negative trend over the long term trials (72 h). This observation was made with both boilers using Torrefied Pellet 1.

Furthermore, this trend was accompanied by higher ash related problems. The granulometric analysis performed with all total ash residues collected from the long-term trials with both boilers clearly show a higher slag formation (while slag is here defined as the fraction above 3.15 mm). For example, the slag formation of Torrefied pellets 1 was in the order of 31 %. This is more or less comparable to miscanthus pellets (about 24 %), which had been tested using the same two boilers during a previous research programme. Also it was observed that from Torrefied pellets 1 hardly any fine ash (which is here defined as the sieve fraction below 1.0 mm) was separated from the collected combustion residues.

Ash and slag related problems in small scale boilers are therefore expected to increase with this new fuel and they can be seen as an inhibiting factor for torrefied fuels being directly introduced as a replacement for wood pellet. For permanent use in small-scale appliances, further boiler adaptations for slag removal need to be made and the prevention of clogging of air supply nozzles must be guaranteed.

4 Conclusions and Outlook

The procedure for standardizing the properties of torrefied fuels is already in progress. As soon as the chemical and mechanical properties are defined, it is necessary to adapt small-scale appliances in order to ensure the applicability. Especially the materials of grate and combustion chamber have to be considered due to higher expected temperatures in the fuel bed. By an adaption of the control system, the combustion behaviour has to be approved. In particular, the settings of the control system of the combustion appliances have to be optimised in order to define the distribution of primary and secondary air supply and the residence time of the fuel on the grate as well as the fuel feeding rate. Therefore, additional research is needed.

The results of the work performed also indicate that the overall combustion process for torrefied pellets seems to be slower than for conventional softwood pellets and therefore correspondingly the residence time on the grate for a complete burnout is increased.

It can be concluded, that the direct applicability of torrefied wood pellets is not given for all small-scale pellet boiler types. This was demonstrated by the failure to achieve a stable operation on a moving grate boiler within the scope of the work performed by TFZ. Underfeed stoker boilers may be less susceptible towards reduced qualities of torrefied fuels and towards larger pellet diameters.

From the presented results the following conclusions can be compiled:

- For torrefied softwood pellets the fuel feeding system has to be adapted regarding the higher energy density of these materials (adaptation of the control settings required).
- The fuel bed increases with torrefied softwood pellets compared to conventional softwood pellets due to the lower combustion rate (higher charcoal content). Torrefied softwood pellets need a longer burnout time in order to completely convert the carbon in the fuel. Adaptations of the grate and the burnout zone are therefore possibly required.
- The grate temperatures do not show large differences but according to the CFD simulations performed the bed temperatures are locally clearly higher for torrefied softwood pellets (slagging problems are likely to occur).
- The air ratio in the PCC and the total air ratio may need some adaptations. This depends on the specific boiler technology applied.
- Torrefied wood pellets have the potential to provide at least the same combustion efficiency as achievable with wood pellets when tested at full or partial load. Under variable load operation (i.e. load cycle) an even higher efficiency may be possible. This seems to be applicable for top feed and underfeed stoker boiler types.
- The level of pollutant emissions is largely similar to that of wood pellets, given that similar wood resources were also used before torrefaction. This was observed for CO, OGC and PM emissions. However, due to the higher expected fuel bed temperatures of torrefied fuels the fine particle emissions may increase.
- Equally as for wood pellets, also for torrefied fuels the risk of causing higher pollutant emissions is increasing with the use of unsuitable raw materials before torrefaction. For small scale heating appliances it is therefore required that future fuel standards

are based on the same critical components and that they define similar limits as already established for wood pellets.

- The diameter of the torrefied pellets should be chosen in accordance with the requirements also given for wood pellets in the specific boiler. Torrefied pellets with 8 mm diameters may create operational problems when nominal boiler heat output is particularly low.
- The direct applicability of torrefied wood pellets cannot be assumed for all boiler types. Underfeed stoker boilers may be less susceptible towards reduced qualities of torrefied fuels and towards larger pellet diameters.
- The use of torrefied pellets may be associated with a higher share of slag formed during combustion. Ash and slag related problems in small-scale boilers are therefore expected to increase with this new fuel and they can be seen as an inhibiting factor for torrefied fuels being directly introduced as a replacement for wood pellet. For permanent use in small-scale appliances, further boiler adaptations for slag removal need to be made and the prevention of clogging of air supply nozzles must be guaranteed.
- Field tests over a full heating season should be performed to verify the individual applicability of torrefied wood pellets in each regarded boiler type after appropriate modifications according to the recommendations given have been made.

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Deliverable No. D7.4 “Combustion screening of three pellet boiler technologies and fuel assessment trials”

Appendix1: Report prepared by partner BIOS

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Nature		
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O	Other	

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1 Introduction

Torrefaction is considered worldwide as a promising key technology for boosting large-scale implementation of bioenergy. It involves heating biomass in the absence of oxygen to a temperature of 200 to 320 °C. As a result, the biomass looses all its moisture, a minor share of volatiles and becomes easy to grind and water resistant, which reduces the risk of spontaneous ignition and biological degradation. By combining torrefaction with pelletisation or briquetting, biomass is converted into a high-energy-density commodity solid fuel or bioenergy carrier with superior properties in view of (long-distance) transport, handling and storage, and also in many major end-use applications (e.g. co-firing in pulverised-coal fired power plants, (co-)gasification in entrained-flow gasifiers and combustion in all size classes. Moreover, torrefaction-based bioenergy carriers may form a good starting point for biorefinery routes.

The SECTOR project is focussed on the further development of torrefaction-based technologies for the production of solid bioenergy carriers up to pilot-plant scale and beyond and on supporting market introduction of torrefaction-based bioenergy carriers as a commodity renewable solid fuel. The core of the project concerns the further development of torrefaction and densification technologies for a broad biomass feedstock range including clean woody biomass, forestry residues, agro-residues and imported biomass. Production recipes will be optimised on the basis of extensive logistics and end-use testing. Much attention is given to the development, quality assurance and standardisation of dedicated analysis and test methods. The experimental work is accompanied by extensive desk studies to define major biomass-to-end-use value chains, design deployment strategies and scenarios, and conduct a full sustainability assessment. The results will be fed into CEN/ISO working groups and international sustainability forums.

The present deliverable report focuses on the work performed by BIOS within the scope of work package 7, Task 7.4.

2 Objectives

The objectives of work package 7 are to evaluate the end-use applications of torrefied biomass in three principal application areas, namely

- medium-to-large scale firing and co-firing in pulverized-fuel boilers,
- medium-large-scale gasification and co-gasification in entrained-flow gasifiers, and
- small-scale combustion in commercial pellet boilers.

BIOS is the leader of Task 7.4 “Small-to-medium scale pellet boilers”. Within the scope of this task, lab-reactor and TGA tests with torrefied pellets were foreseen to evaluate their combustion and volatiles release behaviour as well as to adapt a special particle layer model for CFD simulations of small-scale torrefied pellet combustion. Fuel assessment is then performed with several torrefied fuels in state-of-the-art heating systems (understoker, grate, overfed boilers up to 50 kW_{th}), where standard tests, practise related load cycle tests and longer term test runs are performed. A special focus is also put on additional issues as condensation and corrosion. CFD simulations of selected test runs will support the evaluation and the identification of probably needed modifications of pellet boilers and the related process control settings for the utilization of torrefied pellets.

Within the scope of Task 7.4 BIOS performed the following work:

- TGA tests with 3 different kinds of torrefied pellets to evaluate the decomposition behaviour in comparison to conventional softwood pellets.
- Lab-scale reactor tests with one selected torrefied fuel to evaluate the combustion and volatiles release in comparison to conventional softwood pellets.
- Particle layer model adaptation and performance of CFD simulations.
- Test runs with one selected torrefied biomass fuel in a 21 kW overfed pellet boiler in order to gain data for model validation.

In this deliverable report the work performed by BIOS concerning the TGA tests with 3 different kinds of torrefied pellets, the lab-scale reactor test with one selected torrefied fuel and the test runs performed with a 21 kW overfed pellet boiler with conventional and torrefied pellets is presented and discussed.

3 Methodology

3.1 Methodology of TGA tests performed

TGA experiments were carried out in a Netzsch STA 409 CD (Simultaneous Thermal Analysis) in the TGA/DTA configuration (see Figure 1). Using the Netzsch STA thermogravimetric balance coupled with a data acquisition system, the residual weight of the sample (thermogravimetric analysis, TGA) and the derivative of weight with respect to time and temperature (differential thermogravimetric analysis, DTG) of solid fuel samples are obtained. This apparatus detects the weight loss with a resolution of 5 µg. The specific data of the TGA system used are shown in Table 1. Approximately 50 mg of the solid fuel samples were distributed in 300 µl alumina crucibles. In the first step the sample is heated-up from ambient temperature to 110 °C at 20 K/min and then dried at 110 °C for 15 minutes. The temperature is then increased at a linear heating rate of 20 K min^{-1} to 900 ˚C. Nitrogen gas is used as purge gas at a constant flow rate of 100 ml min^{-1}. In section 4.2, Table 4 the experimental data and the different fuels used for all tests performed are shown. The samples were pre-dried to a moisture content of approx. 2 wt% (w.b.).

In order to account for buoyancy effects, a correction curve with empty crucibles was obtained and then subtracted from the experimental results. The experiments were repeated three times to determine their reproducibility. No significant discrepancies between the triplicate measurements were observed, which showed that the experiments had good repeatability.

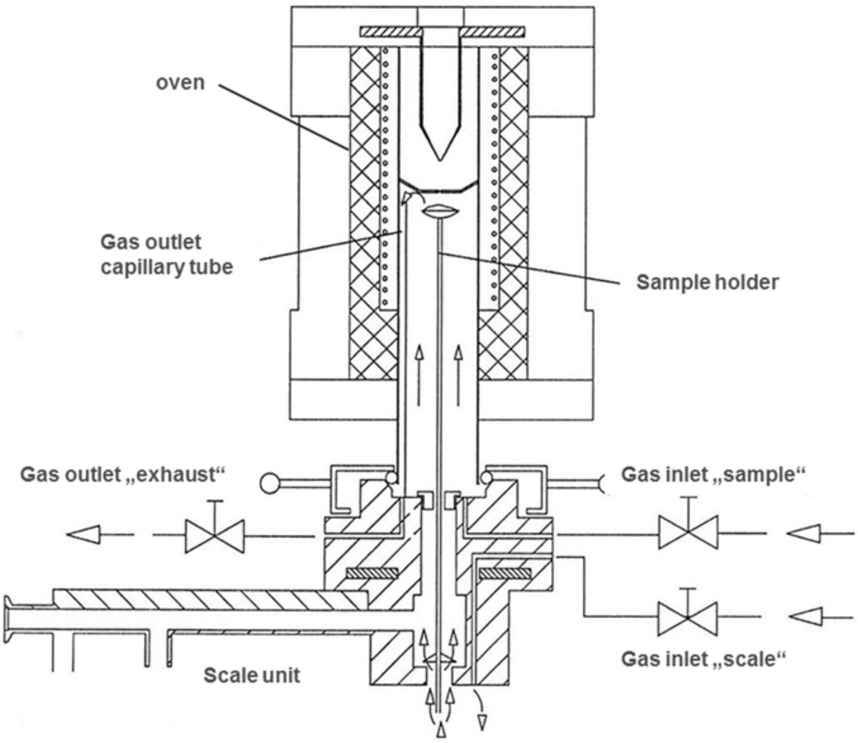

Figure 1: Measuring principle of TGA tests performed
Explanations: cross-section of the TGA (schematic view); the arrows show the purge gas flows; source: Netzsch-Gerätebau GmbH

Table 1: Specific data of the TGA system used

TGA-System applied:	STA 409 CD	
Manufacturer:	NETZSCH Gerätebau GmbH, Germany	
Balance	net weight range:	approx. 50 mg
	sensitivity	approx. 5 µg
Crucible:	Al_2O_3	
Purge gas:	N_2; 80 l/min	
Protection gas	N_2; 20 l/min	
Heating rate:	20 K/min	

The DTG curves (i.e. mass loss rate curves), that are obtained for biomass, contain partially overlapping peaks. This indicates that more than one reaction is involved and that biomass consists of components with different reactivities (i.e. of hemicellulose, cellulose and lignin). Figure 2 shows exemplary the devolatilisation characteristics of biomass fuels, where T_{onset} indicates the temperature at beginning of hemicellulose decomposition, T_{sh} the temperature of the maximum hemicellulose decomposition rate, T_{peak} the temperature of the maximum cellulose decomposition rate and T_{offset} the end of cellulose decomposition. $m_{500°C}$ is the solid residue mass at 500°C (charcoal and ash).

Mathematical models are typically used for the deconvolution of these overlapping peaks in the DTG curves. For biomass fuels, the pyrolysis process is usually described by a three pseudocomponents model with a reaction order of one. The kinetics of biomass pyrolysis are assumed to have three parallel independent reactions, with each reaction corresponding to the decomposition of one of the three pseudocomponents. This assumption is consistent with the nature of biomass fuels which are composed of hemicellulose, cellulose and lignin. In fact, the three pseudocomponents represent a pool of fractions of the main biomass compounds. With regard to practical utilisation this model is considered as the most realistic approach in the case of lignocellulosic materials with satisfying correctness revealed from the comparison of experimental and simulated results. However, during torrefaction processes typically the major part of hemicellulose decomposes. For this reason often no or only minor amounts of hemicellulose are detected in torrefied materials.

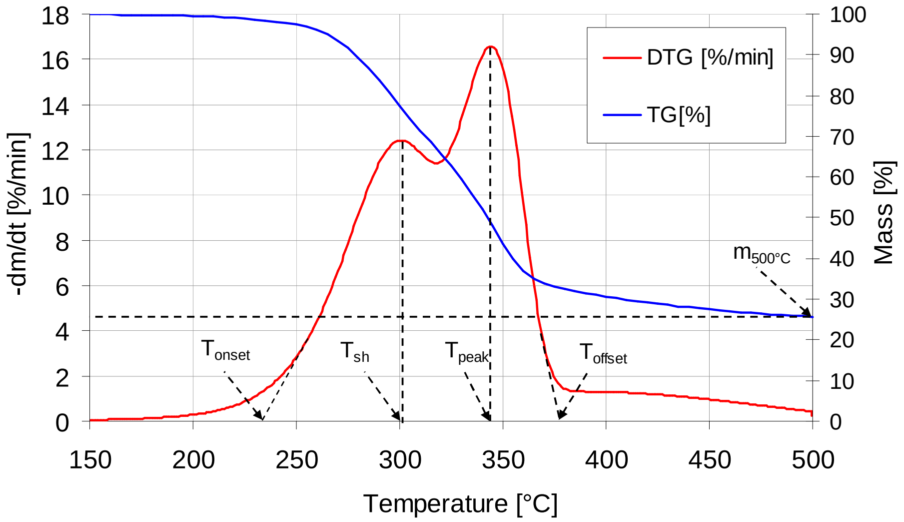

Figure 2: Devolatilisation characteristics – TG and DTG curves

Explanations: TG ... thermogravimetry; DTG ... differential thermogravimetry

Within the modelling the temperature range between 150 °C and 500 °C was used for the kinetic evaluation. The drying section below 150 °C and the carbonisation and carbonate decomposition above 500 °C were not evaluated. At the temperatures higher than 500 °C, there was only a slight change in mass loss.

The overall mass loss rate based on the three independent reactions is given as:

$$\frac{-dm}{dt} = \sum_{i=0}^{3} c_i \frac{da_i}{dt} \qquad (1)$$

i: cellulose (c), hemicellulose (h) and lignin (l)

where c_i is a measure of the relative contribution of the partial decomposition processes to the overall mass loss and da_i/dt is the mass loss rate for each component.

The separate conversion (or mass loss fraction) a_i for each component is given by:

$$a_i = \frac{m_{0,i} - m_{t,i}}{m_{0,i} - m_{f,i}} \qquad (2)$$

where $m_{0,i}$, $m_{t,i}$ and $m_{f,i}$ are the initial dry sample mass (at a temperature of 150 °C), the experimental sample mass at each monitoring time and the final sample mass of component 'i' (at 500 °C) respectively. The components are all assumed to decompose individually according to a one order reaction equation:

$$\frac{da_i}{dt} = A_i \exp\left(\frac{-E_i}{RT}\right)(1-a_i) \qquad (3)$$

where A_i, E_i, R and T denote the pre-exponential factor, activation energy, universal gas constant and temperature respectively. The optimisation is done in MatLab® with the solver lsqcurvefit to estimate the kinetic parameters from the above set of equations. The quality of the fit was calculated by Eq. (4) where k represents the numbers of the data points, $(da/dt)^{exp}$ is the experimentally measured value and $(da/dt)^{sim}$ is the simulated value obtained by solution of the equation with the given set of parameters. Figure 3 shows exemplary results of DTG curve peak separation.

$$\text{Fit}=100\frac{\left(\sum_{i=o}^{k}\left[\left(\frac{da}{dt}\right)_k^{\exp}-\left(\frac{da}{dt}\right)_k^{sim}\right]^2/k\right)^{1/2}}{\left(-\frac{da}{dt}\right)_{\max}^{\exp}} \qquad (4)$$

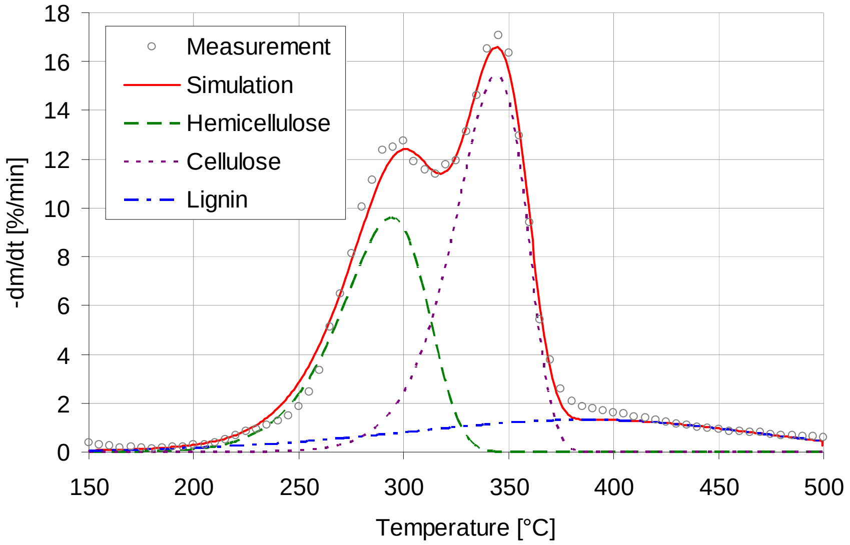

Figure 3: Exemplary results of DTG curve peak separation

3.2 Methodology of lab-scale reactor tests performed

The lab-scale batch reactor used has been designed to be capable for the simulation of the fuel decomposition behaviour in fixed-bed thermal biomass conversion systems. Therefore, the following constraints are given:

- Reasonable sample intake in order to consider secondary reactions in the fuel bed appropriately.
- High heating rates of the fuel comparable with real-scale grate furnaces.
- Inert reactor material in order to avoid reactions of the gases with the reactor.
- High flexibility regarding analytical equipment connected with the reactor.

- Online recording of relevant operation data and emissions as well as of the mass loss.

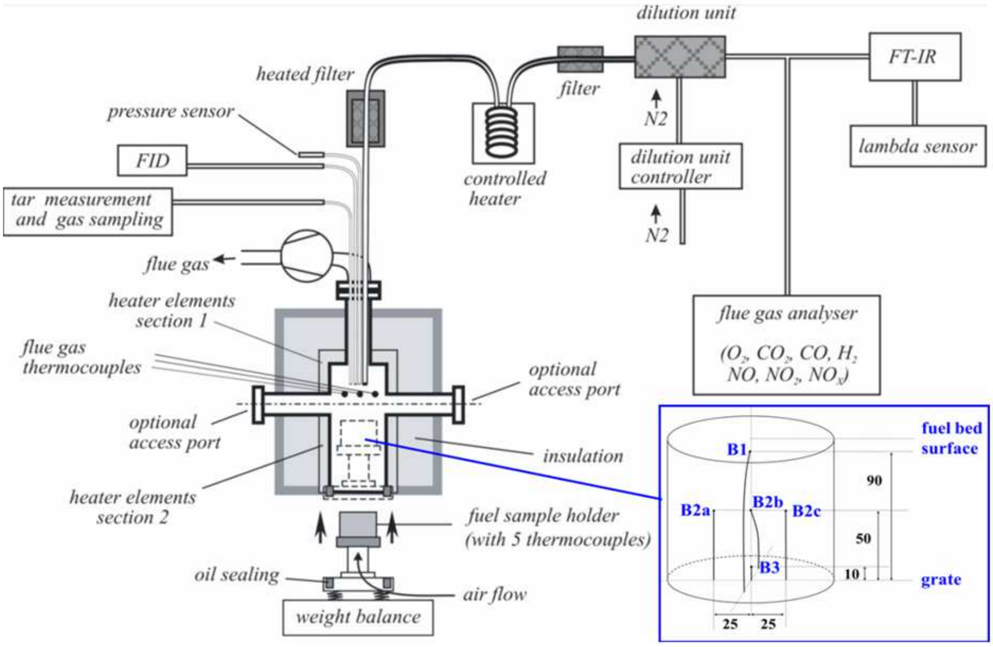

Figure 4: Scheme of the lab-scale reactor used including measurement set-up

Explanations: B1, B2 and B3 indicate the three different height levels of the temperature measurements in the fuel bed; dimensions in mm

Figure 4 shows a scheme of the lab-scale batch reactor. The core of the reactor is a cylindrical retort (height 35 cm, inner diameter 12 cm) which is heated electrically and controlled by two separated PID-controllers (see Figure 4). The fuel is put in a cylindrical sample holder of 100 mm height and 95 mm inner diameter. This size provides the possibility to utilize a fuel mass between around 100 g (for low-density fuels such as chopped or chipped fuels) and more than 400 g (for pelletised fuels) which is a reasonable quantity for the simulation of a packed bed. Moreover, the sample holder is equipped with 5 thermocouples (NiCr-Ni) in order to monitor the fuel bed temperatures during the test runs (see Figure 4). The material of the reactor wall and the sample holder is silicon carbide. This material had already proven its applicability for such types of reactors in former experimental setups and was selected since it is inert under reducing and oxidising conditions, and therefore does not react with the fuel, ash and flue gas.

The mounting and vessel for the fuel bed are placed on the plate of a scale. The scale is mechanically separated from the retort by a liquid sealing (synthetic thermal oil: Therminol 66) and is used to determine the weight loss of the sample over the test run period.

The sample holder with the biomass is introduced into the pre-heated reactor and therefore a rapid heating, which is well comparable with the one in real-scale thermal conversion processes, can be achieved.

Flue gas samples are extracted from the gas volume above the fuel bed, partly treated respectively conditioned (dilution, temperature stabilisation) and introduced into the following gas analysers.

- FTIR (Ansyco): CO_2, H_2O, CO, CH_4, NO, NH_3, HCN, NO_2, N_2O, basic hydrocarbons
- Emerson NGA 2000: Paramagnetism: O_2; NDIR: CO_2, CO; heat conductivity: H_2
- FID (Bernath Atomic 3005): OGC (C_xH_y)
- CLD (ECO Physics CLD 700 EL ht): NO, NO_x
- Wide band lambda sensor (O_2)

Moreover, the flow and temperatures of the reaction medium (e.g.: usually air) as well as several flue gas and reactor temperatures are recorded with NiCr-Ni thermocouples.

The testing protocol was defined as follows:

- A sub-sample of the fuel is forwarded to wet chemical analyses.
- Firstly the fuel is filled into the sample holder.
- Then the reactor is pre-heated applying 750°C and 450°C as pre-setting for the upper and lower heating element. These settings are kept constant during the whole test run.
- Then the sample holder with the fuel is introduced into the reactor and the reaction gas flow through the grate and the fuel bed is activated. All experiments documented in this report have been performed with dry air (21 vol% O_2 and 79 vol% N_2) as reaction agent and a gas flow of 30 l_N/min. The reaction gas flow rate is kept constant during the whole test run.
- All parameters mentioned above are continuously recorded in a 2-second interval over the whole test run, which usually lasts between 30 to 60 minutes depending on the fuel mass applied.
- At the end of the test run, firstly the residues (ashes) are visually evaluated regarding ash sintering and slag formation and then removed and forwarded to chemical analyses.

The lab-scale reactor has been designed to represent the burning conditions of a biomass fuel layer on a grate as good as possible (see Figure 5). It reproduces the behaviour of a fuel segment moving along the grate and thereby passing firstly through the drying zone, then through the devolatilisation and charcoal gasification zone and finally trough the char burnout zone. Since the air flow through the fuel bed remains the same during the whole experiment, the excess air ratios vary depending on the stage of combustion from high lambdas (during drying) over understoichiometric conditions (usually a lambda between 0.6 and 0.9) during the devolatilisation phase back to high lambdas during charcoal burnout which is well comparable with the different stoichiometries prevailing in the different zones of a real-scale moving grate. This approach is valid if diffusional transport and mixing effects on the grate can be neglected compared to the transport of the fuel along the grate. The validation has been achieved in previous research which has shown that the fuel transport along the grate can be fluidically characterised by a plug flow in good approximation. Consequently, with the setup and testing protocol presented comprehensive information on the thermal decomposition process of biomass on a grate can be gained, which can also be transposed to real-scale systems. This includes the mass losses during drying, pyrolysis and charcoal combustion, the compositions of the gases produced as well as comprehensive information about the formation of NO_x precursors. Moreover, the data gained from the fuel and the residual ash analysis as well as the weight measurements can be used to calculate the release of inorganic elements to the gas phase by calculating mass and element balances.

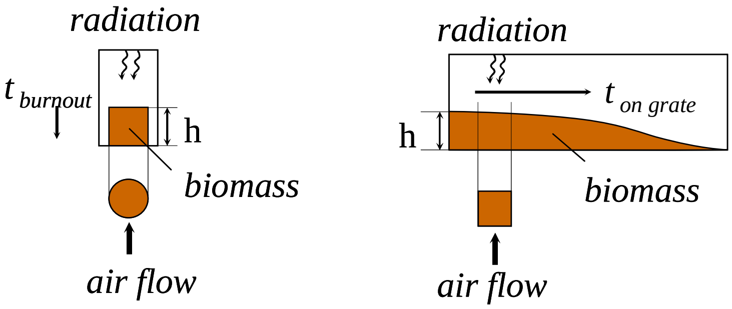

Figure 5: Projection of the lab-scale reactor fuel bed to the fuel layer in a grate furnace
Explanations: h … fuel bed height; t … time

Chemical analyses of the fuels used as well as of the residues play an important role in the evaluation of the lab-scale reactor tests. Therefore, the application of analyses methods, which provide the highest level of accuracy possible, is of relevance. The methods applied for the fuel and ash analyses are described in section 3.4.

3.3 Methodology of test runs performed with a modern pellet boiler

3.3.1 Description of the pellet boiler used and the measurement setup

The test runs were performed with a modern pellet boiler, the Windhager BioWIN 210 with a nominal boiler capacity of 21 kW (see Figure 6) at nominal load and partial load (30% of the nominal load). For all test runs performed the same methodological approach has been applied.

In Figure 7 the measurement and sampling ports used during the test runs are shown. All relevant operational and performance data such as flue gas composition (see section 3.3.2), temperatures and boiler load, etc. as well as PM_1 emissions (see section 3.3.5) were recorded continuously with an ELPI. In addition, TSP emissions according to EN13284-1 (see section 3.3.3) and PM_1 emissions with a Berner-Type Low-Pressure Impactor (BLPI, see section 3.3.4) were measured discontinouosly (see Figure 7). The combustion chamber temperature (at the end of the secondary combustion chamber) was measured with a suction pyrometer (location, see Figure 8) and the surface temperature of the grate and the temperature of the fuel bed was determined with a NiCr/Ni thermocouple (see Figure 9). The velocity of the primary and secondary combustion air was measured with Schmid sensors (measurement principle: thermo-resistance) and the flue gas velocity at boiler outlet with a Prantl tube (see Figure 7 and Figure 8).

During the test runs fuel samples were periodically taken from the fuel storage tank of the pellet boiler. The samples were gathered to mixed samples which have been forwarded to further analyses regarding moisture content, ash content, C, H and N content as well as contents of K, Ca, Si, Mg, S, Cl, Zn and Na.

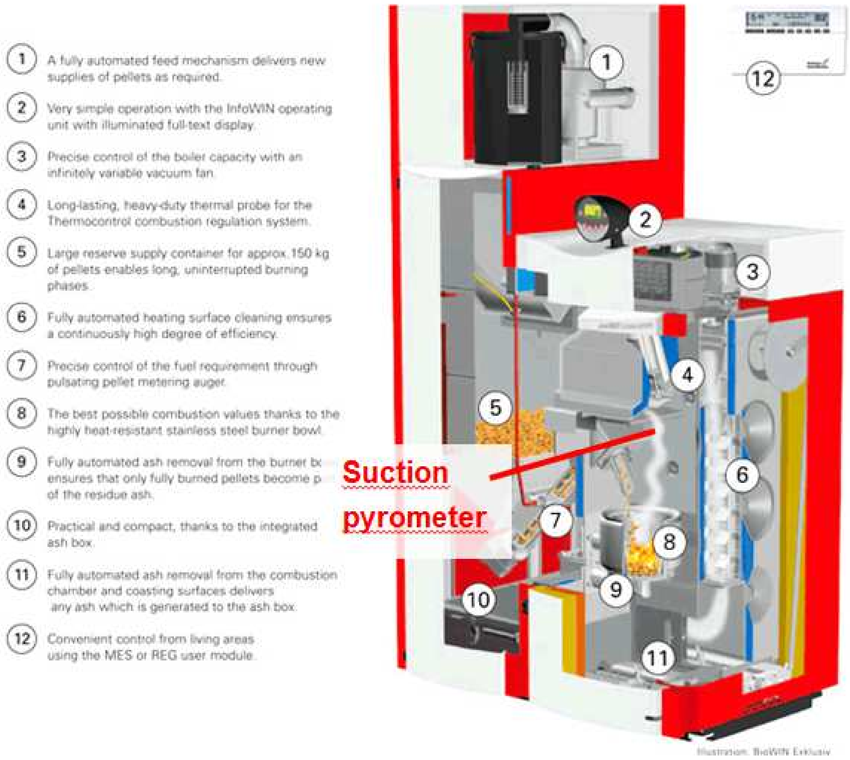

Figure 6: Scheme of the pellet boiler BioWIN 210 used for the test runs
Explanations: source: www.windhager.com

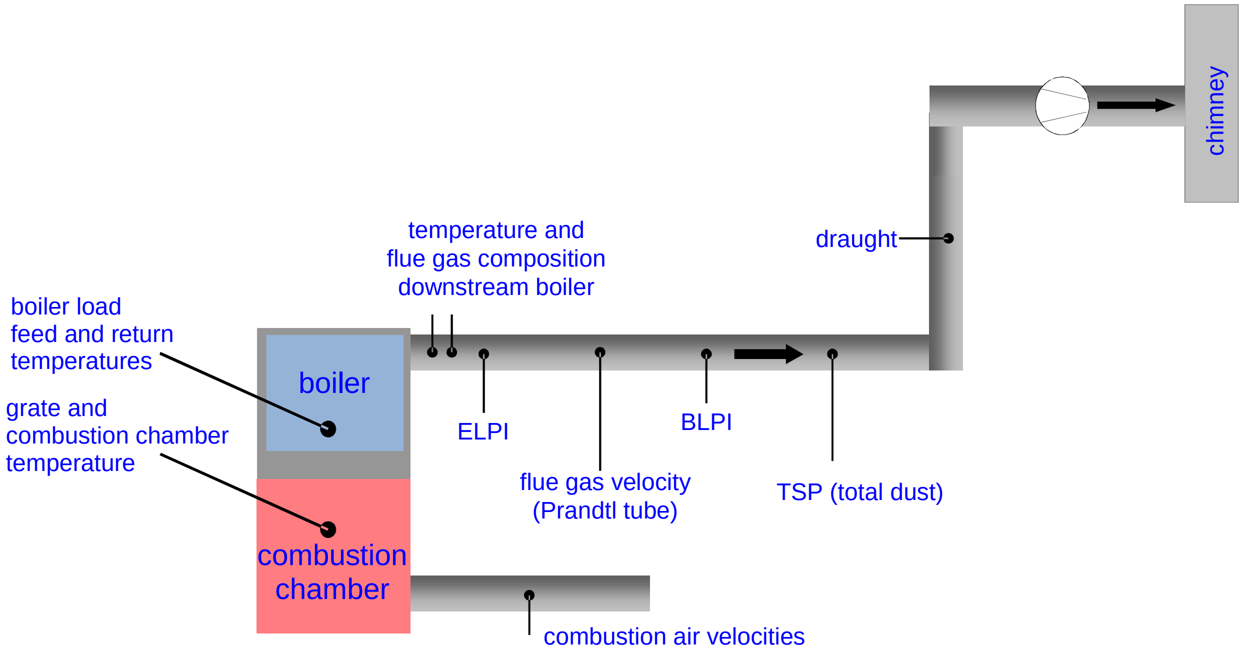

Figure 7: Scheme of measurement and sampling points

The bottom ash has been collected in the ash box of the pellet boiler. At the end of each test run a representative ash sample has been taken from the ash box. The samples have been forwarded to further analyses regarding the parameters total organic carbon (TOC) and total inorganic carbon (TIC). Samples of selected PM1 (BLPI) and TSP samples have been analysed regarding OC (organic carbon), IC (inorganic carbon), EC (elemental carbon), K, Na, S and Cl.

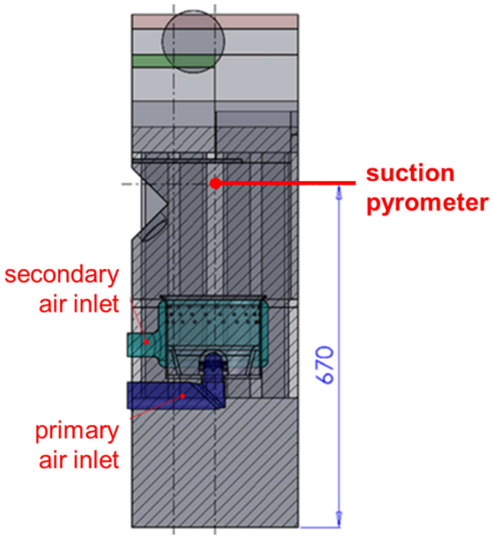

Figure 8: Cross section of the furnace (schematic view) and position of suction pyrometer measurement

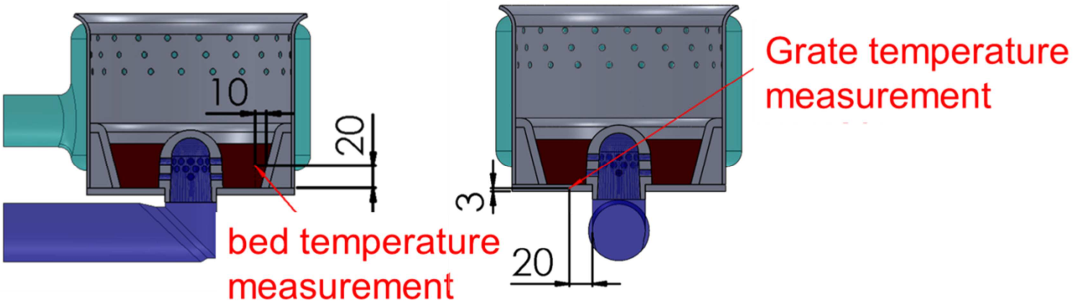

Figure 9: Cross section of the burner (schematic view) and position of the grate and fuel bed temperature measurements

3.3.2 Flue gas analysers

3.3.2.1 Oxygen

Measuring principle

The measuring principle for O_2 in flue gas is based on its paramagnetic properties.

Measuring device

Manufacturer	Rosemount
Type	NGA 2000
Measuring range	0 - 5 % to 0 - 100 % O_2
Reaction time	≤ 5 sec
Linearity	≤ 1 %
Zero drift	≤ ± 1.0 % per week

Sensitivity drift	≤ ± 2 % per week
Material for gas-bearing parts	stainless steel, PTFE
Measuring gas flow	approx. 1 l/min
Data output	4 - 20 mA (analogical)
Measuring range used	0 – 21.5 %
Gas sampling probe	stainless steel pipe
Sampling gas filter	heated ceramic filter
Sampling gas pipe	heated Teflon hose
Blank gas	Nitrogen 5.0
Calibration gas	10.2 Vol% O_2
Accuracy of the measurement:	
Lower detection limit	≤ 1% O_2
Error limit	≤ 1%

3.3.2.2 Carbon dioxide

Measuring principle

The NDIR measuring principle is based on the fact that some gases (e.g. CO, CO2) absorb light at defined frequencies in the IR-section. The absorption of IR-radiation is directly proportional to the gas concentration and is therefore suitable for the qualitative analysis.

Measuring device

Manufacturer	Rosemount
Type	NGA 2000
Measuring range	0 – 25 Vol% CO_2
Reaction time	≤ 2 sec
Linearity	≤ 1 %
Zero drift	≤ ± 2 % per week
Sensitivity drift	≤ ± 0.3 % per week
Measuring gas flow	approx. 1.1 l/min
Data output	4 - 20 mA (analogical)
Measuring range used	0 –20 Vol%
Gas sampling probe	stainless steel pipe
Sampling gas filter	heated ceramic filter
Sampling gas pipe	heated Teflon hose
Combustion air	hydrocarbon-free air
Blank gas	Nitrogen 5.0
Calibration gas	10 Vol% CO_2
Accuracy of the measurement:	
Lower detection limit	≤ 1 % of the upper end of the measuring range
Error limit	≤ 1%

3.3.2.3 Carbon monoxide

Measuring principle

The NDIR measuring principle is based on the fact that some gases (e.g. CO, CO_2) absorb light at defined frequencies in the IR-section. The absorption of IR-radiation is directly proportional to the gas concentration and is therefore suitable for the qualitative analysis.

Measuring device

Manufacturer	Rosemount
Type	NGA 2000
Measuring range	0 - 500 ppm to 0 – 10,000 ppm
Reaction time	≤ 2 sec
Linearity	≤ 1 %
Zero drift	≤ ± 2 % per week
Sensitivity drift	≤ ± 0.3 % per week
Measuring gas flow	approx. 1.1 l/min
Data output	4 - 20 mA (analogical)
Measuring range used	0 –10,000 ppm
Gas sampling probe	stainless steel pipe
Sampling gas filter	heated ceramic filter
Sampling gas pipe	heated Teflon hose
Combustion air	hydrocarbon-free air
Blank gas	Nitrogen 5.0
Calibration gas	297 ppm CO
Accuracy of the measurement:	
Lower detection limit	≤ 1 % of the upper end of the measuring range
Error limit	≤ 1%

3.3.2.4 Nitrogen oxides

Measuring principle

Chemiluminescence reactions comprise gas reactions where the energy released is emitted as photons. This leads for each reaction to a characteristic radiation, the Chemiluminescence, which can be detected photoelectrically.

NO reacts with Ozone (O_3) which is generated in the measuring device. In order to measure also NO_2, NO_2 needs to be converted to NO. The result of the measurements is the sum of NO and NO_2 emissions, referred to as NO_x. The amount of NO_2 is determined by NO_x minus NO.

Measuring device

Manufacturer	Rosemount
Type	NGA 2000
Measuring range	0 – 2,500 ppm

Reaction time	≤ 4 sec
Linearity	≤ ±1 %
Zero drift	none
Measuring gas flow	approx. 1.4 l/min
Data output	4 - 20 mA (analogical)
Measuring range used	0 –1,000 ppm
Gas sampling probe	stainless steel pipe
Sampling gas filter	heated ceramic filter
Sampling gas pipe	heated Teflon hose
Combustion air	hydrocarbon-free air
Calibration gas	340 ppm NO in N_2
Accuracy of the measurement:	
Lower detection limit	0.1 %
Error limit	≤ 0.5 %

3.3.3 TSP emissions

For the determination of TSP (Total Suspended Particles) emissions downstream the boiler the gravimetric method according to EN13284-1 was used. The flue gas is sucked isokinetically through a plane filter which is located outside the flue gas duct (out-stack sampling). The entire fly ash contained in the flue gas is retained. The fly ash concentration in the flue gas is calculated by dividing the mass of the retained fly ash (mg) by the flue gas flow through the filter (m^3). All fly ash collecting filters were prepared under lab conditions, stored in dust-proof containers and transported in desiccators. Directly after the measurements the filters were placed back into the desiccators and were stored dust-proof.

3.3.4 Concentration and particle size distribution of aerosols – discontinuous method

For the determination of the concentrations and particle size distributions of aerosols in the flue gas downstream the boiler low-pressure-cascade impactors (Berner-Type Low-Pressure Impactor BLPI), type Hauke LPI 30/0.0625/2, were used. The technical data of the BLPI used are listed in Table 2. Aluminium foils were used for sampling.

During an impactor measurement flue gas is sampled with a probe from the flue gas channel and is sucked through the impactor using a vacuum pump. The pressure and the temperature downstream the critical orifice of the impactor are measured. The precipitation foils are weighed before and after the measurement and from the particle load per foil divided by the flue gas flow through the impactor the particle concentrations for each impactor stage are calculated. In order to minimize particle losses in the extraction probe of the BLPI as well as to avoid condensation of water vapour in the extraction probe, all parts of the measuring device were pre-heated to flue gas temperature. In addition, the impactor was heated all along the measurements.

Cascade impactors are calibrated for aerodynamic diameters. The aerodynamic diameter represents the behaviour of spherical particles with a density of 1 kg/dm^3 in fluid flows. The conversion into the actual particle diameter, the so-called Stokes-diameter, is made by considering the average density of the particles and the so-called Cunningham-correction-factor. The smaller the particle diameter and the higher the temperature difference between the design temperature of the impactor (20°C) and the actual flue gas temperature becomes, the smaller is the Stokes-diameter in comparison to the aerodynamic diameter. Since all laws and guidelines which deal with particle sizes use the aerodynamic diameter as basis and most of the fly ash precipitation technologies use it as well, a conversion to the Stokes-diameter was not performed.

Table 2: Technical data of the BLPI type used

Explanations: ae.d. … aerodynamic diameter; cut diameter … smallest particle size, which is separated at the respective stage

Manufacturer: Hauke Ges.m.b.H. & Co. KG
Type: LPI 30/0,0625/2
Flow rate: 31,41 l/min at 20°C and atmospheric pressure

stage	cut diameter [µm ae.d.]	nozzle diameter [mm]
1	0.0625	0.25
2	0.125	0.30
3	0.25	0.45
4	0.5	0.60
5	1	0.70
6	2	1.2
7	4	2.7
8	8	5.0
9	16	15.9

The results of a measurement with the impactor consist of concentrations in mg/Nm³, which are evaluated separately for each impactor stage (= particle size fraction). The correct presentation would therefore be a histogram, with a bar for each impactor stage. If, based on the histogram presentation, the particle size distribution shall be shown as a continuous distribution, the concentration calculated for each stage must be divided by the width of the respective stage (scaled to the class width). The value obtained this way is related to the average diameter of the relevant particle size range. Particle size distributions of aerosols, which are emitted from biomass combustion plants, can be approximated with a logarithmic normal distribution. As shown in Table 2, also the cut diameters of the impactor stages are sub-divided logarithmically. For the presentation of a continuous distribution, a presentation, where the particle mass separated at each impactor stage is scaled with the logarithmic difference between the upper and lower class diameter, is chosen. The class diameter assigned to this value represents the geometric average of upper and lower class diameter. The particle concentration is therefore given as $\delta m/\delta \log(dp)$ in mg/Nm³.

3.3.5 Concentration and particle size distribution of aerosols – continuous method

For the continuous determination of the concentrations and number size respectively particle size distributions of aerosols in the flue gas downstream the boiler an electrical low-pressure cascade impactor (ELPI) was used.

At the ELPI inlet particles are charged and then pass several impactor stages (see Figure 10). As soon as a particle is separated from the flue gas, it looses its electrical charge. The resulting current is measured for each impactor stage and from these data, the particle size distribution is determined (as a number size distribution). The ELPI measurements are compared to the results of the BLPI measurements regarding the mass of PM_1 and based on this calibration the particle concentration (PM_1) in mg/Nm³ can be continuously estimated.

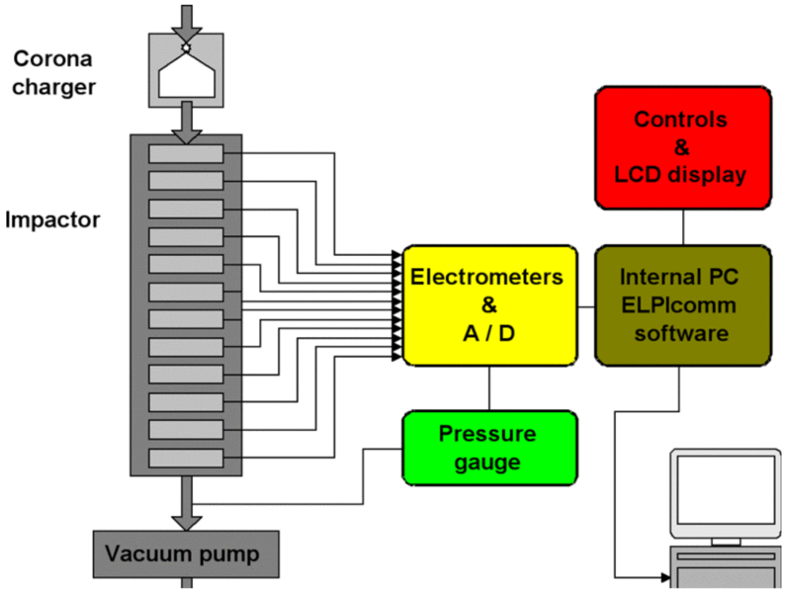

Figure 10: Scheme of the ELPI

3.4 Methodology of chemical analysis performed

3.4.1 Fuel analysis

Determination of moisture content

The moisture content of fuel samples is determined according to ÖNORM CEN/TS 14774 (determination of the weight loss during drying at 105°C until a constant weight is reached).

Sample preparation for further analyses

Fuel sample preparation is carried out according to CEN/TS 14780. Samples are homogenized; a cone is formed and subsequently divided into four portions. The two opposing portions are mixed in order to receive two sub-samples. One of the two sub-samples is stored as a retain sample. The other sub-sample is handled as follows:

- Drying of the sample at 105°C.
- Milling of the whole sample in a cutting mill to a particle size <4 mm.

- Sample division.
- Milling of the final analyses sample in an ultra-centrifugal mill equipped with titanium rotor and screen to a particle size <0.2 mm.

Determination of the ash content

The ash content is determined according to CEN/TS 14775 by determination of the loss of ignition at 550°C. In addition, the TIC (total inorganic carbon) content in the ashed sample is determined and subsequently the ash content without carbonates (oxide based fraction) is calculated.

Determination of the C, H and N contents

The determination of C, H and N contents of fuels is carried out according to ÖNORM CEN/TS 15104:2011 04 01 by combustion and subsequent gas-phase chromatographical separation and measurement in an elemental analyzer.

Determination of the Cl content

The determination of chlorine is carried out according to ÖNORM CEN/TS 15289.

Digestion:	bomb combustion in oxygen; absorption in NaOH (0.05 molar)
Measurement:	ion chromatography

Determination of the concentrations of major and minor elements in fuels (except Cl)

The determination of the concentrations of major and minor elements in fuels is carried out according to ÖNORM CEN/TS 12290 or 15297.

Digestion:	multi-step pressurized digestion with HNO_3 (65%) / HF (40%) / H_3BO_3 (saturated).
Measurement:	by inductively coupled plasma optical emission spectroscopy (ICPOES) or inductively coupled plasma mass emission spectroscopy (ICPMS) (depending on detection limits)

3.4.2 Ash, fly ash and aerosol analysis

Ash sample preparation

Sample preparation is carried out according to ÖNORM CEN/TS 14780.

Grate ash

- Milling of the samples in a planetary mono mill (material: silicon-carbide) to a particle size <0.2 mm.
- Preparation of a lab-scale sample by sample division and storage of parts of the sample as retain sample.

Aerosol and TSP (Total Suspended Particles) samples

The samples are dissolved from the impactor foils in the respective fluid, which is used for the digestion.

Vaporization of the silica (quartz filter) used for sampling with HF (40%).

Determination of the Cl content

Digestion: elution for 24 hours with deionized water
Measurement: ion chromatography

Determination of the concentrations of main and minor elements (except Cl)

The determination of main and minor elements in ash samples is carried out according to ÖNORM CEN/TS 15290 and 15297.

Digestion: multi-step pressurized digestion with HNO_3 (65%) / HF (40%) / H_3BO_3 (saturated).
Measurement: by inductively coupled plasma optical emission spectroscopy (ICP-OES), inductively coupled plasma mass emission spectroscopy (ICP-MS) or flame atomic absorption spectrometry (FAAS) (depending on detection limits)

The Si content in the total fly ash sample was not determined, because the filters used contain silica. During the analyses of the aerosol (impactor) samples Al was not determined because the separation foils used in the impactor are made of Al. In addition, the determination of the Si content in aerosol (impactor) samples is usually not possible due to the very small sample weight (only a few µg) and the very low Si content of the samples.

Determination of TOC and TIC in bulk ashes

The determination of TOC (total organic carbon) and TIC (total inorganic carbon) is carried out according to ÖNORM EN 13137.

Determination of TIC in bulk ashes

An aliquot is treated with acid, the generated CO_2 is measured by IR. The measurement instrument is calibrated with $CaCO_3$.

Determination of TOC in bulk ashes

TOC is determined by the amount of total carbon (determined by an element analyzer) minus the TIC.

Determination of total carbon (TC), organic carbon (OC), elemental carbon (EC) and carbonate carbon (CC) in fly ashes

Analysis is carried out with a carbon/hydrogen analyzer (Leco RC-612). The sample is inserted into a quartz tube and heated to defined temperatures. Carbon containing compounds released from the sample are oxidized to carbon dioxide, which is selectively detected by infrared cells. By choosing appropriate temperatures and carrier gases in the quartz tube total carbon (TC) as well as the fractions of organic carbon (OC), elemental carbon (EC) and carbonate carbon (CC) can be distinguished. Carbon released in a temperature window from 200 to 600°C under inert atmosphere is assigned to organic carbon, carbon released between 600 and 900°C is assigned to carbonate carbon, carbon detected after switching to oxidizing conditions to elemental carbon.

4 Results and discussion

4.1 Fuel analysis

In total 3 torrefied fuels (TOPELL_spruce, CENER_beech-270, CENER_pine-300) were analysed regarding their elemental composition. In addition, softwood pellets were analysed as a reference fuel (see Table 3). The torrefaction temperatures were for beech 270 °C and for pine 300 °C. For spruce torrefaction temperatures have not been specified.

The bulk density of the torrefied fuels is higher (680 – 700 kg/m^3 w.b.) than for the softwood pellets (650 kg/m^3 w.b.). The gross calorific value of TOPELL_spruce and CENER_pine-300 is 7.7 to 9.5% higher than for softwood pellets and the energy density is 16.2 to 17.1% higher. For CENER_beech-270 the gross calorific value is only slightly higher (1.5%) and the energy density is 9.2% higher than for softwood pellets.

Table 3: Results of fuel analysis

Explanations: w.b. … wet base; d.b. … dry base; w.b. … wet base; TIC … total inorganic carbon; n.s. … not specified; GCV and NCV were calculated according to GAUR

Type of fuel		Torrefied spruce pellets	Torrefied beech pellets	Torrefied pine pellets	Softwood pellets (spruce)
SECTOR sample ID		TOPELL_spruce	CENER_beech-270	CENER_pine-300	
BIOS Lab-no.		8,779	8,667	8,668	8,780
water content	wt% w.b.	3.2	6.5	6.4	6.7
bulk density	kg/m3 w.b.	680	700	700	650
gross calorific value (GCV)	kJ/kg d.b.	21,954	20,559	22,374	20,254
net calorific value (NCV)	kJ/kg w.b.	19,939	17,870	19,569	17,477
energy density	kWh/m3 w.b.	3,766	3,475	3,805	3,156
ash content	wt% d.b.	0.43	1.57	0.63	0.37
ash content (without TIC)	wt% d.b.	0.35	1.12	0.52	0.30
C	wt% d.b.	54.9	51.5	55.3	50.2
H	wt% d.b.	5.8	5.9	6.0	6.2
N	wt% d.b.	0.07	0.12	0.09	0.05
S	mg/kg d.b.	57.2	137.0	111.0	53.4
Cl	mg/kg d.b.	78.5	11.8	15.8	23.6
Si	mg/kg d.b.	34.7	255.0	139.0	272.0
Ca	mg/kg d.b.	694	3,980	1,200	865
Mg	mg/kg d.b.	154.0	388.0	260.0	113.0
K	mg/kg d.b.	795	1,460	833	430.0
Na	mg/kg d.b.	24.9	36.6	18.5	11.0
Zn	mg/kg d.b.	10.9	41.8	21.9	17.5
2S/Cl	mol/mol	1.61	25.7	15.5	5.0
(K+Na)/(2S+Cl)	mol/mol	3.7	4.4	3.0	2.9
Si/K	mol/mol	0.06	0.24	0.23	0.88
Si/(Ca+Mg)	mol/mol	0.05	0.08	0.12	0.37
K+Na+Zn	mg/kg d.b.	831	1,538	873	458.5
Torrefaction temperature		n.s.	270	300	-
TGA tests		X	X	X	X
Lab-scale reactor tests		X			X
combustion tests with modern pellet boiler		X			X
oxide sum	wt %	96.7	100.4	105.2	91.0

Table 3 shows the elemental composition of the different fuels. As expected the C content of TOPELL_spruce (54 wt% d.b.) and CENER_pine-300 (55.3 wt% d.b.) is higher than for conventional softwood pellets (50.2 wt% d.b.). The C content of CENER_beech-270 is with

51.5 wt% d.b. considerably lower than for the other torrefied materials. The H contents of all torrefied samples examined are slightly lower than for softwood pellets (5.8 – 6.0 wt% d.b. compared to 6.2 wt% d.b.). The N content is the highest for CENER_beech-270 (0.12 wt% d.b.) and lower for CENER_pine-300 (0.09 wt% d.b.) as well as for TOPELL_spruce (0.07 wt% d.b.). The lowest N content was detected in softwood pellets (0.05 wt%).

In general the ash content and concentrations of ash forming elements should be slightly higher in torrefied material compared to the untreated original biomass fuel due to the loss of volatiles during torrefaction process. The ash content (without TIC) of torrefied beech is with 1.1 wt% d.b. the highest and for all analysed torrefied materials higher compared to softwood pellets.

The Si contents of CENER_beech-270 are on a similar level compared to softwood pellets. For CENER_pine-300 the Si contents are approx. 2 times lower and the Si content in TOPELL_spruce is extremely low (7.8 times lower than for softwood pellets). The ash forming elements Ca and Mg have the highest concentations in CENER_beech-270, are lower in CENER_pine-300 and on the same level for TOPELL_spruce as softwood pellets. The contents of K and Na are also the highest in CENER_beech-270 and generally for all torrefied materials higher compared to softwood pellets. The highest contents of Zn are detected in the CENER_beech-270, for CENER_pine-300 they are on the same level as for softwood pellets and for TOPELL_spruce 1.6 times lower than for softwood pellets.

The molar 2S/Cl ratios for all samples analysed, expect for TOPELL_spruce, are above 4, so corrosion related problems in the boiler system shall be of minor relevance for these fuels. For TOPELL_spruce the 2S/Cl ratio is with 1.61 low and thus a corrossion risk is given. Due to the rather high molar ratios of (K+Na)/(2S+Cl) no elevated SO_x and HCl emissions have to be expected for all fuels analysed. Due to the extremely low Si content in TOPELL_spruce, the molar ratios of Si/K are very low, so an elevated release of K (which contributes to the formation of aerosols) can be expected. The molar ratios of Si/K are also for CENER_pine-300 and CENER_beech-270 considerably lower than for softwood pellets. The sum of the concentrations of relevant areosol forming elements (K+Na+Zn) is generaly higher for the torrefied materials compared to softwood and therefore higher aerosol emissions can be expected. The molar ratio of Si/(Ca+Mg) is for all torrefied materials lower than for softwood pellets (well below 1). Consequently no relevant ash melting problems are to be expected.

4.2 Results of TGA tests performed

The 3 torrefied materials (TOPELL_spruce, CENER_beech-270, CENER_pine-300) have been investigated by means of TGA analysis. In this section the results are also compared with results from TGA tests performed with softwood pellets. The methodology applied for the TGA tests is described in section 3.1. The results of the fuel analysis are discussed in section 4.1.

Table 4 shows the experimental data for all tests performed. The average mass of the samples amounted to 49.7 to 52.6 mg w.b. and the moisture content ranged between 0,7 and 2.2 wt%. A temperature window between 150 and 500 °C has been evaluated and the heating rate was set to 20 K/min. Nitrogen was used as gas. In total 3 test runs with each fuel have been performed. They showed similar results which demonstrates that the results are replicable and representative. In the following tables and diagrams the mean values from the three individual test runs are presented.

Table 4: TGA tests performed - experimental data
Explanations: w.b. ... wet base, the fuels were pre-dried

Fuel		Torrefied spruce (pellets)	Torrefied beech (pellets)	Torrefied pine (pellets)	Softwood pellets (reference)
SECTOR sample ID number		TOPELL_spruce	CENER_beech-270	CENER_pine-300	
Average mass	[mg w.b.]	51.6	52.2	52.6	49.7
moisture content	[wt% w.b.]	2.2	1.8	2.1	0.7
Number of samples		3	3	3	3
Temperature window	[°C]	150 - 500	150 - 500	150 - 500	150 - 500
Heating rate	[K/min]	20	20	20	20
Gas atmosphere		N2	N2	N2	N2
Gas flow rate	[Nml/min]	100	100	100	100

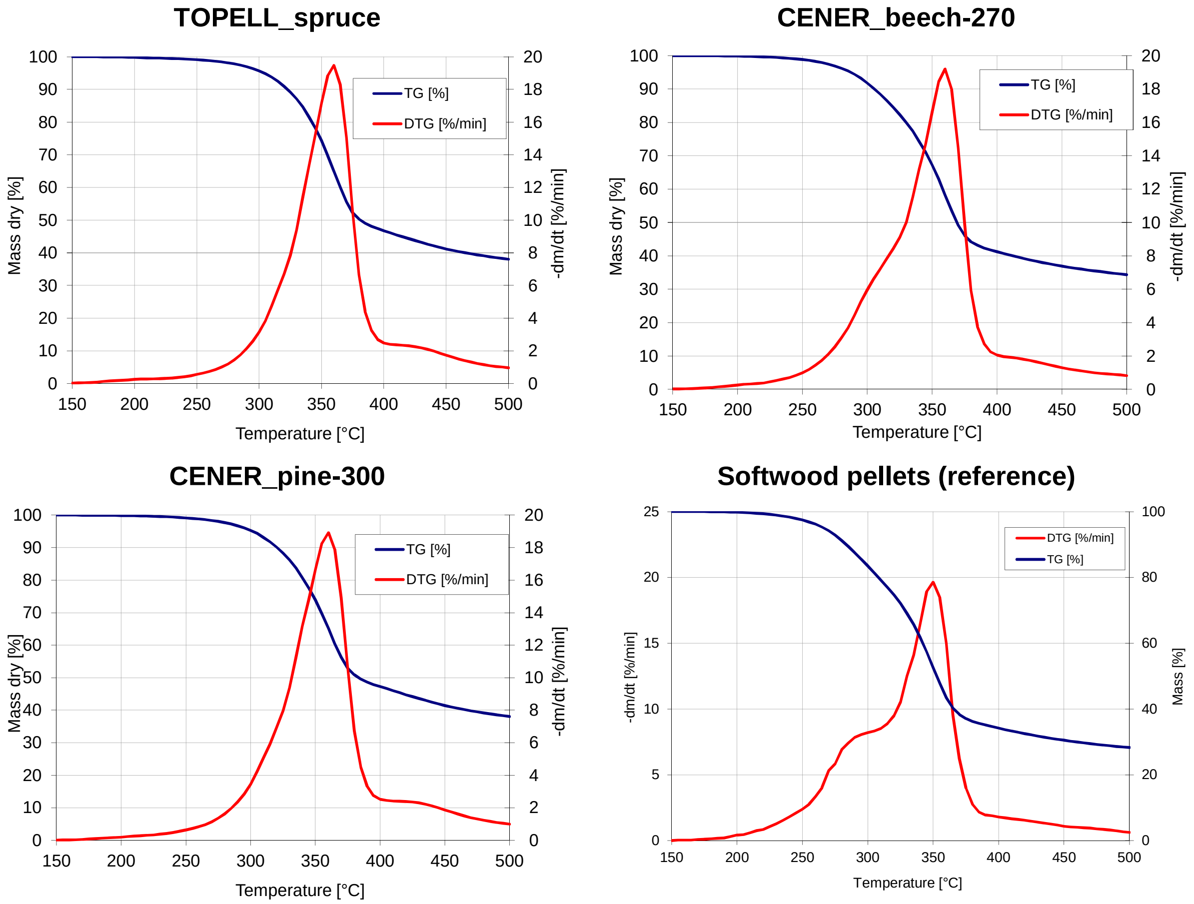

Figure 11: TGA tests performed –TG and DTG curves - mean values from 3 individual test runs
Explanations: TG ... thermogravimetry; DTG ... differential thermogravimetry; % ... based on original sample mass

Figure 11 shows the TG and DTG curves for the four fuels examined and Table 5 the volatiles and fixed carbon contents according to the TGA tests performed. The volatiles content of the torrefied materials is lower than for softwood pellets (62 – 65.8 wt% d.b. compared to 73 wt% d.b.) and the fixed carbon content is with 32.6 to 37.6 wt% d.b. higher than for softwood pellets (26.7 wt% d.b.). Comparing the torrefied materials, the volatiles content of CENER_beech-270 is the highest for all torrefied materials tested (65.8 wt% d.b.) and the fixed carbon content is the lowest (32.6 wt% d.b.).

Table 5: TGA tests performed - volatiles and fixed carbon contents

Explanations: * ... Values at 500°C (the decomposition above 500 °C can be linked with coking reactions); ** ... ash content based on the fuel analysis (TIC corrected); d.b ... dry basis; af ... ash free

	Torrefied spruce (pellets) TOPELL_spruce		Torrefied beech (pellets) CENER_beech-270		Torrefied pine (pellets) CENER_pine-300		Softwood pellets (reference)	
	[wt% d.b.]	[wt% af d.b.]	[wt% d.b.]	[wt% af d.b.]	[wt% d.b.]	[wt% af d.b.]	[wt% d.b.]	[wt% af d.b.]
Volatiles*	62.0	62.2	65.8	66.9	62.0	62.3	73.0	73.2
Fixed Carbon	37.6	37.8	32.6	33.1	37.4	37.7	26.7	26.8
Ash content**	0.4		1.6		0.6		0.3	

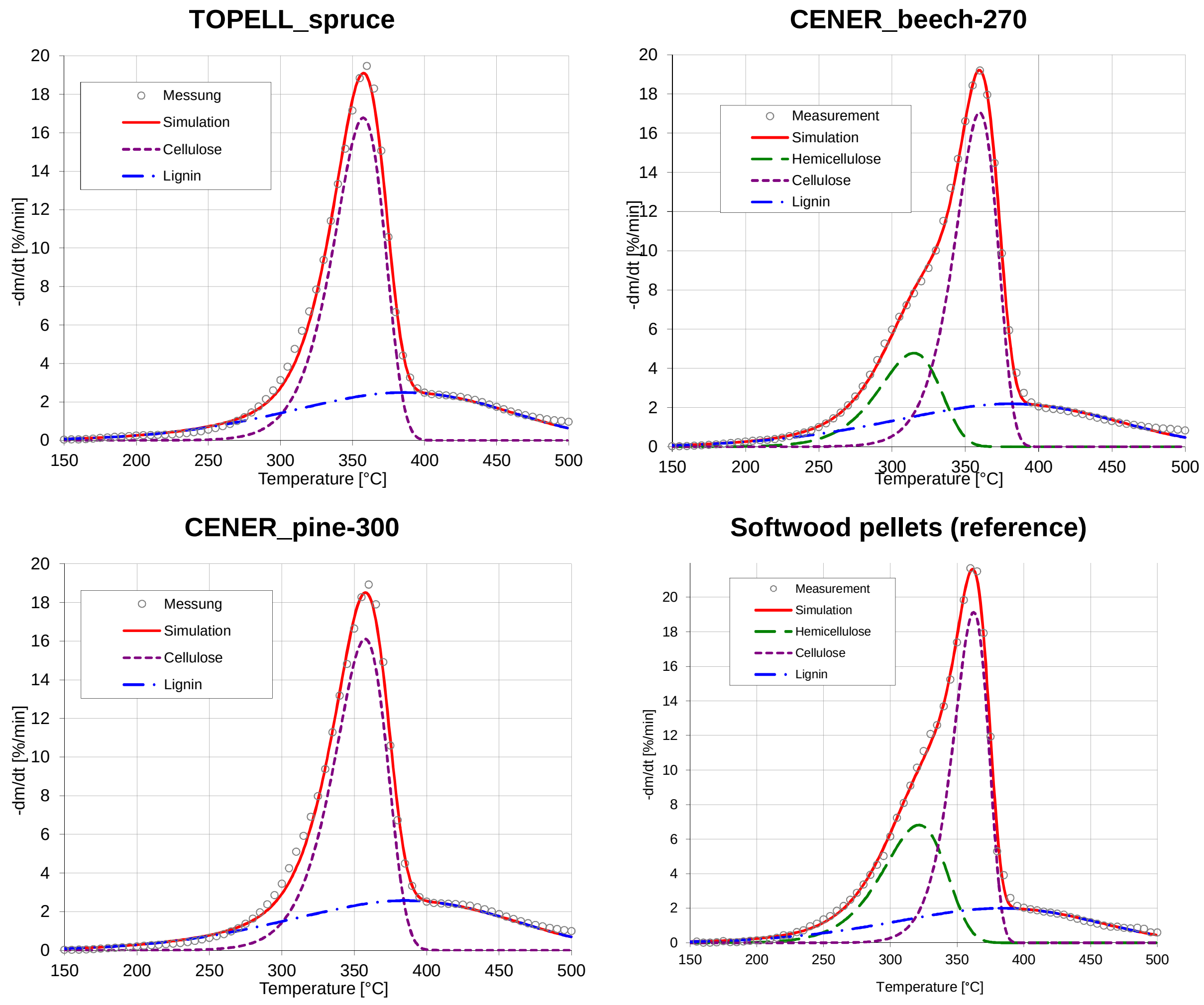

Figure 12: TGA tests performed – peak separation

Figure 12 shows diagrams of the calculated peak separation curves. The diagrams show that an acceptable fit of the model with the experimental data and indicates that the pyrolysis of the fuels is well described by a first order parallel reactions model. The deviations between the experimental and simulated curves are below 2%. The calculated values of the parameters of the pyrolysis kinetics for the different types of biomass fuels investigated and the calculated mass fractions of the pseudo-components (hemicellulose, cellulose and lignin) are summarised in Table 6.

The thermal degradation of biomass comprises normally three main degradation phases. In the first phase the moisture in the fuel is evaporated (drying phase). Within the scope of the TGA tests drying is performed at 110 °C (for 15 minutes). The second degradation phase starts at approx. 150 to 200 °C and ends at approx. 500 °C. In this phase the highest mass losses occur. The second degradation phase shows three overlapping sub-phases (the hemicelulose, the cellulose and the lignin release sub-phases). In the third degradation phase which starts at approx. 500 °C coking reactions prevail and typically only small weight losses occur.

During the torrefaction process hemicellulose is released and usually no or only a small amount of hemicellulose is detected in torrefied materials, which is the case for TOPELL_spruce and CENER_pine-300. However, in the CENER_beech-270 a considerable amount of hemicellulose is detected (14 wt% d.b., in comparison: untreated softwood: 21 wt% d.b.). This indicates that the torrefaction rate was considerably lower for the CENER_beech-270 sample. Comparing the results between the torrefied materials it can be estimated that the torrefaction temperature of TOPELL_spruce should also be around 300 °C as the results are very similar to CENER_pine-300.

Table 6: TGA tests performed - decomposition phases and decomposition kinetics
Explanations: * ... maximum decomposition rate; ** … activation energy; *** … frequency factor (pre-exponential factor); d.b ... dry basis; af ... ash free; N … not calculated

Component	Mass fraction	Mass fraction (ash free)	Decomposition start	Decomposition end	[-dm/dt] (max)*	EA**	ln(A)***
	[wt%d.b.]		[°C]	[°C]	[wt%/min]	[kJ/mol]	$[s^{-1}]$
Torrefied spruce (pellets) - TOPELL_spruce							
Cellulose	38.6	38.7	270	395	16.8	181.3	31.2
Lignin	23.4	23.5	157	585	2.5	42.3	2.2
Torrefied beech (pellets) - CENER_beech-270							
Hemicellulose	14.0	14.2	212	365	4.8	126.4	22.5
Cellulose	30.9	31.4	288	389	17.0	230.1	40.4
Lignin	20.9	21.2	212	532	2.2	40.1	2.2
Torrefied pine (pellets) - CENER_pine-300							
Cellulose	37.5	37.7	267	395	16.1	174.9	29.4
Lignin	24.5	24.6	227	526	2.6	41.2	1.9
Softwood pellets (reference)							
Hemicellulose	21.0	21.1	216	371	7.1	126.4	21.3
Cellulose	32.6	32.7	298	389	19.2	260.0	45.5
Lignin	19.3	19.4	N	N	2.2	45.4	2.9

The cellulose fraction in the TOPELL_spruce sample amounts to 38.6 wt% d.b., in the CENER_beech-270 sample to 30.9 wt% d.b., in the CENER_pine-300 sample to 37.5 wt% d.b. and in softwood to 32.6 wt% d.b..

The lignin fraction amounts to approx. 23.4 wt% d.b. for TOPELL_spruce, to 20.9 wt% d.b. for CENER_beech-270, to 24.5 wt% d.b. for CENER_pine-300 and to 19.3 wt% d.b. for softwood. Cellulose decomposition rates are considerably higher than the lignin decomposition rates (see Table 6).

The activation energy (EA) shown in Table 6 is for softwood pellets in line with literature data. For TOPELL_spruce and CENER_pine-300 the activation energy for cellulose is considerably lower and for ligin slightly lower than for softwood pellets. For CENER_beech-270 the activation energy is in the same range for hemicellulose and slightly lower for cellulose and lignin.

4.3 Results of lab-scale reactor tests performed

Lab-scale reactor tests have been performed with torrefied softwood pellets (TOPELL_spruce) and are in the following section compared to lab-scale reactor tests performed with conventional softwood pellets. The methodology of the lab-scale reactor tests are described in section 3.2. The chemical composition of the fuels used can be taken from Table 3 (see section 4.1). Three test runs have been performed for both fuels in order to investigate the reproducibility of the results. Since all three tests showed similar results, here one test run for each fuel is discussed.

For TOPELL_spruce a fuel mass of 453 g (w.b.) respectively 438 g (d.b.) and for softwood pellets 410 g (w.b.) respectively 381 g (d.b.) was used (see Table 7). The rate of recovery of the residual ash is 99 wt% for TOPELL_spruce and 103 wt% for softwood pellets.

Table 7: Results of lab-scale reactor tests – experimental data and ash balance
Explanations: the estimated amount of ash according to the ash content is based on the determination of the ash content (without TIC) multiplied with the sample mass of the fuel (in g d.b.); the recovery rate is calculated based on the output weight of the ash (without TIC and TOC) divided by the estimated amount of ash multiplied with 100; TOC ... Total Organic Carbon; TIC … Total Inorganic Carbon (Carbonate Carbon)

		Softwood pellets	Torrified softwood pellets TOPELL_spruce
Input (fuel)	[g w.b.]	410.2	452.8
	[g d.b.]	381.1	438.1
moisture content (fuel)	[wt% w.b.]	7.1	3.2
Output (ash, without TIC + TOC) - measured	[g d.b.]	1.31	1.49
Estimated amount of ash according to ash content (fuel, without TIC)	[g d.b.]	1.27	1.50
Rate of recovery	[%]	103	99

Figure 13 shows the mass decrease of TOPELL_spruce in comparison with softwood pellets, Figure 14 the progression of the bed temperatures and Figure 15 the concentrations of the main gas species in the gas produced.

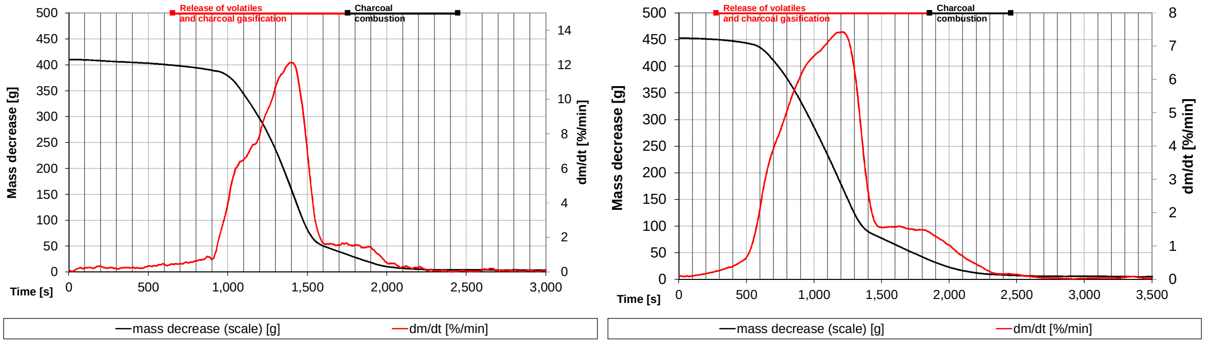

Figure 13: Results of lab-scale reactor tests – mass decrease
Explanations: left: softwood pellets, right: torrefied softwood pellets (TOPELL_spruce)

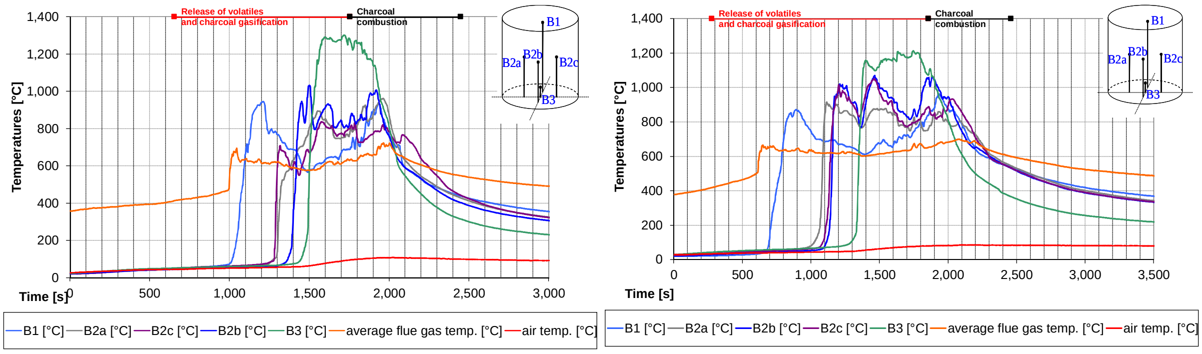

Figure 14: Results of lab-scale reactor tests – temperatures
Explanations: left: softwood pellets, right: torrefied softwood pellets (TOPELL_spruce)

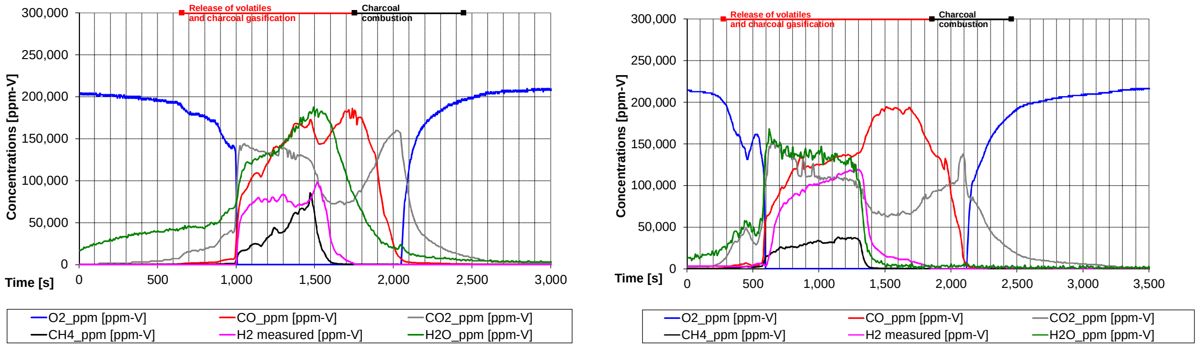

Figure 15: Results of lab-scale reactor tests – flue gas components
Explanations: left: softwood pellets, right: torrefied softwood pellets (TOPELL_spruce)

Table 8 shows characteristic data of the lab-scale reactor tests performed. As it can be seen, the test run duration was about 2,500 seconds for both fuels investigated. At the beginning, mainly drying took place indicated by a moderate mass loss, low fuel bed temperatures and the release of H_2O. After about 274 seconds, fuel decomposition started for TOPELL_spruce indicated by decreasing O_2 concentrations and increasing CO_2 concentrations in the flue gas. For softwood pellets the drying phase took longer (approx. 652 s) due to the higher moisture content. The main decomposition phase starts with a rapid decrease of the O_2 concentration to zero level. Release of volatiles and parallel charcoal gasification take place and a rapid mass loss, a rapid increase of the bed temperatures as well as combustion air ratios below 1 can be observed. Mainly CO_2, CO, H_2O, CH_4 and H_2 as well as minor amounts of other hydrocarbons are released to the gas phase. After 1,854 seconds for TOPELL_spruce and

1,752 seconds for softwood pellets H_2 and CH_4 drop to zero which is taken as an indicator for the end of the release of volatiles and the start of the main charcoal combustion phase. This phase is characterized by smaller amounts of CO and increasing CO_2 concentrations in the flue gas as well as increasing O_2 concentrations (increasing excess air ratio). During this phase typically the highest fuel bed temperatures are measured which is for TOPELL_spruce with 1,213 °C lower than for softwood pellets (1,301 °C).

The degradation rate during volatiles release and charcoal gasification for TOPELL_spruce amounts to approx. 3.6 %/min (% related to the input weight) and approx. 0.53 g/l (related to the air supplied). The corresponding degradation rate for softwood pellets related to input weight amounts to 5.2 %/min and related to the air supplied 0.66 g/l, which shows that in this phase the degradation rate of TOPELL_spruce is lower than for softwood pellets. The average air ratio is in this phase similar for both fuel (0.68 and 0.71 respectively).

The degradation rate of charcoal combustion related to the input weight is with approx. 0.6 %/min similar for both fuels. However, the degradation rate related to the air supplied is for TOPELL_spruce (0.10 g/l) somewhat higher than for softwood pellets (0.08 g/l). The air ratio during charcoal combustion phase is for TOPELL_spruce (1.44) slightly lower than for softwood pellets (1.52). The velocity of the reaction front is for TOPELL_spruce considerably lower (0.13 mm/s) than for softwood pellets (0.19 mm/s). The results of the lab-scale reactor tests indicate that the overall combustion process for TOPELL_spruce is slower than for softwood pellets which is likely due to the fact that the higher amount of charcoal and the lower volatiles content increase the time needed for complete burnout.

Table 8: Results of lab-scale reactor tests – characteristic data

Explanations: Air ratio = (amount of air during the test run) / (amount of air required for stoichiometric combustion). The amount of air required for stoichiometric combustion is the amount of air needed to fully oxidize the fuel

		Softwood pellets			Torrefied softwood pellets TOPELL_spruce		
		Release of volatiles + charcoal gasification	Charcoal combustion	Overall reaction phase	Release of volatiles + charcoal gasification	Charcoal combustion	Overall reaction phase
Degradation rate and air ratio							
Start	[s]	652	1,752	652	274	1,854	274
End	[s]	1,752	2,446	2,446	1,854	2,456	2,456
Duration	[s]	1,100	694	1,794	1,580	602	2,182
Degradation rate based on							
input weight	[%/min]	5.2	0.6	3.5	3.6	0.6	2.8
time	[g/min]	20.0	2.5	13.2	15.7	2.8	12.2
amount of air	[g/l air]	0.66	0.08	0.44	0.53	0.10	0.41
Mass (balance)	Start	399.1	33.3	399.1	449.8	36.0	449.8
[g]	End	33.3	3.9	3.9	36.0	7.5	7.5
Average air ratio according to measurement (lambda sensor)		0.71	1.52	0.89	0.68	1.44	0.80
Characteristic parameters							
Max. bed temperature	[°C]		1,301			1,213	
Velocity of the reaction front	[mm/s]		0.19			0.13	

Figure 16 shows the NO_x-precursors released from the fuel bed and Figure 17 the total conversion rate of N to TFN (related to N content in the fuel). The total conversion rate of N to TFN is for both fuels high (for softwood pellets 95% and for TOPELL_spruce almost 100%, see Figure 17) which represents under consideration of the N contents in the fuel (0.05 wt% d.b. for softwood pellets and 0.07 wt% d.b. for TOPELL_spruce) a normal conversion rate.

For TOPELL_spruce the release of NO_x precursors is dominated by NH_3 (see Figure 17). Approx. 62% of the total TFN (total fixed nitrogen) is NH_3 which is mainly released during the release of volatiles and charcoal gasification. HCN and NO are released to a comparably smaller extent. Approx. 27% of the total TFN is HCN (also mainly released during the release of volatiles and charcoal gasification). NO amounts to approx. 10% of the total TFN. The amounts of NO_2 und N_2O are negligible. For conventional softwood pellets on the other hand the release of NO_x precursors is more dominated by HCN (48%) (see Figure 17). NH_3 amounts to 26% and NO to 19% for this fuel. It is interesting that the typically occurring HCN domination during softwood degradation is not given for torrefied spruce. This is possibly due to the fact that part of the nitrogen is already released during torrefaction (usually 25 – 40 % at torrefaction temperatures of 300 °C)

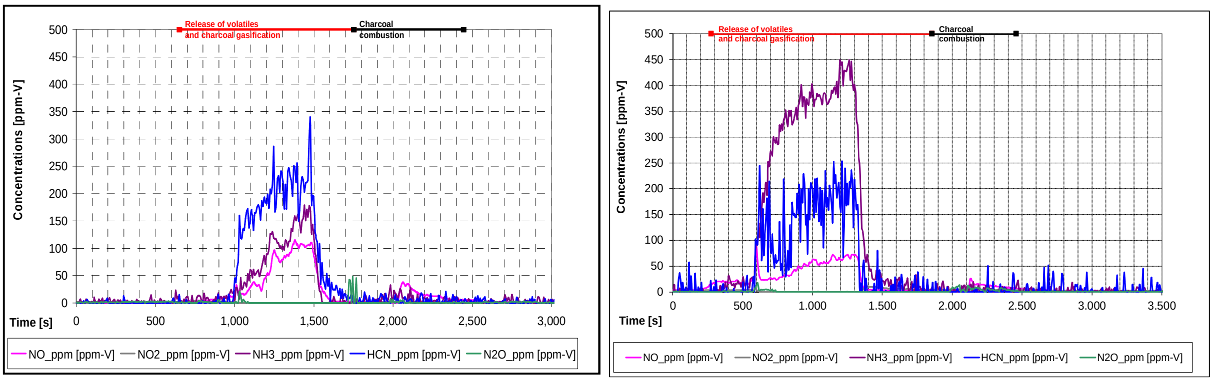

Figure 16: Results of lab-scale reactor tests – NO_x-precursors released from the fuel bed
Explanations: left: softwood pellets, right: torrefied softwood pellets (TOPELL_spruce)

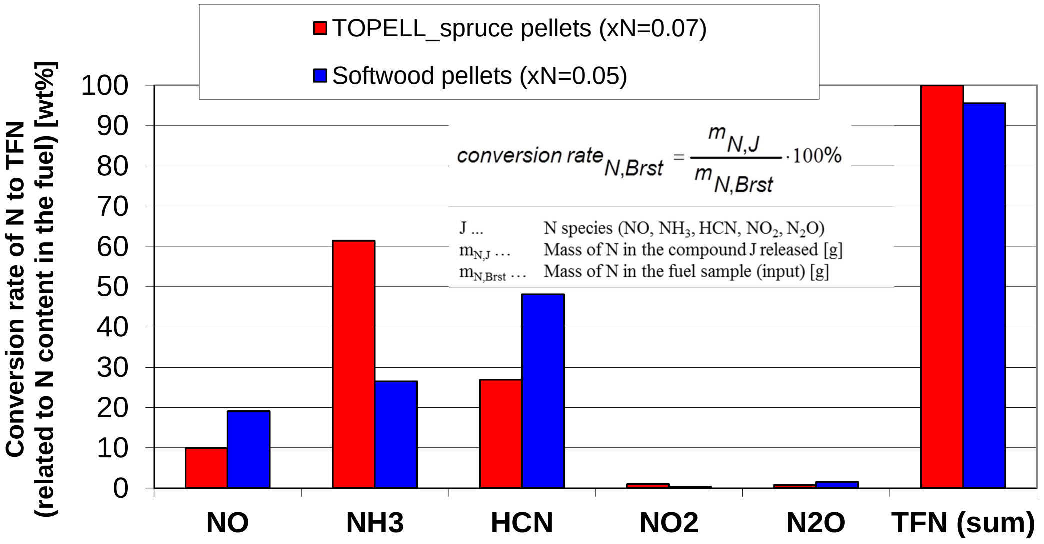

Figure 17: Results of lab-scale reactor tests – conversion rate of N to TFN related to the N content in the fuel
Explanations: TFN ... Total Fixed Nitrogen (sum of NO, NH_3, HCN, NO_2, N_2O); xN ... N-content in the fuel [% (w/w, d.b.)]

Figure 18: Photos of the fuel before (above) and the ashes (below) after the test run
<u>Explanations:</u> left: softwood pellets, right: torrefied softwood pellets (TOPELL_spruce)

Figure 18 shows photos of the fuel before and the remaining ashes after the test run. The ashes of TOPELL_spruce are dark brown and loose and for softwood pellets grew-brown and loose. For both fuels the original form of the pellets remains partly intact and no sintering or slagging was observed.

Table 9 shows analysis results of the residual ash. The S and Cl contents of the residual ash from TOPELL_spruce are considerably higher than in the residual ash from softwood pellets (factor 4 and 9.2 respectively). The Ca content in the residual ash is lower for TOPELL_spruce compared to softwood pellets and the Mg content is on a similar level. Due to the low Si content in TOPELL_spruce the Si content in the residual ash is considerably lower (factor 3.3). The content of alkali metals (K and Na) is higher for TOPELL_spruce compared to softwood pellets (factor 1.5 and 1.6 respectively) most probably due to the higher contents in the fuel (see Table 3). The Zn content is considerably higher (factor 13.7). The TOC content in the residual ash is considerably higher for TOPELL_spruce than for softwood pellets.

Table 9: Results of lab-scale reactor tests – analysis results of residual ash
Explanations: TOC ... Total Organic Carbon; TIC … Total Inorganic Carbon (Carbonate Carbon)

Description of fuel		Softwood pellets - Residual ash	Torrified softwood pellets - Residual ash TOPELL_spruce
S	[mg/kg d.b.]	936	3,780
Cl	[mg/kg d.b.]	139	1,280
Ca	[mg/kg d.b.]	277,000	162,000
Si	[mg/kg d.b.]	81,600	24,600
Mg	[mg/kg d.b.]	36,400	35,600
K	[mg/kg d.b.]	114,000	172,000
Na	[mg/kg d.b.]	3,170	5,230
Zn	[mg/kg d.b.]	22.8	313.0
TOC	[mg/kg d.b.]	1,000	28,100
TIC	[mg/kg d.b.]	23,000	30,400

Based on the results of the fuel and ash analyses element balances for ash forming elements have been performed. They show an acceptable closure for non-volatile elements such as Ca (82% for TOPELL_spruce and 109% for softwood pellets) and Mg (85% for TOPELL_spruce and 112% for softwood pellets) which is an important pre-requisite for the plausibility of the release rates calculated for ash forming elements from these data. Also the rate of recovery of the total residual ash shows an acceptable closure (99 wt% for TOPELL_spruce and 103 wt% for softwood pellets, see Table 7).

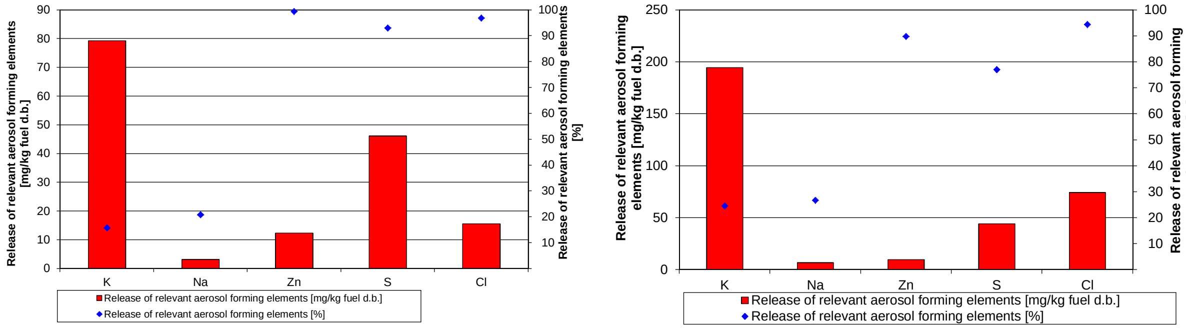

Figure 19: Results of lab-scale reactor tests – release of relevant aerosol forming elements
Explanations: left: softwood pellets, right: torrefied softwood pellets (TOPELL_spruce)

$$release_X = \frac{\left(c_{X,input} \cdot m_{input}\right) - \left(c_{X,output} \cdot m_{output}\right)}{m_{input\ (d.b.)}} \qquad release_{X,\%} = \left(1 - \frac{c_{X,output} \cdot m_{output}}{c_{X,input} \cdot m_{input}}\right) \cdot 100\%$$

$c_{x,input}$ ... concentration of element X in the original sample [mg/kg d.b.];
$c_{x,output}$ ... concentration of element X in the output material (residue) [mg/kg d.b.]

In Figure 19 these release rates are presented. For TOPELL_spruce the easily volatile elements S and Cl show as expected high release rates (77 wt% and 94 wt% respectively). Also for Zn the release rates are high (90 wt%). Moreover, 24 wt% of the K and 27 wt% of the Na contained in the fuel have been released to the gas phase. For conventional softwood pellets the release rates for S (93 wt%) and for Cl (93 wt%) are in the same range than for TOPELL_spruce. The release rate for Zn is with 99% also in a comparable range. For K and Na the release rates are clearly lower than for TOPELL_spruce (16 and 21 wt% respectively) which is probably due to the lower Si content in TOPELL_spruce. Si usually binds a certain amount of K in the grate ash.

Assuming that K and Na mainly form sulphates and chlorides while Zn is most likely bound as oxides, the potential for fine particle (aerosol) formation can be estimated based on these release rates. For the test run presented the maximum potential for aerosol emissions amounts to 32 mg/Nm³ (related to dry flue gas and 13 vol% O_2) for TOPELL_spruce pellets. For softwood pellets the maximum potential for aerosol emissions is considerably lower (16 mg/Nm³, related to dry flue gas and 13 vol% O_2) which is due to the lower K content in the fuel (see Table 3) and the lower release rate for K compared to TOPELL_spruce (see Figure 19). This estimation of the maximum aerosol emission potential does of course not take into account particle losses caused by condensation of ash forming vapours on walls and deposit formation in the furnace and the boiler sections of real-scale plants. Moreover, particle losses caused by reaction of ash forming vapours with coarse fly ash particles or condensation on coarse fly ash particles as well as gaseous emissions of S (i.e. SO_x) and Cl (i.e. HCl) are not considered. Following, it is an approximation but suitable to evaluate the aerosol emission potential.

4.4 Results of test runs performed with a modern pellet boiler

The test runs with a modern pellet boiler (nominal boiler capacity 21 kW) have been performed in August and September 2013. The following fuels have been used: standardised softwood pellets according to EN 14961-2 (ENplus-A1)) and torrefied softwood pellets (TOPELL_spruce). The results of the fuel analysis are discussed in section 4.1. Test runs have been performed at continuous full load and partial load for each fuel. For the test runs with TOPELL_spruce the same control settings than for conventional softwood pellets were applied. Only the fuel feed was reduced in order to adapt to the higher energy density of torrefied material. The energy density of conventional softwood pellets amounts to 3,156 kWh/m^3 w.b. and of TOPELL_spruce to 3,766 kWh/m^3 w.b. (see chapter 4.1, Table 3). Figure 20 shows pictures of the burner and the grate ash during test runs with TOPELL_spruce and furnace settings 1. The results showed that the TOPELL_spruce pellets brake into pieces during combustion which subsequently did not completely burn out. Consequently, the burnout quality of the grate ash was not satisfying (see also section 4.4.3, Figure 43). Furthermore, the shape of the fuel bed was different for conventional and torrefied pellets (see Figure 21). The fuel bed was almost flat for conventional pellets. Using torrefied pellets the height of the fuel bed increased from the centre to the outside of the grate.

Based on this experience it was decided to increase the primary air ratio in order to test if this measure improves the burnout quality of the grate ash. Tests at full load and partial load have been conducted with these adapted furnace settings (furnace settings 2) with the TOPELL_spruce pellets. For these tests the secondary air duct was partly closed and the speed of the flue gas fan was increased. Since there is no lambda control applied in the furnace system used the total air ratio was reduced during the test runs with furnace settings 2.

Table 10 gives an overview over relevant parameters for all test runs. In total measurements have been performed over 10 days and the results of 6 measurement days are presented in this report. During the test runs operating data and concentrations of O_2, CO_2, CO and NO_x as well as PM_1 emissions (with ELPI) at boiler outlet have continuously been measured. Furthermore, TSP and BLPI measurements have been repeatedly performed. The methodology of the test runs is described in section 3.3.4.

Table 10: Overview over relevant parameters and results for all test runs

Explanations: FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce); fg … flue gas; mg/Nm^3 is related to 13 vol% O_2, dry flue gas; PCC … primary combustion chamber

		Softwood pellets FL	TORR FL - funace settings 1	TORR FL - funace settings 2	Softwood pellets PL	TORR PL - funace settings 1	TORR PL - funace settings 2
Evluation period	from	13.08 13:11:24	21.08 12:38:00	11.09 13:06:06	20.08 10:38:36	22.08 10:33:15	18.09 12:55:53
	to	13.08 18:49:25	21.08 17:20:00	11.09 17:30:58	20.08 15:05:00	22.08 15:01:28	18.09 17:03:07
Duration	[h]	5,6	4,7	4,4	4,4	4,5	4,1
boiler load [kW]	[kW]	19,2	20,8	19,9	6,4	6,6	6,3
T grate	[°C]	507,1	525,4	509,2	394,1	415,3	403,3
T bed	[°C]	1.146,9	1.094,1	884,6	955,1	799,2	702,6
T pyrometer	[°C]	916,4	1.023,6	963,1	590,0	610,4	630,8
O2 content	[vol% fg dry]	9,3	8,2	7,5	14,7	14,0	11,6
CO emissions	[mg/Nm³]	10,1	21,7	46,7	99,4	307,3	308,9
NOx emissions	[mg/Nm³]	160,5	160,2		162,0	140,4	
PM1 emissions (BLPI)	[mg/Nm³]	5,7	8,2	6,6	7,5	20,3	25,1
TSP emissions	[mg/Nm³]	9,8	12,8	15,6	15,7	37,7	34,9
total air ratio	[-]	1,79	1,64	1,56	3,35	2,98	2,23
air ratio in the PCC	[-]	0,57	0,45	0,63	1,01	0,84	0,95
primary air	[Nm³/h]	10,8	9,3	12,3	6,7	5,6	5,9
secondary air	[Nm³/h]	13,1	13,4	7,3	8,1	8,1	4,6
false air	[Nm³/h]	9,6	10,7	10,8	7,0	6,2	3,3

Figure 20: Pictures of the burner and the grate ash during test runs with TOPELL_spruce (furnace settings 1)

Explanations: left above: burner filled with TOPELL_spruce pellets; right above: burner in operation with TOPELL_spruce pellets; below: grate ash

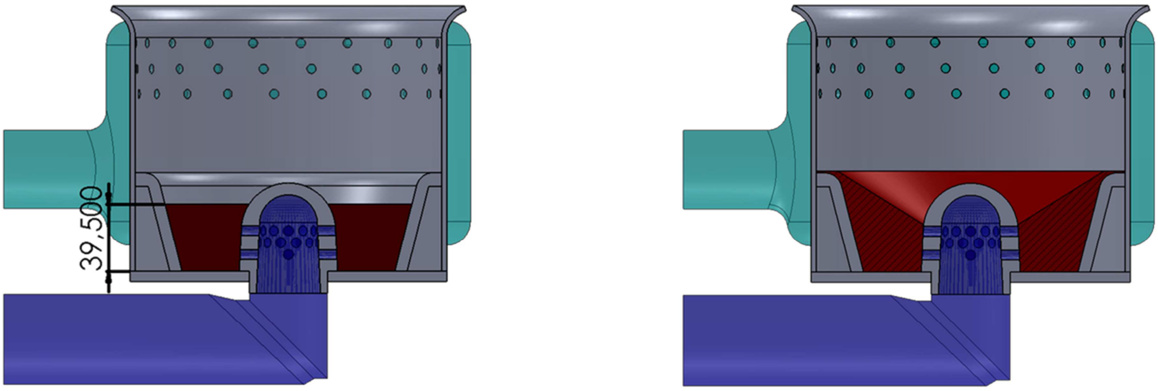

Figure 21: Schematic illustration of the fuel bed for conventional pellets (almost flat, left picture) and for torrefied pellets (increasing height to the outside, right picture)

In section 4.4.1 trends of the gaseous and particulate emissions as well of important operating data for all test runs performed at full load and in section 4.4.2 for partial load operation are shown and briefly discussed. In section 4.4.3 mean values of the data over representative operation periods are compared and discussed.

4.4.1 Results of test runs performed at full load

Figure 22 shows the boiler load, the feed and return temperatures as well as flue gas temperatures and Figure 23 the gaseous and particulate emissions for the reference tests with conventional softwood pellets at full load. The return temperature provided by the cooling system of the test facility was not completely stable which caused some fluctuations in the boiler load. However, boiler operation was stable and slightly below nominal boiler capacity (19.2 kW).

CO emissions were generally at a very low level and only few CO peaks occurred. NO_x emissions amounted on average to 160 mg/Nm^3 (see Figure 23). The PM_1 emissions measured continuously with ELPI and discontinuously with BLPI were low (5.7 mg/Nm^3) and the TSP emissions amount to 9.8 mg/Nm^3.

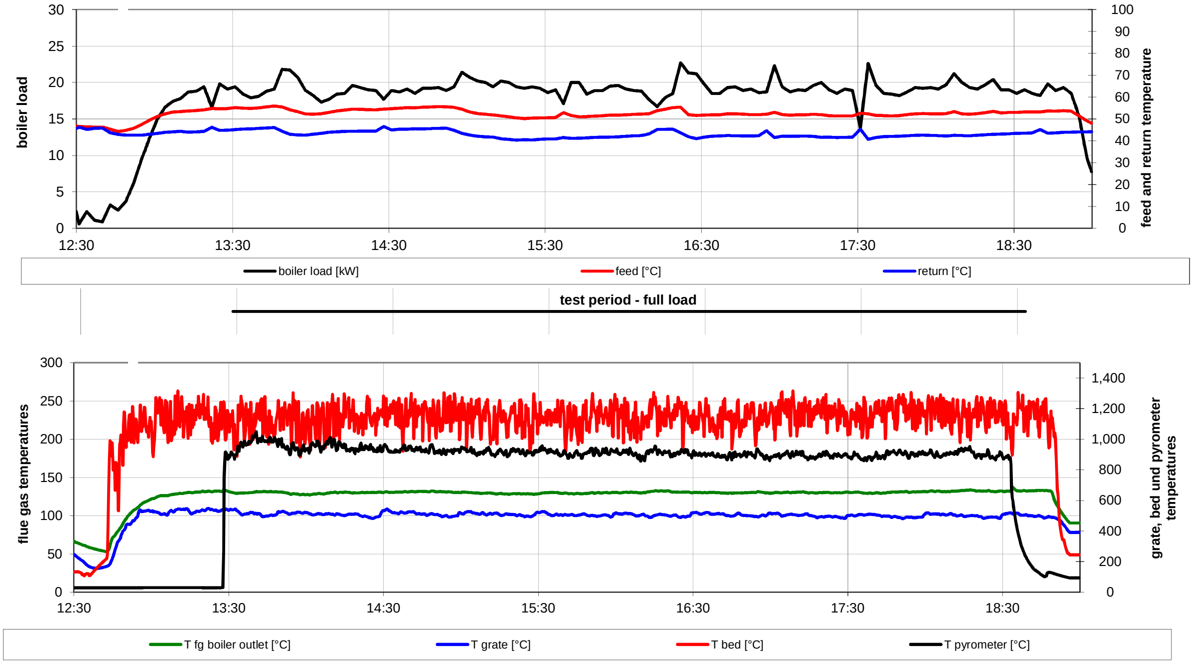

Figure 22: Boiler load, net and flue gas temperatures as well as feed and return temperatures – reference tests with softwood pellets at full load

Explanations: fg … flue gas; T pyrometer … flue gas temperature measured with a suction pyrometer in the secondary combustion chamber (from 13:28 to 18:35)

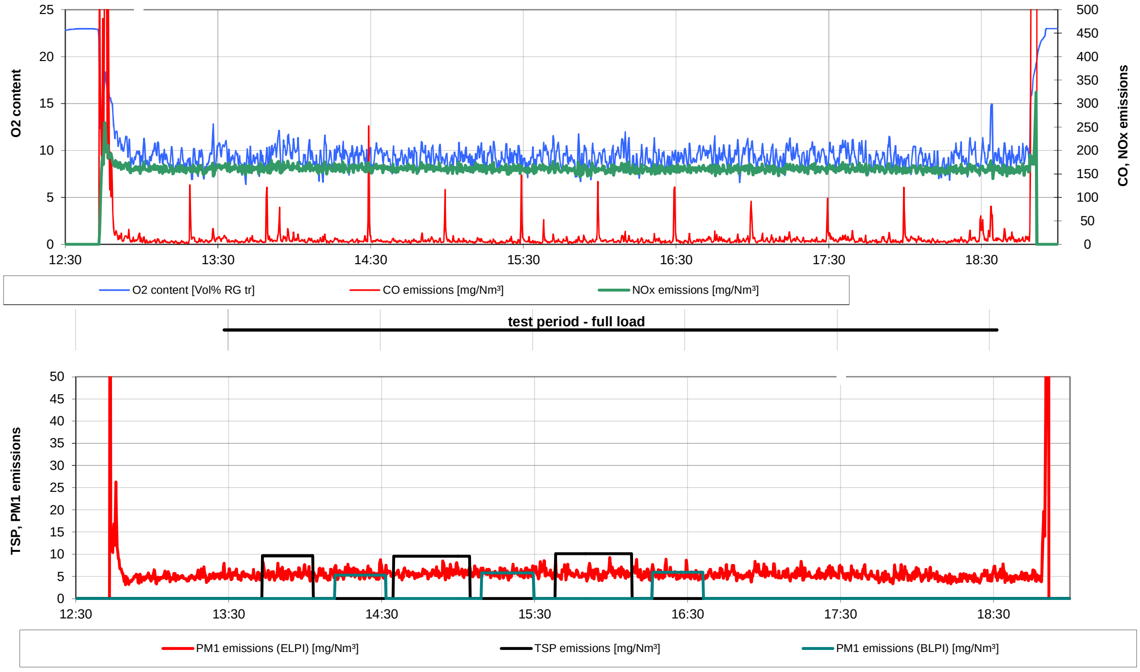

Figure 23: Gaseous and particulate emissions – reference tests with softwood pellets at full load

Explanations: TSP … Total suspended particles; NO_x calculated as NO_2; mg/Nm^3 is related to 13 vol% O_2, dry flue gas

Figure 24 and Figure 25 show measurement data of the test runs performed with TOPELL_spruce pellets at full load with furnace settings 1. For this test run the same control settings used for conventional softwood pellets were applied. Only the fuel feed was reduced in order to adapt to the higher energy density of torrefied material. The boiler load was 20.8 kW and stable load conditions were achieved.

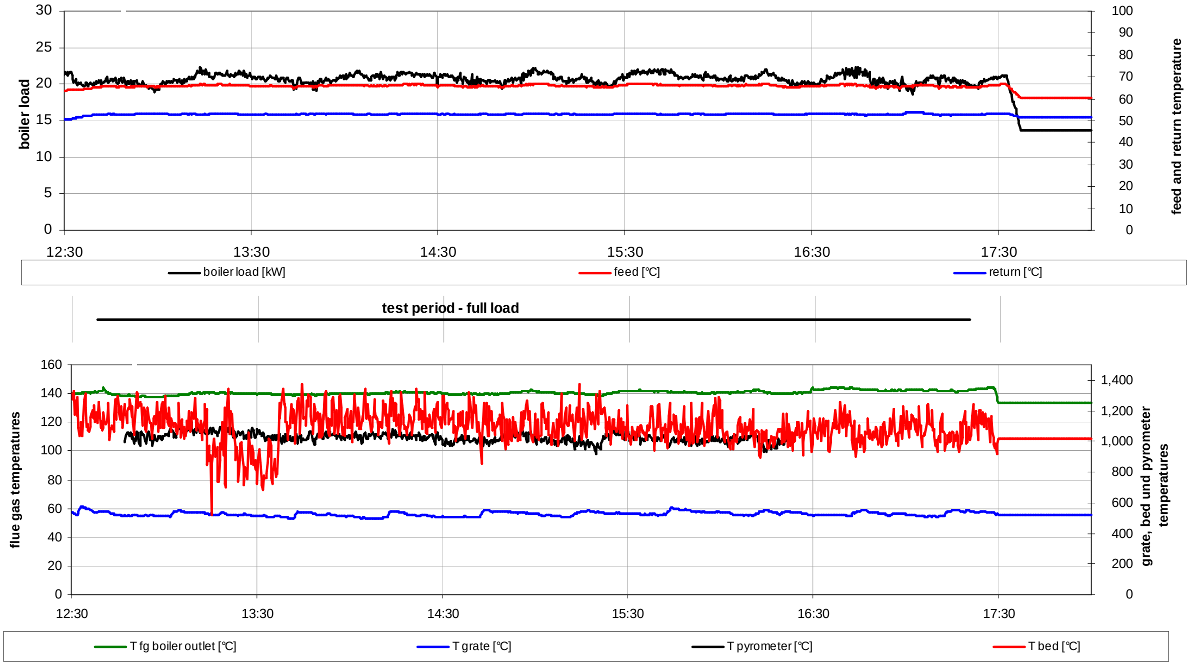

Figure 24: Boiler load, net and flue gas temperatures as well as feed and return temperatures – tests with TOPELL_spruce pellets at full load – furnace settings 1

Explanations: fg … flue gas; T pyrometer … flue gas temperature measured with a suction pyrometer in the secondary combustion chamber (from 12:45 to 18:25)

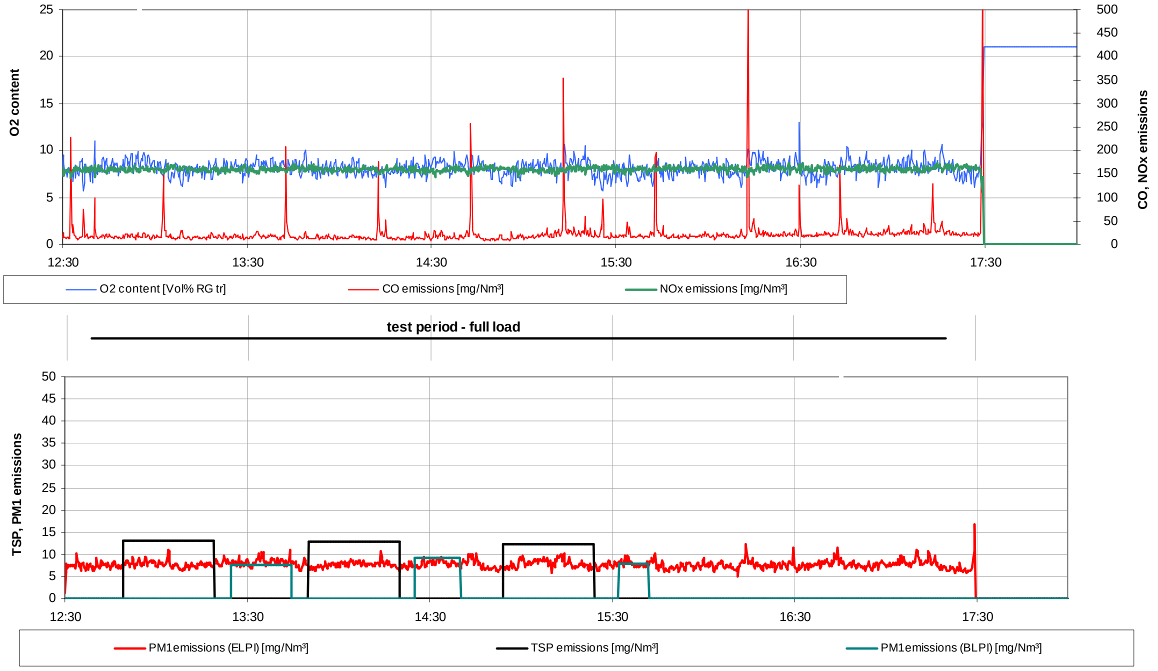

Figure 25: Gaseous and particulate emissions – tests with TOPELL_spruce pellets at full load – furnace settings 1

Explanations: TSP … Total suspended particles; NO_x calculated as NO_2; mg/Nm^3 is related to 13 vol% O_2, dry flue gas

The base level of the CO emissions was slightly higher than for conventional softwood pellets. In average they amounted to 21.7 mg/Nm^3. NO$_x$ emissions were at the same level as for conventional softwood pellets (see Figure 25). The PM$_1$ emissions (8.2 mg/Nm^3) and the TSP emissions (approx. 12.8 mg/Nm^3) were somewhat higher than for conventional softwood pellets.

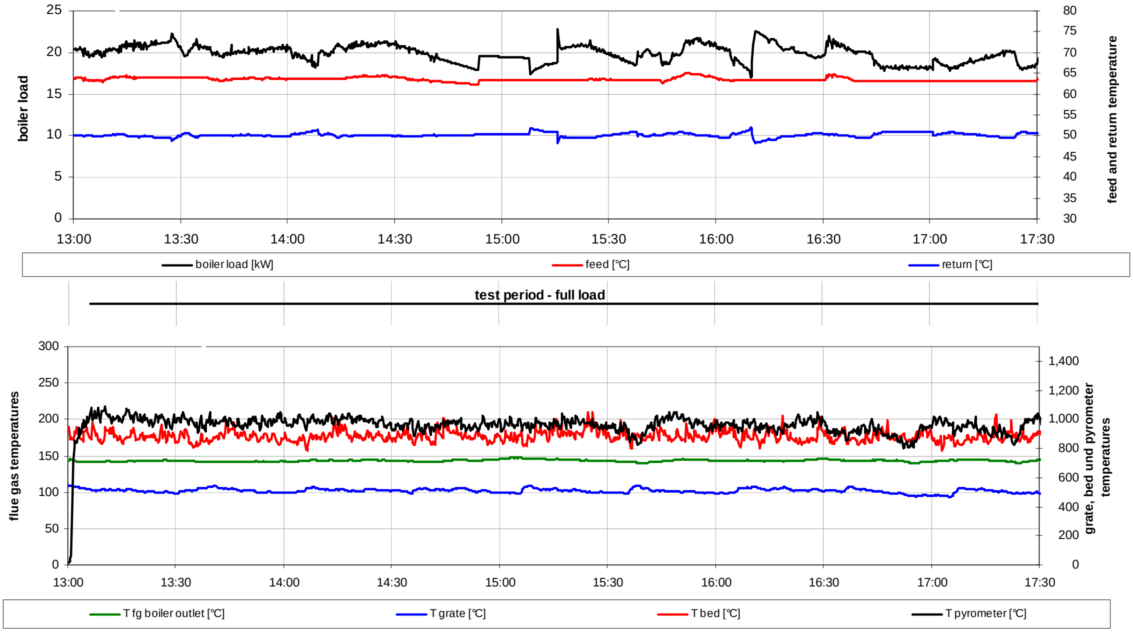

Figure 26: Boiler load, net and flue gas temperatures as well as feed and return temperatures – tests with TOPELL_spruce pellets at full load – furnace settings 2

Explanations: fg … flue gas; T pyrometer … flue gas temperature measured with a suction pyrometer in the secondary combustion chamber (measurement over the entire evaluation period)

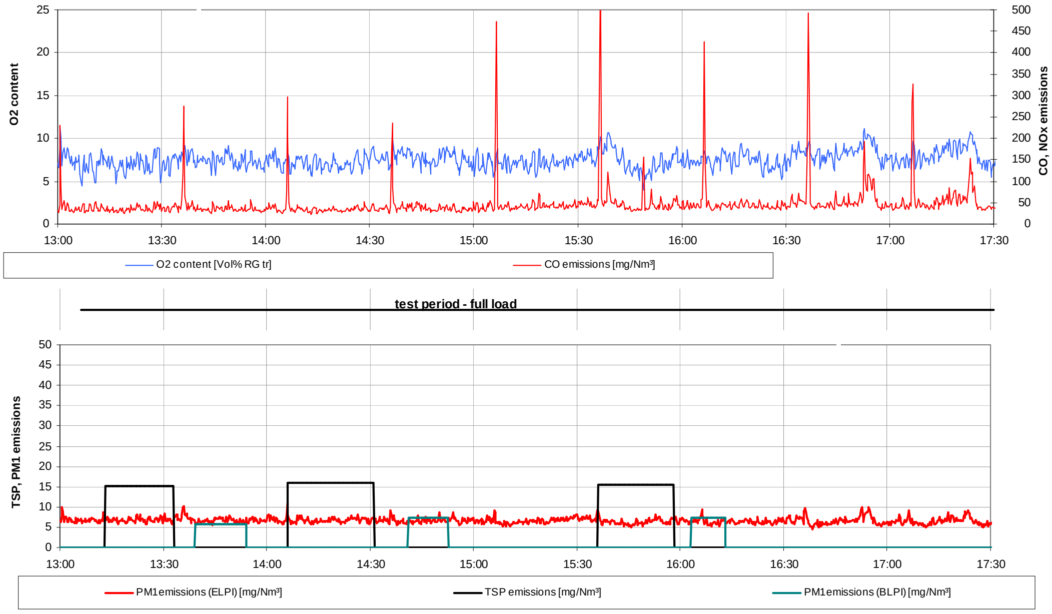

Figure 27: Gaseous and particulate emissions – tests with TOPELL_spruce pellets at full load – furnace settings 2

Explanations: TSP … Total suspended particles, mg/Nm^3 is related to 13 vol% O$_2$, dry flue gas; NO$_x$ emissions have not been measured during the test runs with furnace settings 2

Figure 26 and Figure 27 show measurement data of the test runs performed with TOPELL_spruce pellets at full load with furnace settings 2. For this test run the primary combustion air was increased since it was expected to improve the burnout quality of the grate ash with this measure. The fuel feed was again reduced in order to adapt to the higher energy density of torrefied material. The boiler load was sufficiently stable (19.9 kW, on average).

CO emissions were for furnace settings 2 at a higher base level compared to conventional and TOPELL_spruce pellets with furnace settings 1 (on average 47 mg/Nm^3, see Figure 27) which is most likely due to the reduced amount of secondary air for furnace settings 2 and consequently a less efficient mixing of air and flue gas (see section 4.4.3). NO$_x$ emissions were not measured during this test run. PM$_1$ emissions and TSP emissions amounted to 6.6 and 15.6 mg/Nm^3, respectively. The analysis results of the grate ash showed that the burnout quality could not be improved with furnace settings 2 (see section 4.4.3).

4.4.2 Results of test runs performed at partial load

Figure 28 and Figure 27 show the measurement data of the test runs performed with conventional softwood pellets at partial load. The boiler operation was stable at approx. 6.4 kW (30% of the nominal boiler load) on average.

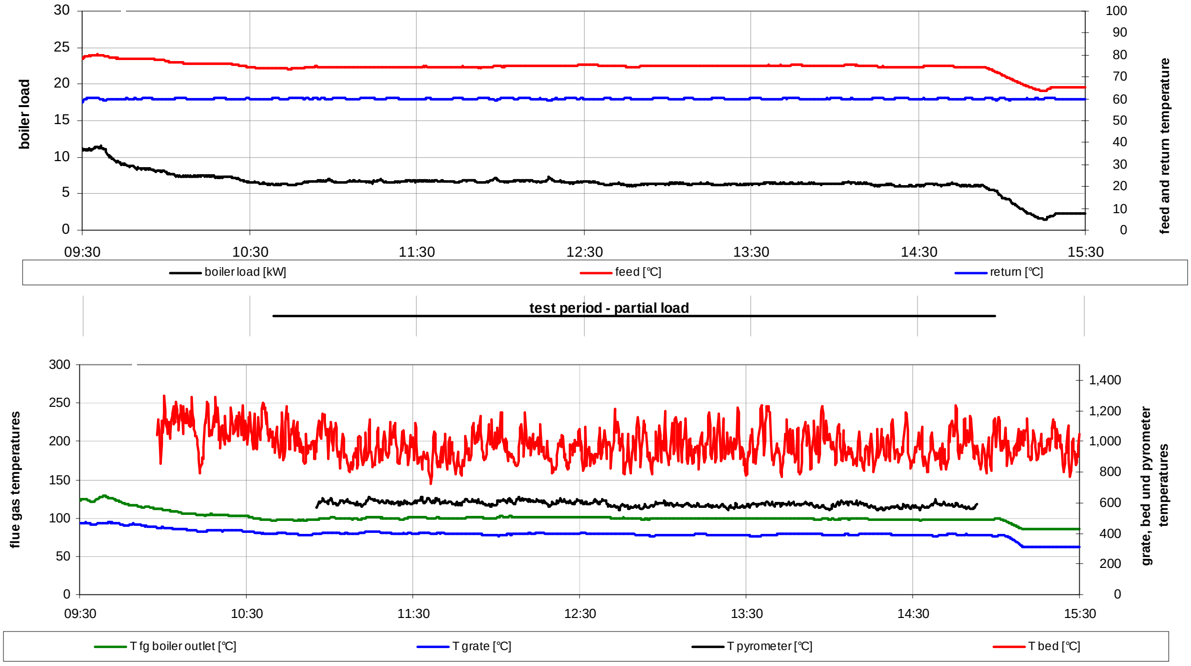

Figure 28: Boiler load, net and flue gas temperatures as well as feed and return temperatures – reference tests with softwood pellets at partial load

Explanations: fg … flue gas; T pyrometer … flue gas temperature measured with a suction pyrometer in the secondary combustion chamber (from 13:50 to 14:45)

CO emissions were in general higher for partial load compared to full load with a base level 100 mg/Nm^3 and some peaks above 500 mg/Nm^3 (see Figure 29). NO$_x$ emissions were at the same level as for full load (162 mg/Nm^3). The PM$_1$ emissions and the TSP emissions were higher than at full load operation with conventional softwood pellets (8 respectively 15.7 mg/Nm^3).

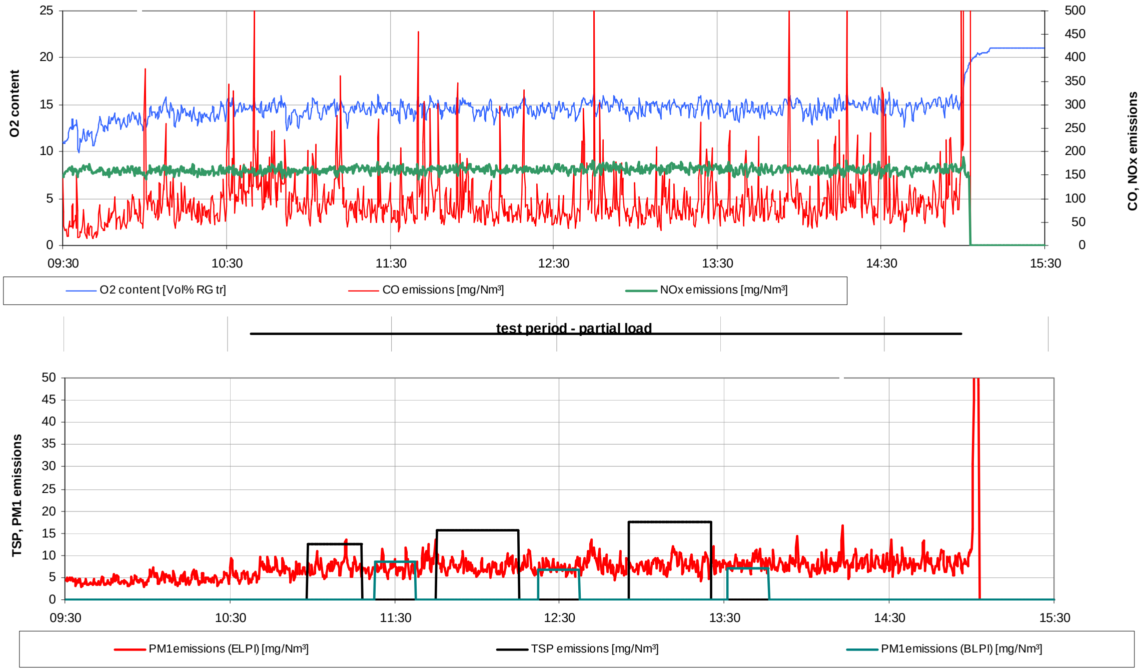

Figure 29: Gaseous and particulate emissions – reference tests with softwood pellets at partial load

Explanations: TSP … Total suspended particles; NO_x calculated as NO_2; mg/Nm^3 is related to 13 vol% O_2, dry flue gas

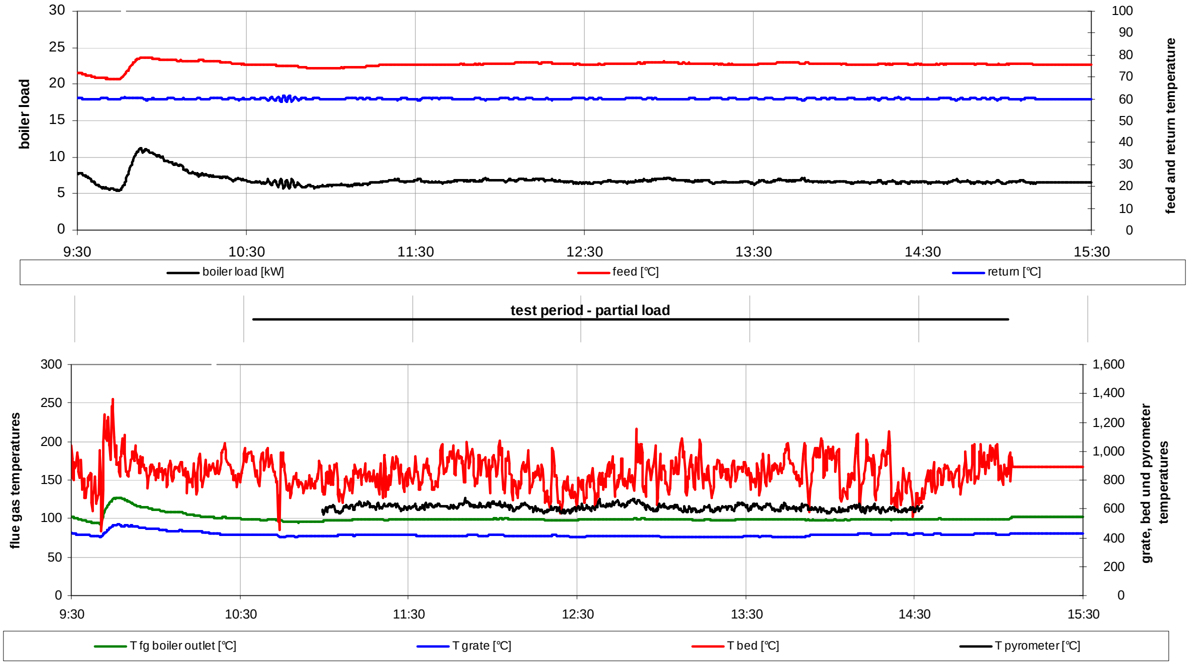

Figure 30: Boiler load, net and flue gas temperatures as well as feed and return temperatures – tests with TOPELL_spruce pellets at partial load – furnace settings 1

Explanations: fg … flue gas; T pyrometer … flue gas temperature measured with a suction pyrometer in the secondary combustion chamber (from 10:55 to 14:35)

During the tests with TOPELL_spruce pellets with furnace settings 1 (same settings as for softwood pellets, only reduced fuel feed) at partial load also stable load conditions at 6.6 kW on average have been reached (see Figure 30).

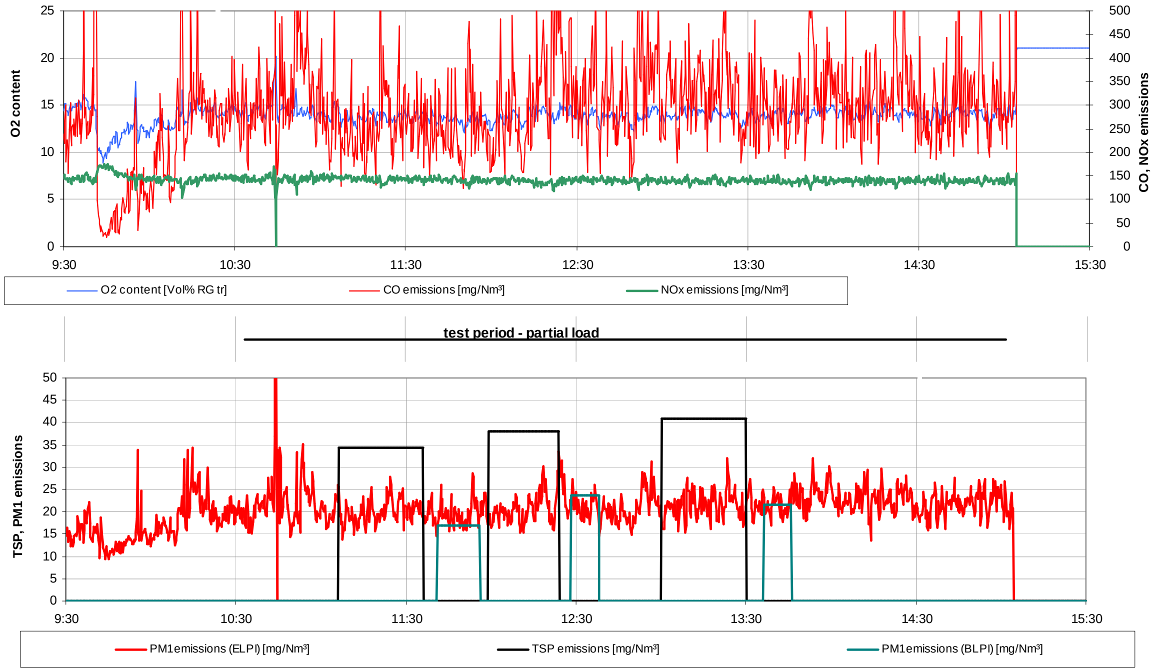

Figure 31: Gaseous and particulate emissions – tests with TOPELL_spruce pellets at partial load – furnace settings 1

Explanations: TSP … Total suspended particles; NO_x calculated as NO_2; mg/Nm^3 is related to 13 vol% O_2, dry flue gas

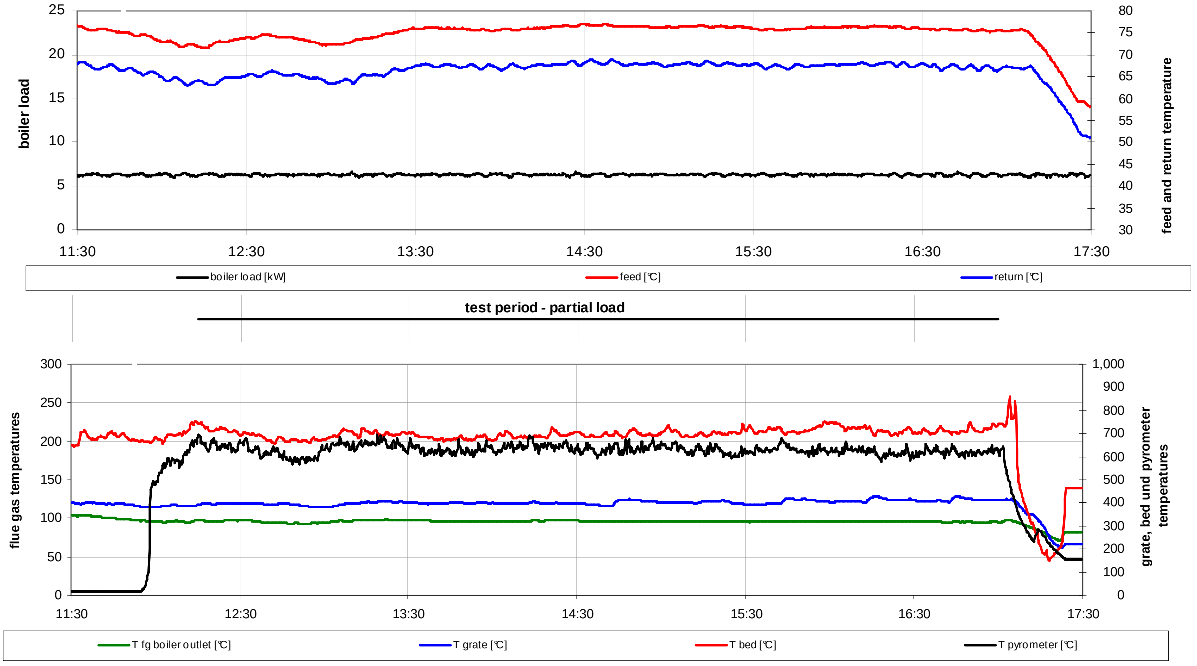

Figure 32: Boiler load, net and flue gas temperatures as well as feed and return temperatures – tests with TOPELL_spruce pellets at partial load – furnace settings 2

Explanations: fg … flue gas; T pyrometer … flue gas temperature measured with a suction pyrometer in the secondary combustion chamber (measurement over the entire evaluation period)

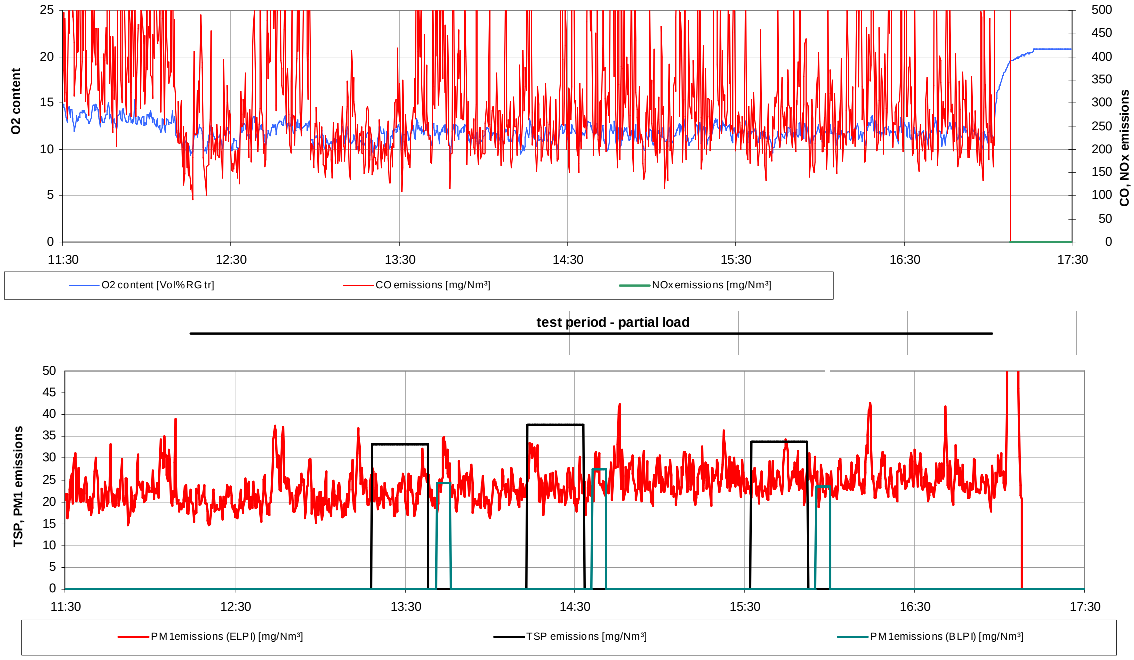

Figure 33: Gaseous and particulate emissions – tests with TOPELL_spruce pellets at partial load – furnace settings 2

Explanations: TSP … Total suspended particles; mg/Nm^3 is related to 13 vol% O_2, dry flue gas; NO_x emissions have not been measured during the test runs with furnace settings 2

The CO emissions were approx. 3 times higher with TOPELL_spruce pellets and furnace settings 1 at partial load compared to conventional softwood pellets (307 mg/Nm^3 on average, see Figure 31) and the NO_x emissions lower (140 mg/Nm^3). The PM_1 emissions and the TSP emissions were considerably higher at partial load compared to conventional softwood pellets (approx. 20 and 38 mg/Nm^3, respectively).

Figure 32 and Figure 33 show the measurement data of the test runs performed with TOPELL_spruce pellets at partial load with furnace settings 2. The boiler load was on average 6.3 kW and stable operating conditions were obtained (see Figure 32).

Again the CO emissions were higher with TOPELL_spruce pellets and furnace settings 2 compared to conventional softwood pellets and at the same level compared to TOPELL_spruce pellets and furnace settings 1 (see Figure 31) and the PM_1 and TSP emissions were high (approx. 25 and 35 mg/Nm^3, respectively).

4.4.3 Comparison of the results of all test runs performed

In this section average values for relevant parameters over representative operation periods for all test runs performed with conventional softwood pellets and TOPELL_spruce pellets at full and partial load are compared. Table 10 gives an overview over relevant parameters for all test runs (see section 4.4).

In Figure 34 the average boiler load for the different test runs performed is shown. At full load the boiler load ranged between 19 and 21 kW which proves that full load conditions have been reached for all test runs performed. For the partial load test runs the boiler load was in the range from 6.3 to 6.6 kW (approx. 30% of the nominal boiler capacity). Furthermore, for all test runs performed stable load conditions have been achieved.

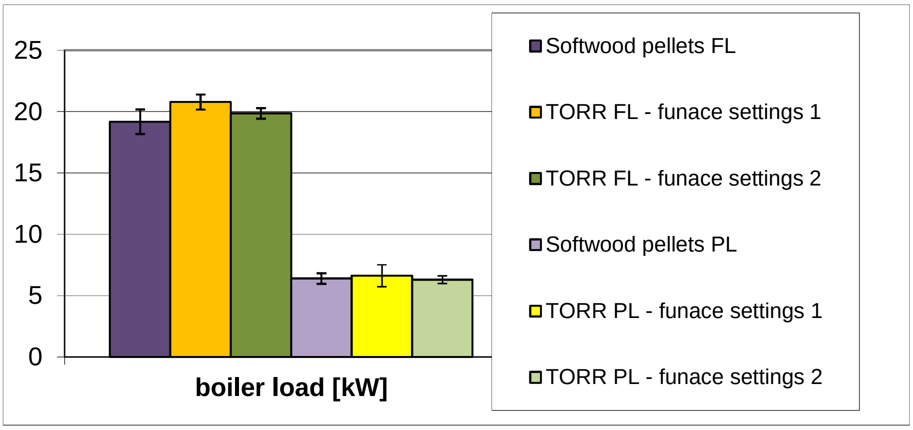

Figure 34: Comparison of the test runs performed – boiler load
Explanations: FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce)

Figure 35 shows the amounts of primary, secondary and false air for all test runs performed. At full load the amount of primary air is lower for TOPELL_spruce pellets with furnace settings 1 than for conventional softwood pellets and the highest for TOPELL_spruce pellets with furnace settings 2. At partial load only a comparably small increase of the primary air could be reached for furnace settings 2 compared to furnace settings 1. The secondary air is for furnace settings 2 considerably lower than for conventional softwood pellets and furnace settings 1. Consequently, the mixing of secondary air with flue gas is less efficient and the burnout quality decreases. The amount of false air was high and amounted to 24 to 35% of the total combustion air which shows that a considerable optimization potential for the boiler used is given. False air should be avoided as good as possible since it does not efficiently mix with the flue gas and consequently the burnout quality is decreased and the efficiency of the boiler is reduced.

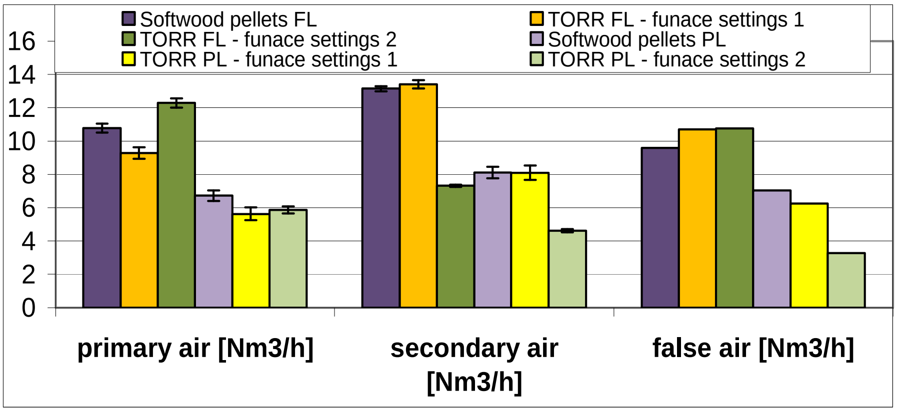

Figure 35: Comparison of the test runs performed – amounts of primary, secondary and false air
Explanations: FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce)

The air ratio in the primary combustion chamber (PCC) amounted to approx. 0.57 for conventional softwood pellets and is lower for TOPELL_spruce pellets with furnace settings 1 (0.45, see Figure 36). For TOPELL_spruce pellets with furnace settings 2 the highest air ratio in the PCC has been reached (0.63) which was the goal in order to check if increased primary air improves burnout of the grate ash (the control settings have been adapted accordingly). During the partial load tests the air ratio in the PCC is the highest for conventional softwood pellets (1.01) and lower for TOPELL_spruce pellets with furnace settings 1 (0.84). The goal to considerably increase the amount of primary air with furnace settings 2 has not been fully reached. Only an increase to 0.95 was measured. The total air ratio is in general lower for TOPELL_spruce pellets compared to conventional softwood pellets and considerably higher for partial load than for full load which is due to the control system of the pellet boiler used. The total air ratio is not directly measured and controlled (it is indirectly controlled by the furnace temperature).

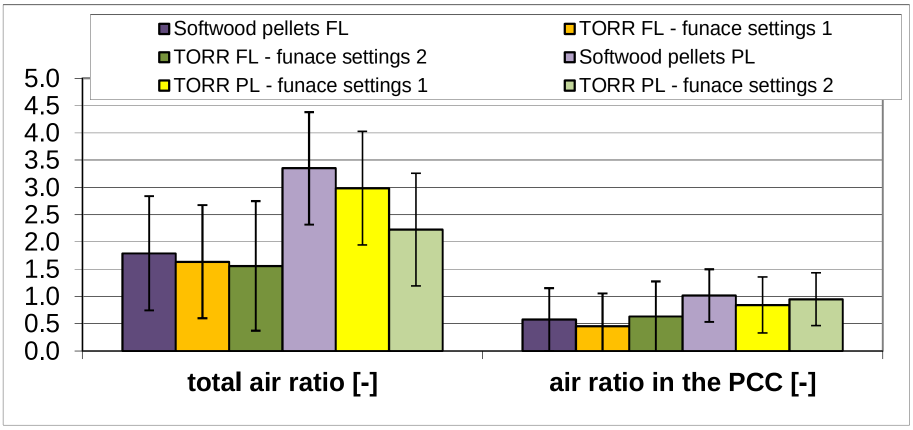

Figure 36: Comparison of the test runs performed – air ratio
Explanations: FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce); total air ratio … total excess air ratio (calculated from fuel, primary air and secondary air flows); air ratio in the PCC … air ratio related to the primary combustion chamber (calculated from fuel and primary combustion air supplied)

The grate temperatures at full load were the highest for TOPELL_spruce pellets with furnace settings 1 (524 °C) and lower for TOPELL_spruce pellets with furnace settings 2 (509 °C) and for conventional softwood pellets (507 °C, see Figure 37). The measured bed temperatures were the highest for conventional softwood pellets (1,147 °C), lower for TOPELL_spruce pellets with furnace settings 1 (1,094 °C) and the lowest for TOPELL_spruce pellets with furnace settings 2 (885 °C). However, it was expected that due to the higher energy density and the higher carbon content the bed temperatures for torrefied softwood are higher compared to untreated softwood. The CFD simulations performed by BIOS also show considerably higher gas temperatures in fuel bed for TOPELL_spruce pellets compared to conventional softwood pellets (see deliverable report 7.7 “Modified particle layer model and CFD-simulations of selected combustion trials”). It can be concluded that the measurement of the bed temperatures are difficult to interpret because one does not know to which amount the gas and particle temperatures contribute. Due to the fact that according to CFD simulations strong temperature gradients in the fuel bed occur temperature measurements in the fuel bed should be performed at several different locations in future in order to gain more reliable results. The temperatures measured with the suction pyrometer at the end of the secondary combustion chamber were higher for TOPELL_spruce pellets (1,024 and 963 °C) compared to conventional softwood pellets (916 °C), which is primarily due to the lower total air ratio measured for TOPELL_spruce pellets.

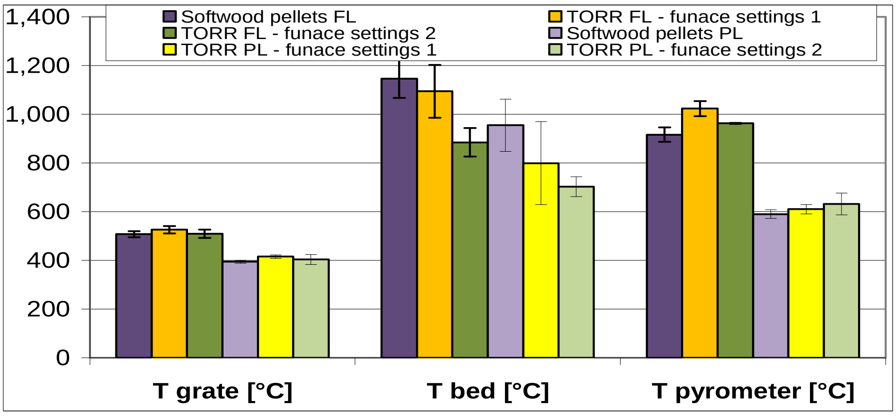

Figure 37: Comparison of the test runs performed – grate, fuel bed und gas temperatures
Explanations: fg … flue gas; FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce); the suction pyrometer temperature have been measured at the end of the secondary combustion chamber

At partial load the temperatures at the end of the secondary combustion chamber are considerably lower than for full load (590 – 610 °C) and are slightly higher for TOPELL_spruce pellets compared to conventional softwood pellets. The grate temperatures amount to 395 to 415 °C (see Figure 37).

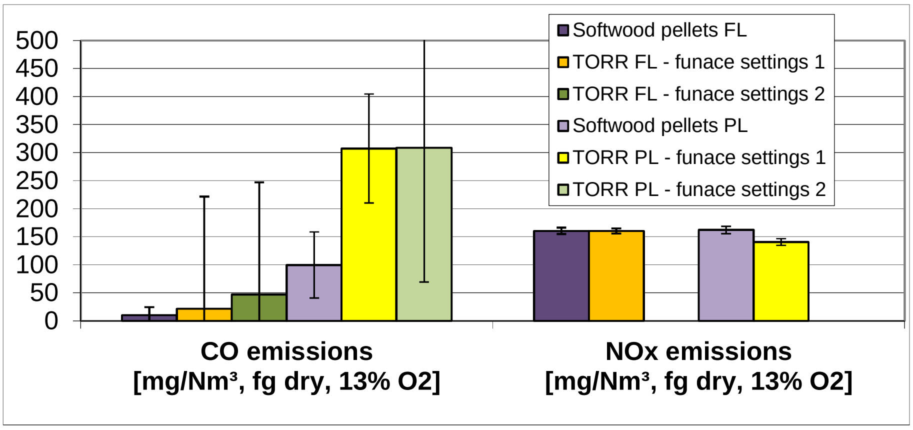

Figure 38: Comparison of the test runs performed – CO and NO_x emissions in the flue gas
Explanations: FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce); NO_x emissions have not been measured during the test runs with furnace settings 2

The CO emissions increase at full load from conventional softwood pellets (10 mg/Nm^3 related to 13 vol% O_2, dry flue gas) to TOPELL_spruce pellets with furnace settings 1 (22 mg/Nm^3) and to TOPELL_spruce pellets with furnace settings 2 (47 mg/Nm^3, see Figure 38). As expected the CO emissions are generally higher at partial load than at full load which is due to the lower flue gas temperatures and the insufficient mixing of flue gas and secondary air at partial load. For conventional softwood pellets CO emissions amount to approx. 100 mg/Nm^3 related to 13 vol% O_2, dry flue gas. For TOPELL_spruce pellets the CO emissions are approx. 3 times higher (approx. 300 mg/Nm^3). This shows that further modifications and optimizations of the control settings are required in order to guarantee a complete burnout of the flue gases with torrefied pellets in the pellets boiler used. The NO_x emissions amount to approx. 160 mg/Nm^3 related to 13 vol% O_2, dry flue gas at full load and for conventional softwood pellets at partial load (see Figure 38). For TOPELL_spruce pellets at partial load they are approx. 13% lower (140 mg/Nm^3) most likely due to the elevated CO concentrations.

The PM_1 emissions were for conventional softwood pellets at full load even for state-of-the-art pellet boilers on a very low level (5.7 mg/Nm^3 related to 13 vol% O_2, dry flue gas, see Figure 39). For TOPELL_spruce pellets they were somewhat higher (6.6 to 8.2 mg/Nm^3) but also on a low level which is primarily due to the higher K content in the TOPELL_spruce pellets compared to softwood pellets (see section 4.1). For conventional softwood pellets at partial load the PM_1 emissions were slightly higher than at full load (7.5 mg/Nm^3). However, PM_1 emissions increase considerably for TOPELL_spruce pellets at partial load (20.3 – 25.1 mg/Nm^3). TSP emissions are generally higher than the PM_1 emissions for all test runs performed (by a factor 1.4 to 2.4) which shows that a certain amount of coarse fly ash particles is entrained from the fuel bed (see Figure 39). The stronger entrainment at partial load is most likely due to the high primary air ratio which is a boiler specific and not a fuel specific problem.

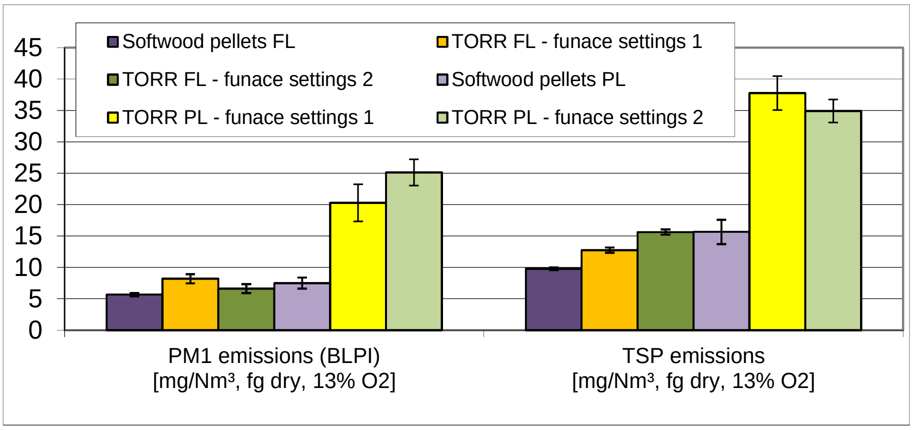

Figure 39: Comparison of the test runs performed – PM_1 and TSP emissions
Explanations: FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce)

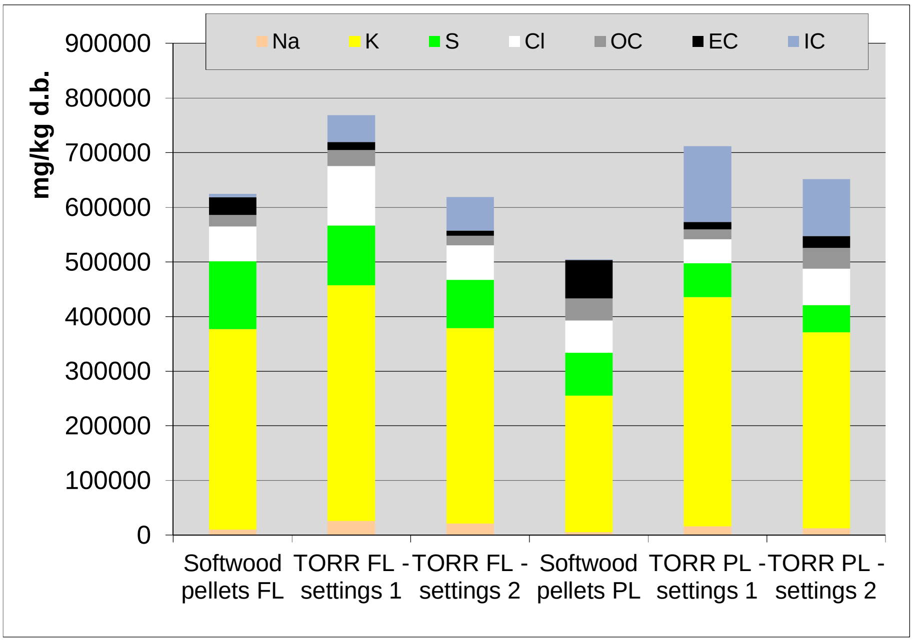

Figure 40: Elemental composition of TSP samples analysed
Explanations: FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce); OC … organic carbon, EC … elemental carbon

Figure 40 shows the chemical composition of different TSP samples analysed (in mg/kg d.b.) and Figure 41 the calculated composition of the TSP samples based on the analysis results and the TSP emissions measured in the flue gas (in mg/Nm^3). The results show that the elemental and organic carbon contents of the TSP samples at full load as well as at partial load are low which proofs a good burnout quality. The fly ashes of conventional softwood pellets contain primarily K_2SO_4 and KCl (see Figure 41). TSP samples of TOPELL_spruce pellets contain in addition K carbonates (in particular at partial load) and $NaSO_4$.

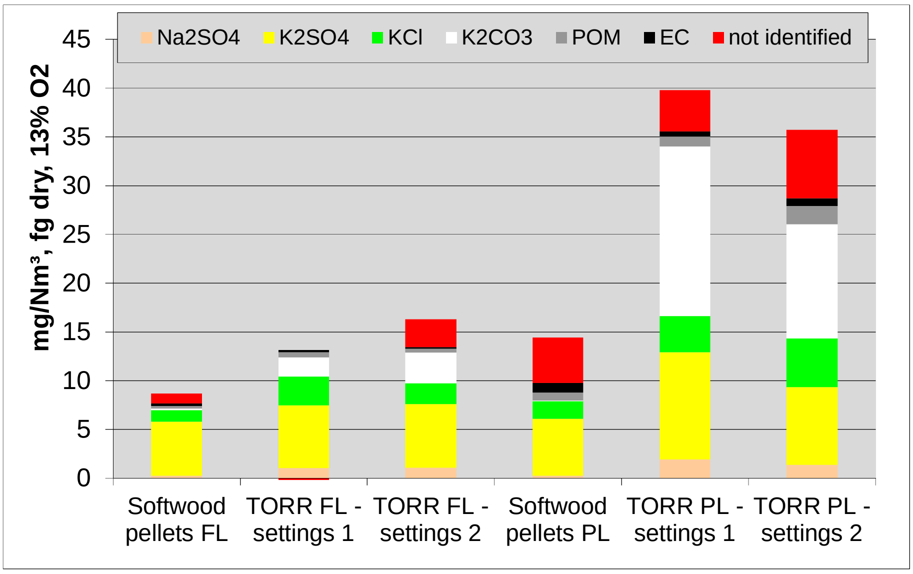

Figure 41: Composition of TSP samples analysed – probable compounds present
Explanations: FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce); POM … particulate organic matter, EC … elemental carbon

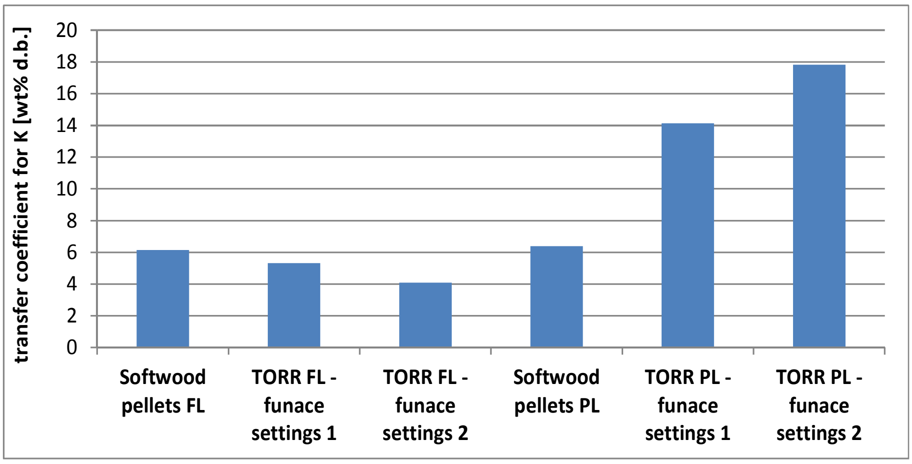

Figure 42: transfer coefficients from the fuel to the fly ash for K [wt% d.b.]
Explanations: FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce); OC … organic carbon, EC … elemental carbon

In Figure 42 the K transfer coefficients from the fuel to the fly ash are shown (amount of K in the fly ash in g/h divided by the amount of K in the fuel in g/h). The transfer coefficient of K calculated for the test runs with softwood pellets at full load amounts to approx. 6.1 wt% d.b. and is for the test runs with TOPELL_spruce pellets at full load lower (4.1 and 5.3 wt% d.b.). At partial load the transfer coefficient of K for softwood pellets is slightly higher compared to full load (6.4 wt% d.b.). However, it considerably increases for TOPELL_spruce pellets at partial load (14.1 and 17.8 wt% d.b.) and is 2.8 to 3.5 times higher than at full load for this fuel. The reason for the high transfer coefficients for K at partial load for TOPELL_spruce pellets is not fully understood yet. However, it is most likely that the air ratio in the PCC for TOPELL_spruce was not favourable at partial load and that the bed temperatures were higher (according to CFD simulations performed) which leads to a higher K release from the fuel bed. The subsequent carbonate formation is due to the low S and Cl contents in the fuel. The results are repeatable and only slightly affected by the furnace settings applied (furnace settings 1 in comparison with furnace setting 2).

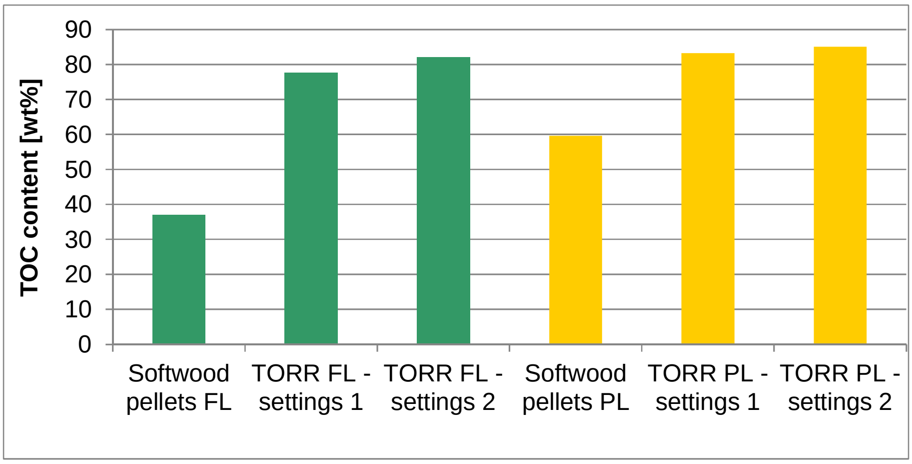

Figure 43: TOC content in the grate ash samples
Explanations: FL … full load; PL … partial load; TORR … torrefied softwood pellets (TOPELL_spruce); TOC … total organic carbon

Figure 43 shows analysis results regarding the TOC content in the grate ash samples. The TOC content of the grate ash of conventional softwood pellets at full load is the lowest (37 wt% d.b.) and at partial load approx. 1.6 times higher (60 wt% d.b.). The TOC content in grate ashes of the TOPELL_spruce pellets is considerably higher (78 – 85 wt%) and the results show that the increase of primary air (furnace settings 2) did not improve the burnout quality of the grate ashes. However, it has to be mentioned that the burnout quality of the pellets boiler used for the test runs performed is not sufficient even though standard de-ashing intervals and burnout periods defined by the boiler manufacturer have been applied. Since the boiler used has a retort burner which is discontinuously de-ashed it is probable that by increasing the burnout period before de-ashing the burnout quality can be considerably improved in general by a comparably easy adaptation of the control settings.

5 Summary and conclusions

In this deliverable report the work performed by BIOS concerning the fuel analysis and TGA tests with 3 different kinds of torrefied pellets, the lab-scale reactor test with one selected torrefied fuel and the test runs performed with a 21 kW overfed pellet boiler with conventional and torrefied pellets is presented and discussed.

In total 3 torrefied fuels (TOPELL_spruce, CENER_beech-270, CENER_pine-300) were analysed regarding their elemental composition. As expected the C content of the torrefied materials is higher and the H content slightly lower than for softwood pellets. However, the C content of CENER_beech-270 is with 51.5 wt% d.b. considerably lower than for the other torrefied materials. The N content is the highest for CENER_beech-270 (0.12 wt% d.b.) and lower for CENER_pine-300 (0.09 wt% d.b.) as well as for TOPELL_spruce (0.07 wt% d.b.). The lowest N content was detected in softwood pellets (0.05 wt%). In general the ash content and the concentrations of ash forming elements should be slightly higher in torrefied material compared to the untreated original biomass fuel due to the loss of volatiles during torrefaction process. The ash content of torrefied beech is with 1.1 wt% d.b. the highest and for all analysed torrefied materials higher compared to softwood pellets.

The results of the TGA tests performed show that the volatiles content of the torrefied materials is lower than for softwood pellets (62 – 65.8 wt% d.b. compared to 73 wt% d.b.) and the fixed carbon content is with 32.6 to 37.6 wt% d.b. higher than for softwood pellets (26.7 wt% d.b.). The volatile content of CENER_beech-270 is the highest for all torrefied materials tested and the carbon content is the lowest. Since hemicellulose is released during the torrefaction process usually no or only a small amount of hemicellulose is detected in torrefied materials, which is the case for TOPELL_spruce and CENER_pine-300. In the CENER_beech-270 a considerable amount of hemicellulose is detected ((14 wt% d.b.). This indicates that the torrefaction rate was considerably lower for the CENER_beech-270 sample compared to the other torrefied materials.

Lab-scale reactor tests have been performed with torrefied softwood pellets (TOPELL_spruce) and conventional softwood pellets. The test run duration was about 2,500 seconds for both fuels investigated. The drying phase took longer for softwood pellets. The main decomposition phase (release of volatiles and charcoal gasification) took longer for TOPELL_spruce compared to softwood pellets and the respective degradation rate was smaller. The degradation rate of charcoal combustion related to the input weight is similar for both fuels. However, the degradation rate related to the air supplied is for TOPELL_spruce somewhat higher than for softwood pellets. The results of the lab-scale reactor tests indicate that the overall combustion process for TOPELL_spruce is slower than for softwood pellets. The total conversion rate of N to TFN (related to N content in the fuel) is for both fuels approx. 95 to 100% which is a normal conversion rate under consideration of the low N content in both fuels. The calculated maximum potential for aerosol emissions is approx. two times higher for TOPELL_spruce pellets compared to softwood pellets, which is due to the higher K content in the fuel and the higher release rate for K measured.

Furthermore, combustion tests with a modern pellet boiler have been performed with torrefied softwood pellets (TOPELL_spruce) and conventional softwood pellets at full load and partial load. For TOPELL_spruce two different control settings have been tested (same settings as for conventional softwood pellets (furnace settings 1) and an operation with increased the primary air ratio (furnace settings 2). For all test runs stable conditions could be obtained at nearly full load conditions and at partial load (approx. 30% of the nominal boiler capacity). The results show that the CO emissions increase at full load from conventional softwood pellets (10 mg/Nm^3 related to 13 vol% O_2, dry flue gas) to TOPELL_spruce pellets with furnace settings 1 (22 mg/Nm^3) and to TOPELL_spruce pellets with furnace settings 2 (47 mg/Nm^3). The CO emissions are generally higher at partial load than at full load. For conventional softwood pellets CO emissions amount to approx. 100 mg/Nm^3 related to 13 vol% O_2, dry flue gas. For TOPELL_spruce pellets the CO emissions are approx. 3 times higher which shows that further modifications and optimizations of the control settings are required in order to guarantee a complete burnout of the flue gases with torrefied pellets in the pellets boiler used. The NO_x emissions amount to approx. 160 mg/Nm^3 (related to 13 vol% O_2, dry flue gas) at full load for conventional and TOPELL_spruce pellets.

The PM_1 emissions at full load were for conventional softwood pellets on a very low level (5.7 mg/Nm^3 related to 13 vol% O_2, dry flue gas). For TOPELL_spruce pellets they were somewhat higher (6.6 to 8.2 mg/Nm^3) but also on a low level. At partial load the PM_1 emissions for conventional softwood pellets were slightly higher than at full load (7.5 mg/Nm^3). However, PM_1 emissions increased considerably for TOPELL_spruce pellets at partial load (20.3 – 25.1 mg/Nm^3). TSP emissions are generally higher than PM_1 emissions for all test runs performed (by a factor 1.4 to 2.4) which shows that a certain amount of coarse fly ash particles is entrained from the fuel bed. The fly ashes of conventional softwood pellets contain primarily K_2SO_4 and KCl whereas the fly ashes of TOPELL_spruce pellets contain in addition K carbonates (in particular at partial load). The K transfer coefficients from the fuel to the fly ash are at full load for softwood pellets slightly higher than for TOPELL_spruce. However, they are 2.8 to 3.5 times higher at partial load than at full load for TOPELL_spruce. The reason for the higher transfer coefficients for K at partial load for TOPELL_spruce pellets is not fully understood yet. However, it is most likely that the air ratio in the PCC for TOPELL_spruce was not favourable at partial load and that the bed temperatures were higher (according to CFD simulations performed) which leads to a higher K release from the fuel bed. The subsequent carbonate formation is due to the low S and Cl contents in the fuel. The results are repeatable and only slightly affected by the furnace settings applied.

The TOC content of the grate ash of conventional softwood pellets at full load is the lowest (37 wt% d.b.) and at partial load approx. 1.6 times higher (60 wt% d.b.). The TOC content in grate ashes of the TOPELL_spruce pellets is considerably higher (78 – 85 wt%) and the results show that the increase of primary air (furnace settings 2) did not improve the burnout quality of the grate ashes. However, it has to be mentioned that the burnout quality of the pellets boiler used for the test runs performed is not sufficient even though standard de-ashing intervals and burnout periods defined by the boiler manufacturer have been applied. Since the boiler used has a retort burner which is discontinuously de-ashed it is probable that by increasing the burnout period before de-ashing the burnout quality can be considerably improved in general by a comparably easy adaptation of the control settings.

Based on the test runs performed and their evaluation the following conclusions and recommendations can be derived regarding the boiler system tested and the utilization of torrefied softwood pellets in this system:

- False air should be reduced in general since it inefficiently mixes with the flue gas and reduces the burnout quality as well as the efficiency of the boiler.

- The burnout period before de-ashing should be increased in order to improve the burnout quality of the grate ash.
- For torrefied softwood pellets the fuel feeding system has to be adapted regarding the higher energy density of these materials (adaptation of the control settings required).
- The fuel bed in the retort burner tested increased for torrefied softwood pellets compared to conventional softwood pellets due to the lower combustion rate (higher charcoal content). Torrefied softwood pellets need a longer burnout time in order to completely convert the carbon content in the fuel bed. Adaptations of the grate and the burnout zone are probably required (needs more detailed investigations).
- The grate temperatures measured do not show large differences between conventional softwood and TOPELL_spruce pellets but according to the CFD simulations performed the bed temperatures are locally higher for torrefied softwood pellets (slagging problems could occur) and large gradients over the fuel bed.
- The air ratio in the PCC and the total air ratio do not seem to need relevant adaptations (at least for the boiler system tested)

Concluding, the results of the work performed indicate that the overall combustion process for TOPELL_spruce seems to be slower than for conventional softwood pellets and therefore correspondingly the residence time on the grate for a complete burnout is increased. Regarding the application of torrefied pellets in the modern pellet boiler used, further optimization primarily of the control system in order to improve burnout quality of the flue gases and of the grate ash is required.

GA no 282826

Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction

Deliverable No. D7.3 “Combustion behaviour of torrefied pellets in pellet boilers and corrosion load on chimneys”

Deliverable No. D7.4 “Combustion screening of three pellet boiler technologies and fuel assessment trials”

Appendix 2: Report prepared by partner BE2020

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Nature		
R	Report	x
O	Other	

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Draft/Final:	Final	
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Table of content

1 Introduction and objectives

The objectives of the work package are to evaluate the end-use applications of torrefied biomass in principal application areas. One of these areas is the small-scale combustion in commercial pellet boilers. The combustion behaviour of torrefied fuel utilized in a pellet stove was investigated recently [1]. This report summarizes the results of the combustion experiments operated at BE2020 testing facilities in order to give an input to the deliverables D7.3 (Combustion behaviour of torrefied pellets in pellet boilers and corrosion load on chimneys) and D7.4 (Combustion screening of three pellet boiler technologies and fuel assessment trials).

The assessment of torrefied biomass during the combustion process as well as the respective emission behaviours were the focus of task 7.4. The operation with small-to-medium scale pellet boilers was investigated during lab-reactor tests with different kinds of torrefied pellets and was performed to evaluate their combustion and volatiles release behaviour. Fuel assessment was performed with several torrefied fuels in state-of-the-art heating systems. Standard tests were implemented. A special focus was also put on additional issues as condensation and corrosion, i.e. the determination of the corrosion load on chimneys. Combustion technology screening was carried out by operating tests in 3 different small-scale combustion technologies namely grate, overfeed and understoker appliances with capacities of up to 50 kW. Furthermore, a prototype boiler was investigated. For the fuel assessment trials, additional test runs were operated in one boiler with up to 5 different fuels with particular focus on start-up procedures and start-up emissions.

2 Materials

2.1 Testing setup

The chimney draught was measured directly after the combustion appliance with a differential pressure transmitter. This way, the draught was controlled on a level of 12 Pa.

The temperatures on the grate, inside the combustion chamber and inside the chimney (flue gas) were measured during the entire duration of each experiment. The used thermocouples were type K. The determination of the temperature range is one of the significant parameters during the investigation of torrefied fuel caused by the heating value and the different combustion behaviour in comparison to wood pellets.

The volume flow of the flue gas was determined continuously via Prandtl tube. The gaseous emissions (O_2, CO, CO_2, NO_x) were measured continuously with a JCT gas analyser 4000. The measurement interval is every second. The sampling location was selected according to EN 303-5 [1]. The chimney had a diameter of 0.13 m.

The measurements of particulate matter emissions (PM) were based on total dust according to EN 13284-1 [2]. Quartz plane filters with a diameter of 45 and 50 mm were used. For each combustion experiment, three PM measurements were intended as soon as stable combustion conditions were reached. The temperature of the filter holder and the sampling section was kept at 130 °C during the sampling period. The location of the measurement point was selected according to EN 303-5 [1]. The measurement of the corrosive content (HCl and SO_2) was done discontinuously according to EN ISO 10304-1 [3] by absorption of a partial flow of the flue gas in hydrogen peroxide solution (0.3 %). Afterwards the solution was analysed for chlorine and sulphate by ion chromatography (IC).

The heat output of the boiler was calculated based on the volume flow of the water circulation through the heat exchanger and its temperature difference. In order to calculate the efficiency by using the direct method, the entire appliance was set on a balance (Mettler 3000) to measure the fuel input. The mass of residues was determined after each combustion experiment and considered in the mass balance.

Figure 1 overviews the data collection set-up for the combustion experiments schematically. Correspondingly all measured parameters are listed in Table 1.

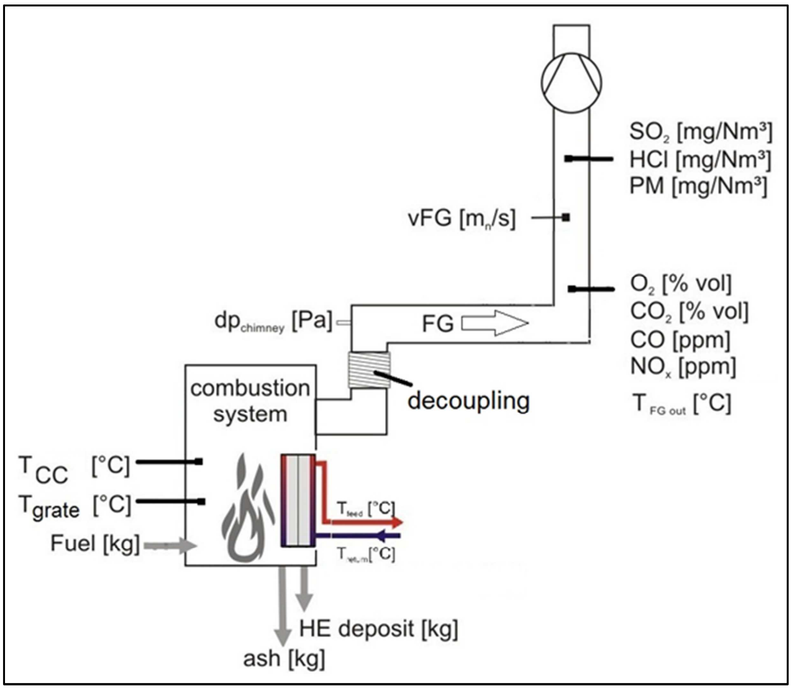


Figure 1: Scheme of the data collection set-up for the combustion experiments (FG: Flue Gas, HE: Heat Exchanger).

Table 1: Parameter measured during combustion experiments.

Short-cut	Unit	Description
T_{grate}	°C	Above the grate on three different locations
T_{CC}	°C	Temperature in the combustion chamber
$T_{FG\ out}$	°C	Flue gas temperature
P	kW	Heat output of the boiler (by measuring the temperatures of the heat exchangers flow and return and volume flow through HE)
O_2	vol.-%	Content of excess oxygen in the flue gas
CO	ppm	Concentration of carbon monoxide in the flue gas
CO_2	vol.-%	Concentration of carbon dioxide in the flue gas
NO_x	ppm	Concentration of nitrogen oxides in the flue gas
SO_2	mg/Nm³	Concentration of sulphur dioxide in the flue gas
HCl	mg/Nm³	Concentration of hydrochloric acid in the flue gas
PM	mg/Nm³	Concentration of total particulate matters in the flue gas
v_{FG}	m/s	Velocity of the flue gas
$dp_{chimney}$	Pa	Pressure measurement of chimney draught
m	kg	Mass of boiler system for the determination of fuel consumption

2.2 Boiler systems

Combustion tests in various commercial pellet boilers, which are dedicated to domestic heating, were conducted. Table 2 overviews the combustion technologies.

Table 2: Investigated combustion appliances.

No.	Producer	Type	Technology
Boiler1	Hargassner	HSV 15	horizontally moving grate
Boiler2	KWB	EasyFire	Underfed stoker
Boiler3	Ligno	Auger burner	auger burner
Boiler4	Windhager	VarioWIN	top fed pot burner

2.2.1 Hargassner HSV15

The HSV 15 is a commercially available pellet boiler. The fuel feeding is operated by an auger from side of the fire bed. The feed is regulated on a certain excess air ration in the flue gas, which is determined by a lambda-probe. The primary air is supplied to the fire bed from the ash box, through the grate, and the secondary air is supplied into the upper part of the combustion chamber. An ID-fan produces the required under pressure and conveys the flue gas of the boiler into the chimney. The ID-fan is the actuating variable for the power control, which is regulated on the boiler temperature. The ash removal procedure is operated in defined intervals. During the ash removal, the fuel feed stops for 10 minutes. Then the grate slides horizontally so that ash and fuel residues fall into the ash collecting box below the grate. Afterwards, another feeding interval begins. The flue gas of the boiler is transferred into the chimney. According to the boiler manufacturer, the combustion appliance is approved only for the application of standardized wood pellets. It has a nominal load of 15 kW. The combustion chamber is made of fire clay.

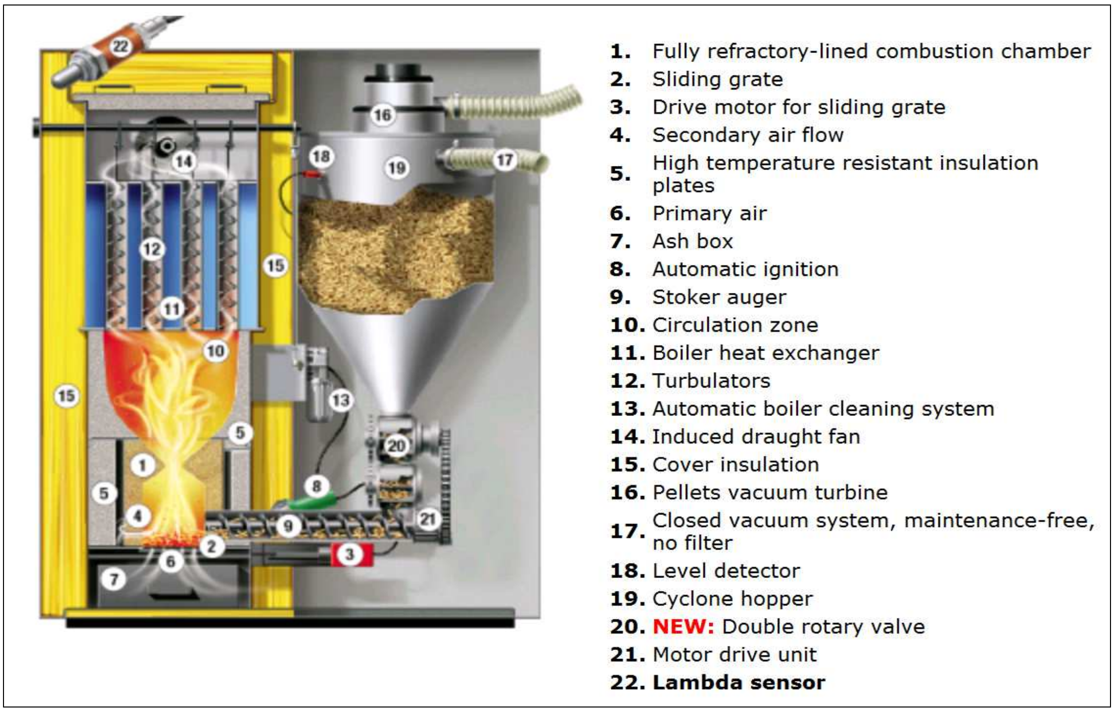
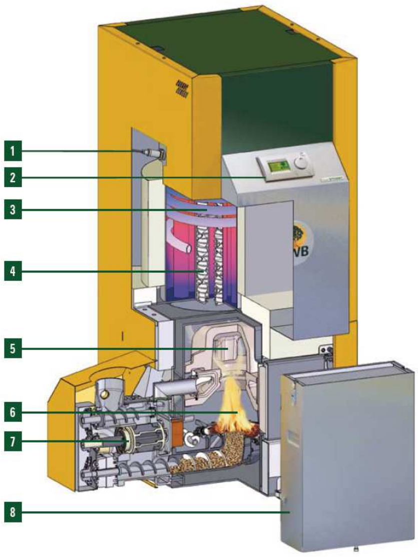


Figure 2: Cross section of HSV 15.

2.2.2 KWB Easyfire

The combustion appliance “Easyfire” produced by KWB is an underfeed pellet heating system. The pellets are pushed upwards to the burner plate. The combustion process takes place in four zones. The primary air is supplied by combustion air blower through the fuel and the secondary air is added via afterburning ring. The system is controlled by wideband lambda probe. An induced-draught fan produces the required under pressure. The fuel feed is the actuating variable for the power control, which is regulated on the boiler temperature. In accordance with the data of the manufacturers’ brochure the temperature inside the combustion chamber is approximately 900 up to 1100°C, in case of usage of pure wood pellets. The formed

The ash is removed from the edge of the burner plate and automatically conveyed into the ash container. The heat exchanger deposits are collected separately. The nominal load of this combustion appliance is 15 kW. Figure 3 shows the cross section of Boiler2.



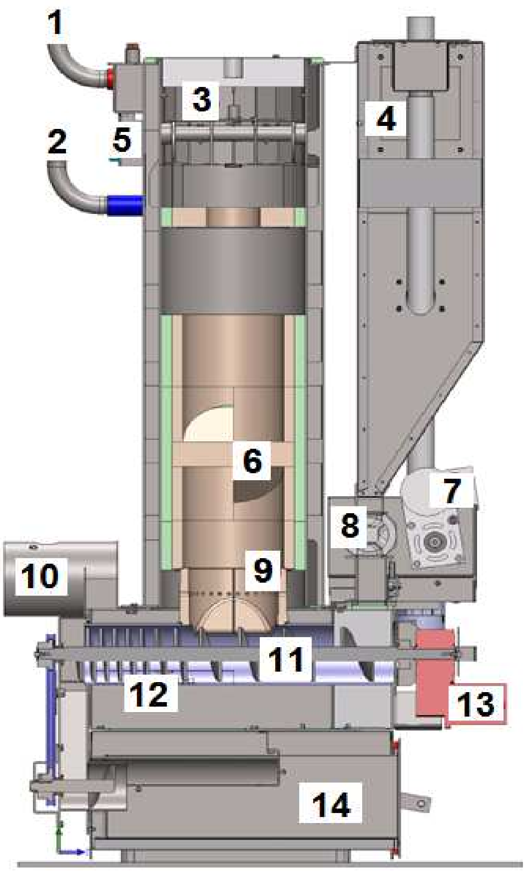
Legend

1 Wideband lambda probe
2 Operating and control system (Display)
3 Return flow temperature increase
4 Heat exchanger
5 Dust separator (cyclone)
6 Combustion system: underfeed-burner
7 Fire protection device (Cellular sluice wheel, metering screw)
8 Automatic ash removal

Figure 3: Cross section of KWB Easyfire [KWB brochure].

2.2.3 Ligno Auger burner

The manufacturer Ligno developed an auger burner that can be adapted to different fuel qualities. The auger has the function to transport the fuel and the ash. The pellets are dosed from the storage tank by a rotary valve and are conveyed sideward through the combustion zone by the auger. The auger also removes the formed ash out of the combustion zone. The residues are transported in an ash tray. The speed of the auger controls the residence time of the fuel in the combustion zone and of the ash in the hot area. The fuel feed is regulated to a certain air excess ratio, measured by a lambda probe downstream of the flue gas pathway. Since the system is a prototype, the air supply, the amount of supplied air, the fuel feed and the speed of the auger is adapted manually. The nominal load of the combustion appliance is 30 kW. Figure 4 shows the cross section of Boiler3.



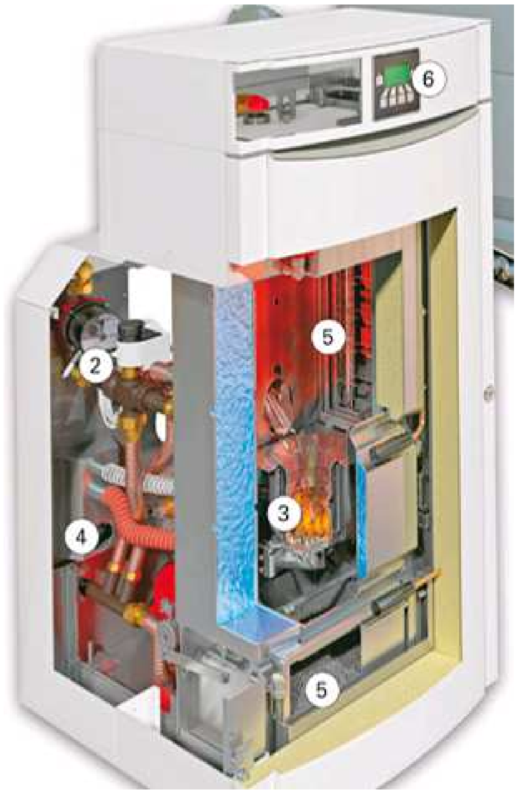
Legend:

1. Boiler water feed
2. Boiler water return
3. Heat exchanging tubes cleaning system
4. Pellet storage tank
5. Heat exchanging tubes cleaning Motor
6. 2nd burning chamber with rotation system II
7. Feeding rotary valve motor
8. Feeding rotary valve
9. 2nd burning chamber with rotation system I
10. Smoke tube
11. Burner auger
12. Primary Air supply
13. Burner auger motor
14. Ash tray

Figure 4: Ligno Auger burner.

2.2.4 Windhager VarioWIN

The boiler VarioWIN of the producer Windhager is fed from top and has a nominal load of 12.0 kW. The pellets fall into a burner bowl. The primary air is supplied by an air pin. The secondary air is supplied via holes in the burner plate. The temperature inside the combustion chamber controls the heat output of the appliance by adjusting the mass flow of the fuel feed. The combustion process is not controlled by a lambda probe. The investigations operated with this boiler are focused on the combustion behaviour of torrefied fuel with a temperature controlled system. The ash removal is operated discontinuously. The standard setting is 6 hours. A cross section of Boiler4 is shown by Figure 5.



Legend

2 Hydraulic components
3 Combustion bowl
4 Adapter for an operation independent from ambient air
5 Ash tray
6 Operating system (display)

Figure 5: Cross section of VarioWIN [homepage Windhager].

2.3 Test fuels

This section overviews the investigated test fuels. In addition to the torrefied fuels, wood pellet fuels according to the standard were utilized in all the combustion appliances. The results of these combustion tests are the reference values concerning combustion parameters, e.g. heat output and CO release. In order to screen different boiler technologies and to investigate their combustion behaviour respectively, a torrefied fuel was chosen as a second reference fuel. The fuels cover a range of different properties concerning raw material and fuel quality. All fuels were analysed in terms of combustion related parameters. Table 3 summarizes the parameters.

Table 3: Relevant parameters, fuel analysis.

Parameter	Abbreviation	Unit
Moisture content	M_{ad}	wt.%, w.b.
Ash content	A_d	wt.%, d.b.
Net calorific value	NCV	MJ/kg d.b.
Volatile compounds	VOC	wt.%, d.b.
Carbon	C	wt.%, d.b.
Hydrogen	H	wt.%, d.b.
Oxygen (calc.)	O	wt.%, d.b.
Nitrogen	N	wt.%, d.b.
Sulphur	S	mg/kg, d.b.
Chlorine	Cl	mg/kg, d.b.

The analysis methods are summarized in the appendix. Table 4 to Table 8Table 4 to Table 8 show samples of the test fuels and summarize the results of the fuel analysis considering the relevant parameters.

Table 4: Spruce_raw.

	**Spruce_raw - Reference Fuel Standardized wood pellets**	
	M_{ad} [wt.%, w.b.]	7.1
	A_d [wt.%, d.b.]	0.4
	NCV [MJ/kg d.b.]	17.6
	VOC [wt.%, d.b.]	83.4
	C [wt.%, d.b.]	51.2
	H [wt.%, d.b.]	5.9
	O [wt.%, d.b.]	42.30
	N [wt.%, d.b.]	0.2
	S [mg/kg, d.b.]	44
	Cl [mg/kg, d.b.]	33

Table 5: Forest_residues.

	**Forest_residues - Torrefied fuel, raw material: forest residues**	
	M_{ad} [wt.%, w.b.]	5.8
	A_d [wt.%, d.b.]	2.5
	NCV [MJ/kg d.b.]	18.9
	VOC [wt.%, d.b.]	76,9
	C [wt.%, d.b.]	50.7
	H [wt.%, d.b.]	5.8
	O [wt.%, d.b.]	40.64
	N [wt.%, d.b.]	0.313
	S [mg/kg, d.b.]	434
	Cl [mg/kg, d.b.]	145

Table 6: Spruce_260.

	**Spruce_260 – Reference fuel Torrefied, raw material: spruce**	
	M_{ad} [wt.%, w.b.]	4.7
	A_d [wt.%, d.b.]	0.41
	NCV [MJ/kg d.b.]	20.6
	VOC [wt.%, d.b.]	76.09
	C [wt.%, d.b.]	52.24
	H [wt.%, d.b.]	6.03
	O [wt.%, d.b.]	41.19
	N [wt.%, d.b.]	0.12
	S [mg/kg, d.b.]	60
	Cl [mg/kg, d.b.]	100

Table 7: Pine_270.

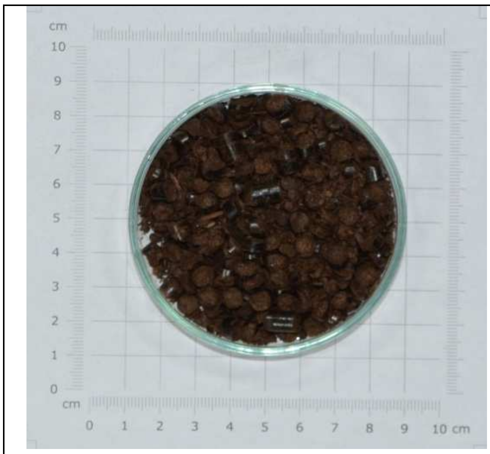
<table>
<tr><td rowspan="11"></td><th colspan="2">Pine_270 - Torrefied Fuel,
raw material: pine</th></tr>
<tr><td>M_{ad} [wt.%, w.b.]</td><td>3.29</td></tr>
<tr><td>A_d [wt.%, d.b.]</td><td>0.48</td></tr>
<tr><td>NCV [MJ/kg d.b.]</td><td>21.0</td></tr>
<tr><td>VOC [wt.%, d.b.]</td><td>75.92</td></tr>
<tr><td>C [wt.%, d.b.]</td><td>52.51</td></tr>
<tr><td>H [wt.%, d.b.]</td><td>6.19</td></tr>
<tr><td>O [wt.%, d.b.]</td><td>40.53</td></tr>
<tr><td>N [wt.%, d.b.]</td><td>0.14</td></tr>
<tr><td>S [mg/kg, d.b.]</td><td>70</td></tr>
<tr><td>Cl [mg/kg, d.b.]</td><td>90</td></tr>
</table>

Table 8: Poplar_270.

<table>
<tr><td rowspan="11"></td><th colspan="2">Poplar_270 - Torrefied Fuel,
raw material: poplar</th></tr>
<tr><td>M_{ad} [wt.%, w.b.]</td><td>4.53</td></tr>
<tr><td>A_d [wt.%, d.b.]</td><td>0.62</td></tr>
<tr><td>NCV [MJ/kg d.b.]</td><td>20.2</td></tr>
<tr><td>VOC [wt.%, d.b.]</td><td>77.73</td></tr>
<tr><td>C [wt.%, d.b.]</td><td>51.42</td></tr>
<tr><td>H [wt.%, d.b.]</td><td>6.09</td></tr>
<tr><td>O [wt.%, d.b.]</td><td>41.90</td></tr>
<tr><td>N [wt.%, d.b.]</td><td>0.10</td></tr>
<tr><td>S [mg/kg, d.b.]</td><td>100</td></tr>
<tr><td>Cl [mg/kg, d.b.]</td><td>80</td></tr>
</table>

In general, the moisture content of the torrefied fuels (3.29 to 5.8 wt%) is lower than the moisture content of the raw material (7.1 wt%). Together with the content of hydrogen, the moisture of a fuel is the source for the humidity in the flue gas and influences the heat transfer and, therefore, also the efficiency. The hydrogen content of all test fuels is in the range of 5.8 to 6.19 wt%. Besides forest_residues (50.7 wt%), the carbon content of the torrefied fuels is higher (51.42 to 52.51 wt%) than the carbon content of spruce_raw (51.2 wt%). The oxygen content of a fuel influences the combustion behaviour in the respect of additional air supply. The highest oxygen content has spruce_raw (42.3 wt%). The oxygen content of the torrefied test fuels is in the range of 40.53 to 41.90 wt%. The differences concerning carbon and oxygen content come along with the reduced content of volatile compounds (VOC). The highest VOC content has spruce_raw (83.4 wt%). The VOC of the torrefied fuels are lower, between 75.92 wt% (pine_270) and 77.73 wt% (poplar_270).

The net calorific value (NCV) of spruce_raw is the lowest one (17.6 MJ/kg), followed by forest_residues (18.9 MJ/kg). The NCV of the other torrefied fuels are higher, 20.3 to

21.0 MJ/kg. The NCV influences the energy density, the combustion temperature and heat output/efficiency. The nitrogen content of forest_residues (0.313wt%) is much higher in comparison to the other torrefied fuels (0.10 to 0.14wt%). The nitrogen content of spruce_raw is 0.2wt%. Also the ash content of forest_residues is not comparable to the other fuels. The value of 2.5wt% is several times higher than the ash content of spruce_raw, which is similar to spruce_260 and pine_270 (0.4 to 0.48wt%). The ash content of poplar_270 is slightly higher (0.62wt%). Spruce_raw has a low content of sulphur (44mg/kg) and chlorine (33mg/kg). The torrefied fuels have higher values (sulphur: 60 to 100mg/kg and chlorine: 80 to 100mg/kg), but forest_residues shows the highest content (sulphur: 434 mg/kg, chlorine: 145mg/kg). These elements are further investigated because of the corrosion risk on chimneys.

Generally, the torrefaction process reduces moisture and VOC of the raw material and increases the content of carbon and ash [1]. With regard to the results of the fuel analysis, the torrefied fuels are comparable with peat fuels. The values regarding CHO-ratio, NCV and VOC are similar to the analysis results of peat [2]. However, peat fuels have even a higher content of ash.

2.4 Experimental design

The experimental setup for the combustion tests was based upon following facts: In total, there were four different pellet boilers and five different test fuels to be investigated. The objectives of the combustion tests were to screen the tests fuels and to screen the combustion technologies.

The following matrix in Table 9 gives an overview on the assignment of test fuels and the respective combustion technologies, they were tested with. The cells marked with X constitute a combustion test. Experiments with the standardized wood pellets are performed as reference tests for every combustion appliance.

Table 9: Combustion testing matrix.

	Spruce_raw	Forest_residues	Spruce_260	Pine_270	Poplar_270
Boiler1	X	X	X	X	X
Boiler2	X		X		
Boiler3	X		X		
Boiler4	x		X		

All test fuels were investigated in one boiler system. This combustion appliance was designated the reference boiler. The applicability of the respective test fuels was investigated in the reference boiler, which assesses the influence of different torrefied fuels. The screening of technology was conducted vice versa: Different boiler systems were investigated by applying the same test fuels spruce_raw and spruce_260.

3 Testing method

A standardised test procedure is defined in order to ensure comparable results. The method enables the investigation of the behaviour of different boiler technologies on a fuel variation from the ignition process until the burnout phase respectively. A distinct focus is set on emissions and temperature behaviour in comparison to a non-torrefied fuel.

3.1 Preparation

The combustion performance mainly depends on the fuel, which is used for the test. Since some parameters, e.g. the water content, vary with the air moisture of the ambience, **samples of the test fuel** are drawn the day the combustion test takes place.

It is essential to **clean the combustion appliance**, the grate, the ash box and the heat exchanger carefully before starting the test. This allows a conditioning of the combustion appliance for every fuel and avoiding any contamination of the samples.

3.2 Testing procedure

The combustion test series with the torrefied fuels consists of several parts:

- Test with reference fuel (standardized wood pellets, Spruce_raw), duration 24 hours
- Switchover process (Spruce_raw→ Spruce_260) without adaptions, in order to investigate the behaviour of the boiler and the influence mainly on the parameters excess oxygen, heat output, temperature range, and CO release.
- 24 hours combustion experiment operated with torrefied fuel, nominal load, including the start-up and burn out phases.
- 3 hours combustion experiment, partial load in order to enable a comparison between the emission tests as usually investigated.

The combustion tests with nominal load conditions last 24 hours. First, the wood pellets (Spruce_raw) are utilized in order to detect the combustion parameters under standard conditions. Then a consecutive switch of fuel is conducted, by which the reaction of the combustion system on a torrefied fuel can be monitored. Afterwards, the behaviour of the small scale appliances during the operation with torrefied fuels is investigated. Within the testing duration of 24 hours, a stationary operation should be reached.

The beginning of each 24h **test** is comparable with a preliminary experiment. Within the duration of maximum 6 hours, the operator defines a stationary phase of the respective test (indication: constant values of the parameters temperature, emissions and heat output with a deviation lower than 10 %). The determination of **averaged values** for the defined stationary phase is necessary.

The combustion process can be affected due to the properties of torrefied fuel with respect to the operation mode of the combustion process. Consequences are unstable conditions concerning temperature range or flue gas content. The defacing can either cause an abortion or demands modifications. **The test** can be repeated in case a stationary phase could not be reached. Modifications concerning air supply, heat output or extension of cleaning interval are possible in order to optimize the combustion process. Before the test is repeated, the boiler is cooled down and the formed residues are removed from the boiler and the grate so that no contamination of the upcoming test occurs. The removed residues are stored as samples.

If stable conditions are not reached after the second repetition, the test is aborted. If the test began successfully and the stationary phase is reached, the abortion criteria (chapter 3.3 below) are defined based on the averaged value respectively. The goal is to detect **deviations** from the determined average values during the stationary phase in beginning of the test.

After the test duration of 24 hours in total, the fuel supply is stopped. The measurement of the relevant parameters is continued with the aim until the CO_2 level falls below 0,5 vol.-% in order to investigate the burn out behaviour as well.

A final investigation of the partial load phase is conducted by reducing the energy demand side. The energy demand reduction is applied by increasing the return flow temperature in this way that a stable 30% part load conditions are achieved. The part load test is continuously monitored for 3 hours.

3.3 Abortion criteria

According to the boiler manufacturer, the combustion appliances are authorised only for the application of standardized wood pellets. Due to the torrefaction process, the properties of the test fuels differ in terms of some parameters extremely. The properties of the torrefied fuels are compared to the reference wood pellets (chapter 2.3). Amongst others, the higher content of ash, the less content of oxygen and the increased NCV lead to different combustion behaviour in comparison to wood-type fuels. Since there is no information on former combustion experiments with such fuels in the surveyed combustion technologies, it is necessary to operate all combustion tests utilized with torrefied fuels with strict security measures. In order to avoid a shutdown of the boiler on its own and also to protect the combustion appliances, an abortion of the experiments might be necessary in some cases. The criteria for an abortion are described by a deviation of the stationary phase determined in the beginning of the experiments. The following Figure 6 shows possible deviations of the considered parameters in case of unstable combustion behaviour in the boiler.

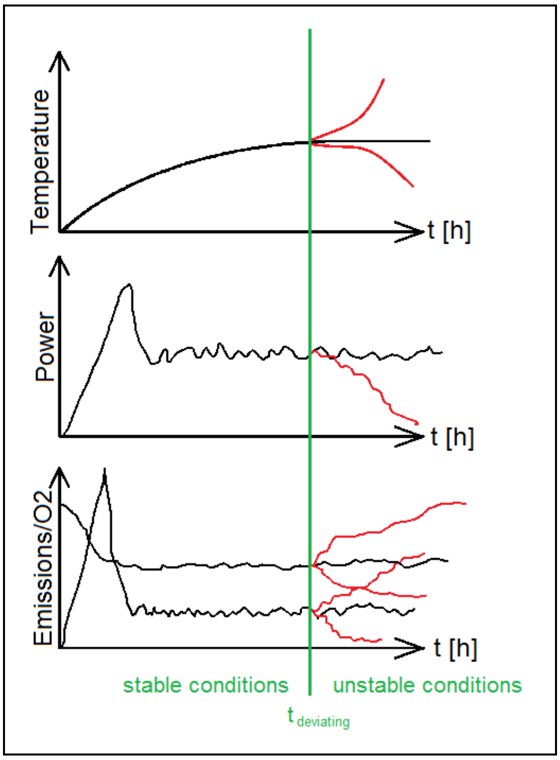


Figure 6: Abortion criteria.

The black graphs show characteristics of the relevant parameters. The green line denotes the beginning of unstable conditions and the red graphs illustrate the possible changes initiated by different causes depending on the properties of the test fuel and the combustion technologies (e.g. control system, ash removal solution, air supply).

Depending on the combustion technology and on the measurement points of the thermocouple the displayed **temperature inside the combustion chamber** can increase or decrease (it depends also on the positioning of thermocouple). Possible reasons are:

- Changes of the height of the fire bed, e.g. agglomerations of ash on the grate
- Fuel mass flow, due to the control system
- Oxygen supply, due to control system or blocked openings (by ash).

The influence of unstable combustion behaviour on the emission and the air excess ratio as well as the heat output of the boiler system is self-evident, since a physical blockage can change the air supply as well as the fuel dosing. In addition, there are several causes for increasing or decreasing values of these parameters.

The **heat output** in conjunction with the efficiency is an important parameter for the assessment of the applicability. A rise or decline of this parameter can be the effect of:

- adaption of the fuel mass flow, due to the control system and the higher NCV of the torrefied fuel
- deposit on the heat exchanger, due to the fuel properties

An increasing CO release is the consequence of an incomplete combustion process. According to the 3-T criteria, 3 requirements need to be fulfilled: Time, Temperature and Turbulence. Concerning this investigations in particular the second and third criteria are of respect. A variation in temperature because of the stability of combustion may occur and thus influence the CO emission. However, the main influence on the emissions is the turbulence, which is influenced in this survey by two reasons:

- Stability of the fuel bed. The mass and stability of the fuel bed can have an influence on the air supply and thus also on the CO emission.
- Air excess ratio. The air demand of torrefied biomass is considerably different to normal biomass an thus can have an influence on the CO emission.

In both cases it depends on the control strategy of the combustion appliance whether the operation with torrefied fuel is feasible. The CO emissions detect a failure of the boiler, e.g. a too high fuel feed or too less oxygen supply.

Caused by the different elemental composition in comparison to wood fuel, the **excess oxygen** has to be considered as an abortion criterion. Corresponding to the values of temperature and heat output, the content of O_2 in the flue gas can increase or decrease as an effect of several opportunities:

- blockage of air supply caused by slagging, too less oxygen available for stoichiometric combustion (decrease of excess oxygen comes along with high CO emissions)
- combustion process inside the combustion chamber stopped e.g. due to too high temperatures, blockage of fuel feed.

Table 10 summarizes the selected combustion parameters to trigger an abortion and shows the criteria values for the respective parameters.

Table 10: Abortion criteria of combustion tests.

Parameter	**Deviation from stable condition**
Temperature (combustion chamber) [°C]	± 100
Heat output [$\%_{rel.}$]	10
Excess oxygen [$\%_{abs.}$]	± 2
Carbon monoxide release [ppm]	+500

If the deviation of one single parameter is higher than the appropriate threshold value of the second column for more than 1 hour (compared to the averaged values determined in the beginning of the combustion test), the test is aborted. In this case, the duration of the combustion test until the abortion is a criterion for the applicability assessment of the torrefied fuels.

3.4 Data evaluation

The data logging is done during the whole combustion test including the start-up phase. Despite the combustion test stops after 24 hours, the data logging is continued as the burn-up behaviour is investigated as well, furthermore the case of an incident is imitated in this way. The deactivation criteria for stopping the data logging: It stops as soon as the value of CO is below 50 ppm and the value of CO_2 decreased below 0.5 vol.-%. By reaching these values, the combustion process is finished.

All the **raw data of the online measured values** were provided electronically as .csv-file. The **average values of temperature, emissions and heat output** were calculated as abortion criteria described in chapter 3.3. Moreover the respective **abortion criteria** are given, e.g. the values of the single parameters. In case of an abortion, the **duration of the combustion test** is documented. The **total fuel input** is either provided electronically. As the ash properties are indicators for the quality of the combustion performance, the mass is determined after each combustion test. In addition, for evaluation of the combustion tests the amounts of ash formed are important parameters.

3.5 Handling of residues

The sintering degree for the collected bottom ash samples is assessed according to a procedure defined and used by the groups at the Universities Umea and Lulea in several previous studies. The **visual classification** system was first defined by Öhman et al, 2004 [3] and later revised, first by Lindström et al, 2007 [4] and recently by Díaz-Ramírez et al, 2012 [5]. The classification is based on both visual inspection and by using a simple strength test (by hand). This "strength test" is done by gently pressing and pinching the ash/slag by hand.

It consists of five categories determining the sintering degree of the ash. Directly after a combustion test, when the ash is cold, the residual ash on the burner/grate and at the boiler bottom, respectively, is photographed (digital color photos). Both general (overview) photos of the appliance and the formed ash/slag as well as close-up photos of slag lumps/aggregates are taken. Pictures of ash lumps/aggregates are taken using a ruler or scale paper. After that, potentially formed (sintered) typical ash lumps/aggregates are identified and collected for further assessment of sintering degree. These ash samples are collected and handled very gentle and with great care. It is important that the assessment is done on-site on the samples taken directly from the burner/boiler to avoid any physical influence by handling and/or transport.

The categories of the visual classification system are summarized in Table 11.

Table 11: Categories for assessment [5].

Category		Definition
1		Non sintered ash residue, i.e., non-fused ash (clear grain structure)
2a		Partly sintered ash, i.e., particles contained clearly fused ash that break at a light touch (distinguishable grain structure)
2b		Partly sintered ash, i.e., particles contained clearly fused ash that hold together at a light touch but they are easily broken apart by hand (distinguishable grain structure)
3		Totally sintered ash, i.e., the deposited ash was fused to smaller blocks that are still breakable by hand (slightly distinguishable grain structure).
4		Totally sintered ash, i.e., the deposited ash was completely fused to larger blocks that are not possible to break by hand (no distinguishable grain structure).

In addition to the mechanical properties the formed slag particles must be described concerning the colour e. g. by using colour controlling stripes for photographing. Furthermore, it is documented in case there are any vitrifications etc.

Beside the size distribution the **granulometric analysis** also considers the mechanical stability of the formed slag particles. During the process of sieving, the slag particles are reduced to smaller pieces. Indicators therefore are the sieving duration and the frequency. For the evaluation it is necessary to document the size of the respective sieves, the weight in sum and the weight of the single fractions. The analysis is operated according to ISO 3310-1 [6] with the following pre-settings:

- amplitude = 2.0
- sieving time = 1 min
- interval time = 0
- sieve sizes: 0.5 mm, 1.0 mm, 2.0 mm, 3.15 mm

After the sieving process a picture is taken of the content of the sieve with size 3.15 mm.

The **completeness of the combustion** is defined as the amount of unburnt residues in the bottom ash. This parameter is a crucial indicator for the performance of the combustion process, especially for the end-user. Therefore, it can also be used as a criterion for the assessment of the fuel applicability. The remaining ash content of the ash is determined if possible. The determination follows the ash content analysis using the standard method (550°C) according to ÖNORM-EN-14775 [10] and is carried out if possible.

3.6 Sampling and labelling

After the combustion tests are completed, documentation is done by taking pictures and describing the condition of the boiler. As soon as the visual inspection, photographing and assessment of sintering degree (as described above) have been performed, the different ash fractions are collected separately by using suitable tools like a small scraper, spoon or broom (not vacuum cleaner), and the formed slag is separated from the non-melted bottom ash. All obviously unburned fuel residues are first removed from the ash material.

The ash fractions and slag deposits are separately weighted and stored in tight cans made of glass, tin or plastic. It is not necessary to store them in a desiccator. Accordingly, no thermal treatment of these samples (ashes and slags) is done related to the weighing process.

The collected slag deposits, the corresponding deposited bottom ash in the boiler and the collected particle matter must be stored to enable a further characterization.

The sampling procedure is consistently (all experiments). Also the labelling of the samples is done uniformly. The name of the samples consists of the abbreviation of boiler and test fuel (see chapter 2) and the abbreviation of the kind of sample (fuel, ash). In case of a failure of the test (e.g. there are more than one try as the test can be repeated) with the same boiler and the same fuel, the labelling includes also the number of the combustion test.

Table 12 explain the fractions of the samples and the respective abbreviations.

Table 12: Abbreviations of sample labels.

Sample	Abbreviation
Formed Ash of the bottom	AB
Formed Ash on the grate section	AG
Residue at the heat exchanger	HE
Particulate matter	PM
Water liquids (corrosive contents)	WL

Samples of the **test fuels** are taken before the combustion test starts in order to determine the content of water and ash of the pellet fuel on the testing day. The sampling procedure is made according to ÖNORM M 7135. At least five samples are drawn each with a minimum weight of 0.5 kg out of the fuel flow, regardless of whether the fuel supply is done automatically or has to be done by filling the storage tank manually.

Samples of the **particulate matter** (PM) are collected during the combustion test. They are numbered as there are at least 3 samples according to chapter 2.1. That chapter also explains the sampling method in detail.

The **ash samples** in general are labelled with “A”. The second capital letter gives information about the location of the respective residue. The ash samples from the **bottom** (AB) are collected inside the ash collecting box and the samples from the **grate** (AG) are taken from the grate or burner plate after the combustion test is finished. The ash which is formed inside the combustion chamber is assigned to the grate ash as well. After the sieving analysis is completed, the bottom ash fraction is ground and homogenised.

The **deposit** formed at the **heat exchanger** is collected if possible. The amount is determined gravimetrically. The samples are labelled with “HE”.

In order to determine the **corrosive content** (HCl and SO_x) according to chapter 2.1, a part of the flue gas is passed to washing bottles. After the combustion experiment, the contents of these bottles are stored in plastic bottles and labelled with “WL”.

3.7 Corrosion testing

The deposits in the heat exchanger are tested towards their corrosive effect. The samples are placed on a metal testing piece made of ST37 steel, which is a low alloy steel (see also Figure 7). The testing pieces are grinded prior to the corrosion tests to remove the passivized layer. Furthermore each piece is degreased with acetone and cleaned with distilled water. The heat exchanger deposits are piled on the testing piece by utilizing a ring of 8.5 mm diameter. The ring is removed and the pile settled by dropping the testing piece three times from 5 mm height. This treatment results in a pile diameter of 15 mm diameter.

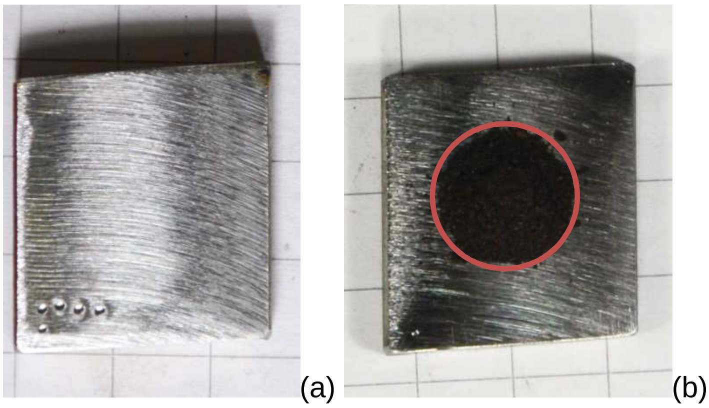


Figure 7: Testing piece for corrosion tests. ST37 steel alloy with grinded surface (a) and with sample pile (b). The red circle indicates the evaluation area.

The test samples are then put into a humidor at a constant humidity of 75%rH at 50°C. This ambient is close to the conditions in a heat exchanger or the chimney during the combustion of biomass. The surface temperature at certain positions and operation conditions can also undergo 50°C resulting in a higher corrosion potential. The samples are stored for 48 hours in this environment. After this time the corroded area within the 15 mm diameter of the covered surface is evaluated visually.

4 Combustion behaviour of torrefied pellets in pellet boilers and corrosion load on chimneys

This section describes the combustion experiments as well as the survey of the test fuels made of torrefied material and the wood pellets as reference fuel. The assessment of the combustion behaviour considers emissions, excess oxygen, heat output, efficiency, temperature range and deposits of every experiment.

4.1 Start-up phase

Figure 8 shows the combustion behaviour of wood pellets (Spruce_raw) in comparison to torrefied fuel (Spruce_260) during the start-up phase.

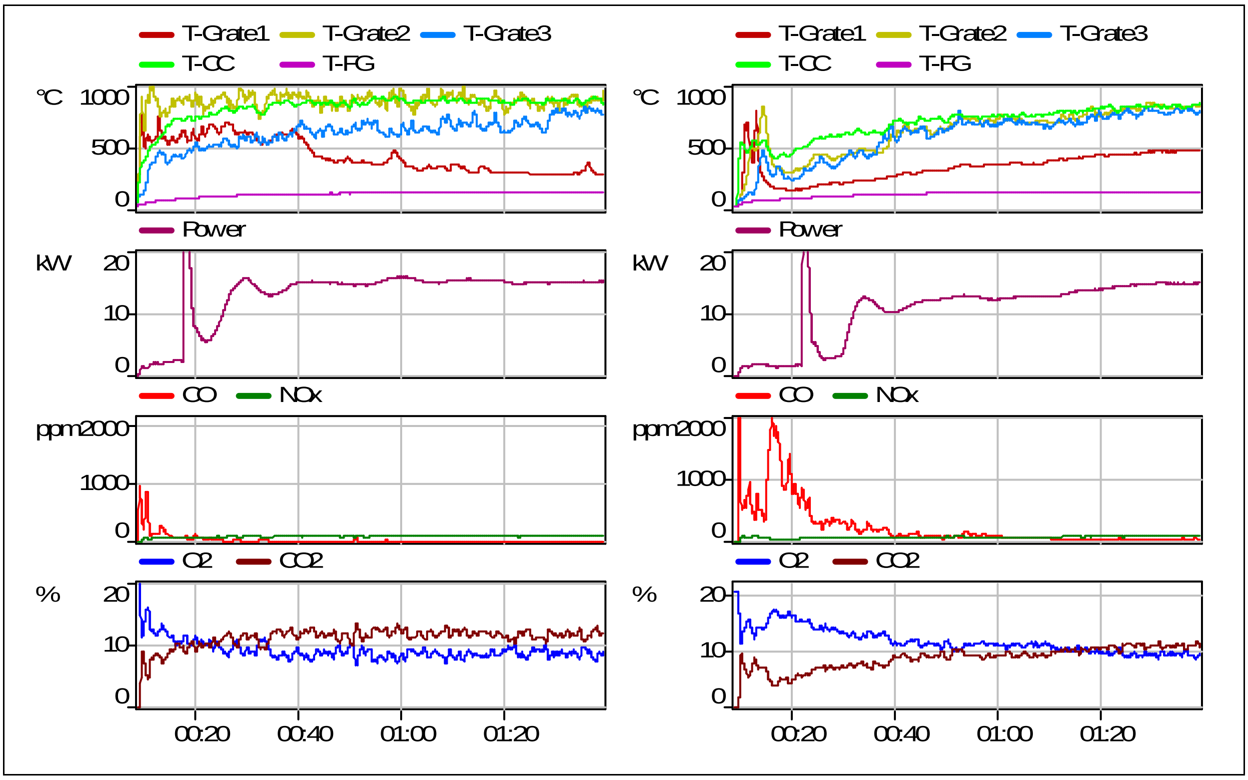


Figure 8: Start up phase of wood pellets spruce_raw (left) and spruce_260 (right) investigated in Boiler1 (time scale in hours).

In general, the temperature range of spruce_260 started to rise later. It took about 30 minutes until the temperatures on the grate and inside the combustion chamber excess 750°C. The range of the flue gas temperature of both experiments was comparable. The temperatures of spruce_raw started to rise after 15 minutes. The CO peaks of spruce_raw had their maximum at about 1000 ppm, the CO peaks of spruce_260 at about 2000 ppm.

Furthermore, it took longer until the CO emissions decreased (about 30 minutes instead of 10 to 15 minutes). The amount of excess oxygen decreased after 7 minutes to 11 vol.-% and after 15 minutes to less than 10 vol.-% (spruce_raw). In case of spruce_260 it took 30 minutes to reach an oxygen level of 11 vol.-%. Overall the torrefied fuel had a delay in controlling the combustion behaviour in comparison to the wood fuel.

The combustion process of wood is divided into different stages (drying, gasification, burn out of combustion gas/char). The duration of these single stages differs during the combustion of torrefied biomass, since the lower content of moisture and volatile compounds of the torrefied fuel leads to a different behaviour after the ignition process and during the start-up phase.

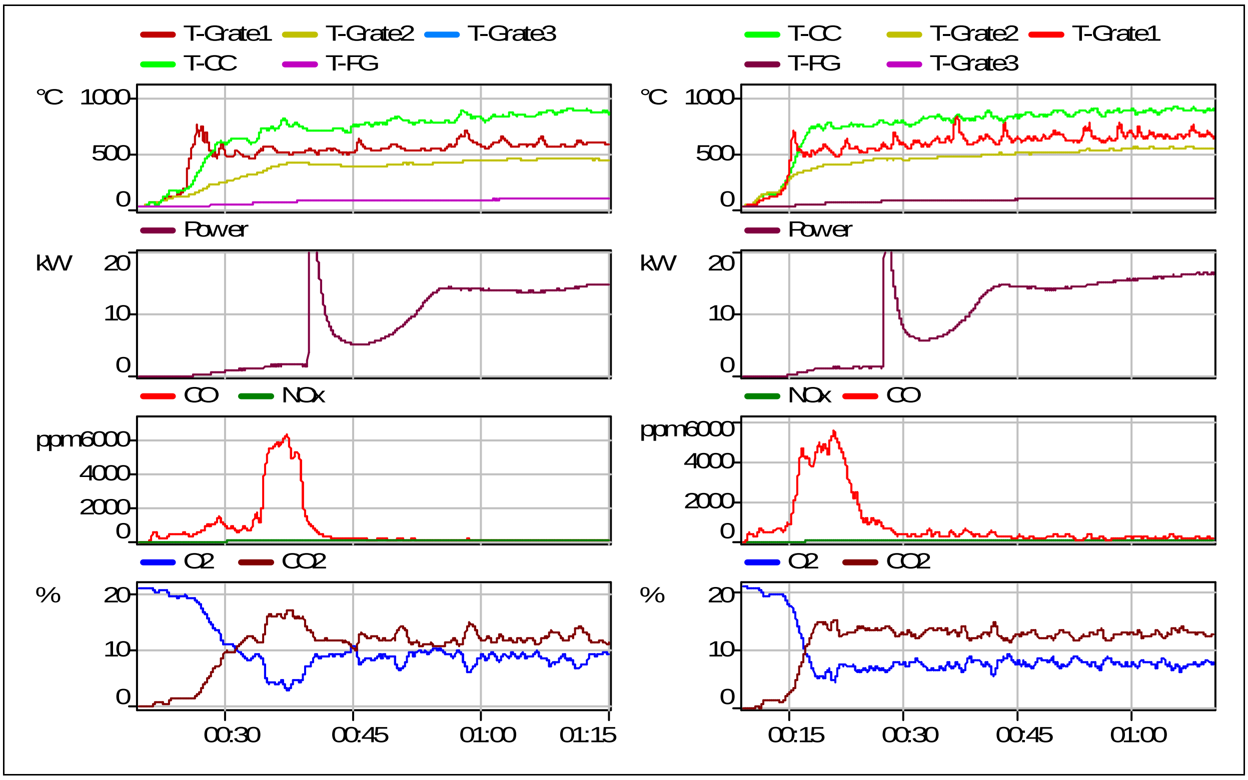


Figure 9: Start-up phase of spruce_raw (left) and spruce_260 (right) investigated in Boiler2 (time scale in hours).

The start-up phases of the tests with Boiler2 are shown by Figure 9. The increase of the temperatures on the grate and inside the combustion chamber was comparable. However, the temperature range during the experiment operated with spruce_260 was slightly higher and the nominal heat output was reached earlier. The CO release of spruce_260 started to rise earlier and it took longer until the value dropped. The maximum was nearly 6000 ppm, this value was even a bit less than the highest value during the test with spruce_raw. The excess oxygen of spruce_raw dropped to 5 vol.-%, afterwards it rose and remained stable at about 9 vol.-%. During the test with spruce_260, the excess oxygen increased to 7 vol.-% and remains stable.

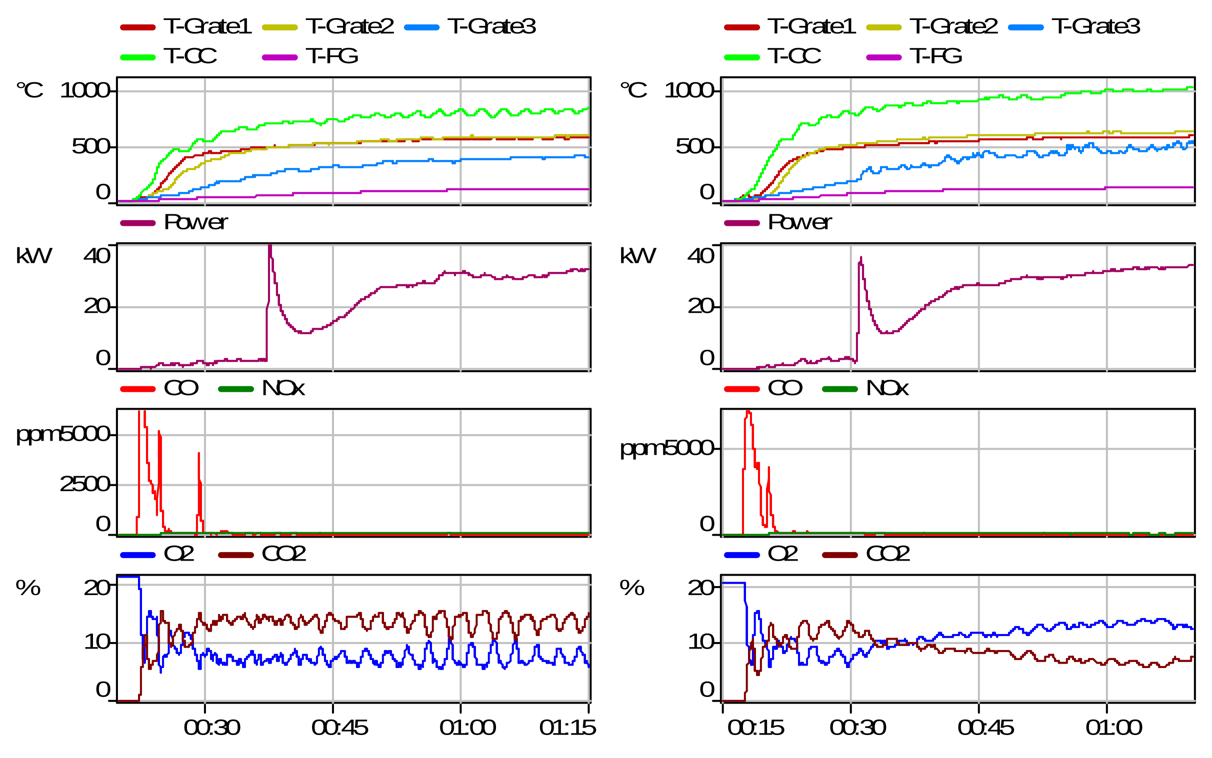


Figure 10: Start-up phase of spruce_raw (left) and spruce_260 (right) investigated in Boiler3 (time scale in hours).

Figure 10 compares the start-up phases of the tests operated with Boiler3 During both experiments with Boiler3, stable conditions are reached quickly within 20 minutes after the ignition process. The temperature range of the flue gas and on the grate was comparable in both the experiments. The temperature inside the combustion chamber however was higher 15 minutes after the beginning of the test. The CO emissions increased during the ignition process up to more than 6000 ppm, however this value dropped and stable combustion processes during both experiments were reached quickly. The excess oxygen level during the utilization with spruce_raw was stable 10 minutes after the ignition. It oscillated between 6 and 10 vol.-% due to the speed of the auger burner of the combustion appliance. The excess oxygen of the test with spruce_260 fluctuated longer and after a stable combustion process was reached, the value was higher than 10 vol.-%. Both experiments were operated with the same settings without any adaptions.

The combustion appliance is a prototype and the control system is not developed so far. The operator has to set the control parameters manually, e.g. speed of the auger burner, air supply, and set point for excess oxygen. There is an enormous improvement potential for the future, especially for the utilization with non-standardized fuel.

Figure 11 compares the experiments operated with Boiler4. The diagram on the left hand shows the utilization with wood pellets. The combustion process started immediately after the ignition. The temperature range on the grate and inside the combustion chamber was stable in an early stage. The CO release had its maximum at about 500 ppm and dropped quickly after stable conditions were reached. The excess oxygen approached 10 vol.-% during the start-up phase. The diagram on the right hand reflects the combustion behaviour of torrefied fuel during the start-up phase. In comparison to the operation with wood pellets, it took longer until the temperature range reached the required level. The CO release had an average value of 500 ppm during the first 20 minutes of the experiment. Afterwards, the emissions dropped and were comparable with the CO emissions of the experiment with spruce_raw. The excess oxygen first dropped to a value lower than 10 vol.-%, afterwards it rose and got stable at about 12 vol.-%.

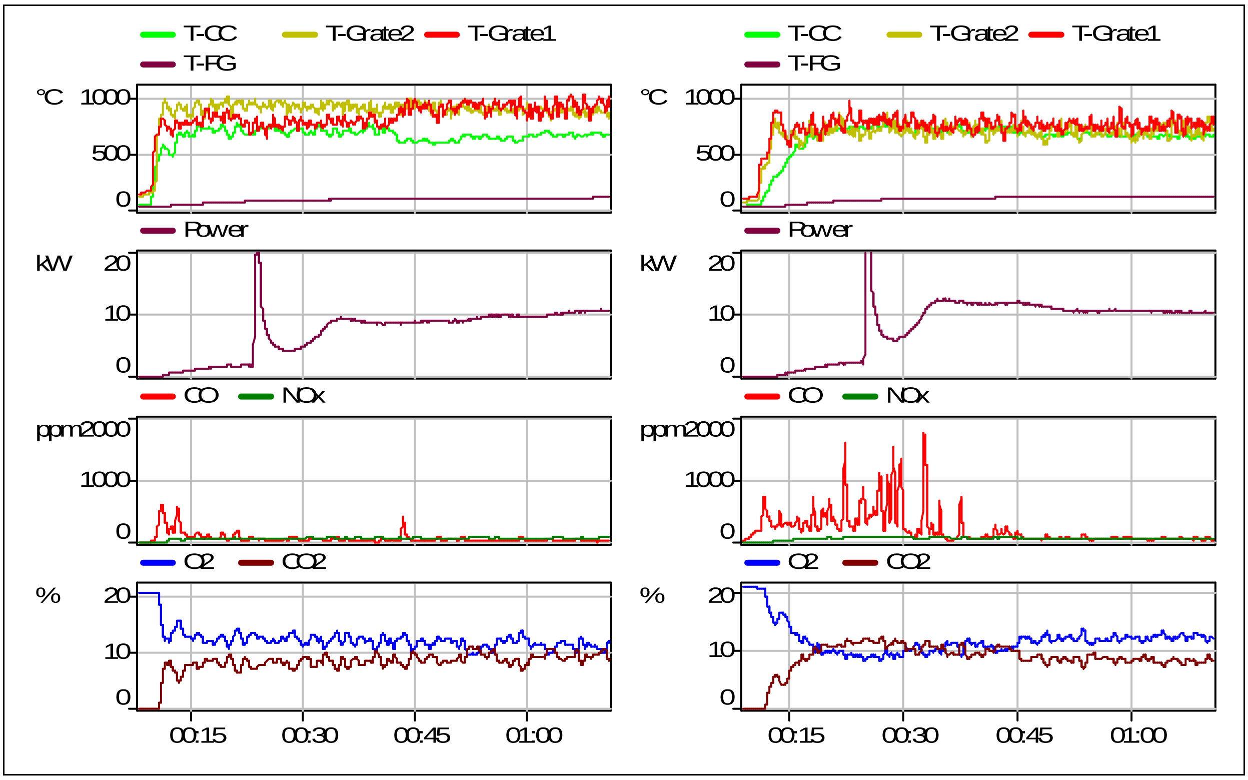


Figure 11: Start-up phase of spruce_raw (left) and spruce_260 (right) investigated in Boiler4 (time scale in hours).

In order to compare the **start-up emissions** of all tested appliances, the CO release during the beginning of the combustion experiments (spruce_raw and spruce_260) is quantified. This way, a comparison between the emissions of wood pellets and torrefied fuels is feasible. The evaluation period begins after the ignition process started and the measured value of the CO emissions is higher than 50 ppm. The duration of the start-up phase is defined as 1 hour.

Table 13 summarizes the results of the determinations of the start-up emissions of the combustion appliances utilized with spruce_raw and spruce_260. Average values are taken into account. The resulting CO-factor quantifies the higher CO release during the application of torrefied fuels.

Table 13: CO emissions averaged during start-up phase (1 hour) [ppm].

	Spruce_raw	Spruce_260	CO-factor [ppm-based]
Boiler1	49	336	6,9
Boiler2	710	917	1,3
Boiler3	247	304	1,2
Boiler4	71	229	3,2

All experiments utilized with the torrefied fuel caused higher CO emissions during the start-up phases (229 to 917 ppm). The highest start-up emissions in general, during the operation with wood and torrefied fuels, were caused by boiler2 (710 and 917 ppm). Due to the comparable emission value, the resulting CO-factor is low (1.2). The highest CO-factor was generated by boiler1, which had the lowest CO emissions during the start-up phase utilized with spruce_raw (49 ppm). Boiler3 reaches the lowest CO-factor (1.2), and the CO emission values of spruce_raw and spruce_260 are almost comparable.

Beside the start-up emissions, the amount of generated flue gas increased during the application of torrefied fuels. Table 14 considers the CO release as well as the amount of flue gas generated during the start-up of the experiments utilized with spruce_raw and spruce_260.

Table 14: CO emissions during start-up phases (1 hour) [g].

	Spruce_raw	Spruce_260	CO-factor [g/Nm³-based]
Boiler1	2796	19313	6,9
Boiler2	29857	36881	1,2
Boiler3	10959	53770	4,9
Boiler4	2565	7678	3,0

Due to the higher CO emissions and the larger amount of flue gas, obviously, the calculated emission values of the experiments with torrefied fuel are higher. Therefore, it reflects the results of Table 13. However, this assessment considers the different load level of the single combustion appliances as well and enables a better diversification. E.g. the nominal load of boiler3 is much higher than the one of the other combustion appliances, thus, the volume of the generated flue gas has to be considered. However, the measurement of the flue gas velocity by Prandtl tube is a very imprecise method. Especially the mean value during the investigation of spruce_260 with boiler3, a flue gas velocity of 6 to 7 m/s (in comparison to 2 m/s during the experiment with spruce_raw) is an unrealistic value. For this reason, the CO factor based on ppm is considered for further investigation and assessment of start-up and burn out phases.

4.2 Burn out phases

Analogously to the start-up phase, the burn out phase of the torrefied fuel is investigated and compared to wood pellets. As an example, Figure 12 shows the behaviour of the operating parameters after the boiler1 is switched off.

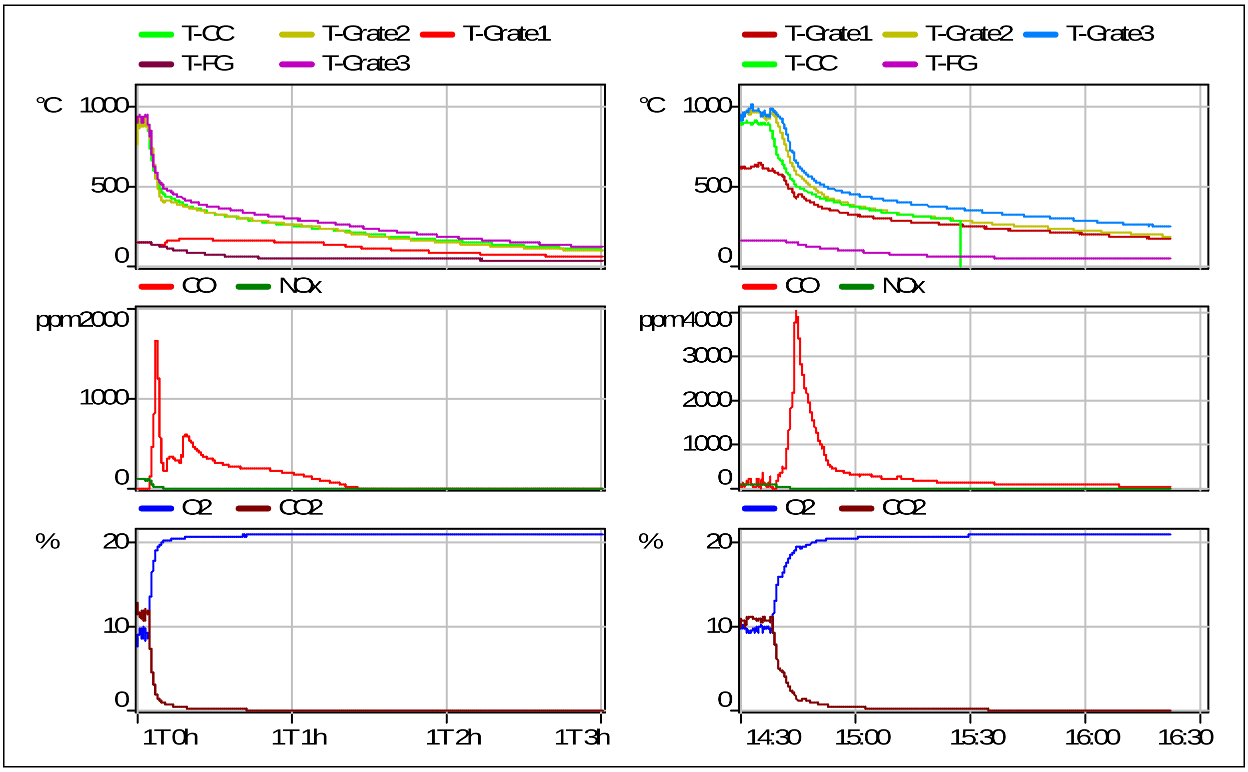


Figure 12: Burn out phase of wood pellets (left) and torrefied fuel (right) investigated in Boiler1 (time scale in hours).

The left diagram shows the parameters during the burn out phase of the test ran with wood fuels and the diagram on the right side shows the behaviour of the torrefied fuel. Both the tests were operated with Boiler1. With regard to the temperature range on the grate and inside the combustion chamber, obviously the temperature decrease took longer after torrefied fuel was utilized. Furthermore, the CO release during the burn out was higher and also the decrease of CO_2 was slower. For the assessment of the burn out behaviour, these three parameters are considered as criteria. The burn out phase begins, as soon as the boiler is switched off and ends after 45 minutes.

Decreasing ratio of the temperature inside the combustion chamber. E.g., the temperature inside the combustion chamber during the test of Boiler1, utilized with Spruce_raw, was 901°C. At the end of the burn out phase, it dropped to 281°C. So the temperature decreased to 31 % of the temperature before the boiler was switched off.

In order to compare the burn out phases of torrefied fuels with wood fuels, the values of each combustion appliance are divided. Finally, there are factors which quantify the different burnout behaviour considering the temperature inside the combustion chamber. Table 15 summarises the temperature ratio (temperature 45 minutes after the shut-down and temperature when switching off) of all the experiments with spruce_raw and spruce_ 260 respectively.

Table 15: Duration of burn out behaviour, temperature drop inside combustion chamber.

T-d[%]	Spruce_raw	Spruce_260	T-factor
Boiler1	31	33	1,1
Boiler2	25	30	1,2
Boiler3	32	65	2,0
Boiler4	9	12	1,4

After the combustion experiments with torrefied fuels, it took longer for cooling down the combustion chamber than after the utilization of wood fuel. The lowest T-factor (1.1) and therefore, the fastest cool down (9% of the switch-off-temperature) was measured during the burnout of spruce_raw utilized in Boiler4. The highest temperature after the burnout phase was detected at Boiler3 operated with spruce_260. The temperature inside the combustion chamber was still 65% of the switch-off-temperature. The resulting T-factor is 2.0.

Peak area of CO release. After the combustion appliances are switched off, there is a higher CO release, comparable with the start-up phase. These CO emissions differ depending on the boiler and the fuel. Figure 13 shows the behaviour of CO release after the appliances were switched off for the duration of 45 minutes.

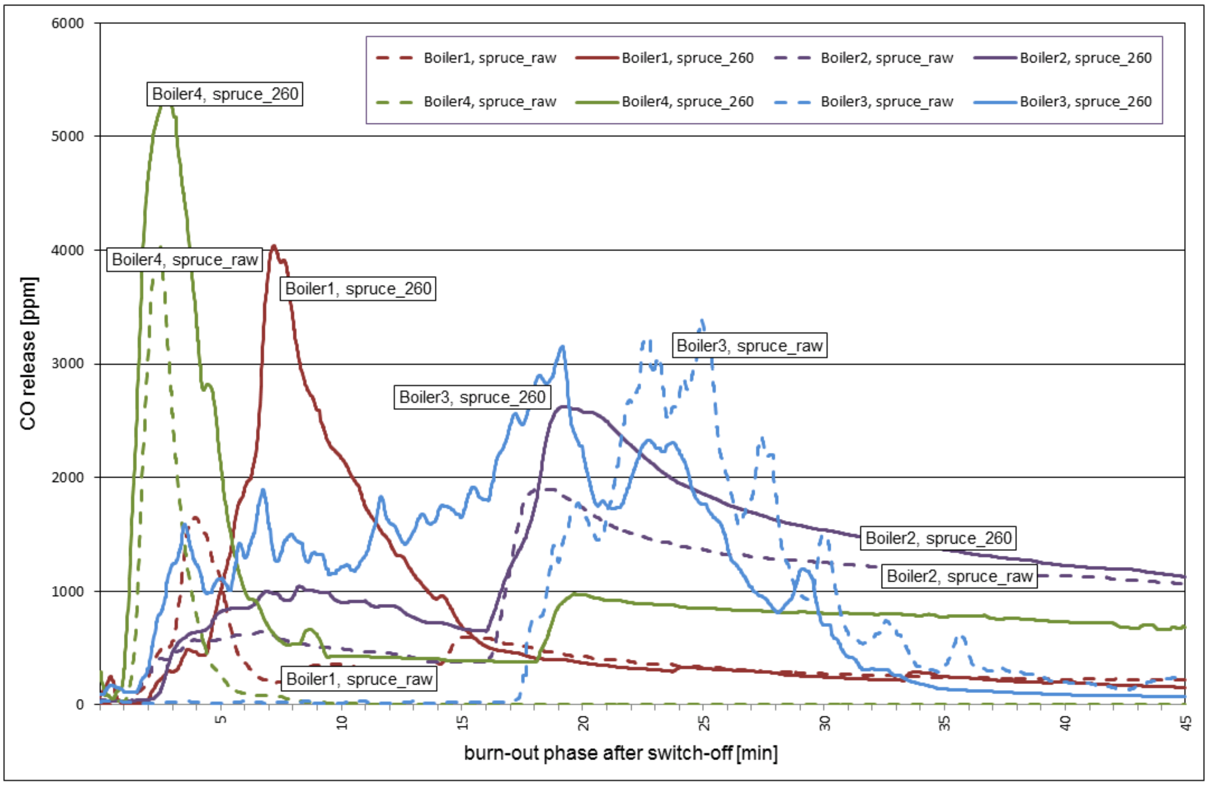


Figure 13: CO release during the burn out phase of the combustion experiments.

The peaks of the two tests operated with Boiler4 are higher than 4000 ppm, however, both graphs drop quickly. The graphs of the CO release of the tests operated with Boiler3 both rise up to 3000 ppm and have a similar peak area. The CO emissions of boiler1 and boiler2 show a clear difference between wood pellets and torrefied fuel. The peak area is calculated for the burn out phase of every test. After the experiment with spruce_raw was stopped, the

CO release of the flue gas of the combustion appliances is summed up. Table 16 summarises the values of the calculated peak areas [ppm] of all the burn out phases with spruce_raw and spruce_ 260 until 45 minutes from switching off during the burn out phases and compares the resulting factors.

Table 16: calculated area of CO release during burn out phase.

CO area [ppm]	Spruce_raw	Spruce_260	CO-factor
Boiler1	968907	1785022	1,8
Boiler2	2663709	3432310	1,3
Boiler3	1816688	3737974	2,1
Boiler4	424257	2612972	6,2

As expected, the CO areas of the tests utilized with torrefied fuels are higher than the experiments operated with wood fuels. The lowest CO-factor was reached by Boiler2. The CO release was only 30% higher while the boiler was operated with torrefied fuel instead of wood fuel. The highest CO factor had Boiler4. During the operation with torrefied fuel, the CO release was 6 times higher than during the operation with wood pellets.

Cumulated biomass during burn out. Based on the content of CO_2 in the flue gas, the amount of fuel is determined by calculating the amount of carbon and considering the content of carbon in the fuel (see chapter 2.3):

$$m_{fuel} = V_{CO2}[Nm^3] \cdot 1989\ \frac{g}{Nm^3} \cdot \frac{12}{44} \cdot \frac{100}{C\ [wt\%\ d.b.]}$$

During the burn out phase of the utilization of spruce_raw, boiler1 releases an amount of 0,175 Nm³. To generate this volume of CO_2, a fuel mass of 186 g is needed. Thus, after the switch off, the combustible biomass on the grate had at least a mass of 186 g. Figure 14 shows the cumulated biomass during the burn out phase of a combustion experiment as a function of time.

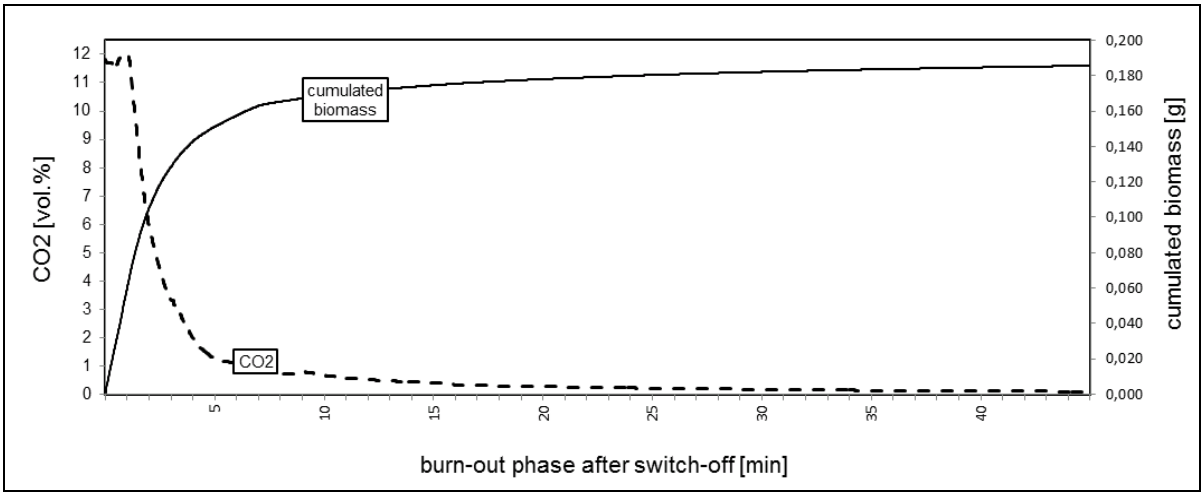


Figure 14: Cumulated biomass during the burnout phase after the combustion of spruce_raw in boiler1.

The graph rises quickly, as immediately after the switch off, the combustion process still continues as there is a big amount of biomass on the grate. As soon as this fuel is combusted, the graph turns flatter and well ahead the increasing amount of cumulated biomass stays stable, after no more CO_2 is generated. For the assessment of the combustion experiments, the first 45 minutes of the burn out phase of every test are considered. Table 17 summarizes the results of the calculations on the cumulated biomass fuel of the experiments with spruce_raw and spruce_260. The resulting factor compares the burn out phases respectively.

Table 17 Cumulated biomass during burn out phase.

Cumulated BM [kg]	Spruce_raw	Spruce_260	CO_2-factor
Boiler1	0,186	0,258	1,4
Boiler2	0,291	0,592	2,0
Boiler3	n.a.	n.a.	
Boiler4	0,064	0,149	2,3

The factors in the last column show, that the mass of cumulated fuel is higher during the burn out phases of the tests operated with torrefied fuel. The lowest value has Boiler1, the highest factor is reached by Boiler4.

Table 18: assessment of burn out phases, summary.

Assessment criteria	T-factor	CO-factor	BM-factor
Boiler1	1,1	1,8	1,4
Boiler2	1,2	1,3	2,0
Boiler3	n.a.	n.a.	n.a.
Boiler4	1,4	6,2	2,3

All assessment factors are summarized as criteria by **Table 18**. The table shows, that it is necessary to consider all 3 criteria for the assessment of the burn out phases. Since the behaviour of every combustion appliance differs, the assessment would not be indicative by selecting just 1 single criterion.

4.3 Residence time on the grate

The combustion technologies used for the experiments differ concerning feeding system and ash removal solution and, therefore, concerning the residence time. Boiler1 and Boiler4 operate the ash removal discontinuously (standard setting: 5 or 6 hours), Boiler2 and Boiler3 have a discontinuous cleaning solution, both based on the movement of the burner plate and the auger burner respectively. The standard settings of the combustion appliances, however, consider a too short residence time.

The tendency of the CO release within one cleaning interval gives information about the combustion behaviour of the fuel. High CO emissions indicate incomplete combustion and a too short residence time. Figure 15 compares one selected phase of two tests with wood fuel (spruce_raw) and torrefied fuel (spruce_260) applied in boiler1.

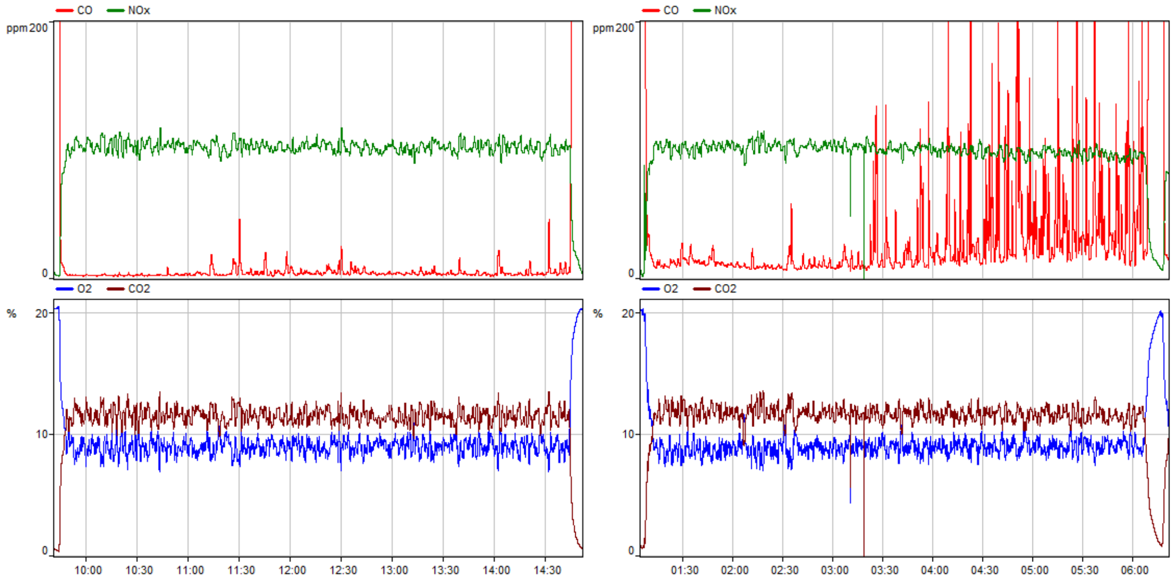


Figure 15: Diagram of combustion tests with Boiler1; left: utilization with spruce_raw, right: spruce_260.

Both diagrams show the flue gas content (CO, NO_x, O_2, CO_2) within one cleaning interval. O_2, CO_2 as well as the NO_X release are stable within the 5 hours duration. Immediately after the cleaning procedure, the CO emissions of both test fuels are steady, however, the value of spruce_260 is slightly higher. After 2 hours testing duration, the CO emissions of spruce_260 start to rise enormously, while the emissions of spruce_raw stay steady. In terms of CO tendency, the fuel spruce_raw enables a stable operation. This comparison indicates an accumulation of fuel on the grate during the experiment with torrefied fuel. Due to the control system, the fuel feeding was not adapted (reduced) and the residence time on the grate was too short. At the end of the cleaning interval, the unburnt material was moved into the ash collecting box, together with the formed ash. After the ash removal procedure, the CO release decreased again.

The results concerning the burn out phase investigated in the chapter before suggest a longer residence time of the torrefied fuel on the grate as well. The extension of the residence time is necessary because the torrefaction process changes the elemental composition and the NCV of the fuel.

The CO emissions are an indicator for an incomplete combustion process. Similar to the controlling related parameters (Lambda, temperature range, heat output), the tendency of the CO release within different phases of a combustion experiment can give information on the completeness. **Table 19** shows the CO emissions of Boiler1, Boiler2 and Boiler3 during the operation with torrefied fuel.

Table 19: CO emissions [mg/Nm³] during the experiments with spruce_260.

CO emissions	Boiler1	Boiler2	Boiler4
Phase 1	68	66	122
Phase 2	37	32	125
Phase 3	70	30	114
Phase 4	127	27	177
Tendency	↑	↓	↑

The CO emissions of boiler1 and boiler2 started at the same level. During the experiment operated with boiler1, the value increased up to 127 mg/Nm³, while boiler2 reduced the CO release to 27 mg/Nm³ within the combustion test. The rise of boiler1 began at the end of the testing duration and is most probably caused by too much fuel on the grate which cannot be combusted due to the capacities of the combustion appliance. The drop of CO emissions of boiler2 started within the second evaluation phase. Obviously, the control strategy managed the change of the fuel properties in a better way. The CO release of boiler4 increased to nearly 200 mg/Nm³, which corresponds to an relative increase of almost 50%. However, the combustion test started already with a high CO value (122 mg/Nm³), so there were no adaptions of the combustion appliance by the control system. Similar to the experiment operated with boiler1, the CO release reached the maximum in the last evaluated phase. A possible reason for this similar behaviour is the ash removal solution, which is discontinuous for both combustion appliances.

During the first experiments within this work package of the SECTOR project, the aspect of residence time was not considered as an assessment parameter. Only during the experiments operated with Boiler3 there was the possibility, to observe the removed ash. Glowing particles were found in the bottom ash which indicates, that the residence time of the fuel on the grate was too short. In the following experiments, the burn out rate of the bottom ash was investigated.

The determination of incomplete combustion is possible only partly since the bottom ash continuous with oxidization process after the ash and the unburnt material are removed from the grate into the ash collecting box. During the last experiments, an additional thermocouple was installed and the temperature range inside the ash tray was measured. So at least it was possible to detect a higher temperature range of torrefied fuels in comparison to wood fuels. Figure 16 gives an overview about the temperature range inside the ash tray by utilization of Boiler1 with the fuels spruce_raw, pine_270 and poplar_270 within the testing duration.

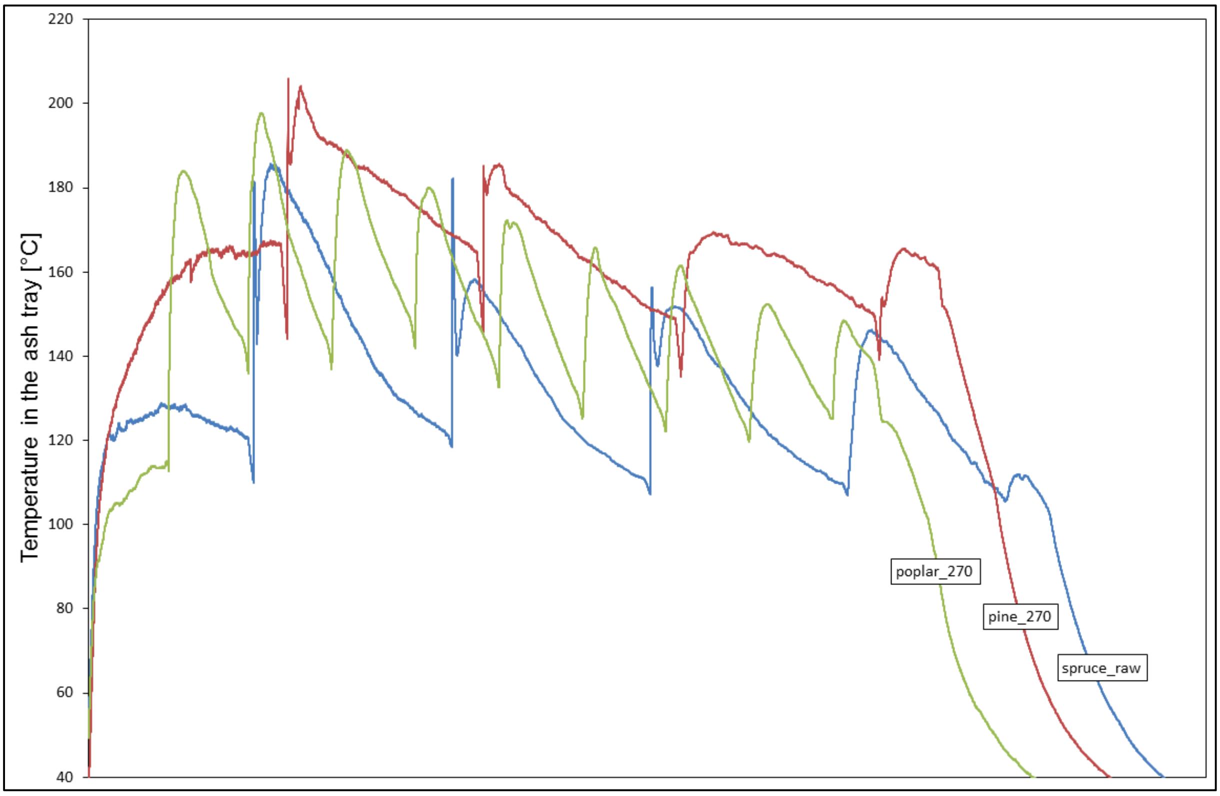


Figure 16: Temperature range inside the ash tray, torrefied fuels (pine_270 and poplar_270) in comparison to wood pellets (spruce_raw).

At the end of every cleaning interval, the sliding movement of the grate transfers the ash into the ash tray. The temperature at the bottom of the ash tray rises immediately. Afterwards, the temperature cools down, while the combustion appliance reaches stable conditions. Also the grate temperature rises, so the high temperature inside the ash tray cannot be due to heat radiation of the grate. Obviously, during the investigation of spruce_raw the temperature level is lower than during the experiments with the torrefied fuels. Additionally, the temperature drops faster during the test with spruce_raw than during the test with pine_270.

Table 20: temperature range inside the ash collecting box [°C] during the combustion experiments in boiler1.

	Phase 1	Phase 1	Phase 3	Phase 4
Spruce_raw	152	134	131	129
Pine_270	159	181	166	162
Poplar_270	166	169	149	140

The content of unburnt material is determined according to section 3.5. Table 21 summarizes the ash content of the formed bottom ashes of spruce_260 utilized in all test boilers.

Table 21: Ash content of bottom ash of spruce_260 utilized in all test boilers.

	Boiler1	Boiler2	Boiler3	Boiler4
Ash content [wt.%]	96.9	34.0	25.8	55.4
TOC [g/kg d.b.]	31	660	742	446

The highest ash content was found in the experiment with Boiler1. The bottom ash of Boiler3 has only an ash content of 25.8 wt.%. Therefore, the combustible content of the bottom ash is almost 75 wt.%. The content of organic carbon (TOC) is rather high (74.2 wt.%).

In general, the values indicate a too short residence time of the torrefied fuel on the grate. For the assessment of the level of the ash content, however, has to be considered, that after the removal, the unburnt material glow inside the ash tray and therefore, the content of ash increases. The original content of unburnt material is higher than the values, however, it is not feasible to determine the initial value. Figure 17 shows the ash of spruce_260 investigated in Boiler4.

Figure 17: Glowing particles in bottom ash of Boiler4, test fuel spruce_260.

Despite of the residence time on the grate (interval 6 hours), there were glowing ash particles inside the ash tray. Figure 18 shows the agglomerations on the burner plate and the sieve with mesh size 3.15 mm after the granulometric analyses of the grate ash.

Figure 18: Agglomerations of spruce_260 on the grate of Boiler2 (left) and after sieving process (right).

Due to the high temperatures on the grate and the residence time, the ash started to slag during the combustion experiment.

The introduction of a characteristic number is useful to quantify the energy density on the grate. The **specific grate load k_A** shows the heat capacity of the fuel in ratio to the surface of the grate. This characteristic number evaluates the energy input with respect to the available grate surface. The higher the specific grate load, the higher is the energy density on the grate and the temperature increases.

$$k_A = \frac{\dot{Q}_{Fuel\ input}}{A_{Grate}} = \frac{NCV \cdot \dot{m}}{A_{Grate}}$$

Legend:

Q = heat capacity of the fuel (input) [W]

A_{Grate} = surface of the grate [m^2]

NCV = net calorific value [MJ/kg]

$\dot{m}$ = mass flow of fuel [kg/h]

For an investigation of two tests operated in the same boiler, only the NCV and the fuel mass flow have to be considered respectively. Table 22 overviews the values of the combustion experiments operated with spruce_raw and spruce_260. A specification on the grate surface was not calculated, however, a comparison is quantified by the resulting k_A-factor.

Table 22: Comparison of the grate load.

	k_A spruce_raw	k_A spruce_260	k_A factor
Boiler1	0,630	0,661	1,049
Boiler2	0,641	0,674	1,051
Boiler3	1,353	1,446	1,068
Boiler4	0,456	0,461	1,012

Despite of the reduction of the fuel mass flow, all combustion technologies generate a higher grate load due to the higher NCV of the torrefied fuel in comparison to the wood pellets. Within the same residence time on the grate, the energy input is up to 7 % higher (Boiler3).

4.4 Effect of the control strategy

The elemental composition of the fuel, especially the CHO ratio, influences the combustion process and therefore, the behaviour of the boiler. Based on the results of the fuel analyses (see chapter 2.3), the chemical composition changes. The volatile compounds affect the combustion behaviour especially during the ignition and start-up phase. The char burnout of the fuel takes longer and the required residence time on the grate may increase. Additionally, the changed content of VOC changes also the elemental composition (particularly the CHO-ratio) of the fuel. Therefore, the air demand for a stoichiometric combustion changes as well. Depending on the control strategy, problems can occur.

As an example, the following reaction equations show the difference between the combustion processes of wood pellets in comparison to torrefied fuel.

Equation a) combustion of fuel spruce_raw

$$C_{3.96}H_{5.44}O_{2.46} + 4.09\,O_2 \rightarrow 3.96\,CO_2 + 2.72\,H_2O$$

Equation b) combustion of fuel spruce_260:

$$C_{4.21}H_{5.79}O_{2.49} + 4.41\,O_2 \rightarrow 4.21\,CO_2 + 2.89\,H_2O$$

Due to the different CHO-ratio, the amount of additional required oxygen increases to 107.7% by the operation with torrefied fuel (4.21 instead of 3.96 mole of O_2 for the combustion of 1 mole of fuel). Also the amount of $CO_{2,max}$ changes (106.2%) with the fuel composition. The maximum values are 20.37% for spruce_raw and 20.14% for spruce_260. Table 23 shows mole shares of the reactants of the reactions.

Table 23: Data for stoichiometric combustion of the test fuels.

Fuel	C	H	O	O_2 [mole]	CO_2 [mole]	H_2O [mole]
spruce_raw	3,960	5,438	2,457	4,091	3,960	2,719
Forest_residues	3,972	5,393	2,398	4,037	3,864	2,822
spruce_260	4,206	5,786	2,490	4,408	4,206	2,893
Pine_270	4,202	5,903	2,435	4,460	4,202	2,951
Poplar_270	4,087	5,769	2,500	4,279	4,087	2,884

Besides forest_residues, the torrefied fuels require a higher air supply caused by the lower oxygen content in the fuel. For stoichiometric combustion of Pine_270, the highest air supply is needed (4.46 mole instead of 4.09 mole for spruce_raw). Spruce_260 generates the highest CO_2 amount (4.21 mole) and forest_residues the lowest (3.86 mole). During the combustion of spruce_raw, 2.72 mole of water is formed. The formed water amount of the torrefied fuels is higher up to 2.95 mole (Pine_270).

During the combustion process, the control system of the boiler has to handle the different fuel properties (CHO-ratio), the different properties of the flue gas concerning amount, excess oxygen and moisture content and the higher NCV. Depending on the control strategy, adaptions in terms of air supply or fuel feed are necessary.

Figure 19 gives an overview about the CHO-ratio of different energy sources. The ternary diagram does not consider the chemical form of these 3 elements, i.e. the molecular components (e.g. the carbon content in VOC). However, it gives an overview and allows an allocation of the torrefied fuel in comparison to raw wood fuels. The content of carbon is higher than the carbon content of wood fuel. The content of oxygen and hydrogen is slightly lower. Concerning CHO-ratio, torrefied fuel is comparable with peat (see also chapter 2.3) or brown coal, depending on the torrefaction process.

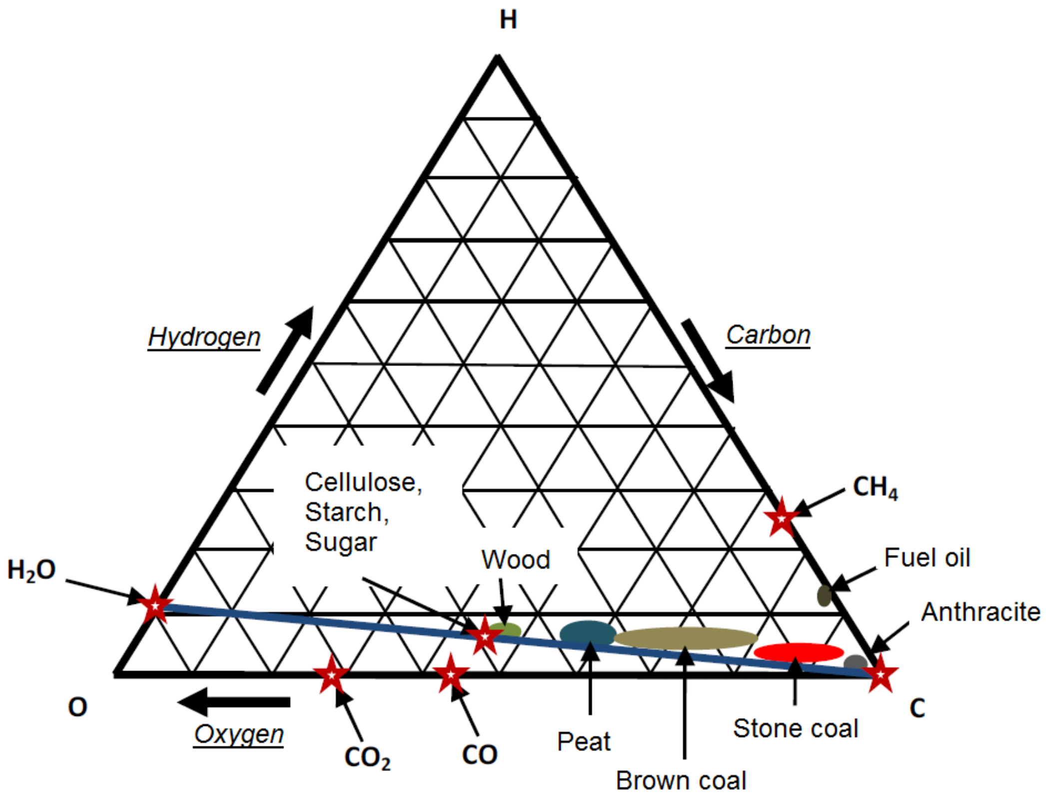


Figure 19: Ternary diagram, content of CHO [wt.-%, waf] [10].

In case of a lambda-controlled combustion system, the parameters are set based on the excess oxygen level in the flue gas. However, by supplying the same amount of air as during the utilisation with wood fuels, the flue gas composition of torrefied material, especially the O_2/CO_2-ratio, differs.

4.5 Corrosion load on chimneys

This section describes the combustion experiments as well as the survey of the test fuels made of torrefied material and the wood pellets as reference fuel. The assessment of the combustion behaviour considers emissions, excess oxygen, heat output, efficiency, temperature range and deposits of every experiment.

4.5.1 Dew point temperature

The basis for the dew point temperature in the flue gas states the formation and release of water vapour from the combustion process. Figure 20 shows the origin of the water in the flue gas for the different fuels investigated in this present work. As can be seen, the formation of water vapour from the fuel hydrogen content was slightly lower for the torrefied fuels than the normal spruce fuel. In average 2% less water was formed from the fuel hydrogen content. Furthermore the water content was significantly lower for all torrefied fuels than for the reference fuel. Overall this resulted in 5% lesser water release to the flue gas per kg combusted fuel. This lower water release is thus reflected also in the dew point temperatures of the flue gases, which are depicted in Figure 21.

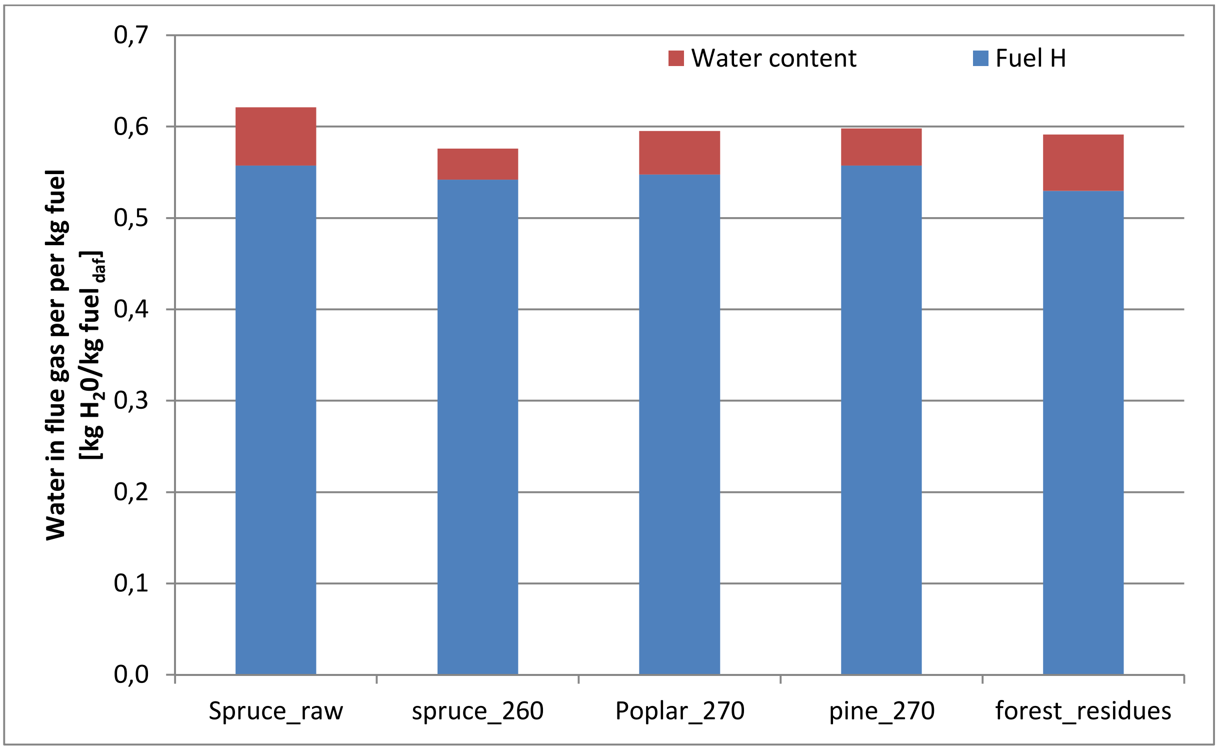


Figure 20: Origin of water in the flue gas.

The dew point temperatures were calculated for each boiler considering the flue gas composition of each combustion test and the fuel composition. Following the standard calculation for flue gas volume (DIN 4702-2 [11] and EN 13229 [12]) the partial pressure of water in the flue gas was determined. By applying the Antoine Equation, the dew point temperature was finally obtained.

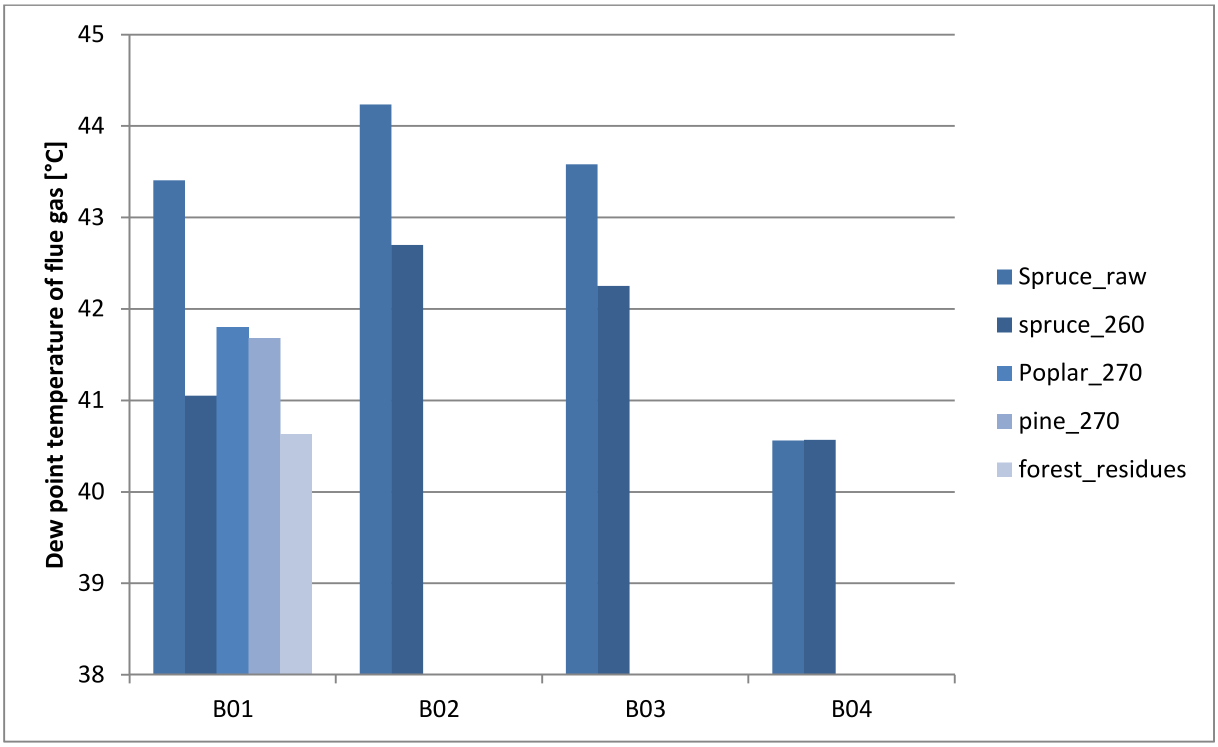


Figure 21: Dew point temperatures of flue gas from combustion of different fuels in the investigated boiler systems.

Figure 21 shows that the dew point temperature was lower for all tests with torrefied fuels in comparison to the reference fuel. The reference fuel showed a dew point temperature between 43 and 44°C, whereas the combustion of torrefied fuels released a flue gas with a dew point temperature in the range of 40.5 to 42.7°C. The sole exception was found in boiler B04. In this combustion system the dew point temperature was constant for both fuels at 40.5°C. These tests also showed a strong difference in the air excess ratio, the torrefied fuel was combusted at a lower air excess (9.4vol%$_{dry}$) than the reference fuel (10.7vol%$_{dry}$). This implies that the flue gas from the combustion of reference fuel was more diluted with air than the flue gas from the torrefied fuel. This behaviour of the combustion system is more likely due to the control system (see also chapter 4.4). The range of the dew point temperatures in flue gases from the combustion of biomass was also studied in Schwabl et.al, showing a range of 38 to 44°C of flue gases from pelletized fuel combustion and up to 50°C from wood chips combustion [8].

To conclude, the dew point temperature of the flue gas from torrefied fuels is lower than in comparison to standard biomass. Thus, the corrosion risk due to condensation of flue gas is to be considered in the same amount or lower.

4.5.2 Acidic emission condensation

The measurement of HCl and SO_2 from all fuel/boiler combinations were without exception below the detection limit. This denotes that the emission of HCl and SO_2 were below 0.1 mg/Nm³. There was no difference detected between the emission from standard and torrefied biomass.

Thus, the corrosion risk due to acidic gaseous compounds is expected to be in the same level for torrefied biomass in comparison to the reference fuel. It is expected, that the HCl and SO_2 emission release of torrefied fuels is dependent on the fuel composition in equal measure as for non-torrefied fuels. However, the release rates for fuels with higher share of Chlorine and Sulphur in the fuel was not investigated in this work. Such fuels are also as non-torrefied fuels still challenging to the combustion system and thus normally not applied to small scale combustion.

4.5.3 Particulate matter emission

The amount of particulate matter release is investigated in chapter 5.1. This chapter deals with the corrosiveness of the particulate matter emission. In the following it is distinguished in particulate matter emission, which is released to the chimney, and in heat exchanger deposits, which agglomerated on the surface and turbulator of the heat exchanger during the combustion test. Figure 23 and Figure 23 show the distribution of selected chemical elements in the particulate matter emission and in the deposits of the heat exchanger.

As can be seen, the major components of the particulate matter emission were Potassium, Sulphur and Chlorine, whereas the heat exchanger deposits also showed a high amount of Calcium. This major difference in the elemental composition is due to the different entrainment mechanism of the Calcium in comparison to Potassium, Sulphur and Chlorine, which are ascribed to the aerosol forming elements [9]. Hence, the variation in the Calcium content in the heat exchanger deposits from different combustion tests originates in the different combustion technologies. Calcium is mostly entrained as solid particles in the coarse mode from the combustion [10], which are deposited due to impaction in the heat exchanger. Another technology based difference can be seen in the particle emission composition of Boiler1 and Boiler3. Boiler3 shows an increase in Chlorine and Sulphur in the particulate matter, which most probably is caused by different temperature and flow regime conditions during the combustion process. However, a difference between torrefied and not-torrefied fuel is not evident.

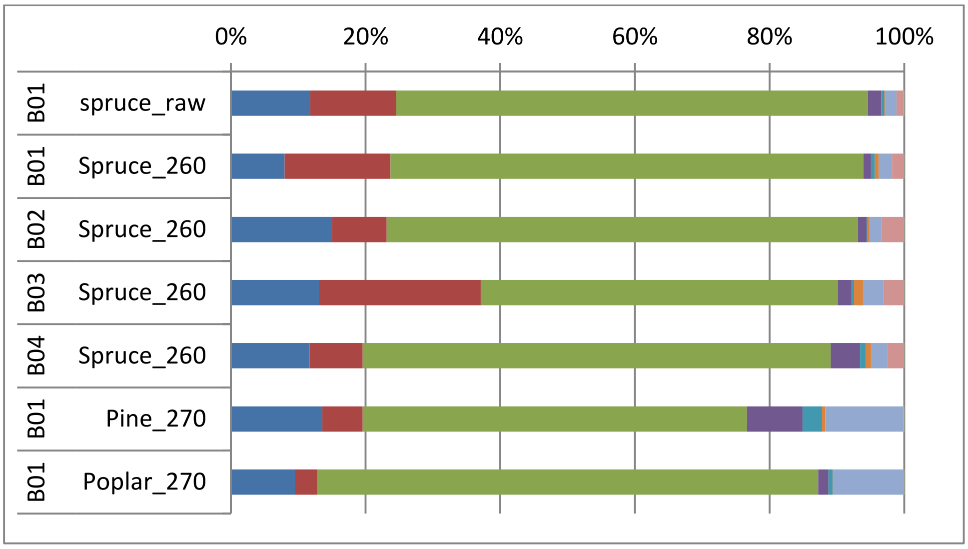


Figure 22: Distribution of selected elements in particulate emission in the flue gas.

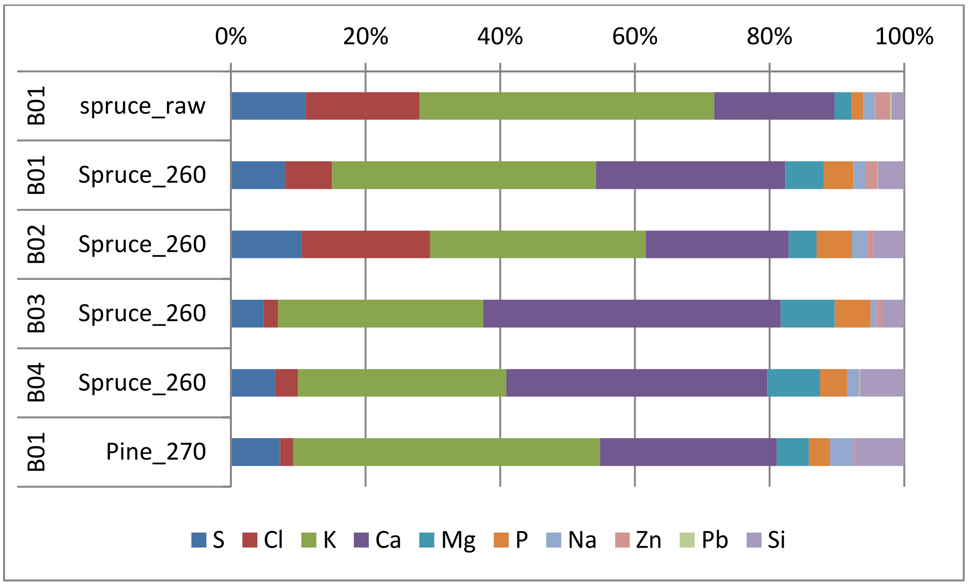


Figure 23: Distribution of selected elements heat exchanger deposits.

Concerning corrosion it is useful to have a look on the ratio of anions versus cations in the particulate matter and the heat exchanger deposits. Three different stoichiometric ratios are depicted in Figure 24 and Figure 25. The first reflects the amount of possible “low melting” Chlorides, the second ratio denotes the capacity of formed Potassium Chlorides and Sulphates; the third ratio denotes the share of Chlorine, Sulphur and Phosphorus as Anions in the solid phase. A ratio lower than 1 means, that different anions are possible, like Oxide or Carbonate. As shown in the diagrams, there is no significant difference between torrefied and non-torrefied material combustion. However, again exceptional is the combustion in Boiler3, which shows a high share of Chlorides and Sulphates in particulate matter and heat exchanger deposits.

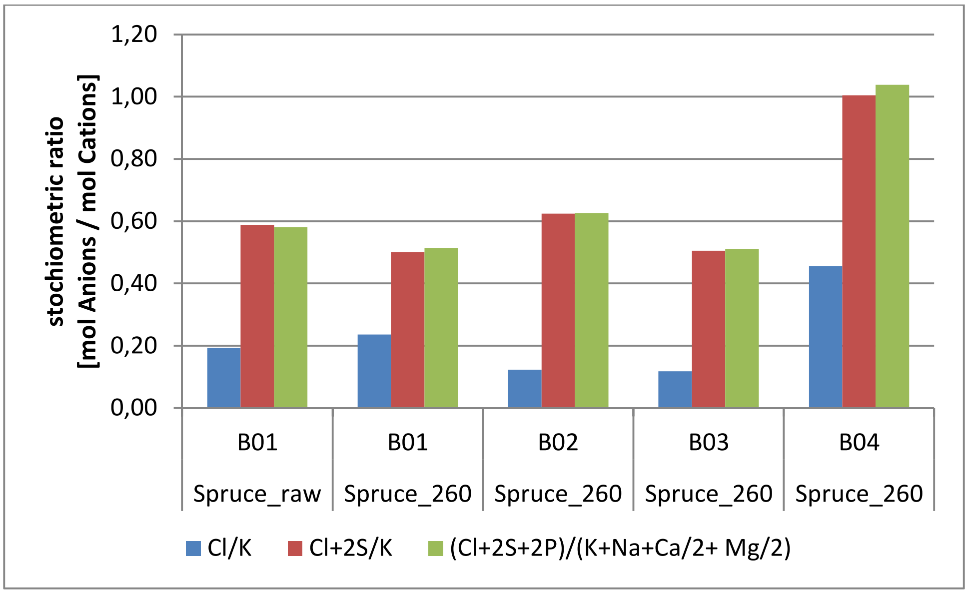


Figure 24: Stoichiometric ratios of anionic and cationic elements in particulate matter emission in boiler1 to boiler4.

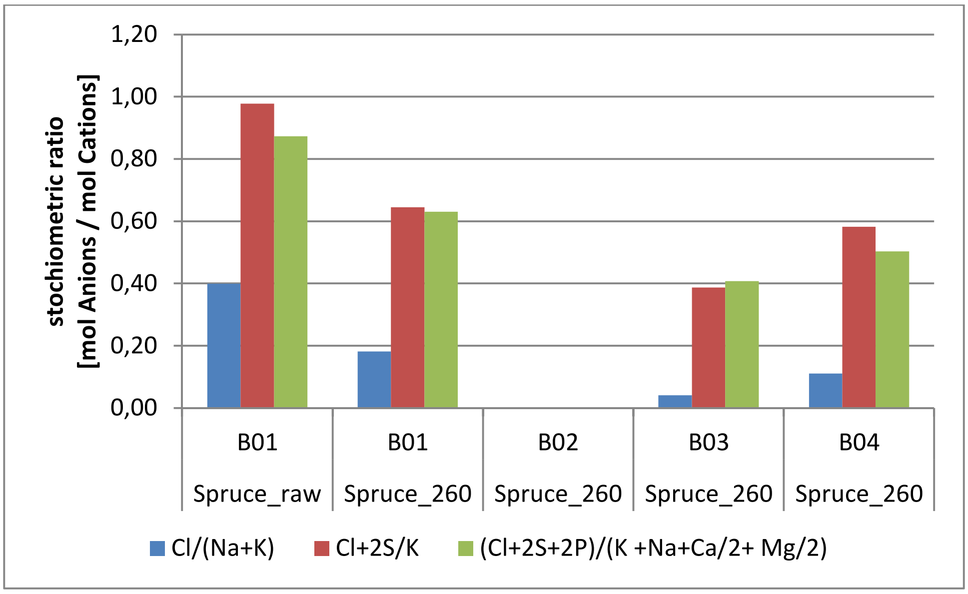


Figure 25: Stoichiometric ratios of anionic and cationic elements in heat exchanger deposits.

Based on the stoichiometric ratios, the risk of high temperature corrosion is low, when the amount of low-melting Chlorides is decreased [11]. This is reflected in the Cl/(K+Na) ratio. Except for the combustion in boiler3 the ratio for torrefied fuel is lower than for non-torrefied. Thus, the potential of high temperature corrosion can be assume to be slightly lower.

The decreased high temperature corrosion potential is also visible, when looking at the stoichiometric ratio Sulphur and Chlorine (2S/Cl), which is considered as an index for Chlorine induced high temperature corrosion [9]. The 2S/Cl ratio for spruce_260 is lower than for the raw spruce, indicating a slightly increased corrosion potential (see Figure 26). Looking at the other torrefied fuels, the 2S/Cl is at a same level. The torrefied forest_residue, however, shows a significantly higher ratio, which originates in the fuel composition of the initial raw material. An investigation on a change of the 2S/Cl ratio during the torrefaction process would be interesting, but beyond the scope of the present work.

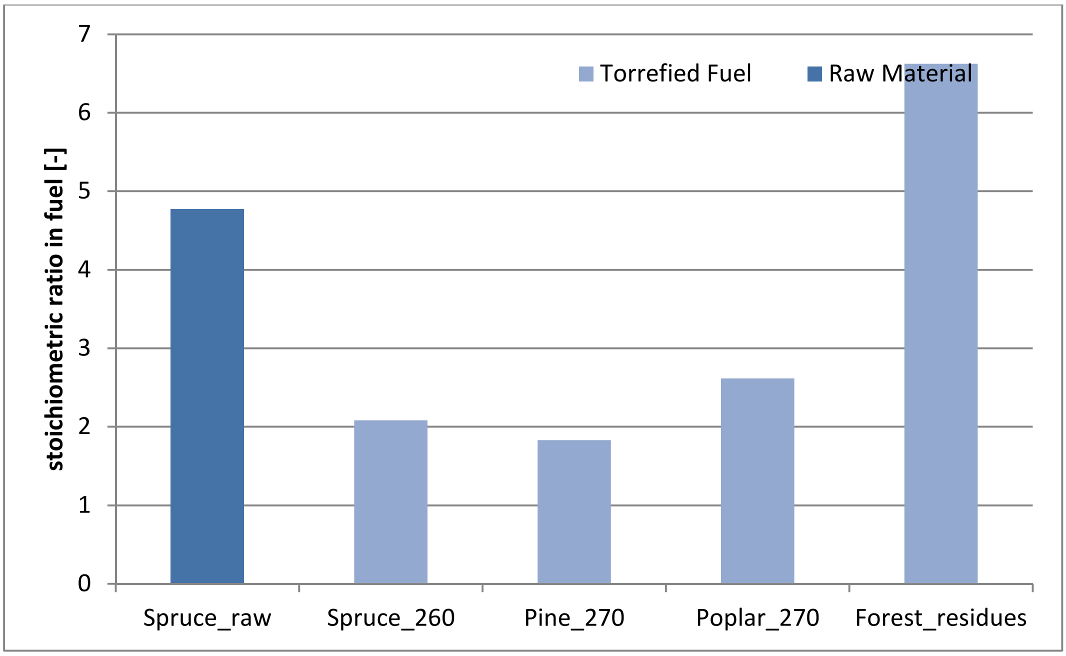


Figure 26: Stoichiometric ratio of Sulphur and Chlorine in the surveyed fuels.

Besides high temperature corrosion, PM and its deposits downstream the heat exchanger of the boiler system can also act as hygroscopic salts, which form an electrolytic solution already above the dew point temperature. This phenomenon is called deliquescence, which denotes the equilibrium of a saturated salt solution with a certain relative humidity in the ambient gas phase. Table 24 shows the relative humidity above saturated solutions of selected salts, which possibly occur in particulate matter and on heat exchanger deposits. As can be seen Potassium Hydroxide already dissolves in an aqueous solution at a relative humidity of 5.7%rH in the ambient. Also Potassium Carbonate and Calcium Chloride show the potential to deliquescence under the ambient conditions of a flue gas in the heat exchanger or in a chimney system.

Table 24: Deliquescence humidity of possible salt phases in PM and heat exchanger deposits according to Greenspan [12].

Temperature level: **Saturated salt solution**	**30°C**	**40°C** **[% rH]**	**50°C**
NaCl	75	74,7	74,4
KCl	83,6	82,2	81,2
KOH	7,4	6,3	5,7
K_2CO_3	43,2	n.a.	n.a.
$CaCl_2$ $6H_2O$	21,6	18,4	16,3

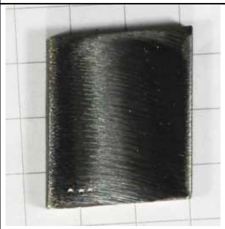
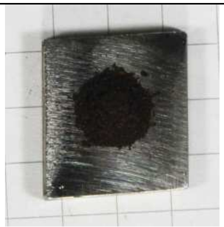
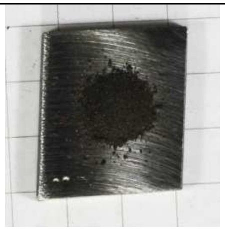
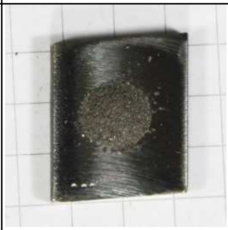
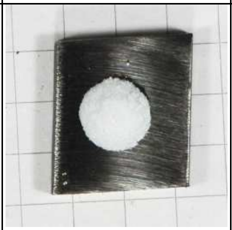
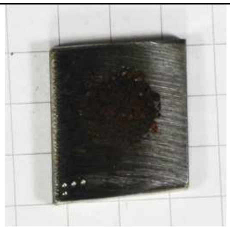
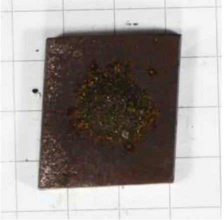
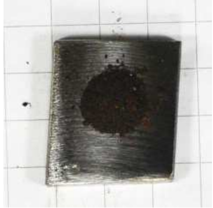
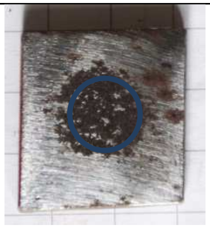
To investigate the corrosion potential of the different fuels an investigation according to the method described in chapter 3.7 was performed. Heat exchanger deposits from the combustion of raw and torrefied spruce are compared to deposits from the combustion of short rotation coppice and straw. Additionally an inert material was investigated, which consisted of pure Silicate. Two distinct blank samples denote the reference point, one was stored in the humid ambient and the other under dry conditions. Another sample with heat exchanger deposits was also stored in dry conditions. The photo documentation of this investigation is shown in Table 26 and the mass uptake is shown in Table 25.

As can be seen in both tables, the heat exchanger deposits from combustion torrefied fuel shows a slightly lower corrosion potential than those from raw spruce fuel combustion. However, the variance of the corrosion potential is within the range of normal wood fuels, as can be seen when looking at the deposits from willow combustion. This fuel showed an even lesser corrosion potential than the torrefied fuel. The deposits from straw combustion, on the other hand, showed a really high corrosion potential. The corrosion even spread out across the border of the sample pile. The inert silicate, as well as the other blank samples showed almost no corrosion at all. The minimal mass uptake of the Silicate sample is most probably reasoned in a decontamination of the sample and is thus on the same level as the sample from willow combustion.

Table 25: Mass uptake of corrosion test pieces exposed to different solid samples.

Heat exchanger deposits from combustion of	Mass uptake [mg] after 48h incubation in 75%rH at 50°C
Spruce_raw	1,96
Spruce_260	1,08
Willow (not from SECTOR)	0,30
Straw (not from SECTOR)	13,01
Silicate	0,50
blank	0,14
Spruce_raw 0%rH	0,08
Blank 0% rH	-0,02

Table 26: Deliquescence corrosion test of various heat exchanger deposits ([#] these samples were not from SECTOR project).

sample:	**Spruce_raw**	**Spruce_260**	**Willow**[#]	**Straw**[#]	**Silicate**	**Blank**	**Spruce_raw** at 0%rH	**Blank** at 0%rH
Test piece								
Initial piled sample								
Sample after 48h exposure								
Test piece after 48h exposure								
Test piece after 48h exposure under directed light								

4.5.4 High temperature scaling

Two distinct facts concerning torrefied fuels result in a higher temperature on the grate during the combustion of such, which is also displayed in Figure 27. A) Due to the increased heating value is also the energy density increased, whereby more energy is released on a smaller spot. B) The volatile fraction in torrefied fuels is reduced, which results in a different share in energy release for grate combustion and secondary gas phase combustion. These facts are also discussed in chapter 5.1. Concerning corrosion, this increased temperature means an increase in scaling of metallic compounds in the grate vicinity.

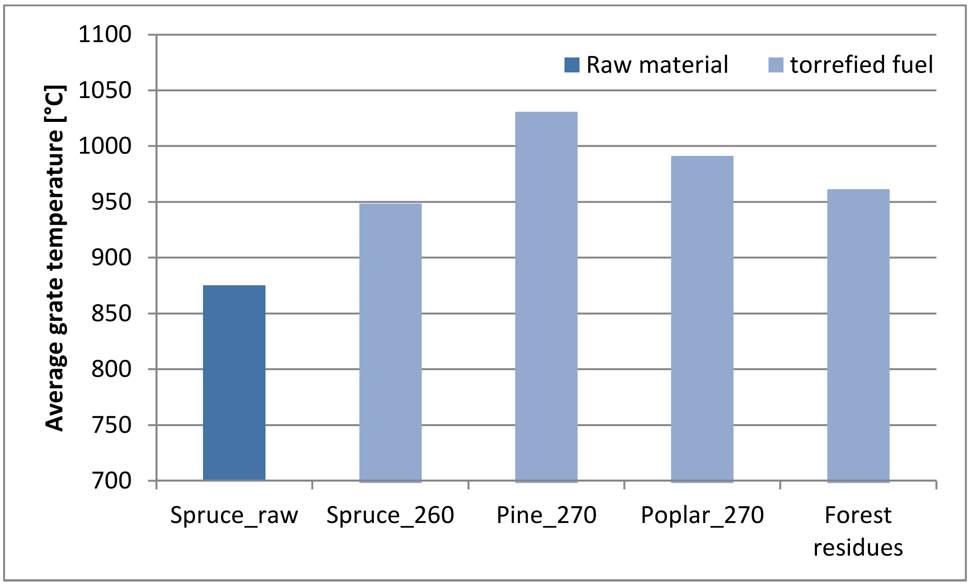


Figure 27: Average temperatures on the grate of boiler1 during combustion of torrefied and non-torrefied fuels.

5 Combustion screening of three pellet boiler technologies and fuel assessment trials

5.1 Comparison of stable conditions

This section compares the stable conditions of the tests operated with the different boiler technologies. With regard to the properties of torrefied fuel, the technology-related parameters which have to be considered mainly are

- heat output of the combustion appliance,
- lambda ratio, based on the excess oxygen,
- emission release (CO, NO_x, PM),
- temperature range (grate, combustion chamber) and
- efficiency.

The average values are the criteria for an assessment of the combustion behaviour. Boiler1, Boiler2 and Boiler4 are taken into account, since these small scale appliances are available on the market. Boiler3 is tested in addition. The controlling of this appliance is not completely developed so far, and it is only possible to set amount of air supply and the ratio of primary and secondary air manually. Thus, it is not possible, to assess the reaction of the control system, since the concerned variables (input and output parameters) are not connected.

Figure 28 compares the average **heat output** of the torrefied fuel spruce_260 with the wood pellets spruce_raw applied in the different combustion technologies.

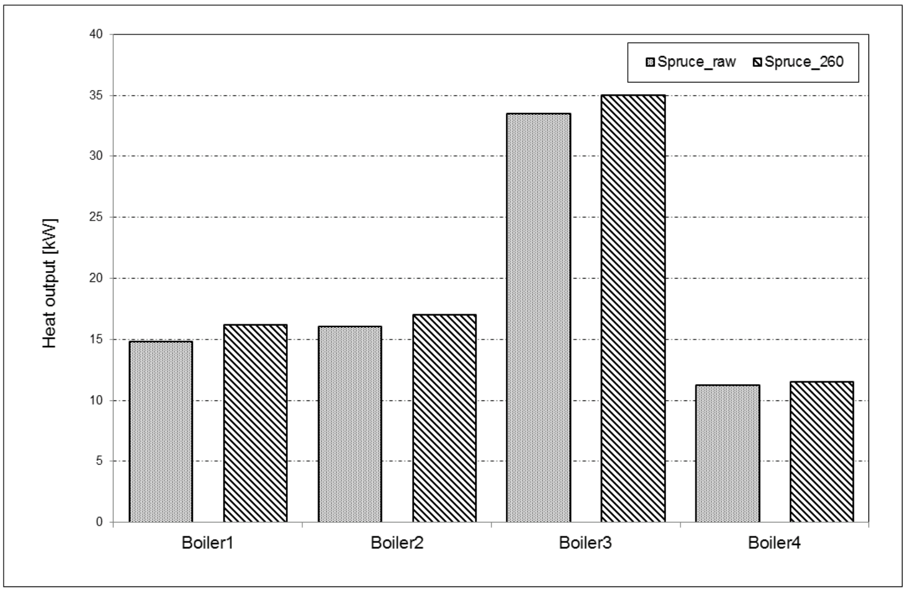


Figure 28: Comparison of the heat output, full load operation.

As expected, the combustion appliances produce a higher heat output due to the higher NCV of the torrefied fuel. The factor in the last column quantifies the increase of the heat output. The highest value reaches Boiler1, the utilization with torrefied fuel increases the heat output almost 10%. Boiler4 increased the heat output slightly (2.7%).

Figure 29 compares the average **lambda values** of the torrefied fuel spruce_260 with the wood pellets spruce_raw applied in the different combustion technologies. The lambda ratio is an indicator for the assessment of the combustion behaviour. Additionally, it enables a comparison between the different control strategies concerning handling the changed CHO-ratio of torrefied fuel and air supply according to chapter 4.4.

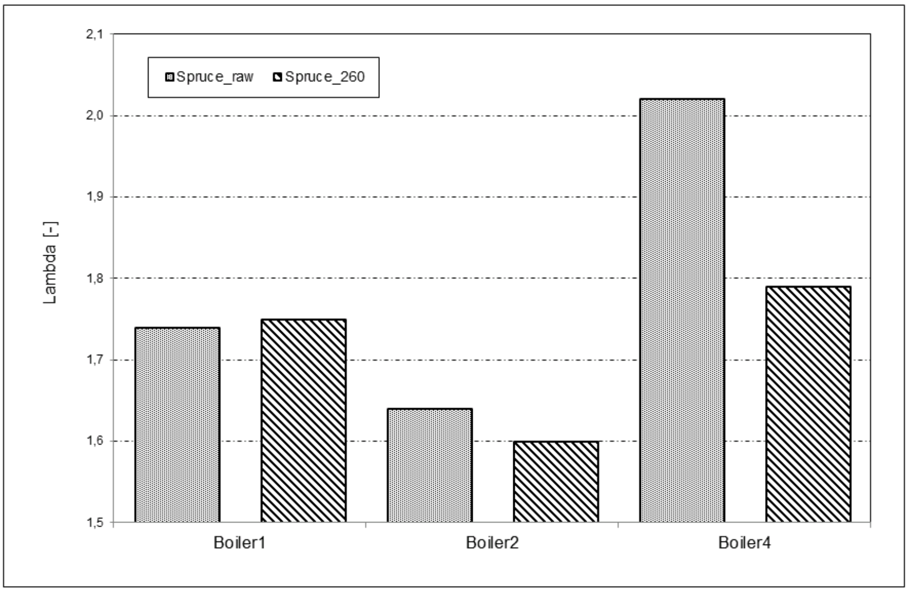


Figure 29: Comparison of the lambda values, full load operation.

The lambda of the tests operated with Boiler1 is almost the same during the tests with spruce_raw (1.74) and spruce_260 (1.75). The control system adapts the air supply. The control systems of Boiler2 and Boiler4 reduce the amount of excess oxygen by utilization with torrefied fuel. The lambda of Boiler2 is slightly less (0.04), so the combustion appliance reacts similar to the controlling of Boiler1 by adapting the air supply. The difference of the lambda ratio of Boiler4 is obvious, the value decreased 0.23. The appliance is not controlled by lambda, so there is no adaption of the air supply.

Table 27 compares the detected **emissions** during the screening of the combustion appliances with nominal load.

Table 27: comparison of emissions during the combustion tests.

Boiler	Fuel	CO	NO_x	PM	Lambda
		[mg/Nm³, 13%O_2]			[-]
1	Spruce_raw	5	139	17	1,74
	Spruce_260	65	131	18	1,75
2	Spruce_raw	39	112	10	1,64
	Spruce_260	39	109	15	1,60
3	Spruce_raw	16	133	17	1,72
	Spruce_260	22	129	16	1,48
4	Spruce_raw	62	134	12	2,02
	Spruce_260	135	126	26	1,79

According to chapter 2.1, the **temperature** is measured on the grate. Despite more than one thermo couple is used, it is not possible, to identify the exact temperature. The behaviour of the fuel in the combustion chamber is not stable. Due to inhomogeneity, air supply, heat radiation and so on, the hot spots can change their locations. Figure 30 shows the view inside the combustion chamber of Boiler1 during the utilization with torrefied fuel. There are differences with regard to the turbulence of the flames and the position of the glowing particles in the fire bed. One of the installed thermo couples (grate temperature 2) covered with ceramic is visible (top right).

Figure 30: Combustion chamber of Boiler1 during the experiment with spruce_260.

In addition to the inhomogeneity on the grate, the measured temperatures are influenced by the height of the fire bed and the coverage of ash. At the beginning of the experiment, the auger feeds the fuel into the combustion chamber. As soon as the ignition process is finished, the fire bed is getting higher and all temperatures rise. The grate temperature 1 drops, after the thermo couple (located 3 cm above the grate) is covered with fuel or ash. The location of the thermo couple measuring grate temperature 2 is 7 cm above the grate. The temperature rises higher and drops later. The thermo couple which detects the grate temperature 3 is located 6 cm above the grate, the measurement point however is at the outer edge of the grate. Therefore, it shows a temperature increase even later. For the further evaluation of the grate temperature, the grate temperature 2 is taken into account.

Figure 31 shows the temperature range on the grate and inside the combustion chamber during an experiment before the first ash removal. The grate temperatures of boiler1, boiler2 and boiler3 rise during the operation with torrefied fuels in comparison to the operation with wood pellets. The highest temperature difference is generated on the grate section of boiler2 (94°C) and boiler1 (79°C). The average grate temperature of boiler3 rises 47°C. Only boiler4 reduces the boiler temperature during the operation with torrefied fuel. The difference between the average temperature generated by spruce_raw and spruce_260 is 158°C. The locations of the temperature measurement differ, only the experiments operated in the same combustion appliance are comparable. By considering the temperature difference as an assessment parameter (instead of the absolute value), the choice concerning the location of the thermo couple does not affect the evaluation.

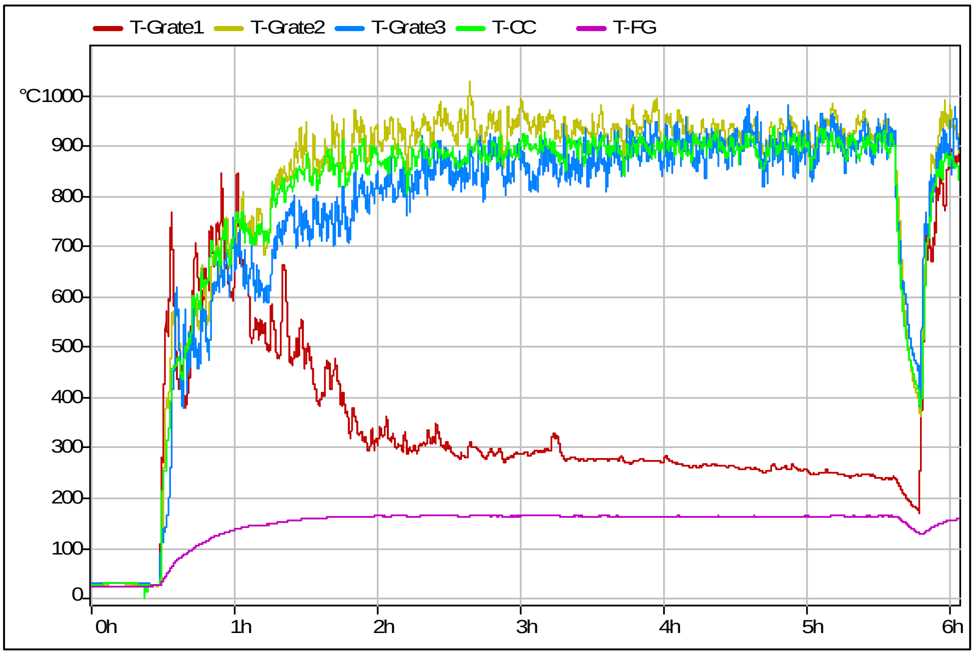


Figure 31: Temperature range within one cleaning interval, fuel spruce_raw operated in Boiler1 (time scale in hours).

Figure 32 compares the average grate temperatures of spruce_raw and spruce_260 utilized in all combustion technologies. The temperature range inside the combustion chamber is summarized by Figure 33. In direct comparison of the temperature range during the experiments with spruce_raw and spruce_260, boiler1, boiler2 and boiler3 show similar values. Boiler1 has the lowest temperature difference with only 4°C, followed by boiler2 (12°C) and boiler4 (14°C). These 3 values are negligible with regard to the high absolute values. Boiler3 however shows an increased temperature range of torrefied fuel compared with wood pellets. The difference is 139°C.

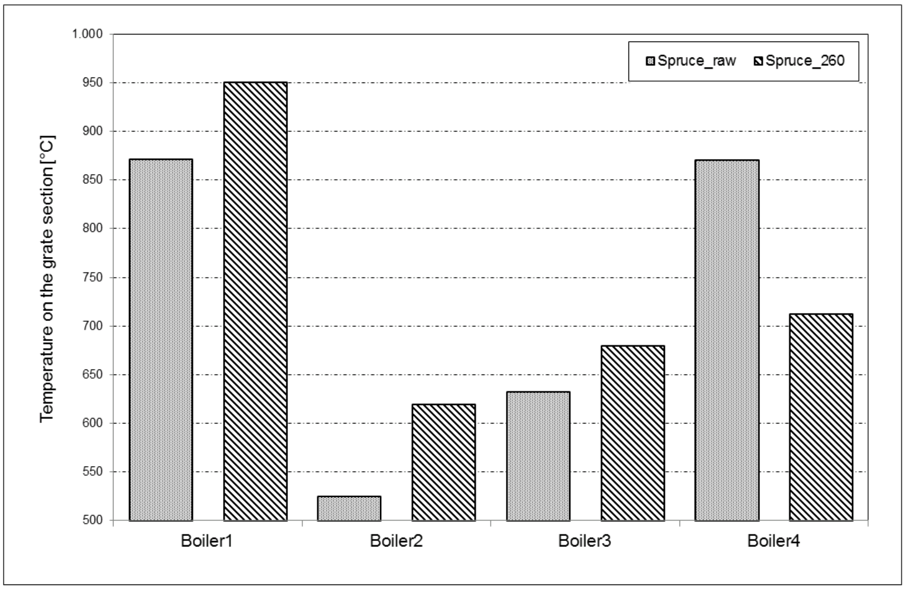


Figure 32: Grate temperatures of the tests with spruce_raw and spruce_260.

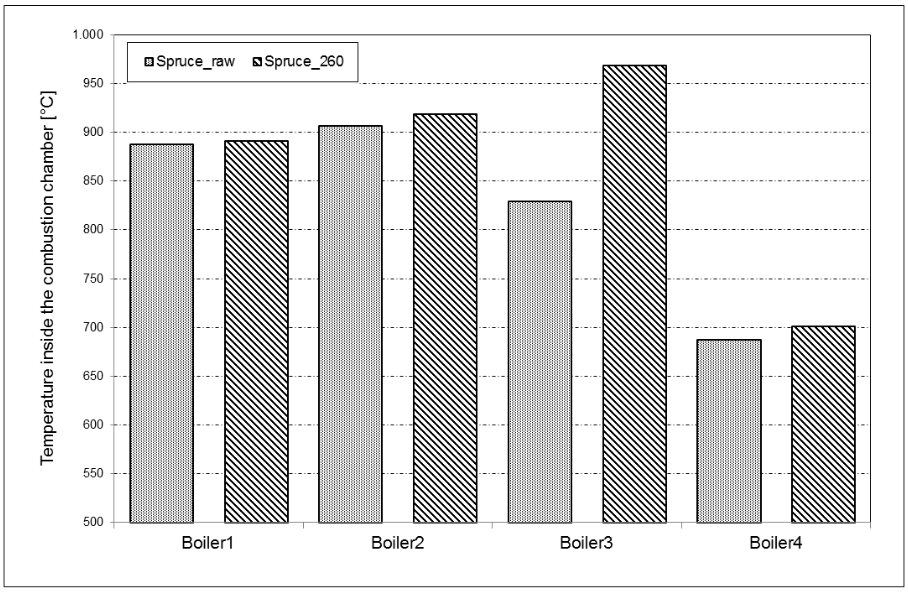


Figure 33: Temperatures inside the combustion chamber of the tests with spruce_raw and spruce_260.

Thus, the evaluation of the temperature on the grate and inside the combustion chamber show a similar behaviour of the combustion appliances boiler1, boiler2 and boiler4, which had increasing temperatures on the grate section during the operation with torrefied fuel, while the temperatures inside the combustion chamber were almost comparable with the values during the operation with wood fuel. According to chapter 2.3, a share of the volatile compounds is released during the torrefaction process. Therefore, the share of carbon, which is combusted during the char burn out phase, increases. The energy output at the grate and also the local temperature rise. Boiler3 however show similar temperature values concerning grate section with only a slight rise, and increasing temperatures inside the combustion chamber. This behaviour is most probably due to the control system. Since the combustion appliance is a prototype, the development is not finished so far. The temperature inside the secondary combustion chamber of the other combustion appliances is comparable with the values during the combustion of wood pellets. The differences concerning temperature range on the grate confirm the different combustion behaviour of the torrefied fuel and the changed processes in terms of primary and secondary combustion.

The **efficiency** of the combustion appliances is determined based on the energy input which is calculated by the heat losses (indirect method). The results are summarized by Table 28. In all boilers the tests operated with spruce_260 have a slightly higher efficiency in comparison to Spruce_raw. The highest efficiency-benefit is reached by Boiler4 (1%). Despite of the differences concerning heat output and NCV, the efficiency increase of Boiler1 is only 0.03%. Thus, the efficiency depends strongly on the control system of the combustion appliance respectively. The temperature controlled system shows a higher efficiency than the lambda controlled systems.

Table 28: Efficiency [%]

	Spruce_raw	Spruce_260
Boiler1	90.48	90.51
Boiler2	93.45	93.99
Boiler4	91.54	92.54

Table 29 shows the resulting factors. The different combustion behaviour of torrefied fuel in comparison to wood pellets is quantified. The table allocates the respective deviations of the single assessment parameters. Concerning the temperatures, the differences of two combustion appliances is enormous. Boiler4 has the highest deviation in terms of grate temperature (158°C) and boiler3 has the maximum difference concerning temperature inside the combustion chamber (139°C). Boiler4 also has the lowest oxygen factor (0.96), which means the highest deviation in comparison to the lambda of wood pellets. The highest heat output factor (1.09) is reached by boiler1. The comparison shows, that there are several differences in terms of combustion behaviour of torrefied fuel, however, the way of deviation depends on the combustion technology.

Table 29: Comparison of the resulting factors.

	Grate Temperature Difference [°C]	CC Temperature Difference [°]	Oxygen Factor	Heat output Factor
Boiler1	79	4	1.02	1.09
Boiler2	94	12	0.97	1.06
Boiler3	47	139	0.94	1.04
Boiler4	158	14	0.96	1.03

5.2 Reaction of control on subsequent fuel change

These experiments give information about the response of the boilers on an immediate change of fuel during the combustion process. Figure 34 shows the combustion parameters during a combustion test which was utilized with spruce_raw first. After 9 hours, torrefied fuel (spruce_260) was filled in the storage. This part of the developed testing method enables an observation of the reaction of the control strategies of all tested combustion appliances on the different fuel properties, with focus on the CHO-ratio and the NCV. The behaviour of the controlling system is monitored directly. The investigation requires stable conditions by the utilization of standardized wood pellets.

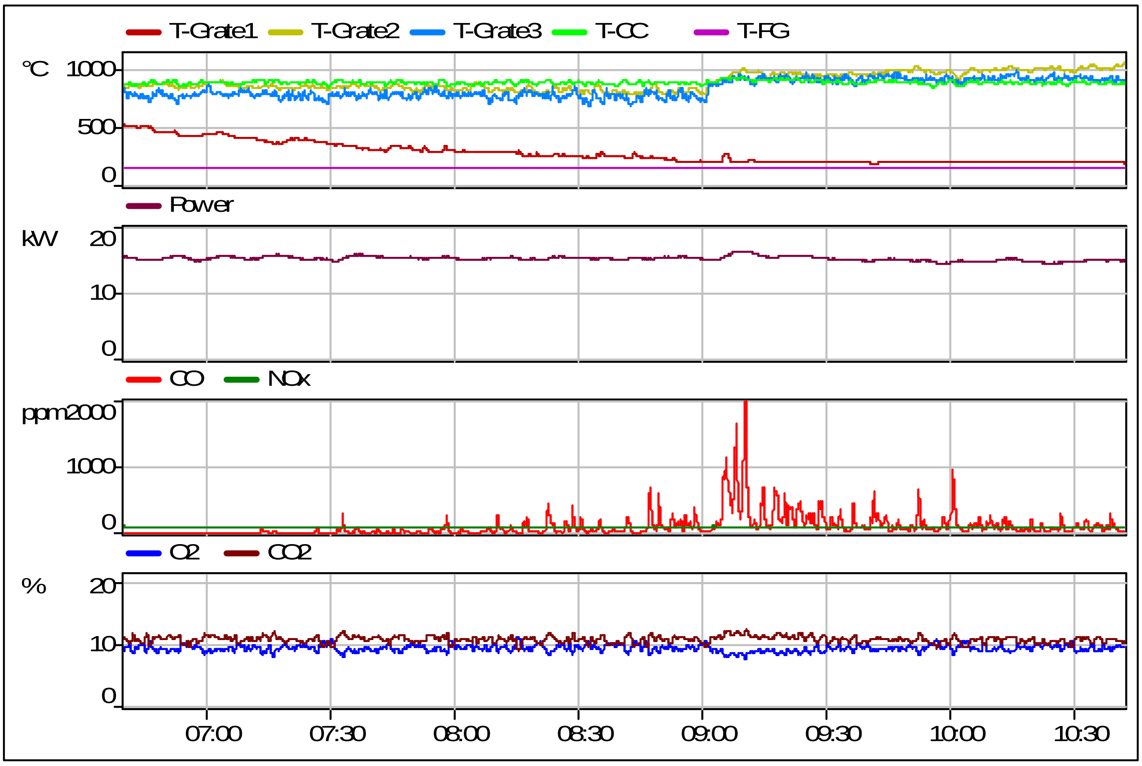


Figure 34: Combustion test started with spruce_raw and continued with spruce_260 in boiler1 (time scale in hours].

Table 30 gives an overview about the respective reaction of the combustion appliances on the subsequent fuel change. As first reaction, most of the boilers have in common the high CO release and the drop of the excess oxygen. This is due to the changed fuel properties. The amount of air supply is not sufficient for torrefied fuels and the combustion controls react slowly. After some time, the boilers were adapted to the torrefied fuel and generate higher temperatures on the grate.

Table 30: Overview about control strategies and reaction on the fuel change.

Boiler	Combustion control	Power control	First reaction	Long-term reaction
1	lambda-probe controls fuel feed	Boiler temperature regulates ID-fan speed	CO-peaks, rise of grate temperature, drop of excess O_2-content in flue gas	Temperatures at the grate higher than before, heat output dropped, CO emissions slightly higher
2	ID fan controls underpressure	Boiler temperature regulates fuel feed	Increase of heat output and grate temperatures, reduction of excess oxygen, co peaks	No CO-peaks anymore, heat output and grate temperatures steady
3	Boiler is equipped with lambda-probe, control system is not developed so far, adaption of parameters (fuel feed, speed of auger burner, air supply) by operator		Increase of temperature inside the combustion chamber, power increase, excess oxygen drops	High CO release, heat output and temperature (CC) higher
4	Defined mount of air supply	Temperature inside the combustion chamber controls fuel feed	Initially no notable changes	Excess oxygen drops

5.3 Comparison of control strategies

For the investigation of the tendency of combustion parameters during the testing duration of 24 hours, the combustion tests utilized with spruce_260 in the respective boilers are split in four phases. These phases are chosen during steady conditions of the combustion appliances, so the start-up and burn out phases as well as the ash removal procedure were not considered. The distribution of the single phases is during the overall testing duration.

The behaviour of the combustion appliance is evaluated focused on the parameters heat output, excess oxygen, temperature range inside the combustion chamber and CO release.

The decrease of the heat output and the increase of excess oxygen indicate a failure during operation longer than 24 hours. However, the deviations are most probably caused by the control strategy of the boiler and can be optimised for the utilization of torrefied fuels in the future. Table 31 gives an overview on the combustion parameters during the test with boiler1.

Table 31: Tendency of combustion parameters, Boiler1.

Boiler1	Excess oxygen [vol.-%]	Lambda [-]	Heat output [kW]	Temperature Combustion Chamber [°C]
Phase 1	8,79	1,71	16,26	887
Phase 2	9,05	1,74	16,32	893
Phase 3	8,92	1,72	16,34	881
Phase 4	9,23	1,77	16,04	897
Phase 5	9,53	1,82	15,87	899

The excess oxygen rises from 8.79 to 9.53 vol.-%, and the temperature rises slightly from 887 to 899°C. The heat output drops from 16.3 to 15.9 kW. Corresponding to the rise of the CO release (chapter 4.3), the combustion behaviour was stable during the first 3 phases and deteriorated in phase 4. Due to the increasing lambda value, the control reduced the fuel feed and the heat output decreased. The rise of the excess oxygen in addition to the higher CO release suggests an incomplete combustion process caused by the too short residence time of the fuel on the grate. Without adaption, the control strategy of boiler1 is not suitable for a long term utilisation of torrefied fuels.

Table 32 shows the combustion parameters of single phases during the operation of Boiler2 utilized with spruce_260. The excess oxygen increased only slightly, finally the value is 0.1 vol.-% higher. The temperature inside the combustion chamber dropped. The average temperature decreased, the difference was 15°C. The heat output did not show a tendency during the 24 hours testing duration, the value first dropped and then rose again. The control system reacted on the different fuel properties by reducing the fuel feed (from 129% during the operation with spruce_raw to 116% during the operation with spruce_260) due to the higher boiler temperature generated by the higher NCV of the fuel. The ID fan reduced the speed (from 34.9 to 33.5) in order to keep the required under pressure (0.196 mbar). In terms of control strategy, boiler2 was suitable for the utilisation of torrefied fuels.

Table 32: Tendency of combustion parameters, Boiler2.

	Excess oxygen [vol.-%]	Lambda [-]	Heat output [kW]	Temperature Combustion Chamber [°C]
Phase 1	7.9	1.59	17.2	927
Phase 2	7.9	1.60	16.8	917
Phase 3	7.9	1.60	16.7	910
Phase 4	8.0	1.61	17.4	916

The averaged combustion parameters of Boiler4 are summarized by Table 33. The excess oxygen dropped (9.6 to 9.2 vol.-%) and heat output (difference: 0.3 kW) as well as the temperature (13°C higher) increased during the testing duration. The higher NCV of the torrefied fuel generated a higher temperature inside the combustion chamber. Due to the lower content of oxygen in the fuel, the excess oxygen in the flue gas and, therefore, the lambda value, decreased. The control strategy is not equipped with a lambda probe, thus, the amount of air supply is not adapted.

Table 33: Tendency of combustion parameters, Boiler4.

Boiler4	Excess oxygen [vol.-%]	Lambda [-]	Heat output [kW]	Temperature Combustion Chamber [°C]
Phase 1	9.6	1.83	11.3	690
Phase 2	9.5	1.81	11.4	699
Phase 3	9.3	1.77	11.6	713
Phase 4	9.2	1.76	11.6	703

The overall tendencies of Boiler1, Boiler2 and Boiler4 are summarized by Table 34. During the operation of the combustion appliances with torrefied fuel, there is a clear difference between the reaction of the single control systems respectively. It makes a big difference, whether the fuel feed is the actuating variable for the control, regulated on the temperature of the boiler (boiler2) or the combustion chamber (boiler4). In case the fuel feed is controlled by lambda (boiler1), the heat output of the combustion appliance decrease despite of the higher NCV of the fuel.

Table 34: Tendency of the combustion parameters during the experiments with spruce_260.

	Lambda [-]	Heat output [kW]	Temperature Combustion Chamber [°C]
Boiler1	↑	↓	↑
Boiler2	↑	↕	↓
Boiler4	↓	↑	↑

These tendencies give an outlook to a long term operation and the behaviour of the combustion appliances after the investigated testing duration of 24 hours. The long-term combustion tests are investigated within the same Task 7.4 of the SECTOR project. The project partner TFZ will run several experiments in its testing facility.

5.4 Assessment of the residues

The residues, especially the formed bottom ashes, are investigated in order to detect agglomerations or slagging caused by higher grate temperatures or a too long residence time of the fuel on the grate. The cleaning interval was set to 300 minutes. During the experiments with the test fuels forest_residues and poplar_270, it was required to reduce the cleaning interval to 120 minutes due to the higher ash content of the fuels.

The bottom ashes of spruce_raw and spruce_260 are in terms of amount and condition comparable. Also the ash amount of pine_270 has a similar value, beside the high amount of formed deposit at the heat exchanger. The mass of bottom ash of the test with poplar_270 is slightly more, however the ash formed during the utilization of forest_residues is almost 10 times higher in comparison to the bottom ash of spruce_raw. After the experiment duration of 24 hours the ash collecting box was almost full.

The differences are caused by the different raw material quality. The fuels spruce_raw, spruce_260 and pine_270 are made of wood with low ash content. The main raw materials of forest_residues were bark and leaves. Table 35 summarises the amounts of the residues.

Table 35: Summary of the residue masses, full load conditions, Boiler1.

Mass of the residues [g ash/kg fuel]	Spruce_raw	Forest_residue	Spruce_260	Pine_270	Poplar_270
Grate ash	1.19	1.23	2.03	1.33	0.80
Bottom ash	1.82	17.40	1.49	2.01	3.94
Deposit heat exchanger	0.47	0.64	0.68	1.05	0.26

The amounts of residues on the grate and inside the combustion chamber are comparable. After the experiments with boiler1, boiler2 and boiler4 were finished, the respective combustion chamber was covered with soot. This coverage did not occur during the tests with spruce_raw. Figure 35 shows the cover of the combustion chamber of boiler2 behind the opening door.

Figure 35: Soot-covered surfaces inside the combustion appliance (Boiler2)

Figure 36 shows the combustion chamber of boiler1 before and after the utilization of torrefied fuel. After the combustion test with spruce_raw, the chamber was slightly covered with ash. It was possible, to remove the formed ash and residues by a brush. So the residues did not agglomerate on the refractory lining. After the experiments with spruce_260, however, it was not possible to remove the deposits completely. The agglomerations inside the combustion chamber accumulated on the fire clay. This deposit is not caused by temperature, since the range inside the combustion chamber is comparable to the temperature range during the utilisation of wood pellets (see chapter 5.1). The agglomerations are most probably caused by the properties of the fly ash formed during the experiments with torrefied fuel. The formation of fly ash comes along with incomplete combustion and therefore, a too short residence time in the primary combustion zone, e.g. on the grate (see also chapter 4.3) and too less oxygen available for the primary combustion process.

Figure 36: Combustion chamber of boiler1 after the operation with spruce_raw (left) and spruce_260 (right).

Figure 37 shows the combustion chamber of boiler4. After the experiment with spruce_raw, there were minor residues, easy removable by a brush. After the tests operated with spruce_260, the combustion chamber was dark coloured and covered with fly ash deposits, similar to the observations made at boiler1.

The mass of bottom ash of forest_residues was ten times higher than the bottom ash of spruce_260 and spruce_raw. The amount of accumulated residue at the heat exchanger was higher by operating the boiler with forest_residues. This deposit might be the reason for the power decrease during the experiment.

Figure 37: Combustion chamber of boiler4 before(left) and after (right) the operation with spruce_260.

Figure 38 shows a sample of the bottom ash of spruce_raw. In terms of the dark brown colour and consistency the ash was similar to potting soil. There were some smaller agglomerations (category 2a) which were unstable and easily breakable by a light touch.

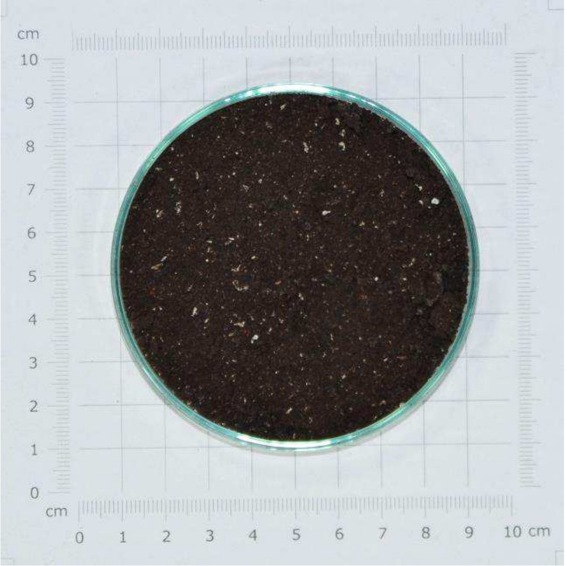


Figure 38: Bottom ash spruce_raw, investigated in Boiler1 as reference.

Figure 39 shows sample of the bottom ashes of the torrefied test fuels forest_residues and spruce_260. The ash of forest_residues had lighter colour asphalt grey with a slight green cast. There were some small and instable agglomerations (category 2b). The bottom ash of spruce_260 is less agglomerated (category 2a) and the colour was similar to the ash of spruce_raw. However, there were red coloured exfoliations in the ash tray, most probably corrosion particles, which are not directly correlated with the use of a torrefied fuel.

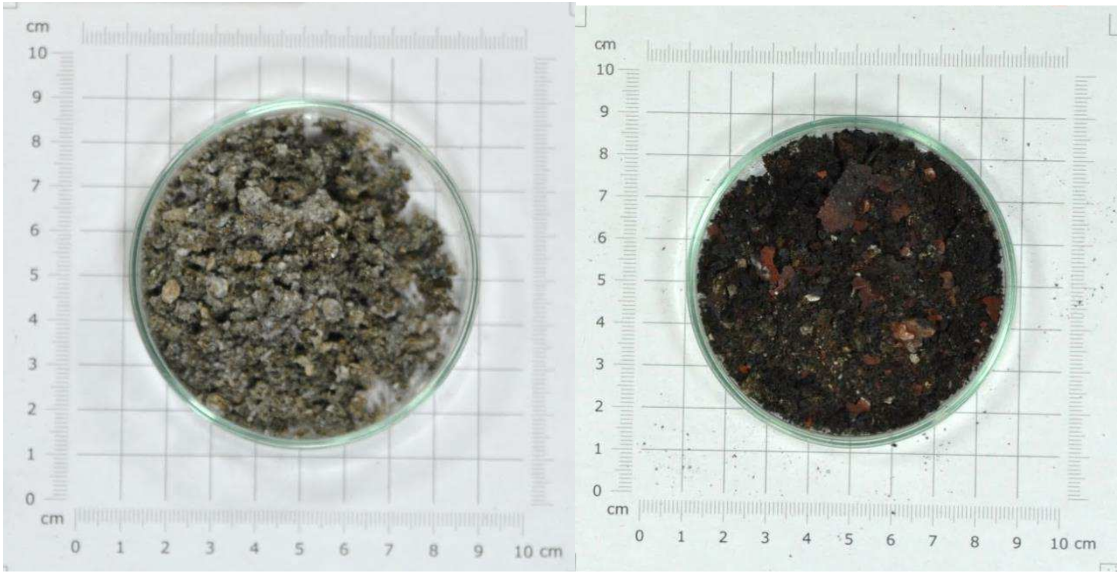


Figure 39: Bottom ash of Fuel forest_residues (left) and spruce_260 (right) in Boiler1.

Figure 40 shows the bottom ashes of pine_270 and poplar_270. The ash of pine_270 was dark grey and showed less agglomerations. These agglomerations were breakable at a light touch (category 2a) and the consistence was close to spruce_raw. The ash of poplar_270 was similar to forest_residues concerning the colour, also there were even more agglomerations (category 2b).

Figure 40: bottom ash of pine_270 (left) and poplar_270 (right), both investigated in Boiler1.

Figure 41 compares the bottom ash of the spruce_260 combusted in different boilers. The left picture shows the ash after the test with boiler3. The material mainly consisted of unburnt material, so the residence time on the grate was too short. The right picture shows the ash of the same fuel, operated in Boiler4. The colour was dark grey, there were no agglomerations (Category 1).

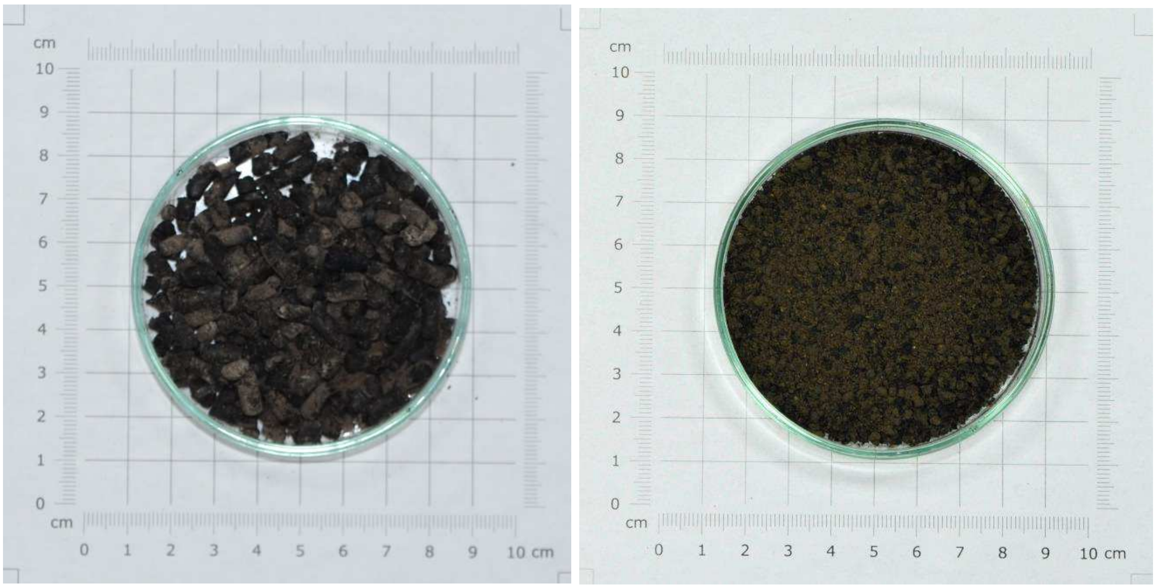


Figure 41: Bottom ash of spruce_260, investigated in Boiler2 (left) and Boiler4 (right).

Figure 42 shows two ash samples of the same test fuel (spruce_260) investigated in the same combustion appliance (Boiler3). The bottom ash of the first experiment (left) was operated without any modifications. Similar to the bottom ash of this fuel, investigated in boiler2, the residence time was too short and the high content of unburnt material is obvious. The test was repeated and the residence time of the fuel on the grate was extended by an adaption of the auger speed. The picture on the right hand shows the bottom ash after this test and the content of unburnt material was evidently much less. There were no agglomerations (category 1), the ash had a dark colour similar to spruce_raw.

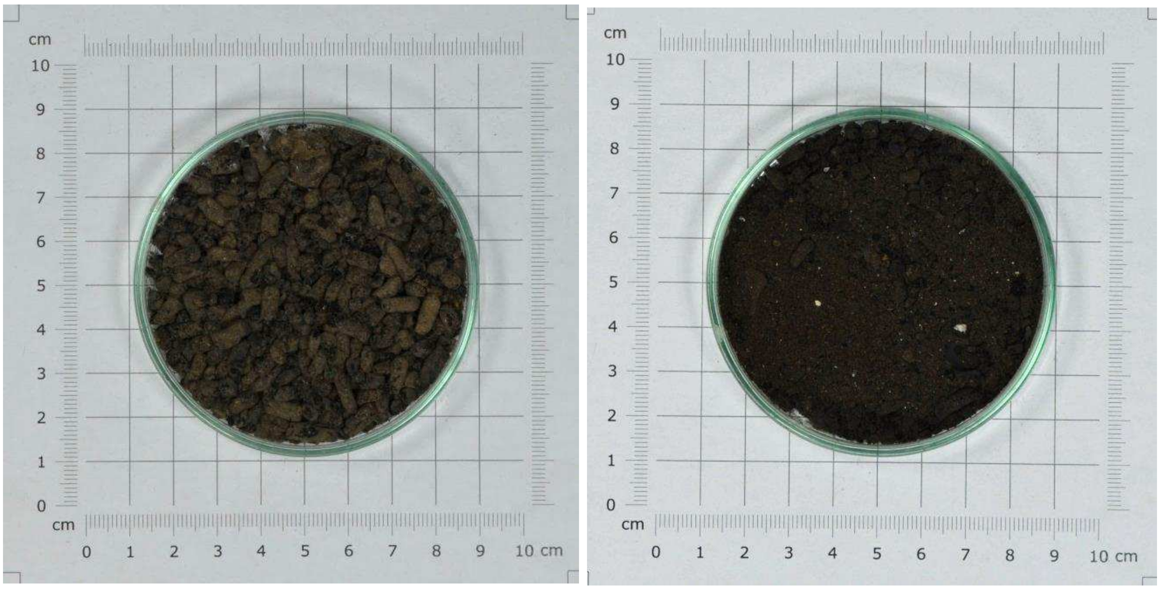


Figure 42: Spruce_260 investigated in Boiler3 without modifications (left) and with adapted settings and a longer residence time on the grate (right).

In order to assess the particle size distribution as well as the mechanical stability of the agglomerations, a granulometric analyses of the bottom ashes (Boiler1) was conducted. Table 36 summarizes the mass shares of the single fractions. Figure 43 shows the resulting particle size distribution.

Table 36: Sieving residues determined by granulometric analysis, Boiler1.

Share of mass [%]	Spruce_raw	Forest_residues	Spruce_260	Pine_270	Poplar_270
> 3.15 mm	2.3	0.4	2.5	6.7	1.8
> 2.0 mm	2.0	14.8	19.9	10.0	1.8
> 1.0 mm	15.4	37.9	25.3	22.7	36.7
> 0.5 mm	28.0	22.5	12.6	21.4	29.2
< 0.5 mm	52.0	24.4	40.4	39.2	30.5

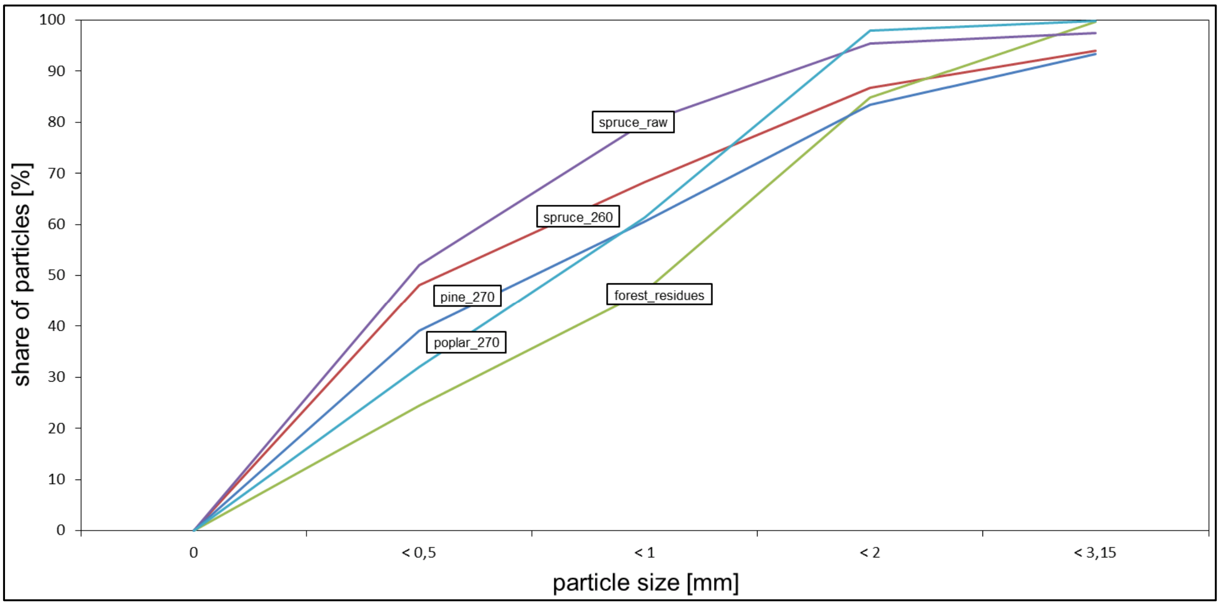


Figure 43: particle size distribution of the residues.

The size distribution of the bottom ash for torrefied and non-torrefied spruce fuel was very uniformly.. They showed also similar average particle sizes d_{50} (spruce_raw: 0.48 mm and spruce_260: 0.55 mm). The d_{50} of the fuels pine_270 (0.75 mm) and poplar_270 (0.80 mm) were close as well, however the ash of pine_270 had a higher share of particles with size bigger than 2 mm (10 wt.%) and bigger than 3.15 mm (almost 7 wt.%). Forest_residues had the biggest d_{50} particle size (1.1 mm). Considering the results of the fuel analyses, there was a clear correlation of the ash content of the test fuels and the respective d_{50} particle size of the formed ash.

5.5 Fuel assessment trials

After all boilers were investigated with spruce_raw and spruce_260, Boiler1 was used for further experiments with different torrefied fuels. This section compares the stable conditions of the combustion experiments. Analogous to chapter 5.1, the parameters which have to be considered are

- heat output of the combustion appliance,
- lambda ratio, based on the excess oxygen,
- emission release (CO, NOx, PM),
- temperature range (grate, combustion chamber) and
- energy efficiency

Table 37 overviews heat output and lambda values of the experiments with the five test fuels. During the tests, the lambda was in the range of 1.72 to 1.76. Only during the test with the fuel forest_residues a higher lambda (1.95) was set. The heat output of the experiments with spruce_raw and forest_residues was comparable (14.8 kW) despite of the higher NCV of forest_residues. This was caused by the power control of the boiler and the changed fuel composition due to the torrefaction process. The combustion technology was controlled by lambda. The excess oxygen content of the flue gas was too high (λ = 1.95), therefore, the fuel feed into the combustion chamber was decreased. This lead to a decrease in the heat output in comparison to the other torrefied fuels. The heat output of the other experiments operated with torrefied fuels were up to 16.2 kW (spruce_260), which is a significant increase in heat output in comparison with the non-torrefied fuel.

Table 37: Fuel assessment trials, Boiler1.

Fuel	Heat output [kW]	Lambda [-]
Spruce_raw	14.82	1.74
Forest_residues	14.80	1.95
Spruce_260	16.17	1.75
Pine_270	15.87	1.72
Poplar_270	15.10	1.76

Figure 44 shows the results of the evaluation of the emission release of all experiments investigated with Boiler1. During stable conditions, spruce_raw showed the lowest CO release in comparison to the other fuels. The emission of NO_X was comparable with spruce_260. Forest_residues showed significantly higher emissions of CO and NO_X. The PM emissions of spruce_260 and pine_270 were comparable to spruce_raw. Poplar_270 had a four times higher PM release. The PM emissions of the test with forest_residues were not determined. The high content of NO_X is due to the high nitrogen content in the fuel.

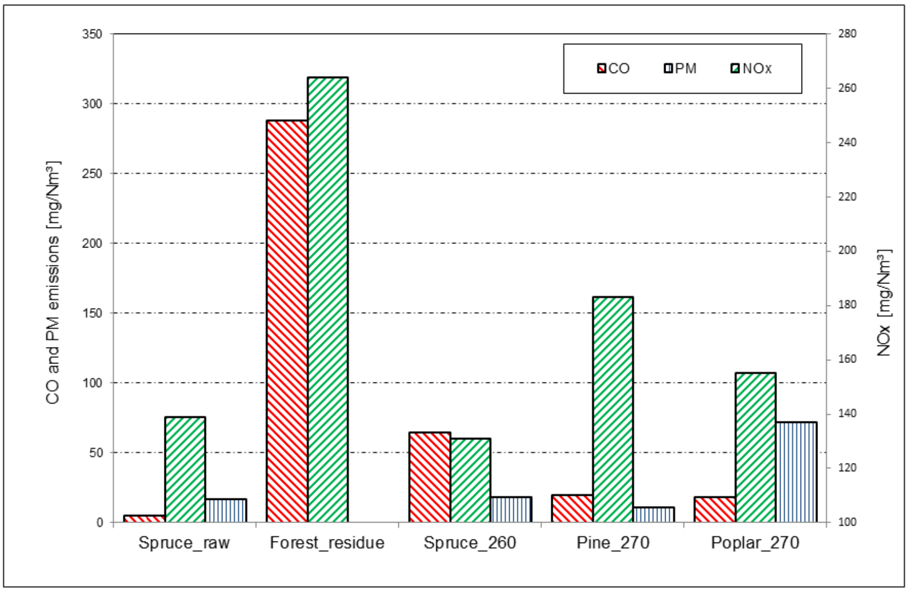


Figure 44 Comparison of emissions, full load conditions.

Table 38 summarizes the average and maximum temperatures detected during the combustion experiments. The average grate temperatures differed regarding average value and maximum value. The detected average temperatures on the grate showed higher values during the investigation of the torrefied fuels. Forest_residues (1050°C), pine_270 (1128°C), poplar_270 (991°C) and spruce_260 (950°C) reached average temperatures of approximately 1000°C. The highest average grate temperature of spruce_raw was 880°C.

Table 38: Temperature range on the grate area [°C].

	Average values			Standard deviation			Maximum
	Grate 1	Grate 2	Grate 3	Grate 1	Grate 2	Grate 3	Grate
Spruce_raw	363	871	880	144	52	48	1054
Forest_residues	187	1050	873	80	130	139	1219
Spruce_260	630	950	947	15	20	30	1031
Pine_270	309	934	1128	58	29	n.a.	1023
Poplar_270	331	n.a.	991	63	n.a.	27	1046

Regarding the highest measured temperature on the grate during the single experiments, there was a difference between ash rich fuels and fuels with less ash content. Both fuels with high ash content generate grate temperatures of 1219°C (forest_residues) or even higher (poplar_270). The temperatures of the other torrefied fuels were comparable (1031°C during the experiment with spruce_260 and 1023°C with pine_270). During the experiment with spruce_raw, the highest temperature value measured on the grate was 1054°C.

In general, the temperature range showed that fuels made of ash rich biomass raw material cause a higher maximum temperature during the primary combustion. This deviation was indicated by different combustion behaviour and the higher energy density in comparison fuels with low ash content. In addition, the torrefaction process concentrated the content of ash. A share of the volatile compounds was released during the torrefaction process. Therefore, the share of carbon, which is combusted during the char burn out phase, increases. The energy output at the grate and also the local temperature increases.

The thermo couple measuring the temperature inside the combustion chamber was located approximately 45 cm above the grate. The temperature was comparable with the values during the combustion of wood pellets. Table 39 shows the average and maximum values as well as the standard deviation of the temperature measurement inside the combustion chamber. The temperatures inside the combustion chamber are similar and all in the range of 884 to 906°C (only 22°C difference). Also the maximum temperatures inside the combustion chambers (919 to 943°C) and the standard deviations (11 to 20°C) were close. This indicates an overall similar heat release and dissipation to the heat exchanger for the combustion of torrefied and non-torrefied materials. Thus the combustion chamber is able to cope with the different energy release of torrefied and non-torrefied fuels.

Table 39: Temperature range inside the combustion chamber [°C].

	Average values	Standard deviation	$Tcc,_{max}$
Spruce_raw	887	14	931
Forest_residues	891	20	935
Spruce_260	891	14	930
Pine_270	884	11	919
Poplar_270	906	18	943

Table 40 summarizes the energy efficiency of the tested boiler – fuel combinations. The influence of the boiler technology on the energy efficiency is significantly higher, than the fuel applied. The slightly lower energy efficiency of the fuel forest_residues might be because of the increased ash content. In boiler1 the highest energy efficiency was found to occur with poplar_270. However, the difference is not very significant, which leads to the conclusion, that torrefied fuels have no influence on the energy efficiency of a small scale combustion appliance.

Table 40: Energy efficiency[%].

	Spruce_raw	Forest_residues	Spruce_260	Pine_270	Poplar_270
Boiler1	90.48	88.61	90.51	89.98	91.66
Boiler2	93.45		93.99		
Boiler4	91.54		92.54		

5.6 Part load operations

In addition to the combustion tests with nominal load, experiments with part load conditions were operated. Objective of this part was the investigation of the emission release; therefore the testing duration was reduced to 3 hours respectively. Table 41 gives an overview of the efficiency, the CO emissions and lambda value.

Table 41: Comparison of the emissions, part load operation (30%).

	Efficiency [%]	CO [mg/Nm³, 13% O2]	Lambda [-]
Boiler1, spruce_260	95,98	88	1,75*)
Boiler1, pine_270	94,93	101	2,41
Boiler1, poplar_270	94,90	140	2,42
Boiler2, spruce_260	95,34	26	2,02
Boiler4, spruce_260	94,01	345	2,89

*) heat output was reduced by ID (instead of reduction by load cycling with heat consumption)

During the part load operations, the boilers reached a higher efficiency in comparison to the efficiency of the boilers during nominal load conditions (see Table 28). The reduction of the heat output enabled most probably a longer residence time of the fuel on the grate and a higher burn out rate. The CO emissions of Boiler1 were several times higher than the emissions during nominal load operation. Boiler4 generated 2 to 3 times more CO emissions. Only Boiler2 reduced the CO release during the part load operation. The excess oxygen ratio was higher. The highest value showed boiler4 which was not controlled by lambda probe.

However, the testing duration of 3 hours is less significant, since the tendencies during the nominal load experiments also detected different combustion behaviour during 24 hours of operations, especially with regard to the CO emissions.

6 Conclusions

The torrefaction changes the properties of the fuels. The content of moisture and volatile compounds is reduced. The combustion behaviour of torrefied fuel differs with regard to the steps of a combustion process, since drying does not require a long time, however the gasification as well as the burn out of combustion char takes much longer in comparison to the utilisation of the small scale appliances with wood fuels. The equilibrium deviates concerning the longer residence time of the fuel on the grate. A too short residence time leads to a high amount of unburnt material in the bottom ash and therefore, to a decreased energy efficiency. Furthermore the end-customer is disturbed by having unburnt residues in the ash box, which might cause warranty claims.

The volatile compounds affect the combustion behaviour especially during the ignition and start-up phase. The char burnout of the fuel takes longer and the required residence time on the grate may increase. Additionally, the changed content of VOC changes also the elemental composition (particularly the CHO-ratio) of the fuel. Therefore, the air demand for a stoichiometric combustion changes as well. The oxygen supply depends on the control strategy of the boiler. Since most of the combustion appliances are controlled by lambda-probe, excess oxygen and heat output are not optimised during the operation of the boiler with torrefied fuels. The respective requirements of primary and secondary air supply change. Caused on the higher content of carbon and the increased residence time due to the combustion char, a higher share of primary air might be necessary. Furthermore higher emissions are possible due to the non-optimal distribution of primary to secondary air.

In general, it is possible to operate the combustion of torrefied material in standard pellet boilers. The combustion behaviour however depends strongly on the raw material which was torrefied and on the combustion technology. Mainly the control strategy, but also the ash removal solution, influence the combustion behaviour of the modified raw material.

Depending on the combustion appliance, torrefied pellets can be combusted without adjustment or modifications when the original material was biomass with a low content of ash. Torrefied pellets from an ash richer material require an adjustment of the ash removal settings. The emission release (CO, NO_x and PM) depends on the raw material as well.

The temperature on the grate area is slightly increased in comparison to the combustion of wood pellets. Depending on the combustion technology, the high temperature can lead to agglomerations on the grate or slagging but also a higher probability of scaling on the grate.

In order to investigate the corrosion load on chimneys, a standard testing method was developed. The corrosion risk of torrefied fuel combustion was found to be very similar to the combustion of wood fuels. The main influencing parameter is still the fuel composition and therefore the quality of the raw material.

According to the “description of work” of the SECTOR project, the tasks of BE2020 were the operations of three different small-scale combustion technologies. In addition, a prototype boiler was investigated. The investigated technologies differ also in terms of the control strategy, so it is possible to make a statement about the combustion behaviour of torrefied fuel in appliances which varies feeding and ash removal system, air supply, control strategy as well as the material and the area of grate and combustion chamber. The second task was to run fuel assessment trials with up to five different fuels with particular focus on start-up procedures and start-up emissions. Additionally, the burn-out behaviour was investigated and differences were discovered.

The combustion experiments were utilized in small scale appliances which are authorised only for the application of standardized wood pellets. Although the application with torrefied fuels turned out to be possible, it is not permitted to operate the heating systems with fuel which is not certified according to the instruction manuals of the boiler manufacturer.

7 Outlook

The procedure for standardizing the properties of torrefied fuels is already in progress. As soon as the chemical and mechanical properties are defined, it is necessary to adapt the small-scale appliances in order to ensure the applicability. Especially the materials of grate and combustion chamber have to be considered due to a higher temperature range. By an adaption of the control system, the combustion behaviour has to be approved. In particular, the settings of the control system of the combustion appliances have to be optimised in order to define the distribution of primary and secondary air supply and the residence time of the fuel on the grate. Therefore, additional research is needed.

8 References

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9 List of figures

10 List of tables

11 Appendix A

The appendix summarizes the methods and results of the laboratory analysis operated at the facilities of BE2020.

Table 42: Analysis methods and applied standards

parameter(s)	Number of standard	title	publication
ash content	ÖNORM EN 14775	Solid biofuels - Determination of ash content	15.11.2012
Al, Ba, Ca, Fe, Mg, P, K, Si, Na, Sr and Ti	ÖNORM EN 15290	Solid biofuels - Determination of major elements - Al,Ca.Fe,Mg,P,K,Si,Na and Ti	01.04.2011
As, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, V and Zn	ÖNORM EN 15297	Solid biofuels - Determination of minor elements - As,Cd,Co,Cr,Cu.Hg,Mn,Mo,Ni,Pb,Sb,V and Zn	15.04.2011
C, H, N	ÖNORM EN 15104	Solid biofuels - Determination of total content of carbon, hydrogen and nitrogen - Instrumental methods	01.04.2011
S, Cl	ÖNORM EN 15289	Solid biofuels - Determination of total content of sulfur and chlorine	01.04.2011
TIC	ÖNORM EN 13137	Characterisation of waste - Determination of total organic carbon (TOC) in waste, sludges and sediments	01.12.2001
Volatile matter	ÖNORM EN 15148	Solid Biofuels – Determination of the content of volatile matter	15.12.2009

12 Appendix B

Table 43: Combustion parameters during stable conditions

Boiler	Fuel	Heat output [kW]	Efficiency [%]	O_2 [vol.-%]	CO [mg/Nm³]	NO_X [mg/Nm³]	PM [mg/Nm³]	T Grate [°C]	T (CC) [°C]
1	Spruce_raw	14,82	90,48	8,94	5	139	17	871	887
1	Forest_residues	14,80	88,61	9,89	288	264	n.a.	1050	891
1	Spruce_260	16,17	90,51	9,10	65	131	18	950	891
1	Pine_270	15,87	89,98	8,90	20	183	11	934	884
1	Poplar_270	15,10	91,66	9,17	18	155	72	991	906
2	Spruce_raw	16,05	93,45	8,36	39	112	10	525	906
2	Spruce_260	17,01	93,99	7,93	39	109	15	619	918
4	Spruce_raw	11,20	91,54	10,74	62	134	12	870	687
4	Spruce_260	11,47	92,54	9,43	135	126	26	712	701
3	Spruce_raw	33,53	92,01	8,82	16	133	17	632	829
3	Spruce_260	34,98	91,14	8,26	82	127	16	679	1027
3	Spruce_260	31,16	92,75	6,80	22	129	n.a.	633	968
1	Spruce_260	5,91	95,98	9,08	88	109	n.a.	877	662
1	Pine_270	4,48	94,93	12,37	101	163	n.a.	735	555
1	Poplar_270	4,63	94,90	12,42	140	138	n.a.	646	566
2	Spruce_260	5,42	95,34	10,61	26	104	n.a.	414	701
4	Spruce_260	3,79	94,01	13,78	345	122	n.a.	520	666

13 Appendix C

The appendix summarizes the results of the laboratory analysis operated at the facilities of BE2020.

Table 44: Laboratory analysis results, PM filters [mg/kg d.b.]

boiler	fuel	S	Cl	Al	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	P	Pb	Zn
1	Spruce_raw	63400	99600	< 3500	< 17400	< 30	< 348	558	2410	376000	< 3480	1590	11000	< 348	< 869	534	11800
1	Spruce_raw	60300	79000	< 3500	< 13900	< 30	< 279	461	2000	351000	< 2790	1480	9890	< 279	< 697	489	11600
1	Spruce_raw	43200	60100	< 3500	< 15400	< 30	< 309	343	2650	267000	< 3090	1200	< 7720	< 309	< 772	< 386	7980
1	Spruce_260	46300	49000	< 8000	8200	< 75	< 834	609	11000	348000	4120	3070	< 20900	< 834	3150	<1040	8640
1	Spruce_260	44900	123000	< 8000	10200	< 7	< 755	774	11000	446000	< 7550	3360	17000	< 755	3250	< 944	10800
1	Spruce_260	39000	85400	< 5000	< 24100	< 50	527	625	14900	354000	5220	3500	15300	< 482	3560	666	9490
2	Spruce_raw	92100	67100	< 700	< 3430	< 10	< 68.5	314	376	353000	< 685	758	6470	< 68.5	279	478	24400
2	Spruce_260	74100	38100	< 500	5110	< 5	164	461	3840	350000	956	1420	8940	< 46.1	1210	258	15700
2	Spruce_260	77700	41400	< 500	5800	< 5	164	441	4210	349000	1080	1450	9050	< 48.3	1290	267	16600
2	Spruce_260	72700	42800	< 500	7710	< 5	170	450	4810	350000	1390	1650	9150	< 45.8	1470	244	16900
4	Spruce_raw	70700	47100	< 700	14000	< 10	830	431	259	393000	1750	2740	8410	< 68.6	978	297	13700
4	Spruce_raw	58200	38000	< 700	12300	< 10	644	378	287	365000	1470	2440	7110	< 70.4	846	281	11200
4	Spruce_raw	71700	45100	< 700	15200	< 10	925	411	142	388000	1920	2970	7920	< 65.7	1050	315	14000
4	Spruce_260	65400	42700	< 700	9750	< 10	128	710	6210	377000	1900	3150	13900	< 62.6	2100	219	13100
4	Spruce_260	64200	42600	< 500	11400	< 5	171	734	6750	396000	2400	3310	14600	37	2300	238	13400
4	Spruce_260	51500	37000	< 500	46500	< 5	189	559	16700	304000	9070	7830	10800	50	7200	195	10600
3	Spruce_260	76700	154000	< 700	11800	< 10	12500	476	7790	325000	2360	3330	18400	144	8080	239	20500
3	Spruce_260	80300	147000	< 1000	13400	< 10	11300	484	8610	330000	2360	3270	18900	121	8380	247	18500
3	Spruce_260	80000	140000	< 700	11900	< 10	10000	506	7030	318000	2190	3160	17800	112	7540	238	18300
3	Spruce_260	83200	147000	< 700	11500	< 10	10100	499	6920	328000	2200	3200	18300	109	8170	244	19000
1	Pine_270	76200	33600	18433	46267	46	219	641	2343	320333	16500	3000	65267	< 106	2583	525	13867
1	Poplar_270	36900	12933	3143	6023	31	79	336	542	289333	2353	136	40933	< 15.4	272	220	7567

Table 45: Laboratory analysis results, bottom ashes [mg/kg d.b.]

boiler	fuel	TOC	TIC	S	Cl	Al	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	P	Pb	Si	Sr	Zn
1	Spruce_260	31000	16000	13500	13800	3970	147000	32	533	515	165000	149000	29300	21900	4710	357	22600	201	16200	950	2640
2	Spruce_260	660000	20000	692	41	835	64300	< 20	127	110	15000	50400	11000	9390	1370	59	6780	<300	5130	380	89
4	Spruce_260	446000	24000	2210	441	1610	90600	< 20	420	188	38800	99500	19000	14100	2000	171	13800	<300	9020	607	346
3	Spruce_260	742000	12300	730	43	431	18500	< 20	327	58	8960	41100	4180	2820	1210	158	3390	<300	3060	142	399

Table 46: Laboratory analysis results, heat exchanger residues [mg/kg d.b.]

boiler	fuel	TOC	TIC	S	Cl	Al	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	P	Pb	Si	Sr	Zn
1	Spruce_260	83500	13600	33300	29000	5450	117000	106	471	472	109000	163000	24000	17600	7610	251	18100	337	16200	733	7310
1	Spruce_raw	91400	11500	35900	54800	1970	57900	152	201	632	225000	142000	8080	6970	5630	222	5700	581	6250	288	7310
4	Spruce_260	377000	15800	13900	6070	1840	127000	60	455	219	35100	87700	23000	18000	2530	163	15300	<300	9240	779	2640
3	Spruce_260	208000	19100	38500	70600	1910	78200	56	1740	287	87500	118000	15300	9290	8090	461	19500	<300	17000	425	3430

GA no 282826

Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction

Deliverable No. D7.3 “Combustion behaviour of torrefied pellets in pellet boilers and corrosion load on chimneys”

Deliverable No. D7.4 “Combustion screening of three pellet boiler technologies and fuel assessment trials”

Appendix 3: Report prepared by partner TFZ

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Nature		
R	Report	X
O	Other	

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Table of Contents

1 Summary

It was the objective of the here presented research to assess the behaviour and direct applicability of new torrefied fuels in several state-of-the-art combustion systems for the residential heating sector. Two types of torrefied wood pellets were tested and compared to standard wood pellets in several combustion trials. Torrefied pellet 1 was produced as 6 mm pellets from similar wood resources as they are normally applied in small scale pellet boilers, it had a low ash content of 0.4 %. The other torrefied fuel was an 8 mm pellet from wood residues with high ash content of 3.2 % (Torrefied pellet 2). Three boilers were applied: Boiler 1 was an understoker feed boiler (15 kW), Boiler 2 was a top feed boiler (12 kW) and Boiler 3 was a moving grate boiler (30 kW). Only Boiler 1 and Boiler 2 enabled a stable operation which allowed to perform the full test program with all three fuels. Combustion trials were performed in partial load and full load operation as well as by using a standard 8 h test sequence with a continuously changing load (standard load cycle test). Furthermore, both boilers were used with Torrefied pellet 1 to perform a long-term test over 72 hours at almost full heating load (90 %); this was done to identify any ash related problems.

With Torrefied pellets 1 the operation in full and partial load operation was non-problematic. Carbonmonoxide (CO), organic gaseous carbon (OGC), NO_x and particulate matter (PM) emissions were on the same level as for reference wood pellets at full load, while at partial load even some advantages were observed for PM emissions which were here reduced by about 50 %. This was however, not the case for Torrefied pellets 2, which mostly caused largely higher PM and NO_x emissions in both boilers. This can be attributed to differences in fuel composition. These unfavourable fuel properties and the higher pellet diameter (8 mm instead of 6 mm) was also responsible for severe operational problems encountered with Boiler 2 (top feed boiler), where the CO and OGC emissions were beyond acceptable limits with Torrefied pellets 2.

The torrefied wood pellets showed the potential to provide at least the same combustion efficiency as achievable with wood pellets when tested at full or partial load, where the efficiency level was mostly in the order of 95 % (i.e. indirect efficiency, excluding the boiler loss). Under variable load operation (i. e. load cycle) the boiler efficiency was directly assessed (instead of indirect efficiency), it reflects the expected annual efficiency. Here even some advantages were observed for the Torrefied pellets 1 compared to wood pellets. The efficiency gain (direct measuring method) was between 4 to 7 percentage points, with highest levels of 87.6 % for the top feed boiler using Torrefied pellets 1.

The load cycle test also proved that concerning emissions the torrefied pellets can generally be compatible with wood pellets, at least this was demonstrated for pellets produced from similar resource quality (Torrefied pellets 1). But equally to wood pellets, also for torrefied wood fuels the risk of causing higher pollutant emissions is increasing with the use of unsuitable raw materials before torrefaction. This is shown by the results with Torrefied pellets 2, where again excessive PM and CO emissions were observed in Boiler 2.

But the flue gas composition as determined during short term operation cannot easily be extrapolated for longer periods. This was shown by the increasing fluctuation of flue gas

parameters, as mainly observed for CO, which also followed a negative trend over the long term trials (72 h). This observation was made with both boilers using Torrefied Pellet 1.

Furthermore, this trend was accompanied by higher ash related problems. The granulometric analysis performed with all total ash residues collected from the long-term trials with both boilers clearly show a higher slag formation (while slag is here defined as the fraction above 3.15 mm). For example, the slag formation of Torrefied pellets 1 was in the order of 31 %. This is more or less comparable to miscanthus pellets (about 24 %), which had been tested using the same two boilers during a previous research programme. Also it was observed that from Torrefied pellets 1 hardly any fine ash (which is here defined as the sieve fraction below 1.0 mm) was separated from the collected combustion residues.

Ash and slag related problems in small scale boilers are therefore expected to be increasing with this new fuel and they can be seen as an inhibiting factor for torrefied fuels being directly introduced as a replacement for wood pellet. For permanent use in small scale appliances, further boiler adaptations for slag removal need to be made and the prevention of clogging of air supply nozzles must to be guaranteed.

It can finally be concluded, that the direct applicability of torrefied wood pellets cannot easily be assumed for all small scale pellet boiler types. This was demonstrated by the failure to achieve a stable operation on a moving grate boiler. Underfeed stoker boilers may be less susceptible towards reduced qualities of torrefied fuels and towards larger pellet diameters. But field tests over a full heating season should always be performed to verify the individual applicability of new torrefied wood pellets in each regarded boiler type.

2 Goal

It was the objective of Task 7.4 to assess the behaviour and direct applicability of torrefied fuels in several state-of-the-art combustion systems (underfeed stoker, grate, overfed boilers) for the residential sector. This assessement was to be done by applying standard test procedures (e. g. type testing routines of full and partial load operation), practise related load cycle tests and long-term test runs for durability assessment. All tests should reflect the direct applicability of the new fuels in modern small scale state-of-the-art boiler systems.

The combustion tests of TFZ were also aiming at contributing to practice related fuel assessment by applying several torrefied fuels and comparing them to the usual standard reference fuels (i. e. wood pellets) for which the boilers are usually designed. Therefore, the selection of small scale testing boilers (capacities up to 50 kW) was made by selecting underfeed stoker, top feed and grate boiler types as they are usually prevailing in practise. Due to the fact that fuel applicability and fuel based differences sometimes do not become visible under steady state conditions it was necessary to perform further tests under repeatable load changes (i. e. variable power output conditions of a standard load cycle test) as it reflects the usual practise of a real-life field operation.

Furthermore, it was the goal to assess the torrefied pellets concerning their behaviour under permanent high power operation over several days, which can have an effect on boiler availability and ash related problems. Such problems would otherwise not be detected in the usual short operation of a boiler in the typical type testing procedure. Continuous emission monitoring was therefore required for a non-stop operation over several days (72 hours).

3 Methodology

3.1 Test stand

The trials were performed on the combustion test stand at TFZ in Straubing/Germany. A drawing of the testing setup including the referenced measuring points of the relevant parameters is shown in Figure 1.

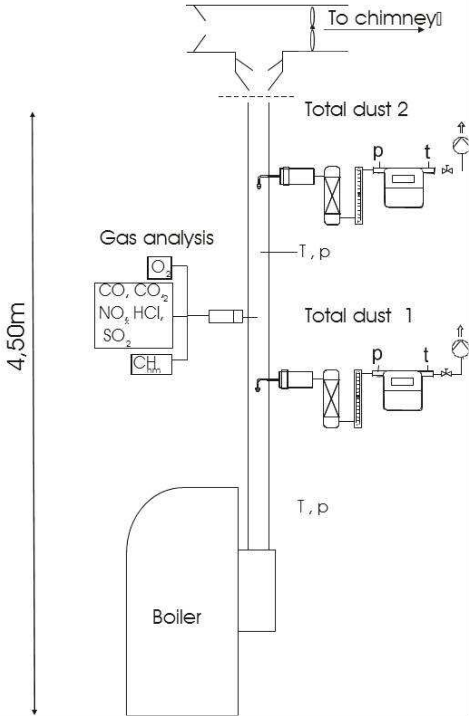


Figure 1: Drawing of the testing setup with measurement

The gaseous emissions, the particulate matter, the velocity and the temperature of the flue gas were continuously measured in the flue gas tract. Moreover, the mass flow of fuel input was determined. Figure 1 and Table 1 give an overview of the measured values and sampling positions, which are further explained in the following.

Table 1: Measuring point description

Parameter	Abb.	Unit	Explanation
Flue gas temperature	T_{FG}	°C	Thermocouple
Heat output	P	kW	Continuously (temperature heat exchanger, heat consumption)
Oxygen	O_2	Vol. %	Continuously by gas analyser
Carbon monoxide	CO	ppm	Continuously by gas analyser
Carbon dioxide	CO_2	Vol. %	Continuously by gas analyser
Nitrogen oxides	NO_x	ppm	Continuously by gas analyser
Particulate matters	PM	mg/Nm³	Discontinuously according VDI Directive (VDI 2066)
Velocity of flue gas	v_{FG}	m/s	Impeller
Chimney draught	p	Pa	Pressure measurement chimney
Mass of boiler system	m	kg	Determination of fuel consumption

- Chimney draught – underpressure

The chimney draught was measured directly after the combustion appliance and was regulated accordingly to the specification of the manufacturer of the combustion appliance.

- Particulate matter

Measurements of particulate matter emissions (PM) were performed based on TSP (total suspended particles) according to EN 13284-1 or a similar procedure based on the same principles (e. g. VDI 2066-1). Quartz plane filters in combination with stuffed filter cartridges were applied. PM sampling was performed three times for each test case after stable combustion conditions were reached it was waited about for one hour before the next PM measurement was conducted. Each PM sampling lasted for 30 minutes, except for the load cycle where PM was continuously determined. PM sampling was done isokinetically and all filter media was thermally treated at 120 °C before and after sampling. Weighing of filters or filter cartridges was done on a 5 digit (±0.01 mg) balance. Moreover, the depositions in the sampling line were also considered through rinsing of the complete sampling tract and subsequent drying of the rinsing liquid to determine the particle mass which was then reallocated to the respective filters by calculation. The mass concentration emissions were reported as mg/Nm^3 (in reference to the oxygen concentration of 13 %).

- Gaseous emissions

The gaseous emissions were continuously recorded starting from the cold boiler. The emissions were calculated based on the continuous measurements of O_2, CO, CO_2, NO_x and OGC (organic gaseous carbon). A calibration of the gas analysers was done before the individual combustion test starts. The determination of the flue gas temperature was performed using a suction pyrometer and it was connected to the gas sampling line.

3.2 Test execution

The tests were executed according to following specifications:

- One test run was performed with wood pellets according EN 14961-2 (Class A1) as reference fuel
- The boiler settings were not changed when the torrefied fuels were used except for Boiler 2 at partial load where the fuel supply was adapted due to the higher NCV of the torrefied pellets.
- Fuel samples for determination of moisture content were taken every day during the measurements
- Photos of slagging and deposits in the combustion chamber were taken after the long-term trial
- Continuous measurement of O_2/CO_2, CO, NO_x and OGC
- Discontinuous measurement of total particle matter (PM) over 30 minutes with 3 replications per fixed load setting

A major work item was to investigate the fuel under different loads and at variable load. These settings are described in the following.

- Fixed load settings

For testing under nominal heat output the load was set according to the manufacturer's specification for wood pellets. Little overload was tolerated. Partial load was set to a range of 40 to 45 % of nominal load.

- Variable load settings (load cycle)

For those tests where a repeatable variable load was required, the load was kept varying according the values shown in Figure 2 and Table 2. Each variable load trial was performed over 8 hours. The test cycle had originally been developed to measure the annual efficiency of a boiler, which would have included another 8 hour cooling down phase (see Heckmann et al. 2011, Rossmann et al. 2013). However, this cooling down phase is here not included in the data evaluation, as it does not provide any extra information concerning the here applied fuels.

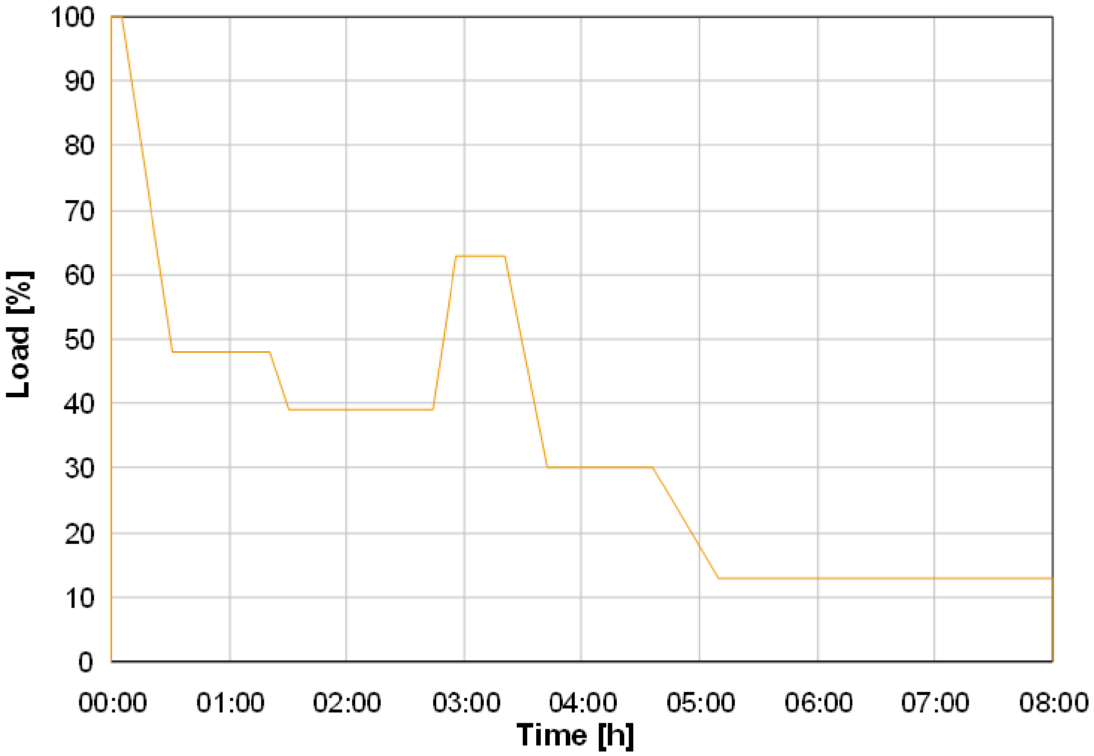


Figure 2: Load cycle for variable boiler operation using a TFZ internal standard (Rossmann et al 2013)

Table 2: Data relating to the annual reference load cycle for the determination of nominal annual efficiency, P_K is actual boiler heat output expressed as % of nominal heat output

P_K	0%	100%	48%	48%	39%	39%
Duration	00:00:00	00:04:52	00:26:00	00:50:15	00:09:00	01:13:44
Time	00:00:00	00:04:52	00:30:52	01:21:07	01:30:07	02:43:51

P_K	63%	63%	30%	30%	13%	13%
Duration	00:12:00	00:24:38	00:22:00	00:53:14	00:34:00	02:50:17
Time	02:55:51	03:20:29	03:42:29	04:35:43	05:09:43	08:00:00

3.3 Boilers

Generally there are several possibilities to arrange the fuel feed. Pellet boilers are divided into horizontally feed technologies, top feed and underfeed stoker charging (Hartmann 2013). Every technology reacts differently with respect to slagging properties of the given fuel. Figure 3 shows the different feeding systems.

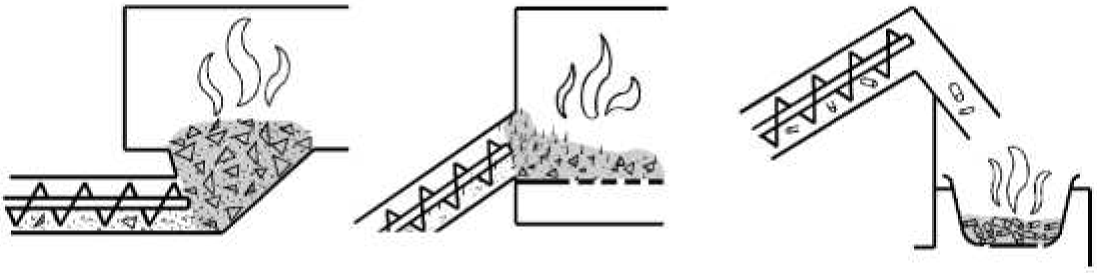
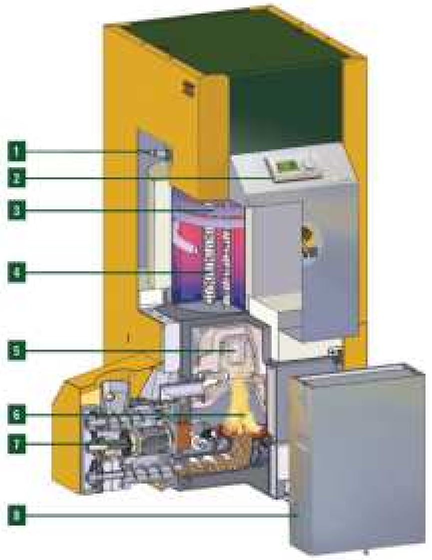


Figure 3: Mainly used feeding systems for automatically charged boilers, from left to right: Underfeed, feed from the side and top feed system (Hartmann 2013)

Boiler 1: KWB Easyfire

The combustion appliance “Easyfire” produced by KWB is an underfeed pellet heating system with a nominal power output of 15 kW for wood pellets. The pellets are pushed upwards to the burner plate. The combustion process takes place in four zones. The formed ash is removed from the edge of the plate and transported into the ash container. Figure 4 shows a cross section of the boiler as well as the key data of the system.



	Legend
1	Wideband lambda probe
2	Operating and control system (Display)
3	Integrated return flow temperature increase
4	Heat exchanger
5	Dust separator (cyclone)
6	Combustion system: underfeed-burner
7	Fire protection device (Cellular sluice wheel, metering screw)
8	Automatic ash removal

Figure 4: Cross section of KWB Easyfire (Source: KWB brochure)

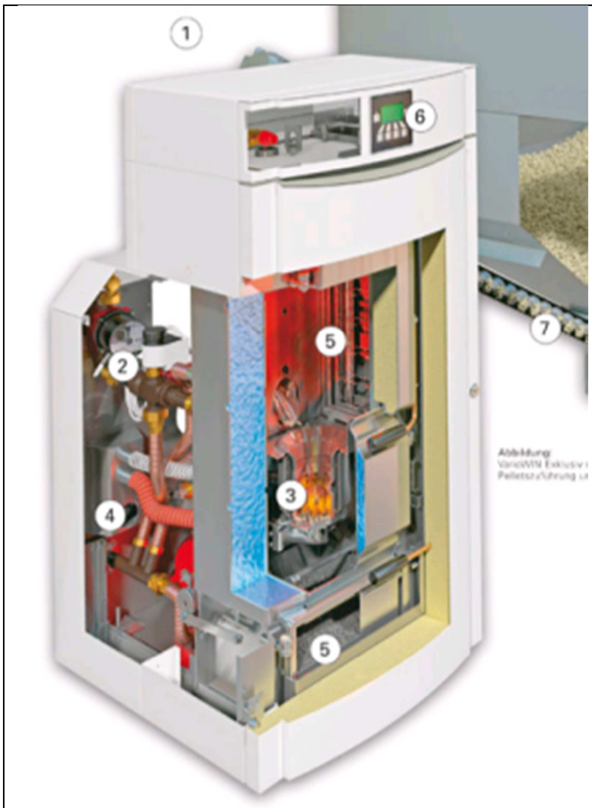
In accordance with the data of the producer’s brochure the temperature inside the combustion chamber is approximately between 900 and 1100 °C, if pellets made of pure wood are used. There is no specification concerning the maximum allowed fuel ash content or the required pellet quality. In Table 3 the properties of this boiler are summarized.

Table 3: Properties of the KWB Easyfire

Influencing parameter	
Power range (wood pellets)	4.4 – 15 kW
Feeding system	Underfeed stoker
Grate design	Burner plate
Air supply	Primary: combustion air blower through fuel Secondary: afterburning ring
Control strategy	Wideband lambda
Ash removal solution	Ash is removed from burner plate and heat exchanger and transported automatically via conveyer into an ash container
Refractory lining	Stainless steel

Boiler 2: Windhager VarioWIN

The boiler VarioWIN of the producer Windhager is fed from top and has a nominal power output of 12.0 kW. Figure 5 shows a cross section of the boiler.



Legend

1 Compact design

2 hydraulic and safety components optional feature

3 Combustion bowl

4 Adapter for an operation independent from ambient air

5 Fully automatic, compacted ash elimination, cleaning of heating surface

6 Operating system

7 Dosing screw

Figure 5: Cross section of VarioWIN (source: homepage Windhager)

The properties of the VarioWIN boiler are summarized in Table 4.

Table 4: Properties of the Windhager VarioWIN

Influencing parameter	
Power range (wood pellets)	3.5…12.0 kW
Feeding system	Top feed (drop down)
Grate design	Burner bowl
Air supply	Primary air pin, secondary air supply: holes in burner plate
Control strategy	Thermo control
Ash removal solution	Ash collecting box (automatic ash compression)
Refractory lining	

Boiler 3: Guntamatic Powerchip

A third boiler was chosen to represent the combustion principle of a moving grate, which for wood pellets is less commonly used in practise, but it is known to be relatively insensitive towards slag forming fuels. Compared to Boiler 1 and Boiler 2 this principle is largely different. Unfortunately, in several pre-trials a stable operation with torrefied pellets could not be achieved for several hours. This was also not possible after adjustment of the boiler settings aiming at a reduction of the excessive boiler water temperature. Particular problems also occurred when a steady partial load operation was to be achieved with torrefied wood pellets. Therefore the decision was made to perform the trials only with the two 2 boilers described above.

3.4 Fuels

The fuels applied in the tests are described in Table 5. Compared to the standard wood pellets the Torrefied pellets 1 were quite similar in moisture and ash content, except for the calorific value (LCV), which was almost 10 % higher. The Torrefied pellets 2 were deviating largely from the other two fuels. As it was produced from wood residues the ash content was largely higher (3.2 %) and the calorific value was even slightly lower than that of wood pellets. Also the pellet diameter was 8 mm instead of 6 mm. The moisture content of 8.6 %, however, this is in the usual range as it would have been expected for standard wood pellets, but their moisture content was comparatively low (only 3.7 %).

The reference fuel (wood pellets) was purchased from the market. This fuel was declared as standard EN_{Plus}-quality. The torrefied fuels were provided by the partners in the SECTOR-project.

Table 5: Fuels used in the combustion tests. Fuel analysis was made for fuel samples taken during the combustion trials and being analysed at TFZ laboratory according to standard CEN methods

Fuel name	Sector fuel name	Pellet diameter	Moisture content (wet basis)	Ash (dry basis)	LCV (dry basis)
Wood pellets	(procured by TFZ)	6 mm	3.7 %	0.3 %	19.1 MJ/kg
Torrefied pellets 1	Topell_spruce (Andritz)-_torrefied pellets_240513	6 mm	4.7 %	0.4 %	20.4 MJ/kg
Torrefied pellets 2	Topell_wood residues-_torrefied pellets_Jun-Oct 12	8 mm	8.6 %	3.2 %	18.9 MJ/kg

4 Results

In the following the results are presented, differentiating between constant load operation, variable load operation ("load cycle") and long-term test trials performed over about 72 hours. In all cases the performance of the boiler/fuel combination is assessed by regarding the major flue gas components (CO, OGC, NO_x and total particle emission) and for combustion efficiency (indirect measuring method).

4.1 Operation under constant load

Constant load operations were performed with both boilers using all three fuels. The tests are reported for constant full (nominal) load and constant partial load operations.

4.1.1 Nominal load measurements

Carbonmonoxid (CO)-emissions are a suitable parameter to evaluate the combustion quality and to characterize how complete the thermal processes were executed. Figure 6 shows the average results from three replications for full load operation. They show, that for Boiler 1 some differences between the fuels can be seen. The CO content increases from 45 to 300 mg/Nm³ (Wood pellets versus Torrefied pellets 2) and can be attributed to the fact that no fuel specific boiler optimisation was performed. However, with Torrefied pellets 2 the Boiler 2 did not perform satisfactorily. Boiler operation was rather unstable and this can partly be attributed to the larger pellet diameter of 8 mm, which is usually less suitable for very low boiler capacities as given for the 12 kW Windhager VarioWin boiler.

Figure 6: Average CO emissions at nominal load (Boiler 1: 15 kW, Boiler 2: 12 kW). Each value represents the mean of three measurements over 30 minutes performed parallel to PM emission sampling

For the particulate matter (PM) emissions a similar observation is made. Wood pellets and Torrefied pellets 1 display the same behaviour in both furnaces. But severe disadvantages are observed for Torrefied pellets 2 with an almost 5-fold increase of PM emissions for Boiler 2. This increase can either be attributed to the high degree of incomplete combustion as shown by the CO emissions in Figure 6 or be a result of critical components in the fuel. However, possible impacts of a higher level of such aerosol forming elements in the fuel (K, Na, Pb, Cd) cannot be assessed here, as the complete elemental analysis was not available at the time of reporting.

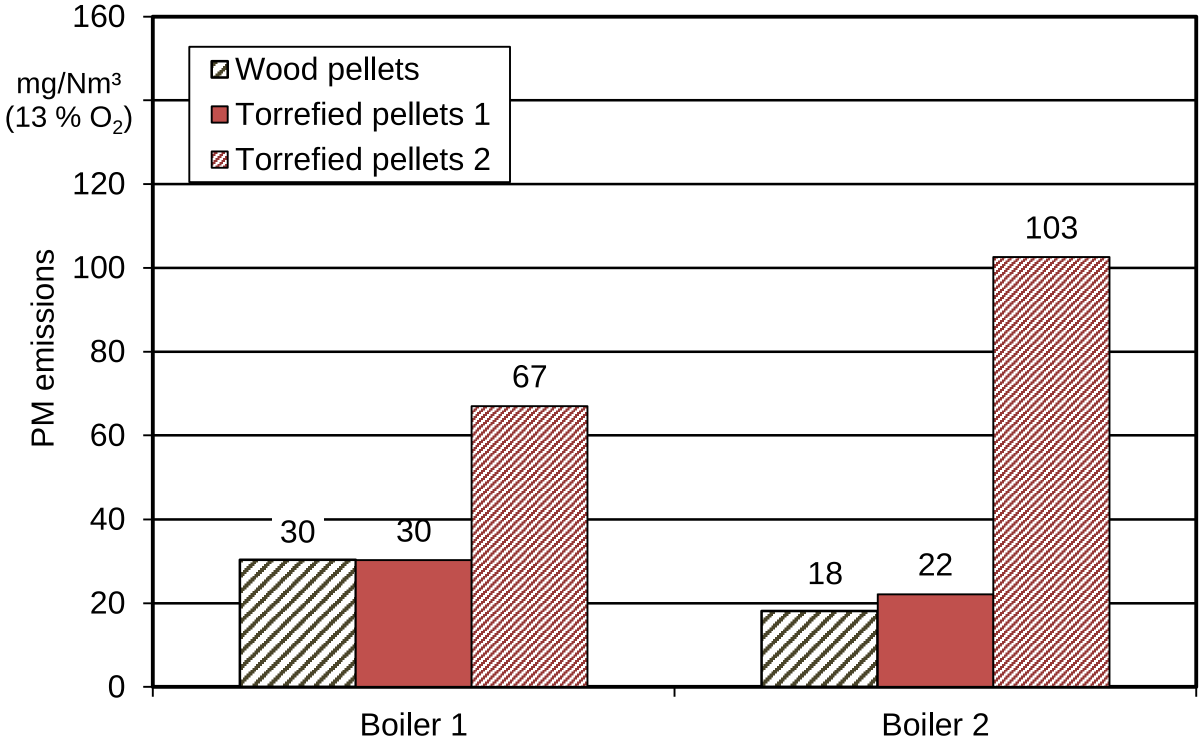


Figure 7: Average PM emissions at nominal load (Boiler 1: 15 kW, Boiler 2: 12 kW). Each value represents the mean of three measurements over 30 minutes of PM emission sampling

For emissions of organic gaseous carbon (OGC) at nominal load (Figure 8) the same pattern as for CO was observed. Here the disadvantages of Torrefied pellets 2 become even more obvious in Boiler 2, while no fuel based differences are observed in Boiler 1.

For NO_X emissions the wood pellets and Torrefied pellets 1 showed no differences (Figure 9). This can most likely be attributed to a similar nitrogen content in the fuel, however no complete elemental analysis was available at the time of measurement. For Torrefied pellets 2 a higher nitrogen content is assumed, as it is typical for the raw material (wood residues) which had been torrefied. This may have led to the NO_x increase in both pellet boilers.

Figure 8: OGC emissions at nominal load (Boiler 1: 15 kW, Boiler 2: 12 kW). Each value represents the mean of three measurements over 30 minutes performed parallel to PM emission sampling

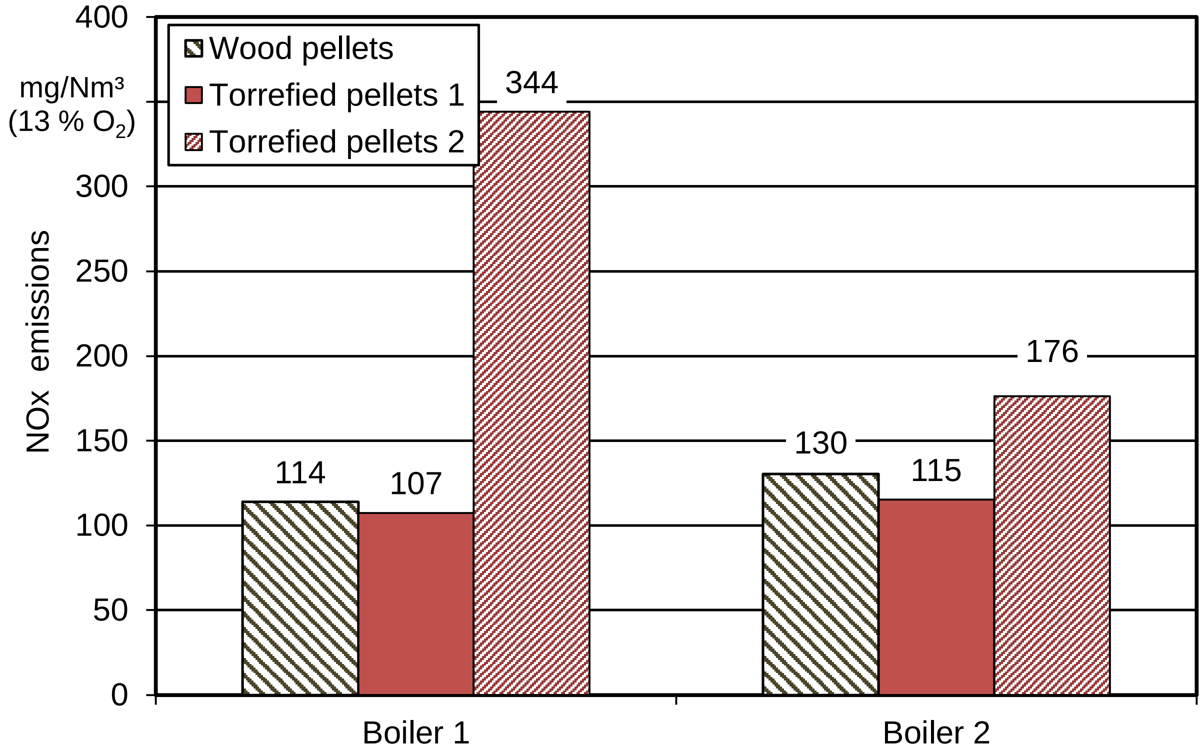


Figure 9: NO_x emissions at nominal load (Boiler 1: 15 kW, Boiler 2: 12 kW). Each value represents the mean of three measurements over 30 minutes performed parallel to PM emission sampling

Further results and combustion parameters from the tests at nominal load are compiled in Table 6. The results show that with torrefied wood pellets the efficiency can be as high or even higher as for wood pellets by reaching values of above 95 % (indirect measuring method). However, if the combustion is disturbed, as it was given with the 8 mm pellets of Torrefied pellets 2, the efficiency drops by several percentage points. The higher power output associated with higher flue gas temperatures and low oxygen content indicate that for Boiler 2 the pellet size was not adequate for the given fuel properties and further boiler adaptations would have been necessary for a successful operation. However, these disadvantages may not be attributed to the actual pre-treatment by torrefaction.

Table 6: Operating conditions and indirect efficiency during tests at nominal power output

Boiler	Fuel	O_2 content	Heat output	Flue gas temperature	indirect efficiency *)
Boiler 1	Wood pellets	10.2 %	17.7 kW	103 °C	94.0 %
	Torrefied pellets 1	9.0 %	18.0 kW	97 °C	95.2 %
	Torrefied pellets 2	9.2 %	16.3 kW	102 °C	95.0 %
Boiler 2	Wood pellets	7.8 %	12.6 kW	94 °C	95.8 %
	Torrefied pellets 1	7.0 %	12.8 kW	117 °C	95.8 %
	Torrefied pellets 2	4.2 %	14.1 kW	131 °C	92.5 %

*) calculated according to the indirect method from 3 measurements over 30 minutes

4.1.2 Partial load measurements

As for full load operations the partial load operations were performed with both boilers and using all three fuels.

The results for CO emissions reflect the same pattern as observed for full load operation (Chapter 4.1.1). Fuel differences for Boiler 1 are negligible, while only in Boiler 2 the Torrefied pellets 2 did not perform satisfactorily. However, the disadvantages are here lower, although for all other trials the partial load combustion was – as expected – generally less complete and efficient. This indicates that the load management of Boiler 2 was disturbed when using the 8 mm Torrefied pellets 2.

For PM emissions both torrefied pellets even show some advantages at partial load, particularly in Boiler 1, where the PM concentration drops to only half of the level for wood pellets (Figure 10). The same observation was made for Torrefied pellets 1 in Boiler 2, while the increase for Torrefied pellets 2 can again be attributed to the disturbance of power management observed in Boiler 2.

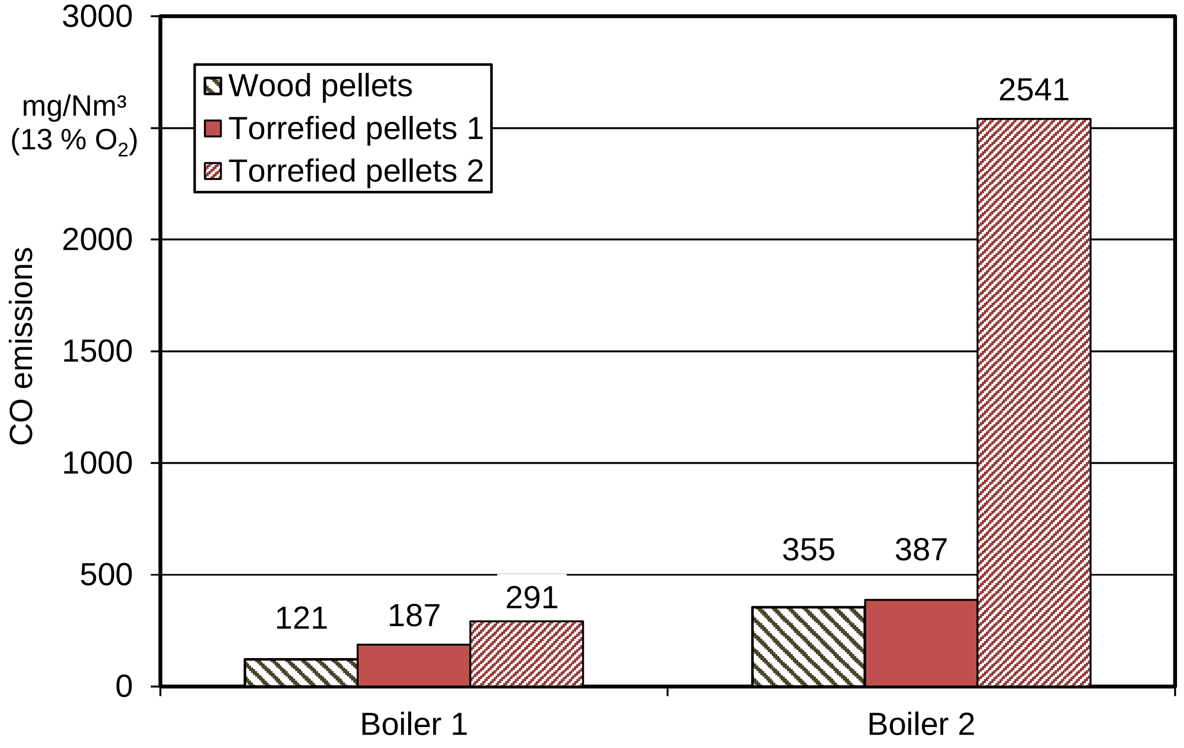


Figure 10: CO emissions at partial load (Boiler 1: 6.8 kW, Boiler 2: 4.9 kW). Each value represents the mean of three measurements over 30 minutes performed parallel to PM emission sampling

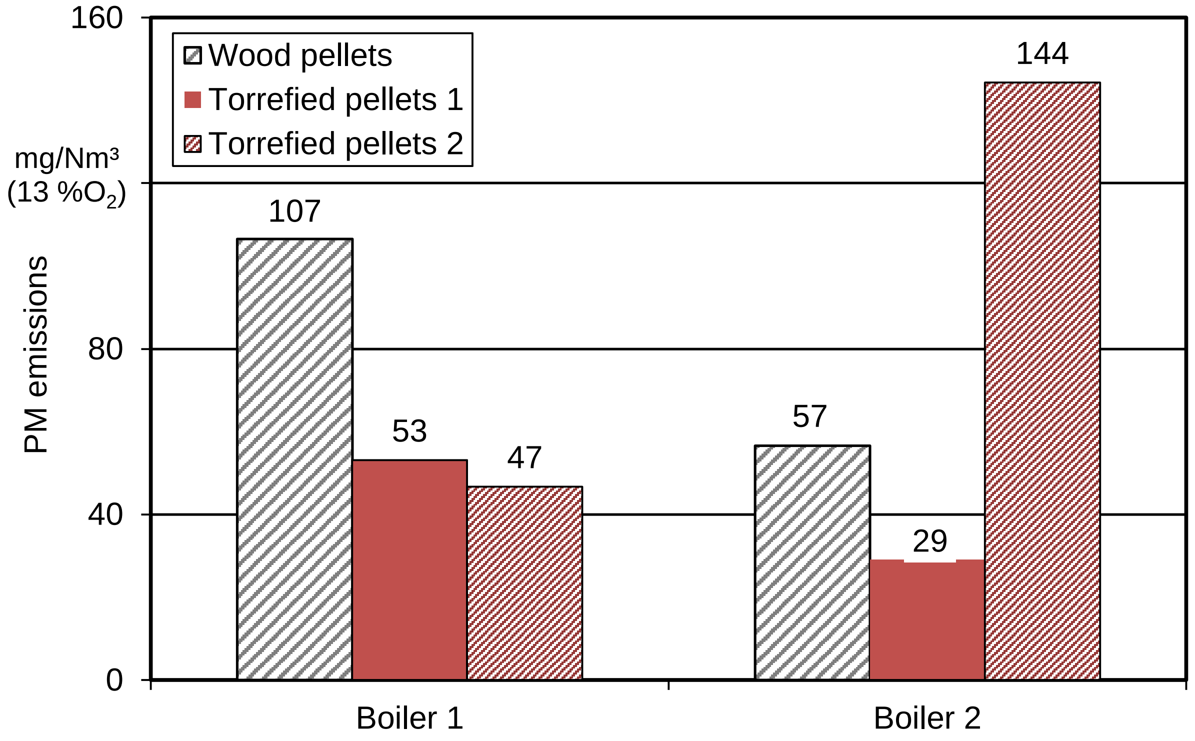


Figure 11: PM emissions at partial load (Boiler 1: 6.8 kW, Boiler 2: 4.9 kW). Each value represents the mean of three measurements over 30 minutes of PM emission sampling

Figure 12: OGC emissions at partial load (Boiler 1: 6.8 kW, Boiler 2: 4.9 kW). Each value represents the mean of three measurements over 30 minutes performed parallel to PM emission sampling

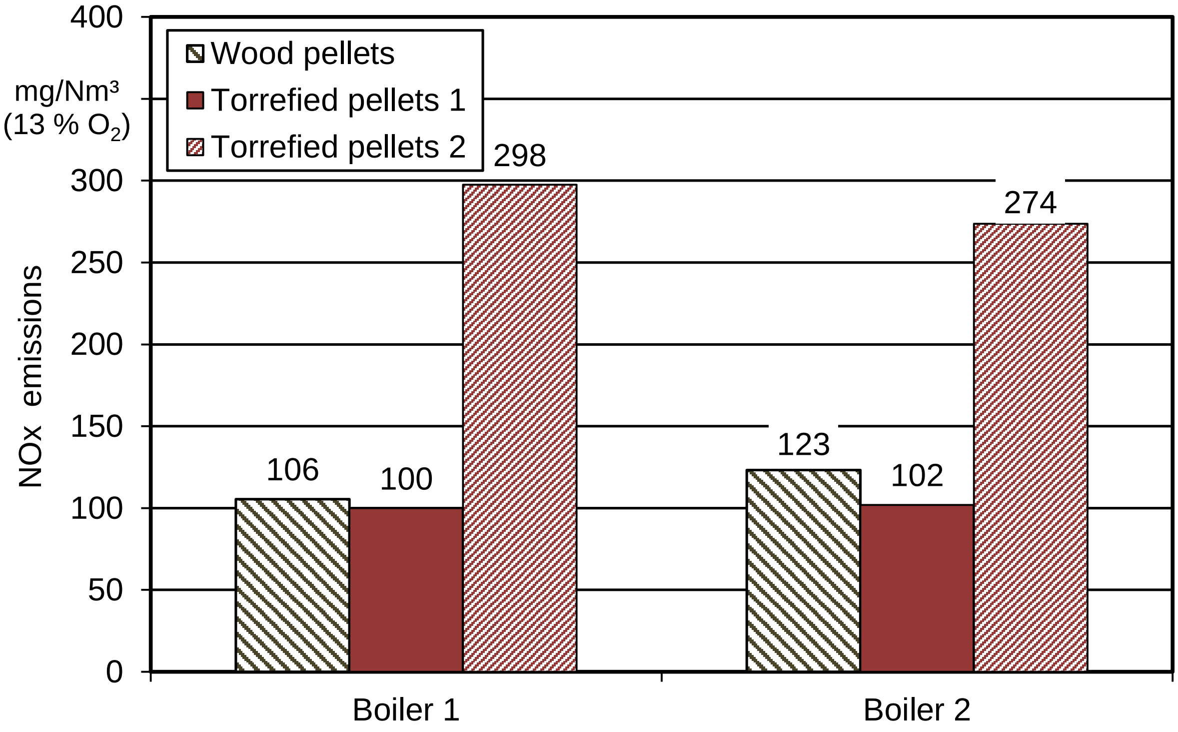


Figure 13: NOx emissions at partial load (Boiler 1: 6.8 kW, Boiler 2: 4.9 kW). Each value represents the mean of three measurements over 30 minutes performed parallel to PM emission sampling

The emissions of organic gaseous carbon (OGC) at partial load (Figure 12) behave according to the same pattern as for full load operation, only with less disadvantages for Torrefied pellets 2.

Practically no differences for NO_X emissions are observed when comparing full (nominal) load and partial load operation (Figure 13 versus Figure 9). This indicates that NO_x emissions are here mainly influenced by the nitrogen content in the fuel, because the usual decrease of NO_X emission at reduced load – as an effect of reduced combustion temperatures – is here not observed. No elemental analysis was however available to verify this assumption. The reduced combustion temperature can also be read from Table 7. Compared to the flue gas temperatures for full load operation (see Table 6) the flue gas temperature was reduced in the order of 20 to 50 K. This also results in a slight increase of efficiency compared to nominal load.

In partial load operation with Boiler 2 using the 8 mm Torrefied pellets 2 the load management was obviously not disturbed. This is read from the O_2 content and the heat power output which was kept in line with the other trials. This indicates, that the severe increase of gaseous and particle emissions for Torrefied pellets 2 can be attributed to the actual fuel properties rather than to any unfavourable combustion settings. But weather the increase was more due to the physical mechanical fuel properties (larger pellet diameter) or due to the chemical fuel properties as either constituted by the raw material composition or by the actual torrefaction process, can here not be concluded.

Table 7: Operating conditions and indirect efficiency during tests at partial load

Boiler	Fuel	O_2 content	Heat output	Flue gas temperature	Indirect efficiency [*)]
Boiler 1	Wood pellets	12.6 %	7.0 kW	64 °C	95.5 %
	Torrefied pellets 1	10.9 %	6.6 kW	75 °C	95.2 %
	Torrefied pellets 2	11.6 %	6.8 kW	74 °C	95.9 %
Boiler 2	Wood pellets	12.2 %	4.9 kW	64 °C	96.3 %
	Torrefied pellets 1	12.4 %	4.9 kW	63 °C	96.2 %
	Torrefied pellets 2	11.5 %	4.8 kW	75 °C	95.1 %

*) calculated according to the indirect method from 3 measurements over 30 minutes

4.2 Operation under variable load (standard load cycle)

The load cycle test method had been created and improved in the course of a previous research cooperation between Bioenergy 2020$^+$ and TFZ (see Heckmann et al. 2011, Rossmann et al. 2013). It is designed to reflect the usual share of a boiler's load stages as prevailing throughout a full heating season in a repeatable load demand pattern within an

8 hour combustion test. Therefore this load cycle is particularly useful to assess a boiler or a new fuel concerning it's suitability under real life conditions. It is pointed out that all values presented here are mean values over the entire 8 hour load cycle. Therefore, no replications were conducted.

As a consequence of the load variations, the pollutant emission results are always significantly higher than under steady state conditions of either a full or a partial load operation as reported in Chapter 4.1. This is also true for the efficiency, which largely decreases under the highly demanding test conditions of the standard load cycle.

These conclusions can also be made for the here presented results. Figure 14 shows the generally increased emission level compared to the above mentioned full and partial load results. Here, the CO emissions either improve with the torrefied pellets (Boiler 1) or they deteriorate (Boiler 2). The disadvantages for Torrefied pellets 2 remain visible, but they are less pronounced compared to the full load operation tests and even to the partial load test (see Figure 6 and Figure 10). This can be explained by the fact, that the obviously unfavourable phase of a full load operation is not largely reflected in the standard load cycle (see Figure 2). In any case the results in Figure 14 confirm the assessment of the Torrefied pellets 2 as not being suitable for the applied top-feed boiler type with the given low nominal power output of only 11 kW.

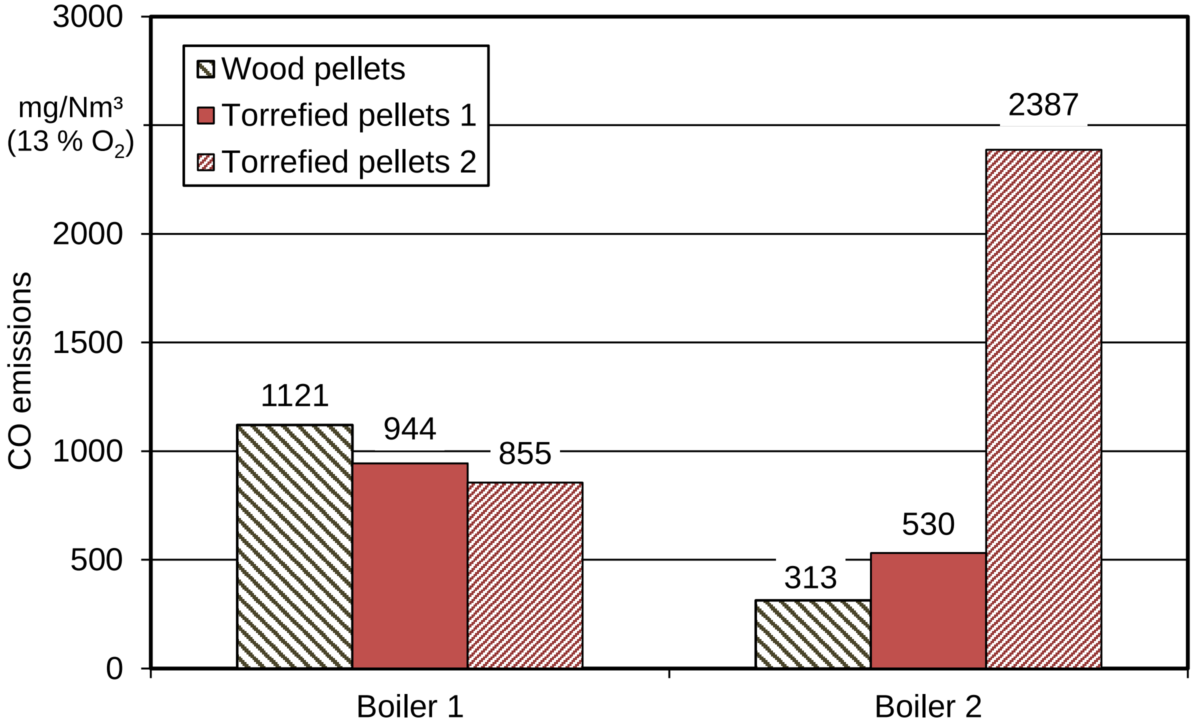


Figure 14: CO emissions at variable load according to standard load cycle

In the "real life operation" of the load cycle tests the PM emissions were even improved for Boiler 1 when using either of the two torrefied pellets (Figure 15). This is however not the case in Boiler 2. Also the boilers themselves perform quite differently. With wood pellets Boiler 2 releases largely lower PM concentrations compared to Boiler 1. But particularly the Torrefied pellets 2 again prove to be rather disadvantageous in the load cycle trials, particularly in Boiler 2.

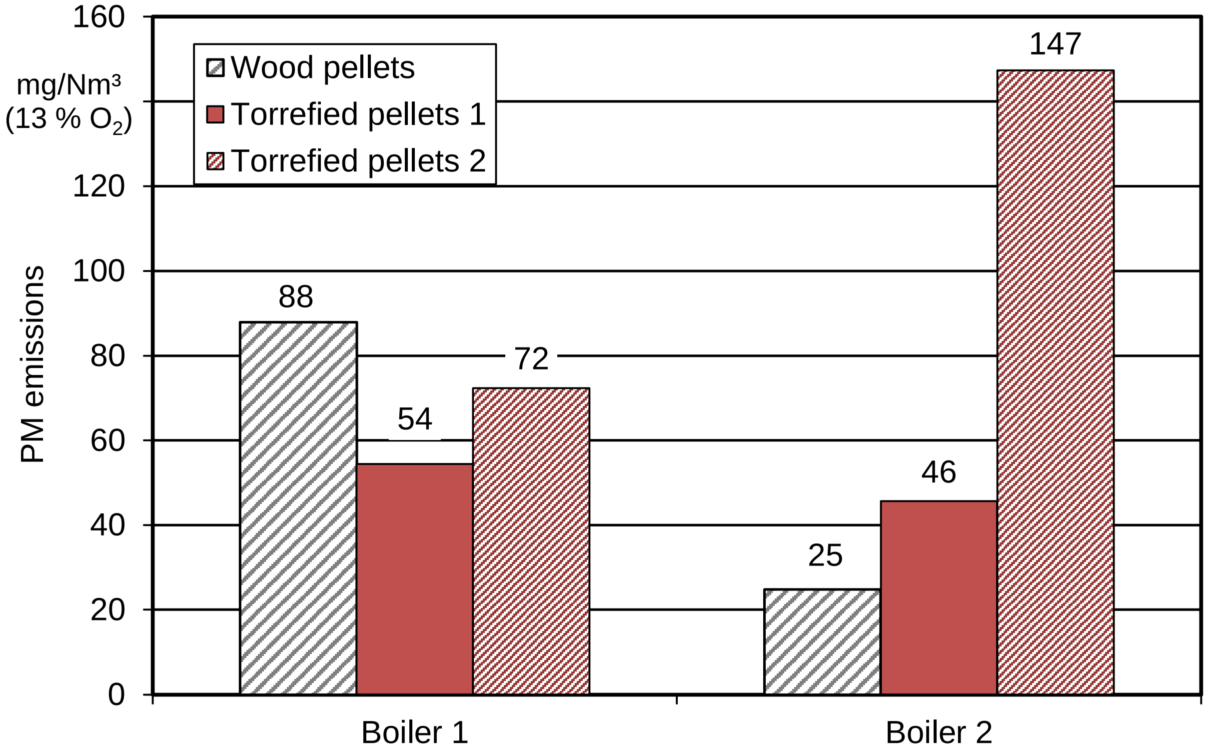


Figure 15: PM emissions at variable load according to standard load cycle

In the load cycle trials the OGC emissions was highest when using wood pellets in Boiler 1 while all other tests had a better performance (Figure 16). NO_x emissions (Figure 17) were again following the same pattern as already observed for full and partial load operations with the same pellets.

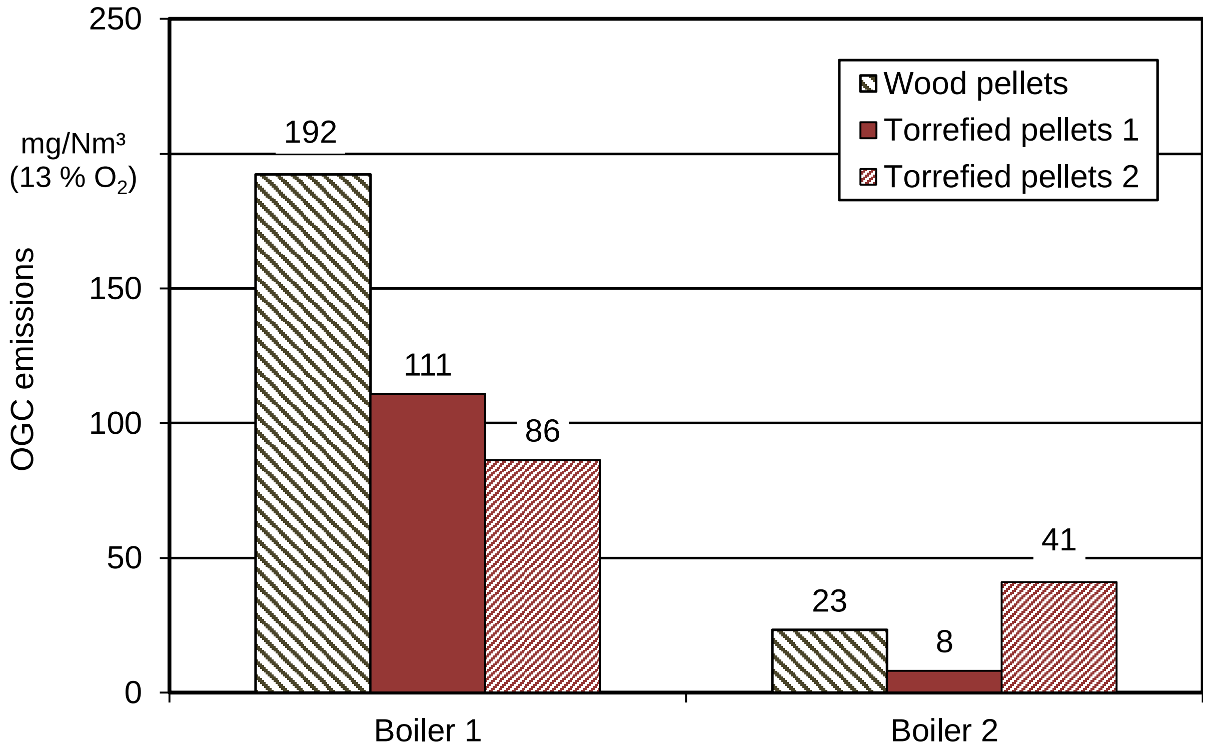


Figure 16: OGC emissions at variable load according to standard load cycle

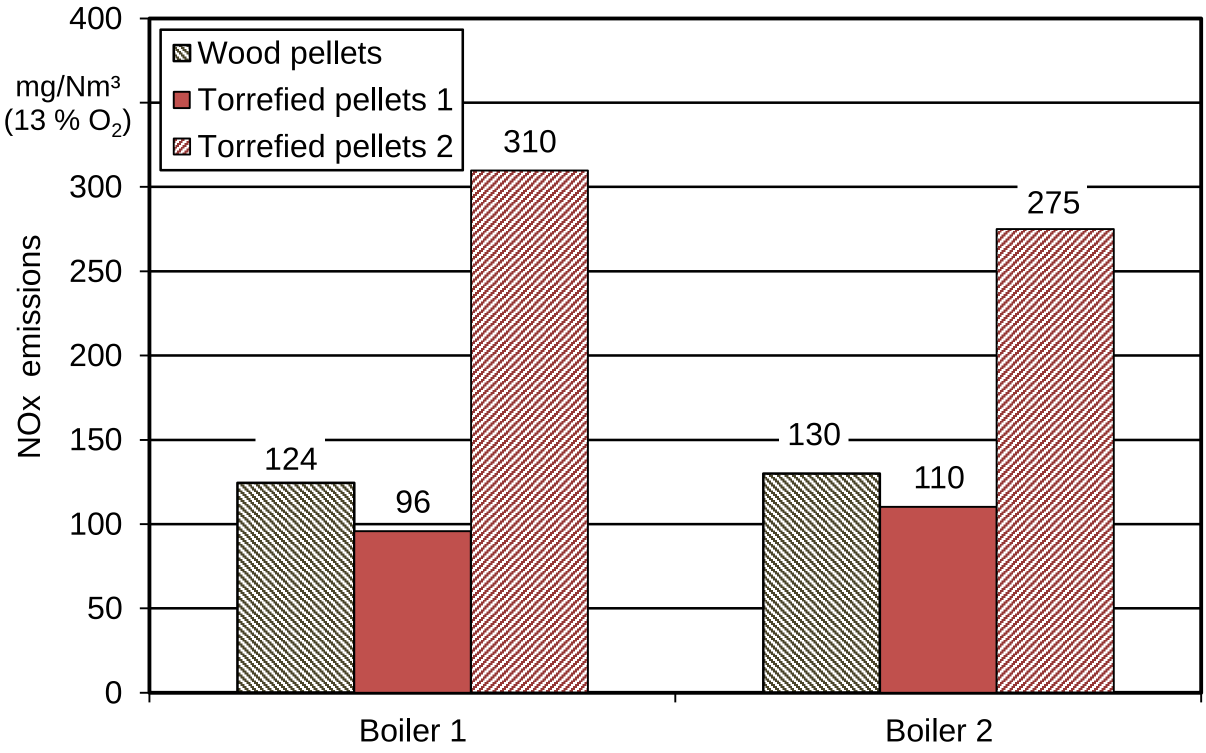


Figure 17: NO_x emissions at variable load according to standard load cycle

The boiler efficiency (direct determination method) in the load cycle operation was also tested with both boilers. The results in Table 8 show a significant increase of the efficiency when using any of the torrefied pellets. This increase is in the order of more than 4.3 and 7.4 percentage points.

Table 8: Operating conditions and boiler efficiency during tests at variable load (load cycle). The table shows average values over the full load cycle.

Boiler	Fuel	O_2 content	Heat output	Flue gas temperature	Boiler efficiency *)	Indirect efficiency **)
Boiler 1	Wood pellets	15.6 %	6.8 kW	72 °C	76.6 %	91.1 %
	Torrefied pellets 1	14.0 %	7.1 kW	74 °C	80.9 %	93.9 %
	Torrefied pellets 2	13.5 %	7.1 kW	79 °C	84.0 %	93.5 %
Boiler 2	Wood pellets	14.1 %	4.7 kW	71 °C	83.4 %	94.8 %
	Torrefied pellets 1	13.8 %	4.4 kW	73 °C	87.6 %	96.1 %
	Torrefied pellets 2	13.2 %	4.6 kW	75 °C	85.2 %	92.9 %

*) calculated according to the direct method over the whole period of 8 hours

**) calculated according to the indirect method over the whole period of 8 hours

4.3 Long-term tests

The long-term tests were performed to assess the torrefied pellets concerning their behaviour under permanent operation at 90 % of the nominal load. Apart from any drift concerning emissions, this test aimed also at identifying any ash related problems, such as solid slag formation, nozzle clogging or blockages occuring with the torrefied fuel. Such problems would otherwise not be detected in the usual short term operation of a boiler when applying a standard testing procedure with less than 8 hours. Thererfore a continuous monitoring of the gaseous emissions over 72 hours was required at 90 % load operation. This was done with both boilers, the underfeed stoker boiler (Boiler 1) and the top feed boiler (Boiler 2). The used fuel was Torrefied pellets 1 in both cases. This fuel was chosen because the observations with Torrefied pellets 2 had indicated, that a stable operation under full load conditions could not be expected, particularly for Boiler 2 (see Chapter 4.1).

The gaseous and particulate emissions for Boiler 1 (the underfeed stoker boiler) are presented in Figure 18 for the complete monitoring period. During the first 12 hours the CO emission was constantly decreasing and constant for the next few hours. After a full day of operation the automatic cleaning was started, this is indicated by the sudden short peaks of O_2 concentration. At the same time the filter for the gas analysis was replaced leading to an increase of O_2. After 30 hours the boiler shifts into a more unstable operation as indicated by the higher fluctuation of the CO emission level while also a generally higher CO emission level is prevailing. OGC emissions remain unaffected by this mild disturbance; it stays on the average level of around 2 mg/Nm³ (Table 9). The NO_X formation remains largely constant at about 160 mg/Nm³ over the entire test duration. Particulate emissions were measured 6 times, they reached an average value of 21 mg/Nm³ (Table 9). Their variation reflects the usual fluctuation for automatically fed wood pellet boilers (Figure 18).

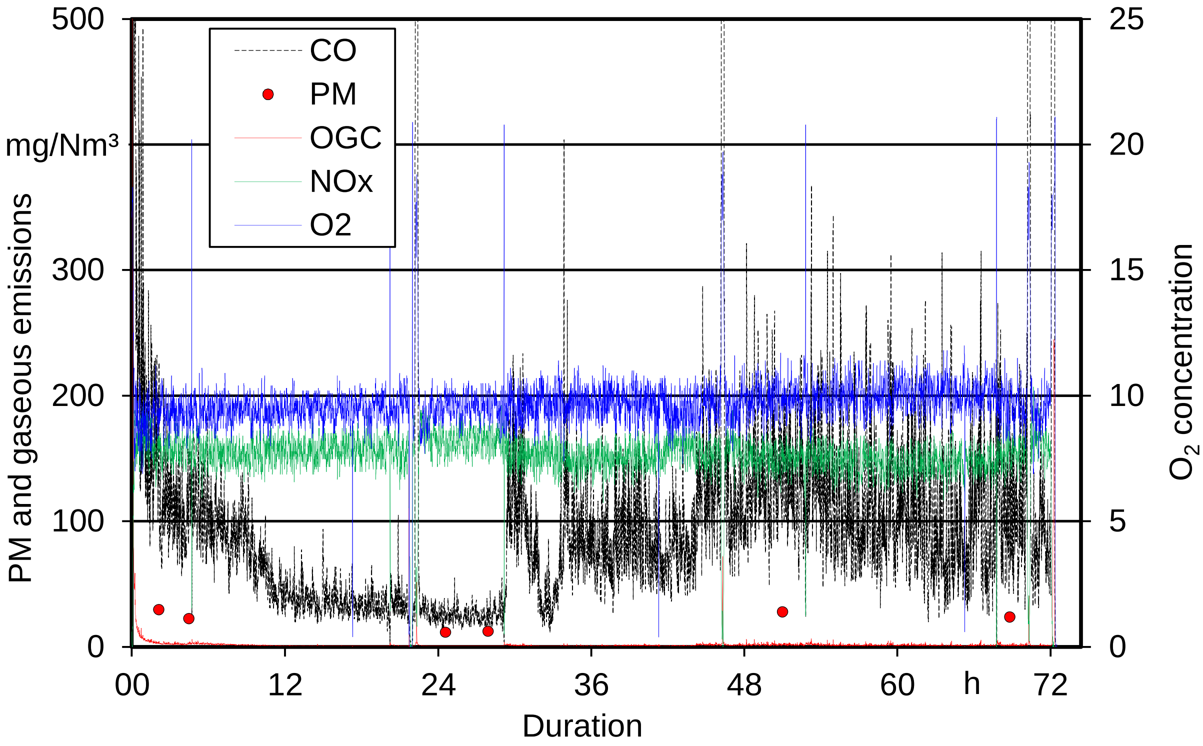


Figure 18: Emissions during long-term test with Boiler 1 (underfeed stoker boiler) using Torrefied pellets 1

With Boiler 2 - the top feed boiler - the general emission level during the long-term operation was mostly higher than for Boiler 1. Such general trend had however not been observed in the full and partial load trials and during the load cycle tests, where from Boiler 2 the PM emissions with Torrefied pellets 1 were always lower. This was mostly also true for the CO emissions. Figure 19 shows the fluctuation of CO, which also increase after about 36 hours, as indicated by the higher frequency of CO peaks.

Every 6 hours the boiler automatically schedules a cleaning operation, where the grate ash is discharged into the collecting container while also the heat exchanger tubes are mechanically cleaned. This cleaning operation can be read from the O_2 content in Figure 19 which abruptly rises due to the fact that fuel feeding is stopped while the ventilation continues to achieve a full burnout of the remaining fuel in the fire bed before it is dropped into the collecting bin as caused by a mechanical grate operation.

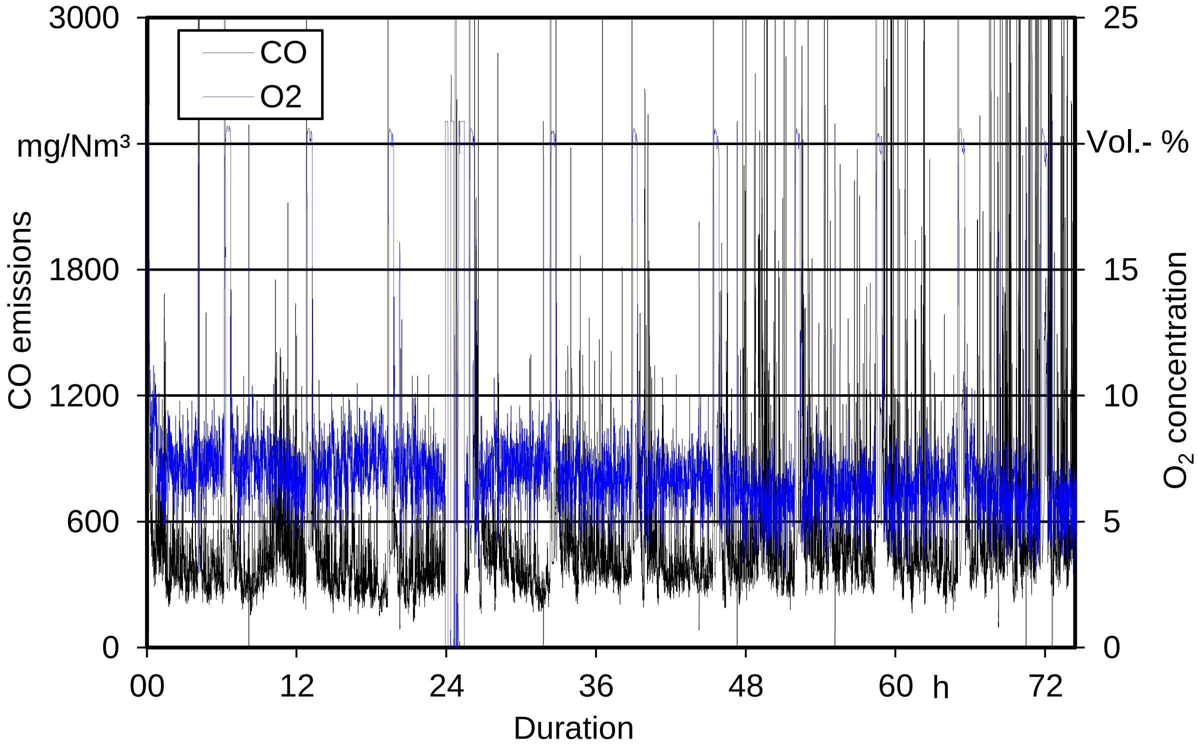


Figure 19: CO emissions during long-term test with Boiler 2 (top feed boiler) and Torrefied pellets 1

Particulate matter (PM) emissions are at an average level of 30 mg/Nm^3 with only little fluctuation, this can be read from Figure 20. No tendency was also observed for OGC and NO_x over the 72 hours test. But the oxygen concentration is gradually decreasing. This can be a result of a reduced cross-section area of the primary air nozzles as they were becoming clogged by sintering ash. This observation was made after letting the boilers cool down before the granulometric assessment of the bottom and grate ash was made (see Figure 25).

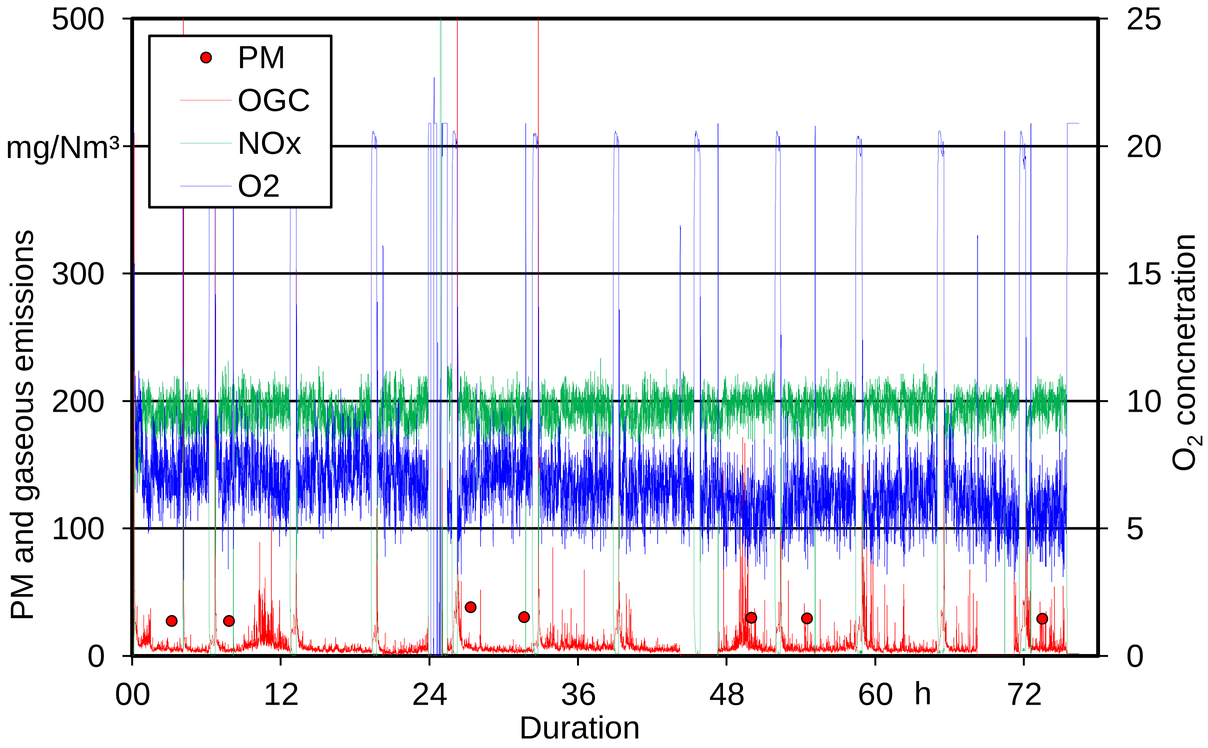


Figure 20: Emissions during long-term test with Boiler 2 (top feed boiler) and Torrefied pellets 1

Concerning the efficiency there were no differences observed. The indirect efficiency of both boilers was on a relative high average level of more than 95 % (Table 10). This is in line with the low average flue gas temperatures which were in both cases at 97°C.

Table 9: Mean emissions during long-term tests (gaseous emissions as mean values over whole period, PM as mean of six samplings, both @ 13 % O_2). Boiler 1: underfeed stoker, Boiler 2: top feed, Fuel: Torrefied pellets 1

	O_2	CO	PM	OGC	NO_x
Boiler 1	9.7 %	79 mg/Nm³	21 mg/Nm³	2 mg/Nm³	108 mg/Nm³
Boiler 2	7.8 %	387 mg/Nm³	30 mg/Nm³	6 mg/Nm³	110 mg/Nm³

Table 10: Operating conditions and indirect efficiency during long-term tests

Boiler	Fuel	O_2 content	Heat output	Flue gas temperature	Indirect efficiency *)
Boiler 1	Torrefied pellets 1	9.7 %	13.5 kW	97 °C	95.1 %
Boiler 2	Torrefied pellets 1	7.8 %	10.1 kW	97 °C	95.5 %

*) calculated according to the indirect method, mean of 6 to 7 measurements over 30 minutes

Slag formation with the Torrefied pellets 1 during the 72 hours of full load operation was not completely harmless. Figure 21 shows the clean grate of the underfeed stoker boiler (Boiler 2) before (left picture) and after the test (right picture). The combustion residues show significant portions of non-adhesive slag crusts mixed with ashes which retain the shape of pellets after being off-gased. For optimal combustion a manual deashing and slag removal from the grate would be required to continue the high performance level of the boiler during the previous 72 hour operation. Figure 22 shows for the same boiler that ash crusts had also been dropped down from the heat exchanger indicating slight corrosion (red flakes).

Figure 21: Slag formation in burner unit of Boiler 1 after long-term test (Torrefied pellets 1). Left picture: clean burner unit before the long-term test. Right picture: burner unit after the tests.

Figure 22: Slag formation and deposits in Boiler 1 after long-term test (Torrefied pellets 1)

For the total ash collected a granulometric examination was performed (Chapter 4.4). The largest agglomerated lumps from Boiler 1 are shown in Figure 23.

Figure 23: Agglomerated ash particles from the bottom ash (left picture) and grate ash (right picture) from Boiler 1

For Boiler 2 the ash was also loose and could be easily discharged to the collecting bin although some small lumps were formed. Figure 24 shows the burner cup having relatively clean surfaces without agglomerates after the trials. However, the cross-section area of the primary air nozzles was gradually reduced as a result of being clogged by sintering ash. This leads to a slow deterioration of the combustion process which can also be observed in Figure 20 where the oxygen content begins to decline over the 72 hours.

Figure 24: Slag formation and deposits in Boiler 2 after long-term test with Torrefied pellets 1. In the picture right the hemispherical primary air head is removed. This head is show in Figure 25.

Figure 25: Slag formation and clogging of air inlets on the hemispherical primary air head of Boiler 2 after long-term test using Torrefied pellets 1. Molten ash is beginning to block the nozzles for primary air supply.

The largest agglomerated pieces collected after the long-term test for Boiler 2 are shown in Figure 26.

Figure 26: Agglomerated ash particles from the bottom ash (left picture) and grate ash (right picture) from Boiler 2

4.4 Granulometric assessment of ash from long-term tests

Of both boilers the total combustion residues from the bottom ash and from the burner cup were collected after 72 hours of operation. With this total ash a granulometric analysis using a sieving machine (200 rounds per minute for 1 minute) was performed. The sieving was done with the sizes of 0.5 mm, 1.0 mm, 2.0 mm and 3.15 mm. All sieves were mesh wire cloth sieves following the requirements of ISO 3310-1. The fraction > 3.15 mm is considered as slag.

Figure 27 shows the share of ash collected in the specified size classes. In the figure the results from using the Torrefied pellets 1 in the two boilers are compared to results available from a previous research activity at TFZ where fuels which were suspected to create slagging problems had been chosen to provide observations for a representative range of possible fuel qualities. These fuels were: a wood pellet made of a mixture of 30 % willow and 70 % spruce, miscanthus pellets and wheat straw pellets, all having a diameter of 6 mm.

Boiler 1 shows generally a higher share of slag than Boiler 2 (while slag is here defined as the fraction above 3.15 mm). This is observed for all fuels. The slag formation of Torrefied pellets 1 is here in the order of 31 % which is more or less comparable to miscanthus pellets (about 24 %). The similarities concerning slag formation between Torrefied pellets and miscanthus pellets are also given for the test with Boiler 2. Also it was observed for Torrefied pellets 1 that hardly any fine ash (which is here defined as the sieve fraction below 1.0 mm) was collected from the assessed ash residues.

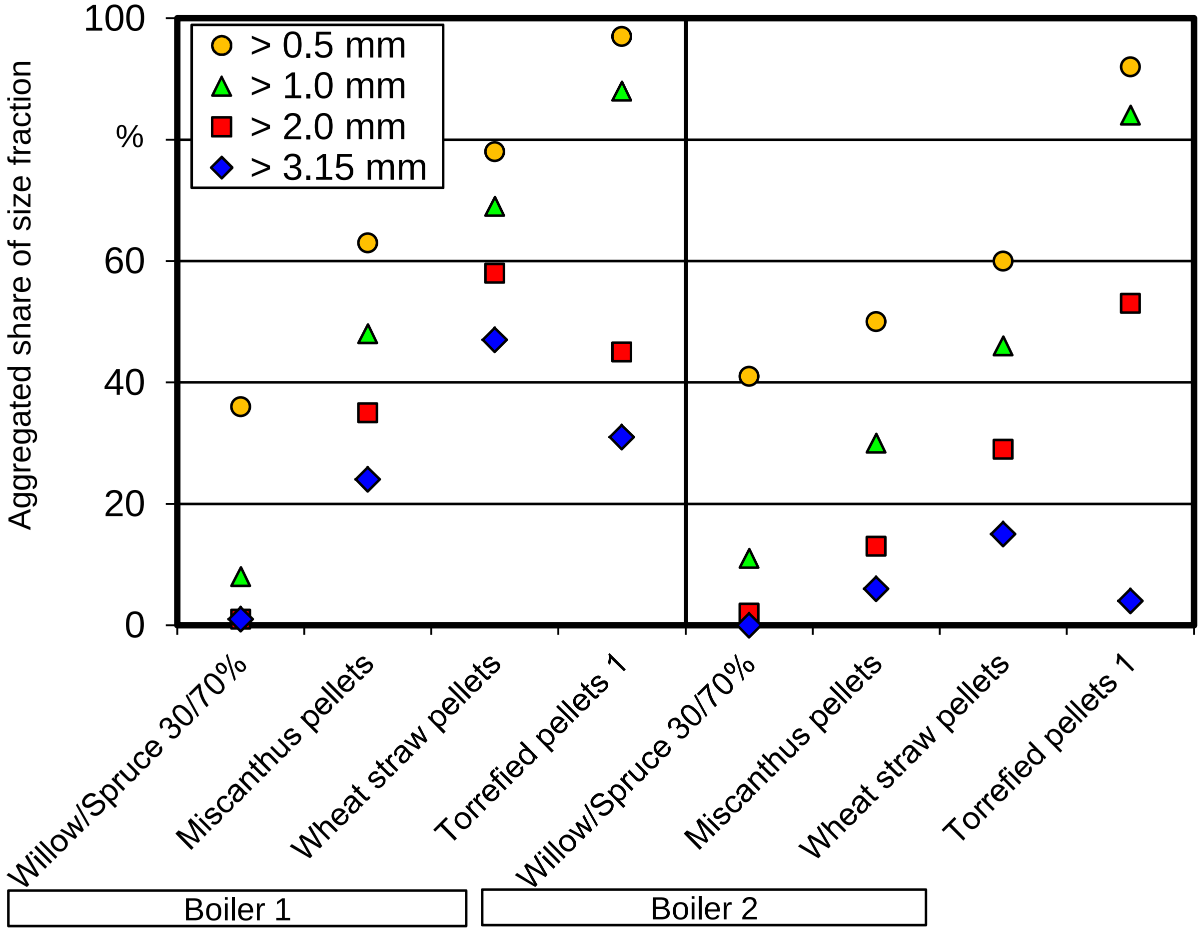


Figure 27: Results of granulometric assessment of ashes from different fuels used in Boiler 1 and Boiler 2

5 Conclusions

From the presented results the following conclusions can be compiled:

- Torrefied wood pellets have the potential to provide at least the same combustion efficiency as achievable with wood pellets when tested at full or partial load. Under variable load operation (i.e. load cycle) an even higher efficiency may be possible. This seems to be applicable for top feed and underfeed stoker boiler types.
- The level of pollutant emissions is largely similar to that of wood pellets, given that similar wood resources were also used before torrefaction. This was observed for CO, OGC and PM emissions (for Torrefied pellets 1).
- Equally as for wood pellets, also for torrefied fuels the risk of causing higher pollutant emissions is increasing with the use of unsuitable raw materials before torrefaction. For small scale heating appliances it is therefore required that future fuel standards are based on the same critical components and that they define similar limits as already established for wood pellets.
- The diameter of the torrefied pellets should be chosen in accordance with the requirements also given for wood pellets in the specific boiler. Torrefied pellets with 8 mm diameters may create operational problems when nominal boiler heat output is particularly low.
- The direct applicability of torrefied wood pellets cannot be assumed for all boiler types. This was demonstrated by the failure to achieve a stable operation on a moving grate boiler. Underfeed stoker boilers may be less susceptible towards reduced qualities of torrefied fuels and towards larger pellet diameters.
- The use of torrefied pellets is associated with a higher share of slag formed during combustion. Ash and slag related problems in small scale boilers are therefore expected to be increasing with this new fuel and they can be seen as an inhibiting factor for torrefied fuels being directly introduced as a replacement for wood pellet. For permanent use in small scale appliances, further boiler adaptations for slag removal need to be made and the prevention of clogging of air supply nozzles must to be guaranteed.
- Field tests over a full heating season should therefore be performed to verify the individual applicability of torrefied wood pellets in each regarded boiler type.

6 Literature

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