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PRODUCTION AND COMBUSTION TESTS OF ALTERNATIVE AND MIXED BIOMASS PELLETS

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1 Introduction

The project MixBioPells is financed by the Intelligent Energy Europe programme. The objective of the project is the enhancement of the market relevance of alternative and mixed biomass pellets. The following partners are participating in the project:

- German Biomass Research Centre (DBFZ),
- Austrian Bioenergy Centre (Bioenergy 2020+),
- Technical Research Institute of Sweden (SP),
- Technical Research Centre of Finland (VTT),
- Danish Technological Institute (DTI),
- Comitato Termotecnico Italiano (CTI),
- Energia y Medio Ambiente S.L. (Protecma).

Project coordination is done by German Biomass Research Centre (DBFZ).

The main objective of the project is to provide vast information about key actors, ongoing initiatives and available technology around the topic of alternative pellets production, trade and utilisation. Compiling an overview about the technological state of the art, also best practice examples for production and combustion chains for alternative pellets are documented. In addition, some pelletizing and combustion tests are conducted with interesting materials and mixtures that have been identified in previous tasks of the project, and that have not been investigated so far or where no reliable data is available.

The present report gives a detailed overview about the pelletizing and combustion tests that have been conducted in three participant countries, i.e. Austria, Finland and Germany. The experiments were carried out in close cooperation with the industry partners involved in the project.

In the following sections results from pelletizing and combustion tests in all three partner countries are summarised, and the choice of raw material mixtures is explained.

2 Raw materials

Each partner selected four batches of the most interesting material mixtures for pelletizing and combustion tests. The selection was based on the biomass report of the MixBioPells project and regional knowledge. The raw materials and mixtures used are shown in Table 1.

Table 1: Raw material mixtures selected for the tests.

	BE2020+	DBFZ	VTT
Batch 1	50% hay, 50% Miscanthus	100% Miscanthus	50% Straw / 50% peat
Batch 2	75% hay, 25% Miscanthus	100% grape marc	50% Straw / 50%peat with kaolin 2%
Batch 3	50% corn cob, 50% Miscanthus	30% Miscanthus / 70% grape marc	20% Reed canary grass / 80% wood
Batch 4	50% hay, 50% vine prunings	70% Miscanthus / 30 % grape marc	50% reed canary grass / 50% wood

BE2020+ has done several tests with pure pellets based on hay, Miscanthus or vine pruning previously. Thus, the main interest is to investigate how pelletizing and combustion characteristics can be improved by mixing these raw materials, e.g. the combination of good pelletizing characteristics of hay with the good combustion characteristics of Miscanthus and vine pruning. For the mixtures the same raw materials as in previous tests. All raw materials are available in the same region.

VTT: Reed canary grass is used as a straw fuel in Finland. However, there are several problems in handling and transportation. Thus, the pelletizing or briquetting of the raw material provides several advantages. For the use in small scale appliances, mixtures with wood are promising to lower slag formation and hazaradous emissions such as total dust. Furthermore, the problematic combustion behaviour of straw, e.g. slag formation in the bottom ash can be improved by mixing with peat. However, the sustainability of peat is low. The slag formation in the bottom ash and critical emissions such as dust emissions can be reduced by using the mineral additive kaolin. All raw materials are local, and they are also used in the other Nordic countries.

DBFZ used grape marc and Miscanthus.
Grape marc: Has a high regional potential (265,000 t/a) in Rhineland-Palatinate. Furthermore, grape marc has a high potential in Austria and Italy. Thus, the results from combustion tests will be interesting for key actors from other regions. The experiences on the combustion of grape marc are very low (especially results on dust measurements are missing). Furthermore, the working group "solid biofuels in small scale combustion appliances" was initiated from the German Federal Environment Agency to specify a positive list which fuels or mixtures can be classified as a regular fuel according to Federal Emission Control Regulation No. 1 (1.BImSchV §3 Abs.1 No.13 /1.BImschV/. Thus, the combustion tests can give significant input to the working group.

Miscanthus: Has not a high potential until now. However, the interest of the key actors in this raw material is quite high due to favourable combustion properties. The demonstration of the feasibility of the combustion can lead to a growing availability of Miscanthus in the near future. Only some experiences on the combustion of Miscanthus are available; there are big differences in the combustion properties depending on the harvest and cultivation of Miscanthus. Therefore, combustion tests should

be done with pure raw material to ensure comparability with the mixtures based on Miscanthus. Furthermore, results from combustion tests with precipitators are missing and certified combustion - precipitator systems are commercially not available.

Despite, straw is an interesting raw material in the partner countries no pelletizing and combustion tests were carried out due to the following reasons:

- Results from the combustion of straw are available.
- Also the combustion and pelletizing characteristics of mixtures with wood and Miscanthus have been investigated previously (e.g. in the project “Biobrennstoffdesign”).
- Furthermore, Denmark has long time experiences in the combustion of straw in CHP. Thus, the available experiences and database for straw is quite good.

3 Pelletizing tests

The main data of the presses used for pelletizing tests are summarized in Table 2.

Table 2: Overview about pellets presses used for tests.

partner country	press	type / principle	capacity/ power	Additional information
Austria	Kahl AK 33-390	flat die	15-30 kW	small basic press
Austria	Kahl 14-175	flat die	3 kW	lab.-scale press
Finland	CPM	ring die	1,5 – 2 t/h	mobile pelletizing unit
Germany	PM 6-28	hydraulic press	1 t/h	-

Experiments from BE2020+ were conducted in a 3 kW and a 15 kW unit. The smaller press belongs to BE2020+ and extra pelletizing tests were made for comparison of the machines.

Pelletizing experiments for BE2020+ were conducted by the Department for Agrar biotechnology, IFA Tulln (instead of FEX Ökofaser GmbH[1]). IFA Tulln runs a pellets mill with a capacity of 500 kg/h, and also the required facilities for pretreatment and mixing of the raw material. Moreover, the required parameters could be documented in order to evaluate the pelletizing process. The amount of fuel produced was reduced to about 250 kg per batch.

Keurak Oy, the VTT´s contractor for pelletizing, tried to pelletize reed canary grass. However, the tests did not succeed. Fibers of the grass twisted around the conveyer screw of the grinder and it was impossible to grind the raw material. Biobotnia Oy has a lot experiences by using straw in a ring die press. Pelletizing tests will create new business possibilities for this small enterprise. Biobotnia Oy produced batches of 5 t, the produced pellets had a diameter of 6 mm or 8 mm respectively.

The Pelletizing experiments of DBFZ were carried out by using the hydraulic press PM 6-28 of Pusch AG.

3.1 Pelletizing tests of BE2020+

In addition to the pelletizing tests at IFA-Tulln, pelletizing experiments were conducted on the laboratory pellets mill at BE2020+ using the same raw material mixtures. Pictures of the equipment used are shown in Figure 1. Results from pelletizing tests are shown in Table 3 and Table 4 respectively.

[1] The pelletizing plant FEX Ökofaser GmbH is designed for a production capacity of about 2 t/h. Thus, the facilities are not appropriate to produce small batches of below one ton. Large amounts of pellets would not be needed and, generate high costs for raw material and transport. Moreover, no adequate facilities for the mixing of raw materials are available. Thus, pretreating and mixing of the raw material would have to be done manually and therefore be very cost intensive. IFA Tulln is able to produce the required test fuels and measure required parameters in order to evaluate the pelltising process.

mixBioPells
Market Implementation of extraordinary biomass pellets
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(a)

(b)

(c)

(d)

Figure 1: Pictures from pellets experiments in AK-33-390 (a)-(b), and AK 14-175 (c)-(d).

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Table 3: Parameters determined during pelletizing experiments with AK 33-393.

Sample	**CH 1**	**CH 2**	**CH 3**	**CH 4**
Name of pelletizer	IFA Tulln	IFA Tulln	IFA Tulln	IFA Tulln
Raw material mixture	Hay + Miscanthus (50:50)	Hay + Miscanthus (75:25)	Corncob residues + Miscanthus (50:50)	Vine pruning + Hay (50:50)
Name of the mill	AK 33-390	AK 33-390	AK 33-390	AK 33-390
Power in kW	15-30	15-30	15-30	15-30
Measures of die (diameter / length)	5/20	5/20	5/20	5/20
Included	press	press	press	press
Mixing	automatic	automatic	automatic	automatic
Moisture, before/after	14/12,7	15,5/12,0	14,2/5,9	13,3/10,6
Bulk density, before/after, kg/m³	439/560	340/490	348/620	386/550
T, after press/after cooling, °C	82/--	82/--	98/--	80/--
Fuel consumption (spec. energy demand [kWh/kg])	0,10	0,08	0,15	0,09
Quality of pellets – Mechanical durability in %	97.2	95.1	98.5	96.2
ratio of compaction	1:1,3	1:1,5	1:1,8	1:1,4
Energy demand related to the energy content of the fuel in %	2,0	1,6	3,1	1,8

Table 4: Parameters determined during pelletizing experiments with AK 14-175.

Sample	CH 1	CH 2	CH 3	CH 4
Name of pelletizer	BE2020	BE2020	BE2020	BE2020
Raw material mixture	Hay + Miscanthus (50:50)	Hay + Miscanthus (75:25)	Corncob residues + Miscanthus (50:50)	Vine pruning + Hay (50:50)
Name of the mill	AK 14-175	AK 14-175	AK 14-175	AK 14-175
Power in kW	3	3	3	3
Measures of die (diameter / length)	6/30	6/30	6/30	6/30
Included	press	press	press	press
Mixing	Manual, weighting	Manual, weighting	Manual, weighting	Manual, weighting
Moisture, before/after	15,75/12,4	15,6/11,3	14,15/7,3	13,75/9,5
Bulk density, before/after, kg/m³	467/612	389/592	371/665	457/605
T, after press/after cooling, °C	77/--	76/--	88/--	80/--
Fuel consumption (spec. energy demand [kWh/kg])	0,065	0,070	0,128	0,066
ratio of compaction	1:1,3	1:1,5	1:1,8	1:1,3
Energy demand related to the energy content of the fuel in %	1,4	1,4	2,6	1,3

Experiments showed a clear influence of the raw material on the pelletizing process. In Figure 2 the specific energy consumption and temperature of the die is shown for different raw material mixtures in both pellet mills.

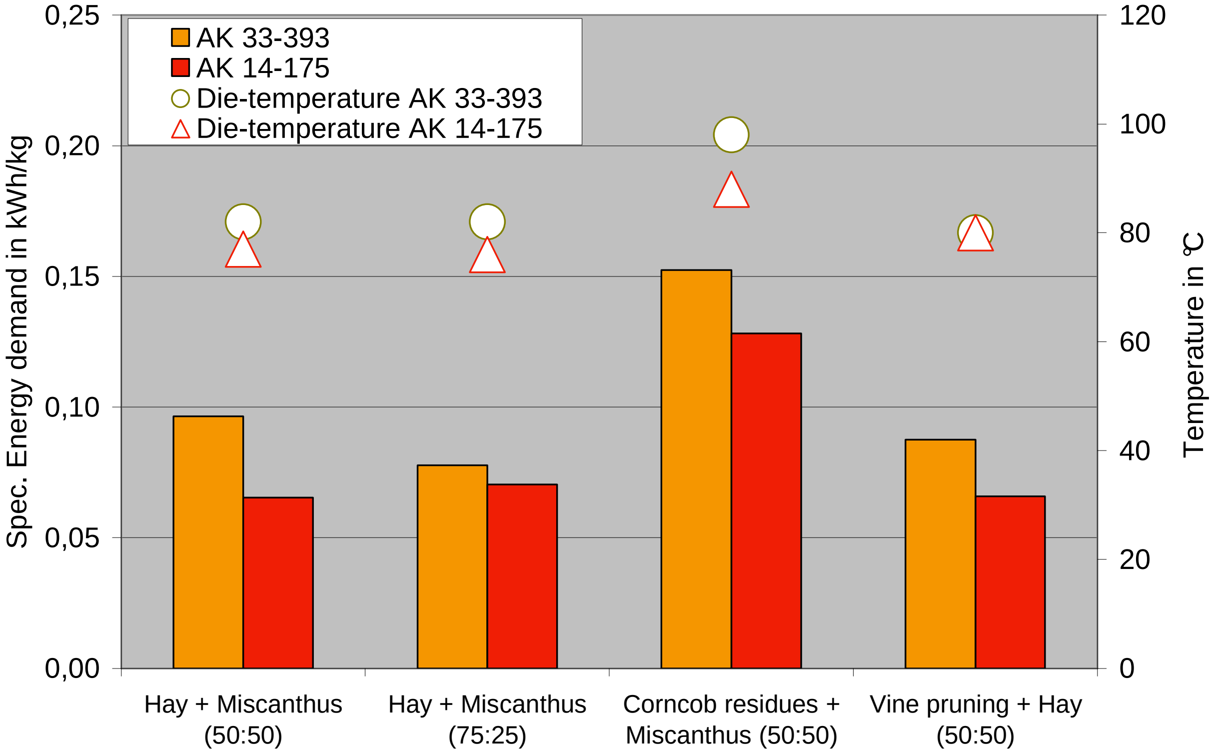


Figure 2: *Specific energy consumption and temperature of the die for 4 different raw material mixtures processed in a laboratory pellet mill (AK 14-175) and a 500 kg/h mill at IFA Tulln (AK 33-393).*

Tests in previous projects (e.g. /Eder 2005/) on the laboratory pellets mill showed a higher specific energy demand for pure Miscanthus compared to the mixtures of Miscanthus and hay. Moreover, previous pelletizing experiments showed that little energy is required for hay pelletizing.

No clear difference can be found for different mixing ratios of Miscanthus and hay, and only for the experiments in the AK-33-390 lower energy demand for the mixture with a higher hay-fraction can be assumed. For the pelletizing of the mixture of Miscanthus and corncob residues significantly higher – almost twice as much – energy was required compared to other investigated mixtures.

Low energy consumption during pellets production is preferable in order to reduce production costs. On the other hand, a certain resistance is required to ensure adequate compaction and consequently high mechanical stability of the resulting products.

In general, pelletizing properties can be optimised by mixing different raw materials. However, it must be considered, that due to strong variations regarding biomass properties, considerable differences may occur even within the same raw material type.

3.2 Pelletizing tests of VTT

The Finnish company Biobotnia Oy has a mobile pelletizing unit, shown in Figure 3. They are experienced producers of straw pellets. A whole bale can be fed into the hammer mill of the unit, which simplifies the process and makes the work faster.

Figure 3: Mobile pelletizing process. Complete bales can be fed into the hammer mill. Press is a ring die CPM.

The production capacity of the pellet mill is about 1.5 - 2 t/h and the machine can be operated with 1-2 persons in a shift. The results from pelletizing tests are summarized in Table 5.

Table 5: Parameters of the pelletizing tests at Biobotnia Oy.

Pelletizer	Biobotnia Oy	Biobotnia Oy
Raw material mixture	Straw/peat (50:50, 50:50 kaolin 2%)	RCG/wood (20:80, 50:50)
Type of the mill	CPM	CPM
Dimensions of the die	8/60 mm	6/60 mm
Includes	Grinding, bin, press, cooling, packaging	Grinding, bin, press, cooling, packaging
Mixing	Manual, weighting	Manual, weighting
Moisture content, before/after	18 – 25/12 -15	15-20/8-11
Bulk density, before/after, kg/m^3	250 /640	100/600
Temperature, after press/after cooling, °C	80 – 90/ 20-25	85 – 90 / 20-25
Fuel consumption, kWh/t	160 kWh/t	180 kWh/t

Sometimes the bales of the reed canary grass and straw are wet. The moist parts of the bales were taken away manually before grinding to avoid problems during the grinding and pelletizing process. This is a time consuming work and also reduces the available amount of raw material. VTT has made a guide on covering the bales (Paappanen et al 2011).

The raw materials were grinded at first. Afterwards, the raw materials were weighted and mixed with a bulldozer. The production of the mixed biomass pellets could be performed without major problems and good quality pellets were achieved. According to Table 9, the bulk density and mechanical durability were rather high. The amount of fines was low. The high quality of the pellets can be traced back to the rather long press channel (60 mm) of the die. The pellets were packed into big bags (about 500 kg per bag) and delivered to Ariterm Oy for the combustion tests. Furthermore, the pellets were delivered to HT-Enerco Oy for gasification test in a small scale appliance and Biofire Palokärki Oy for combustion comparative tests but without emission measurements.

3.3 Pelletizing tests of DBFZ

The pelletizing experiments were carried out by using the pelletizing plant PM 6-28 of Pusch AG which is a hydraulic press and is shown in Figure 4. So far mixtures from herbaceous, fruity and woody biomass have been pelletized. Since the pelletizing plant PM 6-28 has low requirements on mechanical properties and water content of the raw material, usually no pre-treatment is necessary. Therefore, the production of the different mixed biomass pellets was done without changing the press die. Due to these advantages, the Pusch AG has developed and manufactured the pelletizing plant PM 6-28 especially for the production of alternative biomass pellets with a production capacity of 1,000 kg/h. The modular design facilitates an increase of the production capacity to a maximum of 4,000 kg/h.

Figure 4: Pelletizing plant PM 6-28.

The benefits of the technology are:

- User-defined pellets from a mixture of raw materials can be produced.
- Raw materials with residual moisture up to 30 wt. -% can be used.
- No additional grinding (e.g. hammer mill) or pre-treatment processes are necessary for raw material with a length up to 5 cm.

The main technical details of the pelletizing plant as well as the results from the pelletizing tests are listed in Table 6.

Parameters such as specific energy demand and temperature are crucial to assess the pelletizing process. However, these parameters could not be measured at Pusch AG. Due to the big diameter of the pellets, a large amount of fuel samples are needed to analyse all quality physical – mechanical parameters of the pellets, e.g. mechanical durability and bulk density. Due to a low available quantity, the analysis could not be performed for each batch.

Table 6: Parameters determined by Pusch AG during the pelletizing experiments with the PM 6-28 (power: 140 kW, diameter of the die of 20 mm).

Sample	**CH 1**	**CH 2**	**CH 3**	**CH 4**
Raw material mixture	100 % GM	70 % GM / 30 % M	30 % GM / 70 % M	100 % M
Mixing	manual	manual	manual	manual
Moisture, before / after the pelletizing process , Ma.-%	10.4 / 10.2	14.7 / 12.6	13.5 / 9.2	12.3 / 5.8
Bulk density, before / after the pelletizing process, kg/m³	n.a.	- / 476	- / 486	n.a.
Amount of Fines	27.7	0.4	0.2	0.6

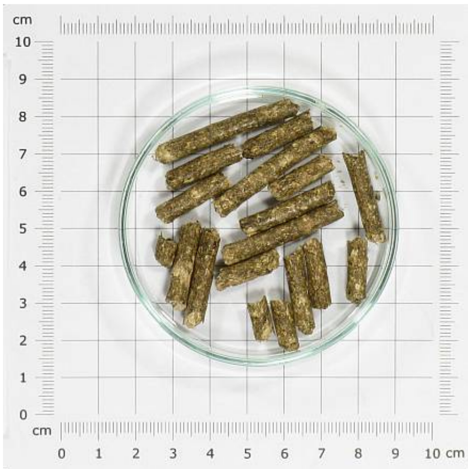
n.a. – not analysed, GM   grape marc, M   Miscanthus

4 Pellets analysis

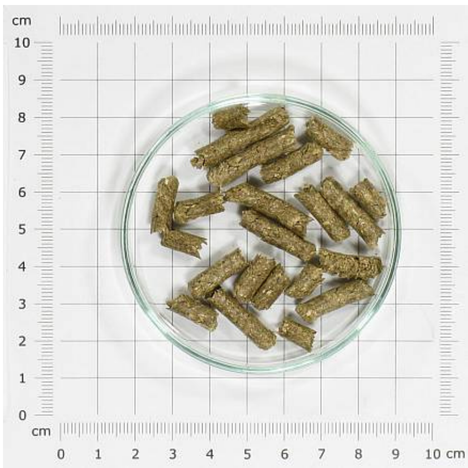
Each partner made analyses of the mixed pellets after their resources. Analyses were conducted according to the existing European standards.

4.1. Pellet analysis of BE2020+

Photos were taken from all types of pellets (c.f. Figure 5), and the main combustion relevant parameters as well as elemental analyses have been conducted. Analysis results are presented in Table 7 and Table 8.



(a)



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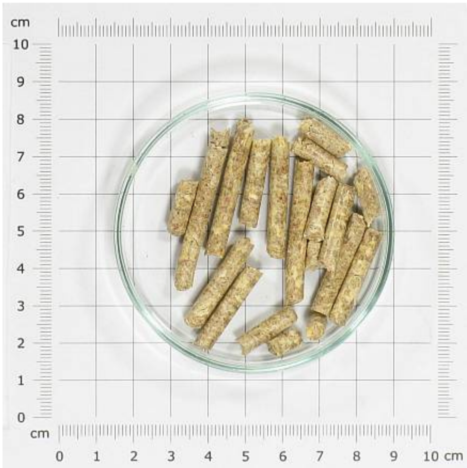

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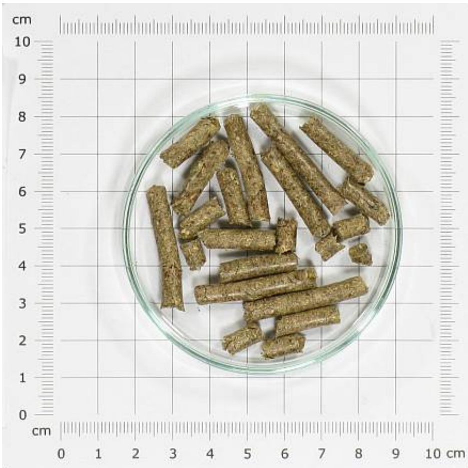

(d)

Figure 5: Mixed biomass pellets (a) CH1, (b) CH2, (c) CH3 and (d) CH4.

Table 7: Combustion relevant fuel properties of the investigated pellets. (d.b…dry basis)

	Unit	CH 1	CH 2	CH 3	CH 4
		Hay + Miscanthus (50:50)	Hay + Miscanthus (75:25)	Corncob residues + Miscanthus (50:50)	Vine pruning + Hay (50:50)
Higher Heating value (db)	MJ/kg (db)	18.63	18.79	18.77	19.16
Lower heating value (db)	MJ/kg (db)	17.38	17.51	17.47	17.87
Moisture	wt.-%	10.8	11.8	7.8	10.5
Ash	wt.-% (db)	5.98	4.58	2.27	3.54
Mechanical durability	wt.-%	97.2	95.1	98.5	96.2
Bulk density	kg/m³	560	490	620	550

Table 8: Elemental composition of the investigated pellets. (d.b…dry basis)

	Unit	CH 1	CH 2	CH 3	CH 4
		Hay + Miscanthus (50:50)	Hay + Miscanthus (75:25)	Corncob residues + Miscanthus (50:50)	Vine pruning + Hay (50:50)
C		47.03	47.83	47.74	48.21
H in wt.-% (db)	wt.-% (db)	5.68	5.85	5.91	5.89
N in wt.-% (db)		0.89	0.64	0.31	0.52
Al		1120	472	82.4	315
Ba		45.6	27.4	5.14	23.3
Ca		3710	3470	875	4580
Cd		< 0.5	< 0.5	< 0.5	< 0.5
Cl		1210	1020	1320	582
Cr		7.49	5.61	4.34	3.52
Cu		4.37	2.88	3.6	9.45
Fe		810	347	123	271
K		11000	8270	4750	5570
Mg		1500	1020	544	841
Mn		172	73.4	31.7	49.4
Na	mg/kg (db)	208	98.6	22.2	56.9
Ni		3.5	2.7	2.2	1.8
P		1280	835	402	667
Pb		< 5.4	< 5.4	< 5.4	< 5.4
S		1030	949	364	687
Si		11600	9490	5940	5580
Sr		19	11.5	2.6	9.2
Ti		143	77.5	18.6	49.1
Zn		24.6	11.8	13.3	14.3
As		< 5.4	< 5.4	< 5.4	< 5.4
Co		< 3.3	< 3.3	< 3.3	< 3.3
Mo		< 1.6	< 1.6	< 1.6	< 1.6
V		< 2.7	< 2.7	< 2.7	< 2.7

4.2. Pellet analysis of VTT

The analyses of pellet properties were carried out in the laboratory of the ENAS Oy. All analyses were done according to the existing European standards for solid biofuels. The produced pellets are shown in Figure 6 and the results of the analyses are listed in Table 9 and Table 10.

Figure 6: Experimental pellets from straw and peat mixture (left) and reed-canary-grass-wood –pellets (right).

Table 9: Combustion related fuel properties of the investigated pellets. (d.b.…dry basis)

Parameter	Unit	Straw/peat 50/50	RGB/wood 50/50
Calorimetric heating value (db)	MJ/kg (db)	19.30	19.63
Lower heating value (db)	MJ/kg (db)	18.01	18.28
Moisture content	wt.--%	11.6	11.6
Ash (550 C)	wt.-% (db)	3.6	1.7
Mechanical durability	wt.-%	-	97.2
Bulk density	kg/m³	676	577

Table 10: Elemental composition of the investigated pellets. (d.b.…dry basis)

Chemical properties	Unit	Straw/peat 50/50	RGB/wood 50/50
C	wt.-% (db).	49.0	49.5
H		5.9	6.2
N		0.8	< 0.2
O(calculated)		41	43
S		0.1	0.03
Cl		0.091	0.01
K	mg/kg (db).	7,200	750
Na		270	21

The lower heating value of both mixtures is almost equal. The main difference is the ash content, which is in the case of straw/peat mixture two fold higher than the value of reed canary grass – wood mixture (3.6 wt.-% db and 1.7 wt.-% respectively). Spring harvested reed canary grass contains also relatively low concentrations of S, Cl, K and Na compared to the straw/peat mixture.

4.3. Pellet analysis of DBFZ

The produced pellets are displayed in Figure 7. The main physical-mechanical and combustion relevant parameters have been determined and elemental analyses have been conducted according to the existing European standards. The results are listed in Table 10.

Figure 7: Produced biomass pellets (A: 100% grape marc; B: 30% grapemarc / 70% Miscanthus; C: 70% grapemarc / 30% Miscanthus; D: 100% Miscanthus)

Physical – mechanical properties

The bulk density of the grape marc and Miscanthus pellets was not analyzed due to the small sample amount. However, the bulk density of the mixed biomass pellets is < 500 kg/m³ and thus below the threshold of the prEN 14961-6 for class A and for Miscanthus pellets. The amount of fines is an indicator for the mechanical stability of the pellets. The values listed in Table 11 indicate that the grape marc pellets show a very high amount of fines. This might be attributed to the fact that there could be a separation of fines and accumulation at the bottom of the batch may have occurred. The values are not representative, see Figure 8. The fines were separated by using a sieve with a circular mesh of 8 mm. The batch with the lower amount of fines was used for the combustion tests. The results from the analysis of the chemical and combustion related fuel properties are listed in Table 11.

Figure 8: Delivered grape marc pellets (before sieving).

Table 11: Fuel properties of the investigated pellets.

Parameter	Unit	100% GM	70% GM / 30% M	30% GM / 70% M	100% M
Diameter	mm	21	21.3	22.6	20.3
Length	mm	18.1	24.7	37.2	36.3
Bulk density	kg/m³	n.a.	476	486	n.a.
Fines	wt..-%	27.7	0.4	0.2	0.6
Ash content	wt.-% (d.b.)	7.86	6.58	3.92	2.66
Moisture content	wt.-%	9.78	10.2	7.36	3.23
Volatiles	wt.-% (d.b.)	64.0	67.5	74.7	80.5
Lower heating value, H_u	MJ/kg	20.78	21.0	20.06	17.34
Carbon, C	wt.-% (d.b.)	53.8	52.3	50.3	48.1
Hydrogen, H		5.57	5.55	5.63	5.9
Oxygen, O		37.43	39.74	42.71	45.69
Nitrogen, N		3.2	2.41	1.36	0.31
Sulphur, S		0.16	0.171	0.121	0.04
Chlorine, Cl		0.004	0.03	0.046	0.045
Phosphor, P	mg/kg (d.b.)	4,800	3,700	1,500	751
Potassium, K		27,800	24,900	10,800	4,710
Calcium, Ca		8,270	6,800	2,430	1,360
Natrium, Na		88.9	74.3	83.4	156
Magnesium, Mg		1,710	1,350	682	545
Silizium, Si		2,790	6,830	7,220	9,990
Iron, Fe		422	712	322	244
Aluminium, Al		294	118	120	351
Arsenic, As	mg/kg (d.b.)	0.15	< 0.007	< 0.007	0.06
Cadmium, Cd		< 0.04	0.048	0.072	0.138
Chromium, Cr		2.65	6.28	10.2	6.57
Chopper, Cu		26	20.3	8.42	6.62
Lead, Pb		1.79	3.42	2.81	3.52
Mercury, Hg		0.007	< 0.072	< 0.0072	< 0.0072
Nickel, Ni		0.942	2.97	4.81	3.0
Zinc, Zn		36.5	48.2	86.2	73.7
n.a. – not analysed, d.b. – dry basis, GM - grape marc, M - Miscanthus					

Combustion relevant properties

The ash content of the fuels decreases with an increased ratio of Miscanthus due to the lower ash content of the latter. For the mixed biomass pellet (70% grape marc / 30% Miscanthus) and the grape marc pellets it is high and the requirements of the prEN 14961-6 for class A cannot be fulfilled. The maximum water content of the pellets is 10.2 Ma. -%, and slightly exceeds the required threshold of the prEN 14961-6 for class A. This can be improved by an optimized conditioning and pelletizing process. The lower heating value of the grape marc pellets is 20.78 MJ/kg (d.b.) and significantly higher compared to Miscanthus or other herbaceous biomass (H_u ~ 17.4 MJ/kg d.b.) or compared to woody biomass (Hu ≥ 18.4 MJ/kg d.b.) /Kaltschmitt 2009/. However, the requirements of the prEN 14961-6 for class A and for Miscanthus pellets can be fulfilled.

Chemical properties

The content of nitrogen, sulphur and chlorine as well as alkaline metals such as K or Na is crucial for the formation of problematic gaseous and particulate flue gas compounds. The requirements of the prEN 14961-6 for class A can be fulfilled for the parameters chlorine and sulfur. Due to the high content of nitrogen in grape marc, only an addition of 30% of Miscanthus can ensure low nitrogen contents which are below the threshold of the prEN 14961-6 for class A.

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5 Combustion tests

Combustion tests have been conducted in different combustion units of 15 - 60 kW. Table 12 gives an overview about the main characteristics of the combustion appliances.

Table 12: Overview about boiler systems used for combustion tests in different institutions.

Boiler	Institution/ country	Nominal heat output	Fuel feeding	Control principle	Grate system
Hargassner HSV 15 (adapted version)	BE2020+ (AT)	15 kW	side feed	Lambda controlled	Moving grate
Ariterm Bequem	VTT (FI)	40 kW	underfeed	-	Bowl pellet burner
Ariterm MultiJet	VTT (FI)	60 kW	side feed	-	Moving grate
A	DBFZ (DE)	30 kW	side feed	Lambda and power controlled	Reciprocating grate
B	DBFZ (DE)	47 kW	side feed	Lambda and power controlled	Horizontal stoker burner

5.1 Combustion tests of BE2020+

5.2.1 Experimental setup and measurement methods

Combustion tests at BE2020+ were carried out in a commercially available pellet boiler (HSV 15) that was adapted with an additional ash removal device. Several tests with different fuels had been conducted using this boiler previously, and thus, a lot of reference data is available, especially from the combustion of pure raw materials used for the mixtures in the present investigations. Furthermore, the settings of the boiler can be adjusted to different fuel qualities.

Each combustion test was conducted for a minimum duration of 8 hours, and average emission values were determined in 4 intervals over the whole experiment.

With the exception of the total dust emissions, all parameters were measured and recorded continuously in intervals of 2 seconds during the whole test. The gaseous emissions were detected in the dry flue gas stream according to ÖNORM M 9466. Dust measurements were carried out with a tubular filter according to VDI 2066/ sheet 2 (1993) "Measurement of particulate matter in flowing gases".

5.2.2 Results

In Table 13 average emission values are shown for the investigated pellets and for wood pellets according to ÖNORM M 7135 for means of comparison.

Table 13: Results of gaseous emissions from the combustion tests with the investigated pellets.

Fuel	Time intervals	O_2	CO_2	CO	NO_x	SO_2	VOC
		[Vol.-%]	[Vol.-%]	[mg/MJ]			
CH 1 Hay + Miscanthus (50:50)	1	9.99	10.46	63	272	60	n.d.
	2	10.05	10.39	48	277	60	n.d.
	3	9.84	10.59	50	270	60	n.d.
	4	9.90	10.54	41	269	59	n.d.
	Average	**9.95**	**10.50**	**51**	**272**	**60**	n.d.
CH 2 Hay + Miscanthus (75:25)	1	9.96	10.46	84	255	55	n.d.
	2	9.73	10.70	59	270	59	n.d.
	3	9.99	10.45	117	250	58	n.d.
	Average	**9.90**	**10.53**	**88**	**258**	**57**	n.d.
CH 3 Corncob residues + Miscanthus (50:50)	1	9.83	10.75	29	183	24	n.d.
	2	9.83	10.73	39	179	25	n.d.
	3	9.87	10.68	31	186	24	n.d.
	4	9.91	10.64	25	183	24	n.d.
	Average	**9.86**	**10.70**	**31**	**183**	**24**	n.d.
CH 4 Vine pruning + Hay (50:50)	1	9.90	10.54	50	234	37	n.d.
	2	9.97	10.44	42	239	36	n.d.
	3	10.02	10.37	61	232	36	n.d.
	4	10.06	10.33	46	229	37	n.d.
	Average	**9.99**	**10.42**	**50**	**233**	**36**	n.d.
Wood pellets (reference)	1	9.60	10.74	27	86	n.d.	n.d.
	2	9.71	10.63	23	87	n.d.	n.d.
	3	9.71	10.62	20	87	n.d.	n.d.
	4	9.79	10.53	20	87	n.d.	n.d.
	Average	**9.70**	**10.63**	**22**	**87**	n.d.	n.d.

n.d. .... not determined

In Figure 8 emission values for NO_x (a) and SO_2 (b) from the combustion of the investigated mixed pellets are shown related to N-content and S-content in the fuel respectively. Moreover, data from pure biomass pellets are shown for means of comparison. Both NO_x- and SO_2-emissions show a clear correlation to the respective elemental concentration in the fuel, and no differences can be found regarding the release of nitrogen and sulphur from raw material mixtures.

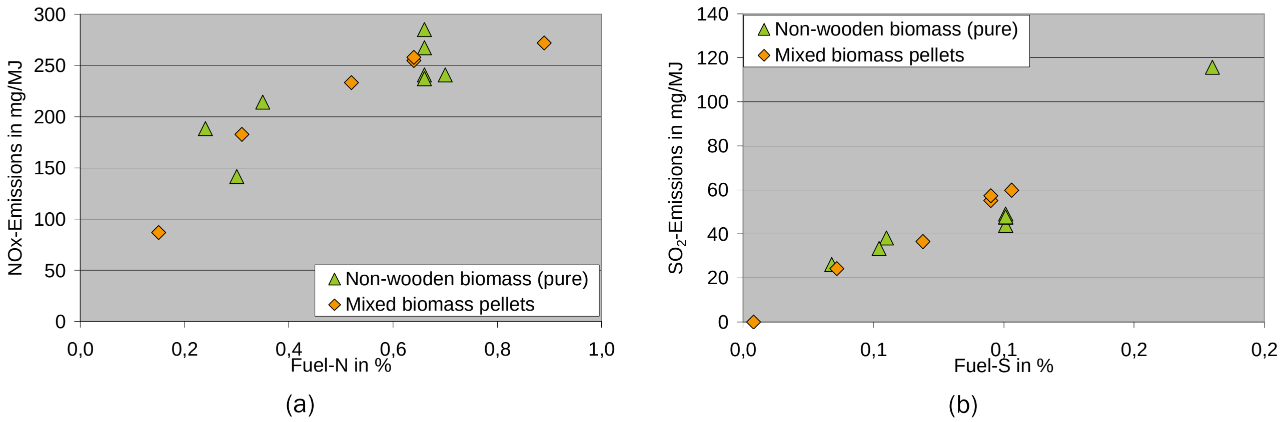


Figure 8: *NOx-Emissions (a) and SO2-Emissions (b) versus fuel-nitrogen and fuel-sulphur respectively for pellets made of pure raw materials and raw material mixtures.*

In Figure 9 (a) and (b) dust emissions of the investigated mixed biomass pellets and some pure biomass pellets are shown. Results show that only very rough qualitative predictions about the dust emissions of mixed biomass pellets are possible based on results gained from pure raw materials, and no quantitative prediction can be concluded.

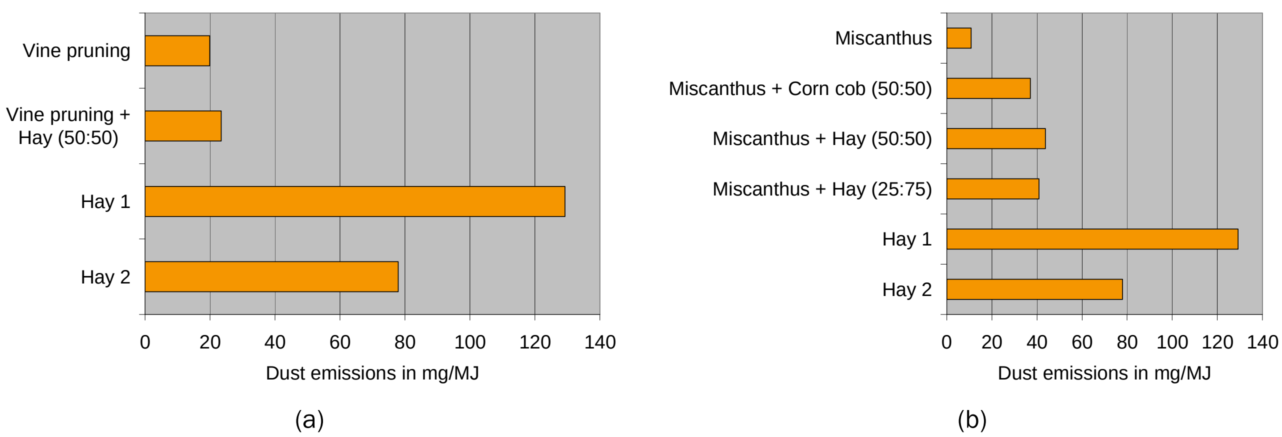
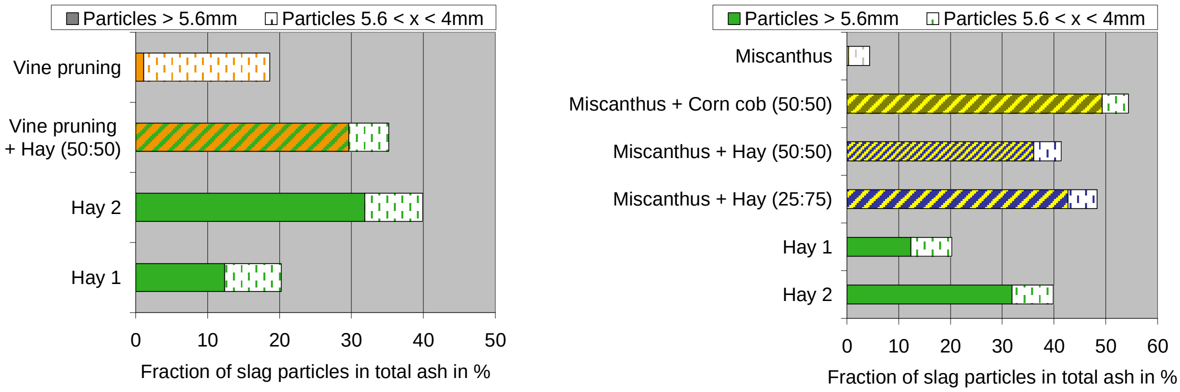


Figure 9: *Dust emissions from the combustion of mixed pellets and pellets made of pure raw material.*

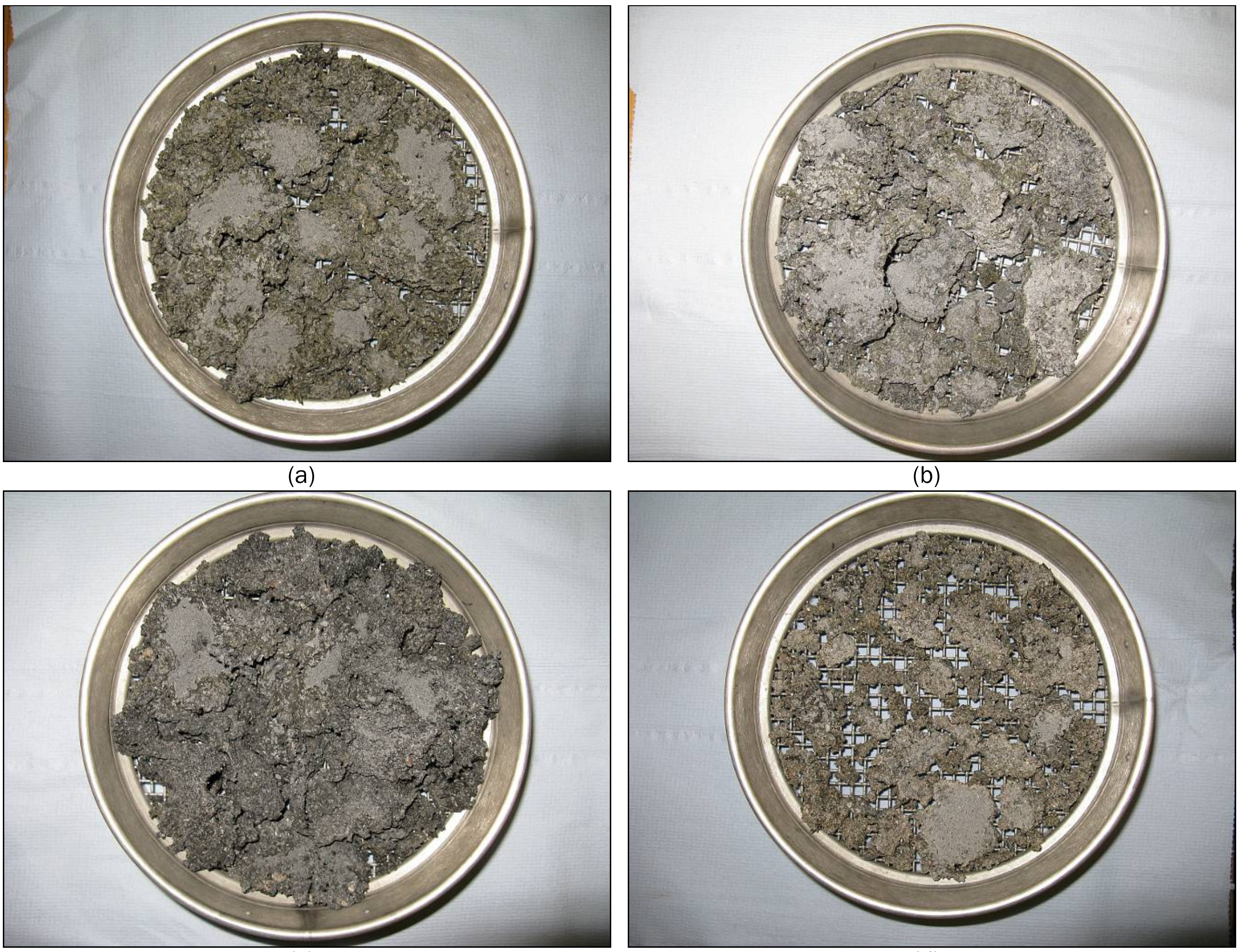
In general, CO-emissions were relatively low for all investigated fuels. However, the level of CO emissions is more dependent to the combustion technology than to fuel properties.

A more difficult issue is to estimate the slag formation tendency based on the properties of the raw materials used. It was found that even small amounts of so-called “problematic” fuels added to e.g. wood or Miscanthus, can lead to a severe increase of the slag formation tendency of the mixture. In Figure 10 (a) and (b) a quantitative evaluation of the slag formation during the combustion of the investigated mixed biomass pellets as well as particular pure raw materials is shown. In Figure 11 pictures of the biggest slag fractions of the mixed biomass pellets are presented.



(a) (b)

Figure 10: Fraction of slag in combustion residues for the investigated mixed biomass pellets and for some pure raw materials.



(c) (d)

Figure 11: Fraction of biggest slag particles after the combustion of mixed biomass pellets (a) CH1, (b) CH2, (c) CH3 and (d) CH4

Conclusions of the Austrian combustion tests

Particular fuel properties such as ash content or elemental concentrations can be set by mixing different raw materials, and in particular pelletizing properties may be enhanced by choosing adequate proportions of the respective raw materials. Therefore, also concentrations of N, S and Cl and consequently the formation of harmful emissions formed by these elements can be controlled. The formation of dust emissions is influenced by complex reactions. Thus, a systematic optimisation by mixing raw materials can be made only for certain groups of raw materials or mixtures. However, a broad database is needed to apply to the considerable range of variation in the fuel properties too.

With regard to ash melting and slag formation, an optimisation of low melting ash-fuels by adding a certain amount of non-slagging fuels is no promising measure since ash melting properties are dependent to complex reactions of ash forming compounds, and also relations of particular compounds are decisive.

5.2 Combustion tests of Ariterm Oy

Only a few flue gas parameters were measured by using the MultiJet –burner of VTT´s subcontractor Ariterm Oy, i.e. CO-content (ppm), CO_2 (%) and O_2 (%). The measurements of Ariterm Oy are usually carried out in an external laboratory. However, this was not possible with the available budget.

Two combustion tests with the barley straw /peat (50/50) pellets were carried out with a 40 kW BeQuem bowl burner at nominal load. The BeQuem bowl burner filled and choked rapidly, probably because of the lack of primary air. The bowl burner operated acceptably at partial load. However, the carbon monoxide emissions were high. The air feed openings of the boiler began to clog. In conclusion, this combustion system is not suitable for the use of straw/peat –pellets. This applies also for the experiments with reed canary grass/wood pellets.

Straw/peat –pellets with 2 wt.-% kaolin were tested in a MultiJet burner with a nominal capacity of 60 kW. The boiler was operated at nominal load. The combustion behaviour was comparable to the use of peat. Only a slight slag formation in the bottom ash was observed after the boiler operation was finished. The moving grate removed the slag from the grate into the ash box. The CO emissions of25 – 75 ppm indicate a good and stable combustion process, see Table 14. The combustion test was repeated three times for 5 hours each.

Furthermore, the peat/straw pellets without additive were used in the 60 kW MultiJet–burner Experiments were done equally to the previous experiments. Only a slight slag formation in the bottom ash was observed after the boiler operation was finished. However, slightly more slag was formed during the combustion process compared to the previous experiments. The moving grate removed the slag from the grate into the ash box. The CO emissions were of 100 – 200 ppm were slightly higher compared to the previous experiments, see Table 14.

Table 14: The average values of the combustion results with Ariterm MultiJet-burner.

Emissions	Straw 50%/ peat 50%	Straw 50%/ peat 50%, kaolin 2%	Reed canary grass 20%/wood 80%
CO, ppm[1)]	100 - 200, peaks 1000	25 – 75, peaks 100-200	150 - 180
CO_2, Vol.-%	12 -15	10 - 14	
O_2, Vol.-%	5 - 10	7 – 10.5	9.5 – 9.9

[1)]CO was measured as basis, not reduced to any reference of O_2.

The combustion behaviour of the reed canary grass and wood (20/80%) pellets can be compared with the use of wood pellets. According to Mr. Kimmo Kantalainen from Ariterm Oy the CO emissions were also low. The boiler efficiency was measured with 94%. Two combustion tests were done with a duration of 6 hours each. Unfortunately the mix of wood and reed canary grass (50/50%) bag disappeared at Ariterm Oy. Thus, the combustion tests could not be carried out.

Figure 12: *Slag particles after the combustion of mixed biomass pellets with Ariterm MultiJet-burner. Left ash particles from straw-peat (50/50% with additive) and right wood-reed canary grass experiment (20/80%).*

In 2008, combustion tests and emission measurements with the former prototype of Ariterm MultiJet-burner and different alternative fuels were done / Oravainen 2008/. The total suspended particles (TSP) and PM10 emissions in the diluted flue gas were measured by using an impactor. Figure 14 and 15 show the results of these experiments. It can be figured out that the dust emissions from the combustion of reed canary grass are comparable with the combustion of wood and bark pellets respectively. Barley straw had the highest emissions in the combustion tests.

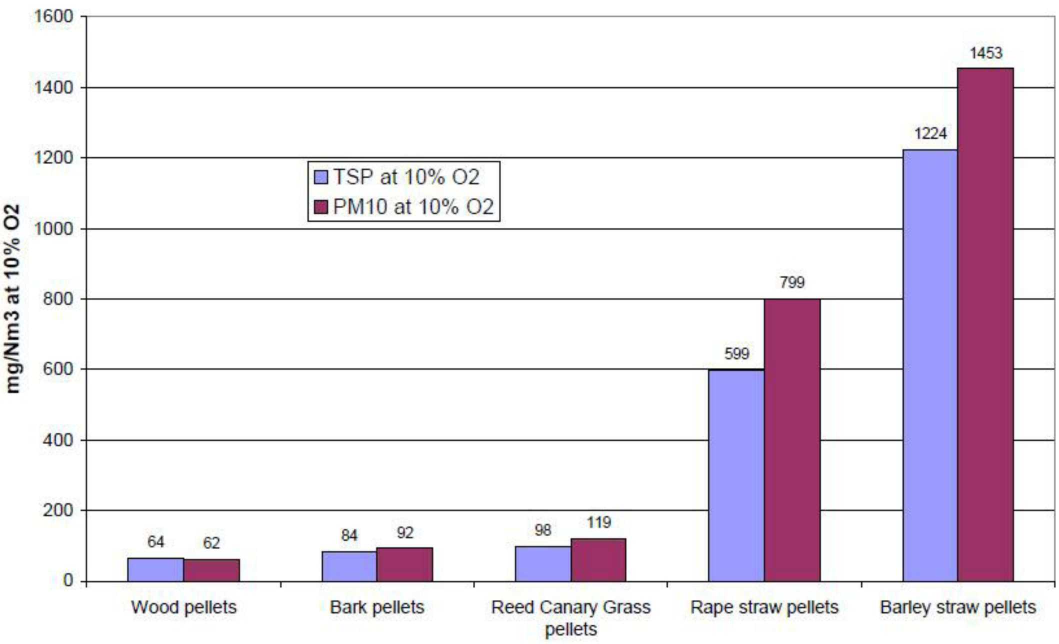


Figure 13: *Small particles in the flue gas /Oravainen 2008/.*

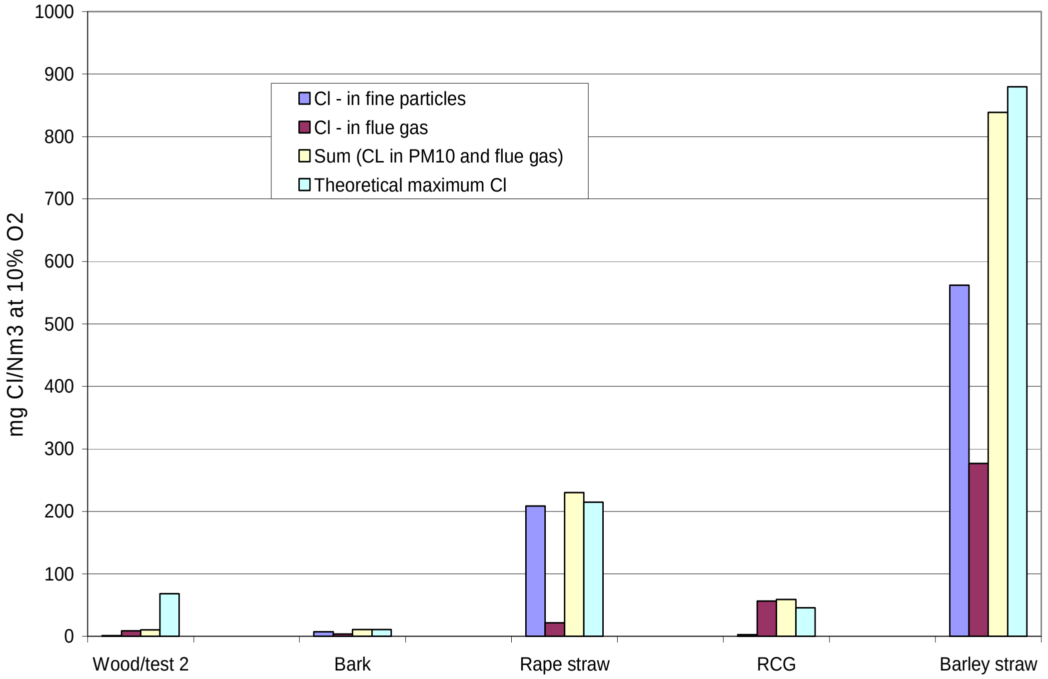


Figure 14: *Chlorine content in the flue gas (Oravainen, 2008).*

Tissari et al. (2008) investigated the combustion behaviour of cereals and woody biomass in a 20 kW boiler. The combustion was stable and the emissions of incomplete burning were low. With cereal fuels the NO_x –emissions were 4 – 6 fold, Cl-emissions 3 – 21 fold and SO_2-emisions 50 – 110 fold higher compared to the combustion of wood. The highest SO_2-emissions were measured during the combustion of rape straw and seeds. Furthermore, the highest Cl-emissions were measured during the combustion of oats and the lowest during the combustion of rape. A high correlation was found between the Cl content of raw material and Cl-emissions.

Conclusions of the Finnish combustion tests

Usually small scale boilers for the use of wood pellets are not suitable for the use of alternative and mixed biomass pellets. Large amounts of bottom ash with partially formed slag are the reason for this (c.f. Figure 13). Thus, the development of the small scale boilers needed. One solution might be the use of moving grate. The combustion of peat/straw (50%/50%) mixture was more problematic compared to the use of wood / reed canary grass pellets (80%/20%). The addition of kaolin lowered the slagging tendencies in the bottom ash during the combustion of straw/peat pellets. Thus, the use of kaolin might be an appropriate solution to reduce slagging tendencies in the bottom ash and to achieve a continuous combustion process with low CO emissions.

5.3. Combustion experiments of DBFZ and Pusch AG

The combustion tests were carried out at the combustion lab of DBFZ and Pusch AG. The used combustion and precipitator systems are commercially available and typically used for non-wood biomass fuels.

5.3.1 Experimental setup and measurement methods

Experimental setup and measurement methods at DBFZ

A boiler with a nominal heat output of 30 kW was used for the combustion tests. The boiler (in the following referred to as boiler A) is specifically designed for the combustion of ash rich fuels as well as for wood pellets and wood chips. Boiler A has the following features:

- Power and load control
- Automatic reciprocating grate
- Air staging (primary air supply to the grate and tangential secondary air supply above the firebed)

The particulate emissions were measured according to the VDI 2066 Sheet 1: „Particulate matter measurement: Dust measurement in flowing gases - Gravimetric determination of dust load" /VDI 2006/. The sampling was done by using the outstack method and the automatic isokinetic control unit ITES (Paul Gothe GmbH), see Table 15. The sampling probe was heated to 160 °C to avoid recondensation of flue gas components. If needed the sampling duration was reduced from 30 to 15 minutes to prevent failure of the isokinetic control in case of high dust load. The measurements were repeated three times for each combustion test.

Table 15: Technical details of the isokinetic control unit ITES (Paul Gothe GmbH).

Producer:	Paul Gothe GmbH
Norm:	VDI 2066 and EN 13284-1
Application:	Automatic isokinetic control
Flow rate:	0,4-4 m^3 /h
Variance of the isokinetic control	-5 % / +15 %
Filter size	45 mm

The gaseous flue gas components were measured continuously by using a GASMET CEMS FTIR-measurement system consisting of a FTIR-Gas analyser, Type CX-4000 (ANSYCO GmbH), an oxygen analyser, Typ PMA 100-L (M&C TechGroup Germany GmbH) and a heated sampling system. The measurement system is certified according to the 13. and 17. BImSchV for flue gas measurements in CHP and waste incineration plants. For the measurement of the VOC emissions a flame ionization detector FID-2010T (Testa GmbH) was used.

Experimental setup and measurement methods at Pusch AG

A boiler with a nominal heat output of 47 kW was used for the combustion tests. The boiler (in the following referred to as boiler B) is specifically designed for the combustion of ash rich fuels and wood pellets. Boiler B has the following features:

- Power and load control
- Tunnel burner with air staging
- Electrostatic precipitator for the reduction of particulate emissions

The particulate emissions were measured according to the scattered light method by using a Sick Maihak, FW102. The dust measurements were done continuously after the electrostatic precipitator and during steady operation of boiler B. The gaseous flue gas components were measured continuously by using a MCS 100 E HA of Sick UPA GmbH. Both measurement systems are certified according to the 13. and 17. BImSchV for flue gas measurements in CHP and waste incineration plants/13.BImSchV/, /17.BImSchV/.

5.3.3 Results

The combustion behavior of all used biomass pellets was continuously monitored visually during the experiments. Only slight slagging tendencies were observed. With an increasing ratio of Miscanthus the amount of slag in the bottom ash decreased, see Figure 15. However, the ash removal system always removed the bottom ash into the ash box. Furthermore, the boiler A had to be ignited with ENplus wood pellets because the ignition system could not comply with the used pellets. It took up to three hours to achieve steady operation depending on the fuel used. An optimal air to fuel ratio could only be adjusted for Miscanthus and mixed pellets (e.g. 30 % Miscanthus / 70 % grape marc). This applies for Boiler A. Similar problems have been only investigated by using grape marc pellets in boiler B.

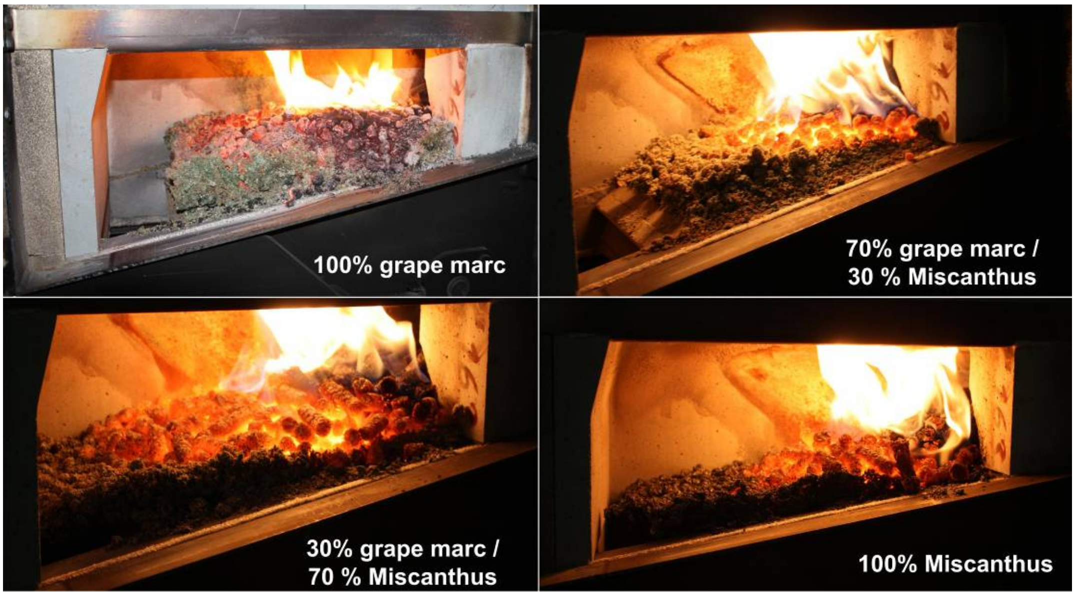


Figure 15: Combustion chamber with firebed and bottom ash during the combustion of the investigated fuels in boiler A.

Each combustion test was conducted for a minimum duration of five to eight hours depending on the available amount of fuel. The average emission values were determined over the whole duration of the experiment. In Table 16 the average emission values are shown for the investigated pellets. Results from other measurements for wood pellets and wood chip combustion according to EN 303-5 are also listed in the Table 16 for comparison.

Table 16: Average values of gaseous and particulate emissions during steady operation of boiler A.

Fuel		CO	VOC	NO_x	HCl	SO_2	Dust
		mg/m³ i.N., 13 Vol.-% O_2					
Boiler A	Grape marc pellets (GM)	1,100	4,0	725	0.9	0.3	1,030
	Mixed pellets (70 % GM / 30 % M)	3,242	21	546	0.4	0.9	796
	Mixed pellets (30 % GM / 70 % M)	117	2.7	438	0.6	0.04	300
	Miscanthus pellets (M)	30	1.0	234	11	42	117
	Wood chips	76*	1.0*	128*	n.m*	n.m.*	14*
Boiler B	Grape marc (GM)	888	11	701	3.0	2.0	337**
	Mixed pellets (70 % GM / 30 % M)	234	5.4	556	1.1	0.0	277**
	Mixed pellets (30 % GM / 70 % M)	133	5,0	416	5.6	16	25**
	Miscanthus-pellets (M)	15	2,0	247	0.5	0.0	6.3**
	Wood pellets	95*	0.73*	169*	n.m.*	n.m.*	13*

* Value from the combustion tests according to EN 303-5
** Value measured after precipitator
n.m. not measured
M...Miscanthus; GM...grape marc

In general, CO-emissions were relatively low for the Miscanthus and mixed biomass pellets (30% grape marc and 70% Miscanthus). In contrast, high CO emissions were observed for the combustion of grape marc and mixed biomass pellets (70% grape marc and 30% Miscanthus) which can be traced back to a non-optimal air to fuel ratio. However, the level of CO emissions is more dependent to the combustion technology than to fuel properties, and both combustion systems are applicable for the combustion of Miscanthus pellets.

Due to the lower nitrogen content, a significant reduction of the NO_x-emissions is observed with an increasing ratio of Miscanthus. Previous investigations showed a logarithmic correlation between the NO_x-emissions and the respective nitrogen concentration in the fuel /Härdtlein 2004/ /Launhardt 2000/ /Lenz 2008/. In contrast, a linear correlation between the NO_x-emissions and the respective elemental concentration in the fuel can be figured out within the combustion tests, see figure 17.

The differing correlations might be influenced by a high load of the combustion chamber and the available oxygen content in the firebed and combustion chamber. /Nussbaumer 1997/ /Zhou 2006/ /Launhardt 2000/. However, both boilers show quite similar NO_x emissions and the same correlation between the NO_x-emissions and the respective nitrogen concentration in the fuel.

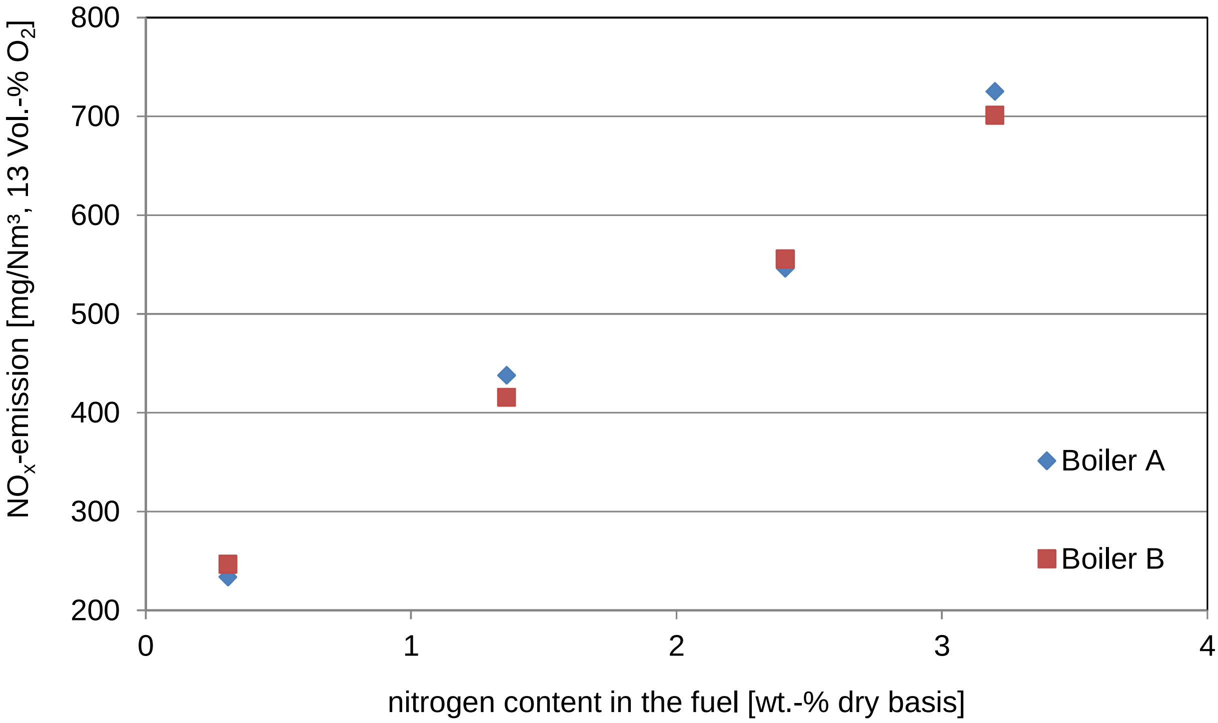


Figure 16: NO_x-emissions versus nitrogen in the fuel for pellets made of pure raw materials and raw material mixtures.

The average SO_2- and HCl-emissions of maximum 42 mg/m³ (i.N., 13 Vol.-% O_2) and maximum 11 mg/m³ (i.N., 13 Vol. -% O_2) respectively are observed during the combustion of Miscanthus in boiler A. Generally, the SO_2 emissions observed for boiler A are decreasing with increasing ratio of grape marc. Since the sulfur content of grape marc is significantly higher compared to Miscanthus, the decrease of the SO_2 emissions might be explained by higher formation of $CaSO_4$ in the bottom ash due to a higher Ca content of grapemarc /Obernberger 2006/ /Härdtlein 2004/. Furthermore, the availability of SO_2 can lead to a sulfatisation of alkalichlorides in the flue gas which leads to a decrease of gaseous SO_2 and an increased integration into dust particles /Christensen 1998/ /Glarbourg 2007/. Further analysis, e.g. of the bottom ash and the particulate matter would provide the opportunity for a detailed conclusion. An increasing formation of HCl emissions in boiler A could also be observed for increasing content of Cl in the fuel. However, the SO_2- and HCl-emissions can be rated rather low for both boilers compared to measurements of other authors /Härdtlein 2004/ /Launhardt 2000/ /Lenz 2008/ /Obernberger 2006/ /Christensen 1998/.

In Figure 17 the dust emissions of the investigated biomass pellets are shown. Due to the high content of aerosol forming elements such as K and S, high dust emissions up to 1,000 mg/m³ (i.N., 13 Vol.-% O_2) were observed with an increasing ratio of grape marc. A reduction of the dust emissions is possible by using appropriate precipitator technologies. Aerosol forming elements are the major influence for the formation of particulate matter at complete combustion /Obernberger 2006/, /Christensen 1998/ /Glarbourg 2007/. Therefore, the sum of aerosol forming elements (K, Na, S, Cl, Pb, Zn) are compared with the dust emissions from boiler A, see Figure 18 /Brunner 2006/. Based on the results of the combustion tests the sum of K, Na, S, Cl, Pb, Zn should be < 0.5 Ma.-% (d.b.) to ensure dust emissions below 100 mg/m³ (i.N., 13 Vol.-%).

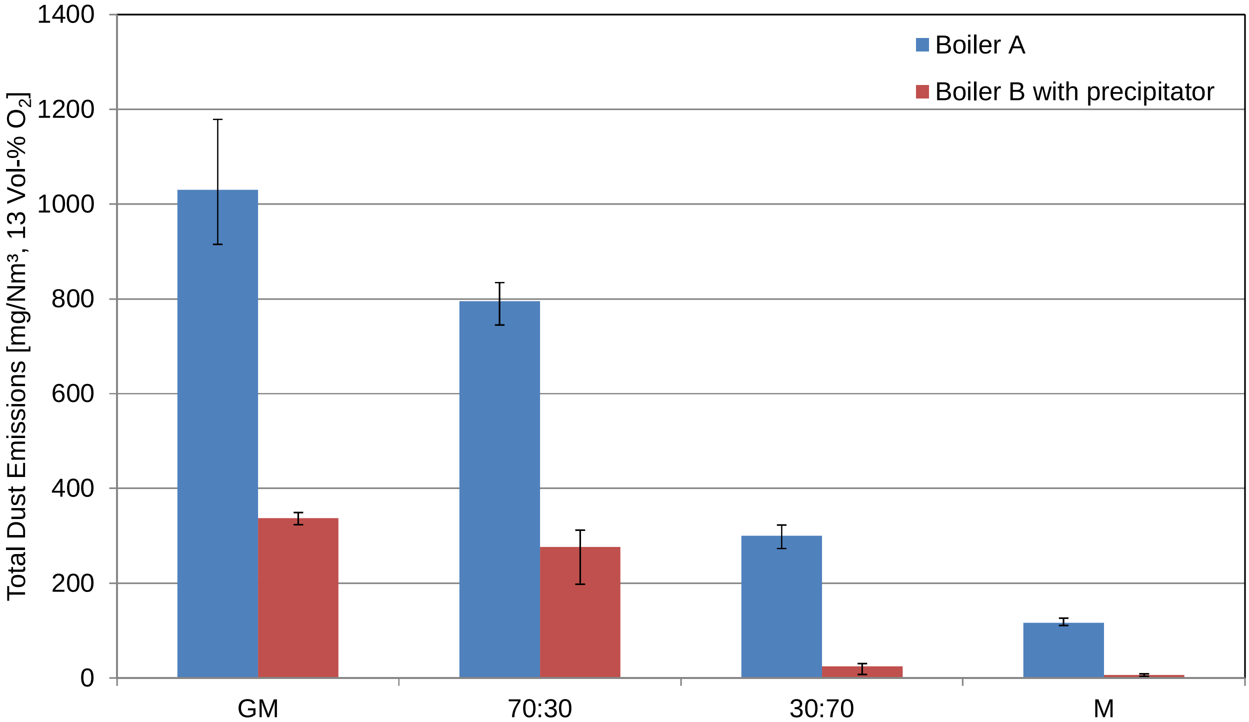


Figure 17: Average values and fluctuation range of the dust emissions.

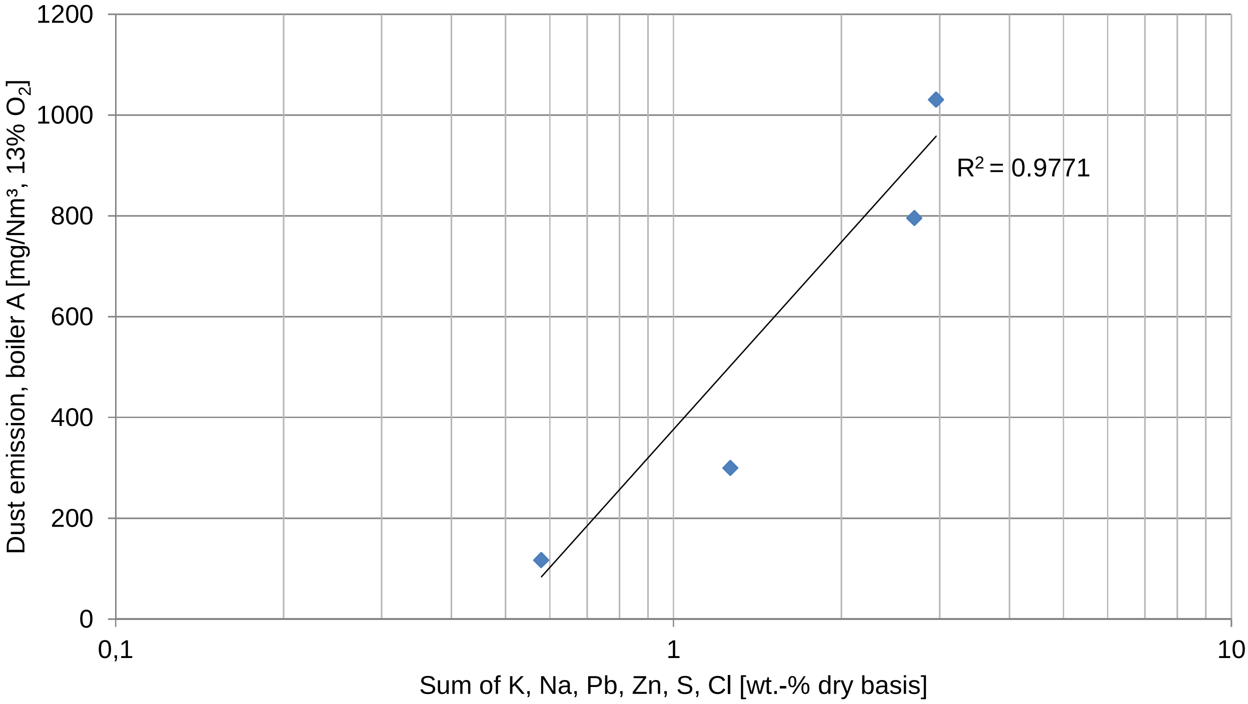


Figure 18: Dust emissions versus sum of aerosol-forming elements K, Na, Zn, Pb, S, Cl in the fuel.

Conclusions of German tests

Certain fuel properties like the ash content and the concentrations of critical elements can be set by mixing different raw materials. Furthermore, pelletizing properties may be enhanced by choosing adequate proportions of the respective raw materials. Consequently, the control of the concentrations of N, S and Cl in the fuel can be used to limit the formation of harmful emissions formed by these elements. For the combustion of the investigated fuels in boiler A a correlation between aerosol forming elements and particulate matter was observed. Thus, the sum of K, Na, S, Cl, Pb, Zn should be < 0.5 Ma.-% (d.b.) to ensure dust emissions below 100 mg/m³ (i.N., 13 Vol.-%) /Brunner 2006/. Since the formation of dust emissions is influenced by complex reactions, the sum parameter only applies for the investigated fuels in the used boiler. Further data is needed to apply to the considerable range of variation in the fuel properties. A reduction of the dust emissions is possible by using appropriate precipitator technologies. In conclusion, key actors should be aware of the following issues:

- The use of appropriate pelletizing, combustion and precipitator systems must be adjusted for certain raw materials to ensure good operation reliability.
- A systematic optimization by mixing raw materials is quite complex and a standardized procedure seems to be difficult. However, an adaption of the fuel properties can be done by the mixture of the raw materials.
- Best practice examples and experiences from other key actors in the certain regions can give important information about the pelletizing and combustion of alternative and mixed biomass pellets.

6 Summary and conclusion

Production and combustion tests with alternative and mixed biomass pellets were conducted with the support of local industry partners in three partner countries, i.e. Austria, Finland and Germany.
Each project partner selected four batches of the most interesting material mixtures for the pelletizing and combustion tests. The selection was based on the biomass report of the MixBioPells project and regional knowledge, aiming at investigating open issues within that field. Thus, the main interest was to investigate how pelletizing and combustion characteristics can be improved by mixing different raw materials. The combustion and pelletizing characteristics of the following raw material mixtures were analysed and compared with the corresponding pellets made from pure raw materials:

- 50% hay, 50% Miscanthus
- 75% hay, 25% Miscanthus
- 50% corn cob, 50% Miscanthus
- 50% hay, 50% vine prunings
- 30% Miscanthus / 70% grape marc
- 70% Miscanthus / 30 % grape marc
- 50% Straw / 50% peat
- 50% Straw / 50%peat with kaolin 2%
- 20% Reed canary grass / 80% wood

Based on the results of the fuel analysis, critical fuel properties such as ash content or elemental concentrations can be set by mixing different raw materials. Concentrations of N, S and Cl can be improved and consequently the formation of harmful emissions formed by these elements can be influenced.

In general, pelletizing properties can be optimised by mixing different raw materials. The results from the pelletizing tests showed a clear influence of the raw material on the pelletizing process, e.g. lower energy demand by using hay. However, it must be considered, that due to strong variations regarding biomass properties, considerable differences may occur even within the same raw material type. According to the analysis of the physical – mechanical properties of the produced fuels, the requirements of the product standard prEN14961-6 can be achieved with existing pelletizing technologies.

The results of the combustion tests showed that the combustion behaviour can significantly be improved by using raw material mixtures. The admixture of the mineral additive kaolin provides a good opportunity to lower slagging tendencies in the bottom ash. Furthermore, even small amounts of so-called “problematic” fuels such as hay or straw added to wood or Miscanthus, can lead to a severe increase of the slag formation tendency of the mixture. However, the formation of slag is also depending on the used combustion appliances and the temperatures in the combustion chamber. Furthermore, certain gaseous emissions such as nitrogen oxide can be significantly improved by using fuel mixtures, e.g. by mixing grape marc with Miscanthus. The formation of particulate emissions is quite complex. Thus, a prediction based on fuel sum parameters can only be done to some extent. Consequently, a targeted and systematic optimisation by mixing raw materials cannot be made in a simple way and must be assessed for specific raw material groups and mixtures.

As a conclusion, the key actors should be aware of the following issues:

- The use of appropriate pelletizing, combustion and precipitator systems have to be adjusted for certain raw materials to ensure good operation reliability.
- A systematic optimization by mixing raw materials is quite complex and a standardized procedure seems to be difficult. However, the adaption of fuel properties can be done by mixing different raw materials.
- Best practice examples and experiences from other key actors in the certain regions can give important information about the pelletizing and combustion of alternative and mixed biomass pellets. Thus, corresponding best practise examples investigated in the MixBioPells project are included in appendix 4-1 to 4-4.

7 References

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Annex

Annex A: Results from the tests of BE2020+

In the following section, several parameters are shown over the whole experimental duration.

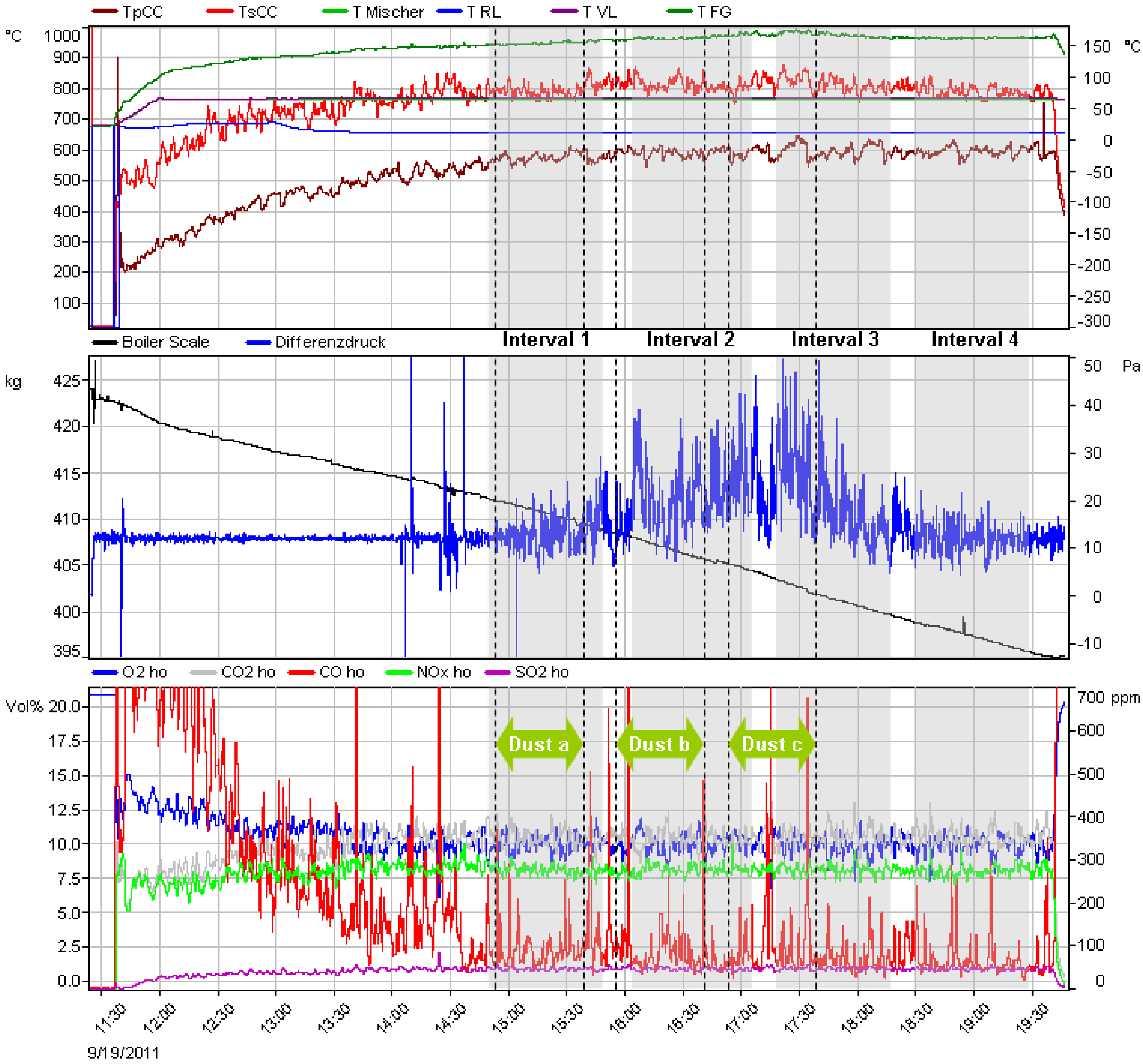

Figure A-1: *CH1 - Hay + Miscanthus (50:50).*

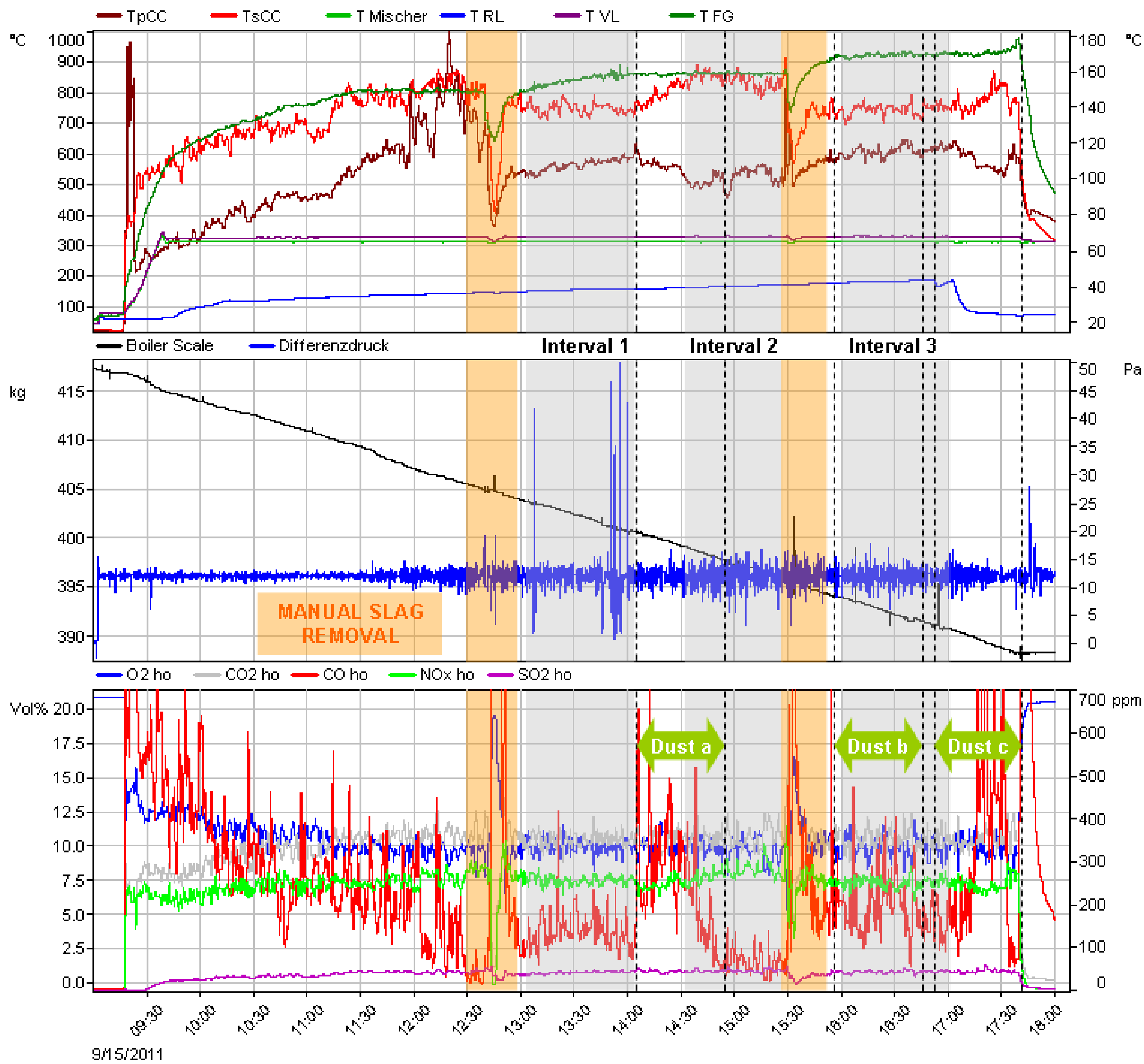

Figure A-2: *Hay + Miscanthus (75:25)*

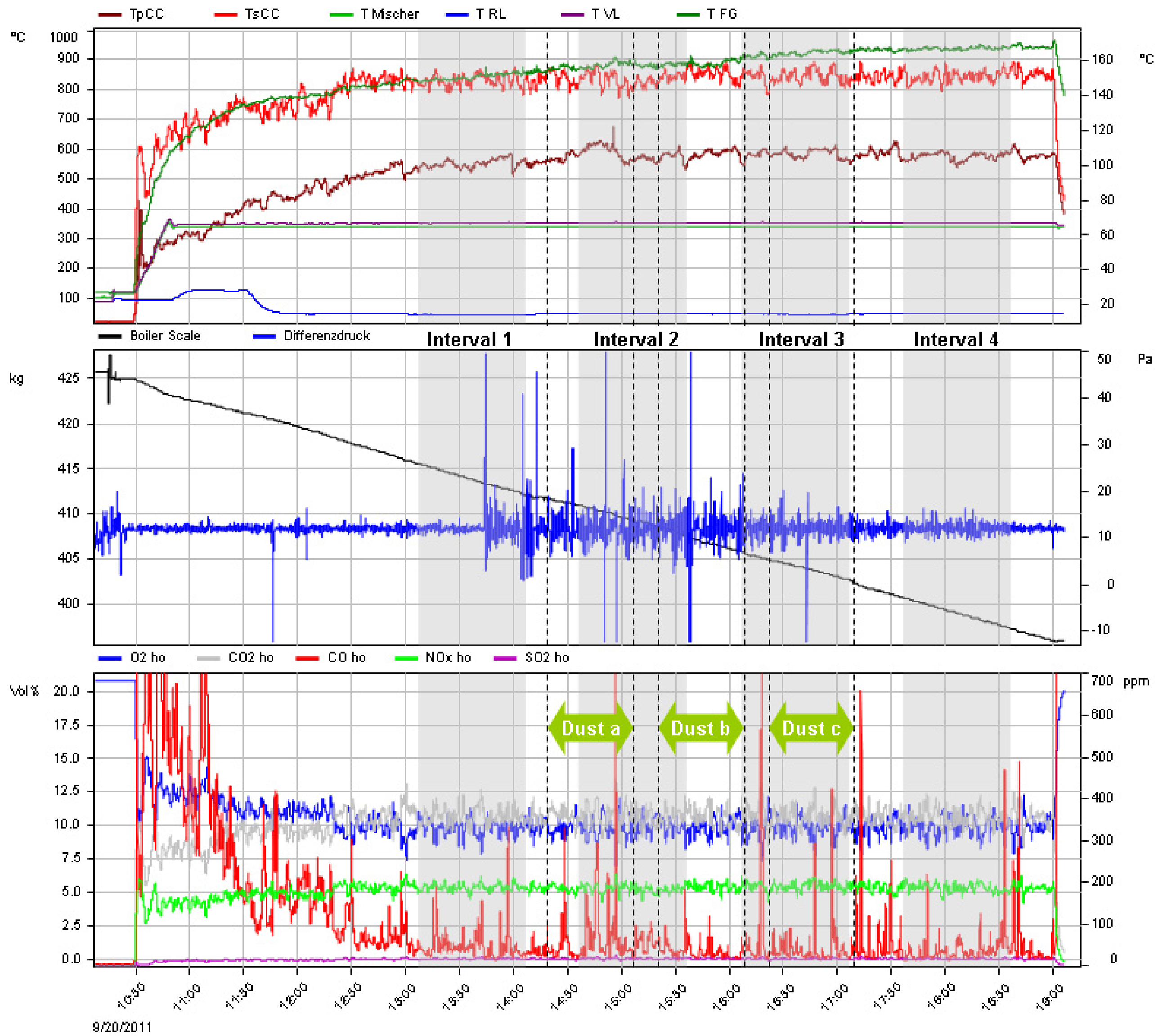

Figure A-3: Corncob residues + Miscanthus (50:50)

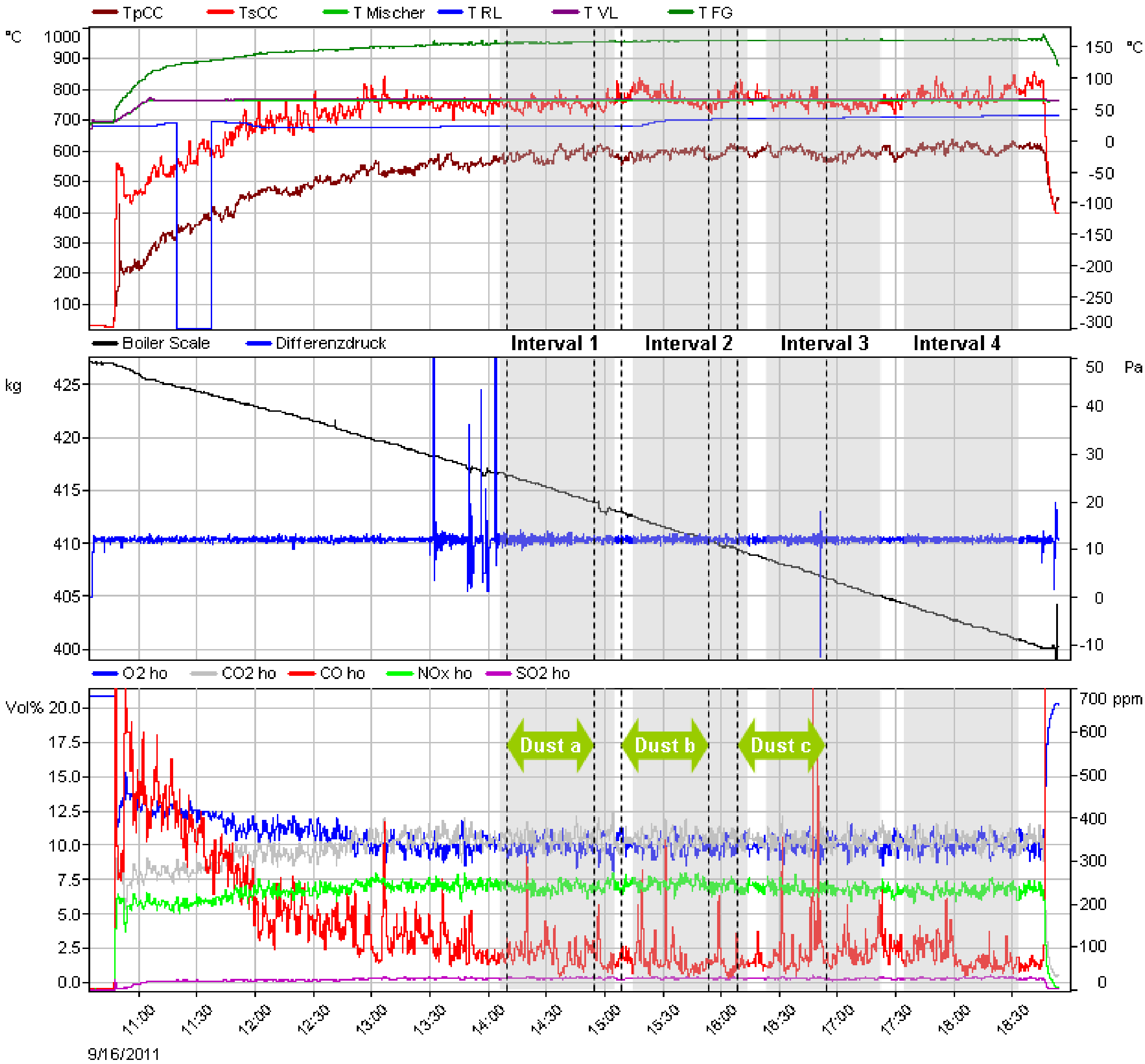

Figure A-4: *Vine pruning + Hay (50:50)*

Annex B: Results from the combustion test of Ariterm Oy (VTT).

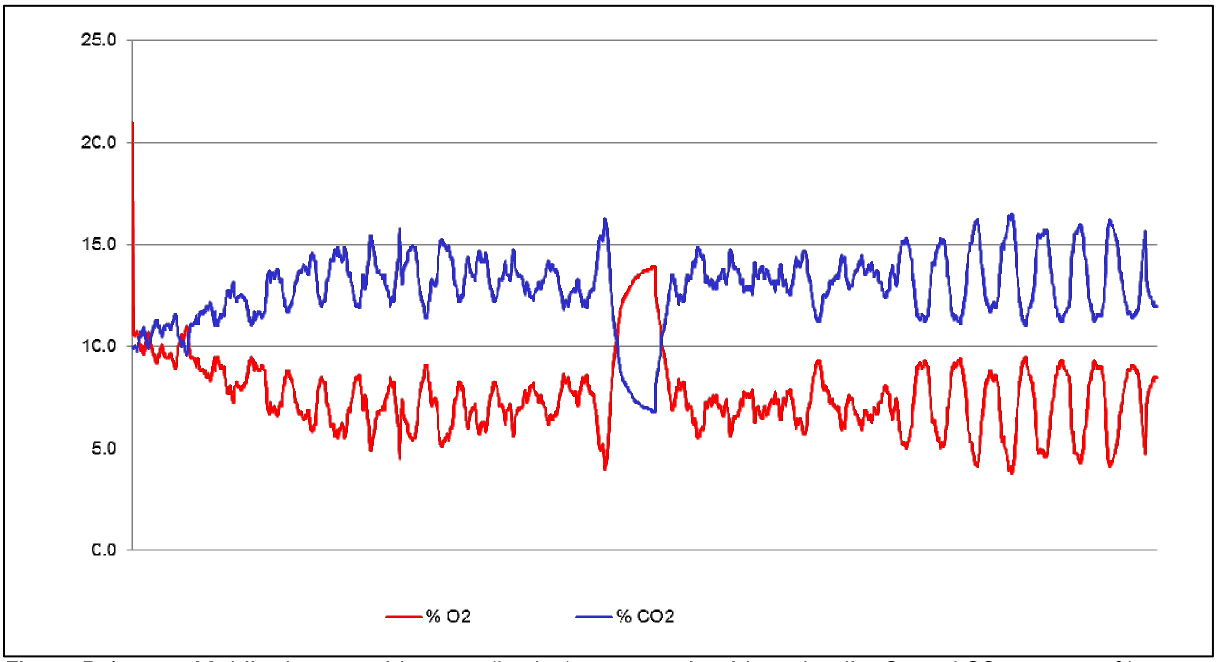

Figure B-1: Multijet burner with straw (barley) - peat –mix without kaolin, O_2 and CO_2 content, %.

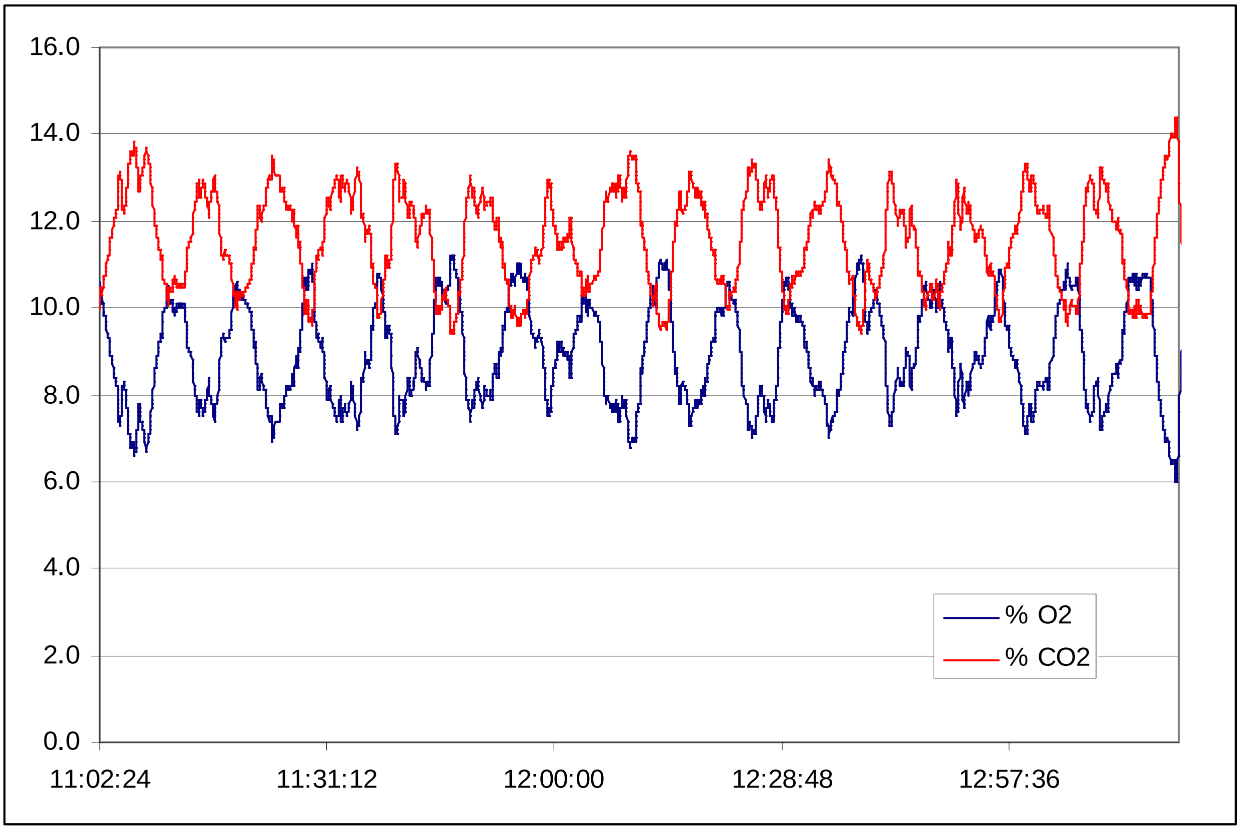

Figure B-2. Multijet burner with straw (barley) - peat –mix with kaolin, O_2 and CO_2 content, %.

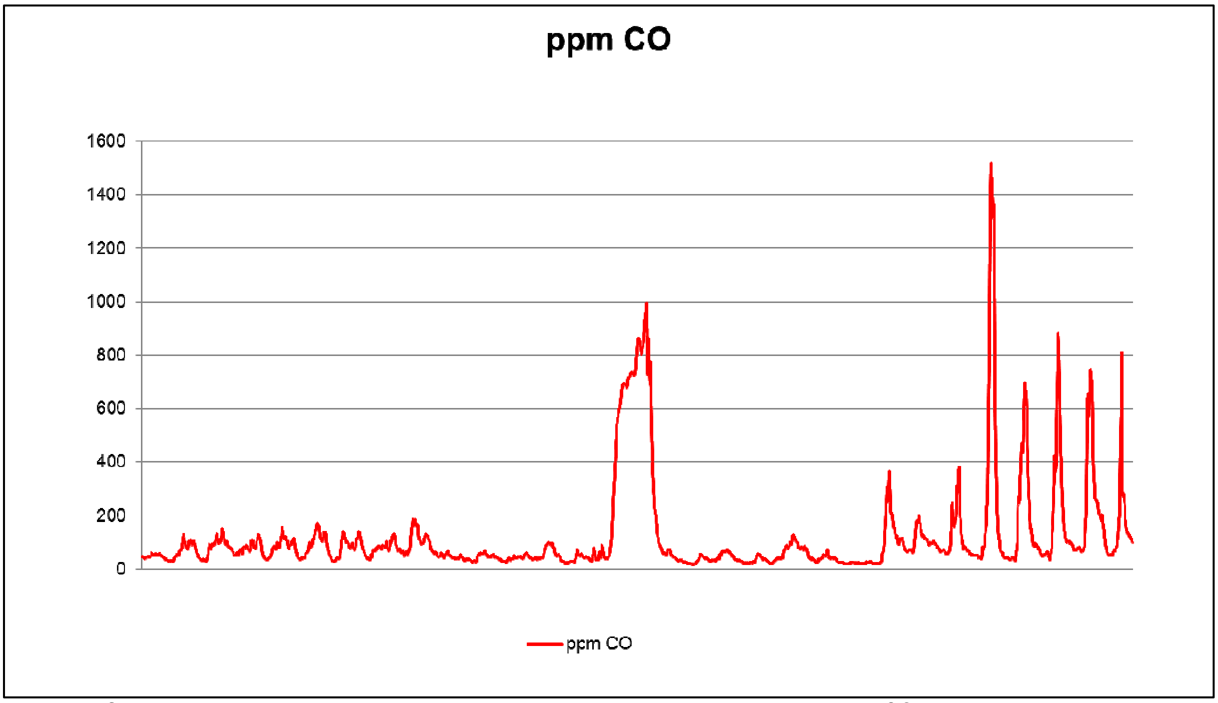

Figure B-3: *Multijet burner with straw (barley) - peat –mix without kaolin, CO-content ppm.*

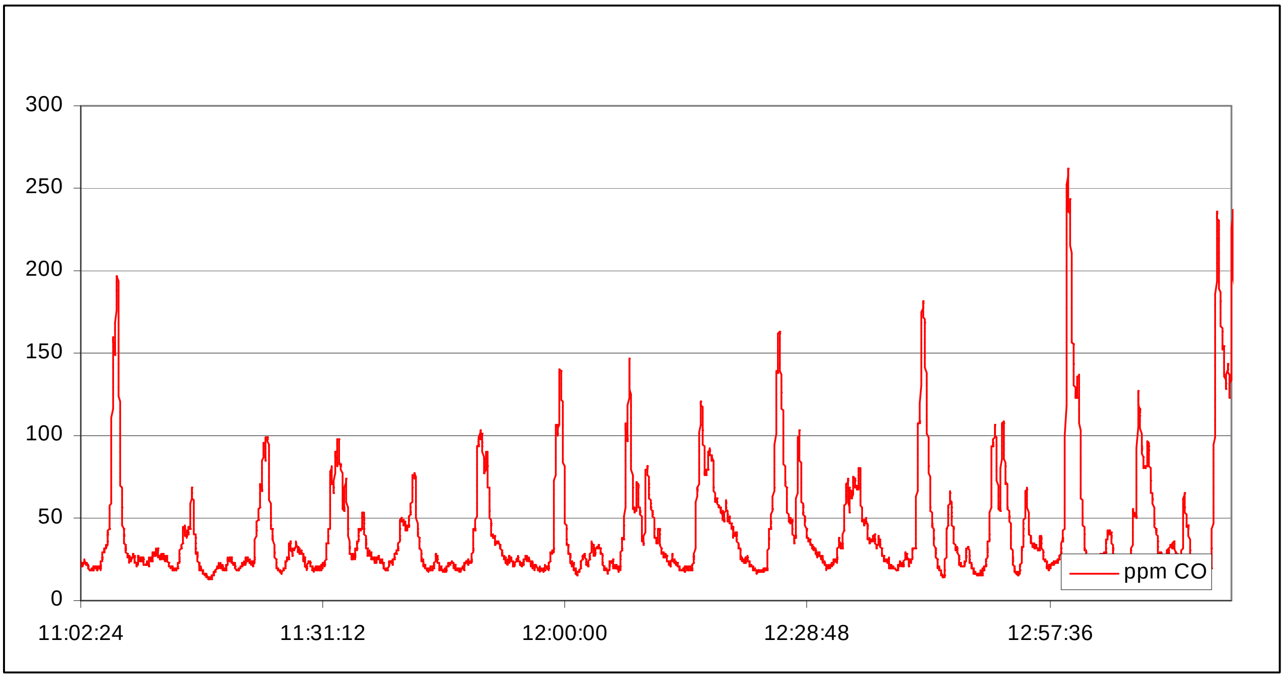

Figure B-4: *Multijet burner with straw (barley) - peat –mix with kaolin, CO-content ppm.*

Annex C: Results from the combustion test of DBFZ.

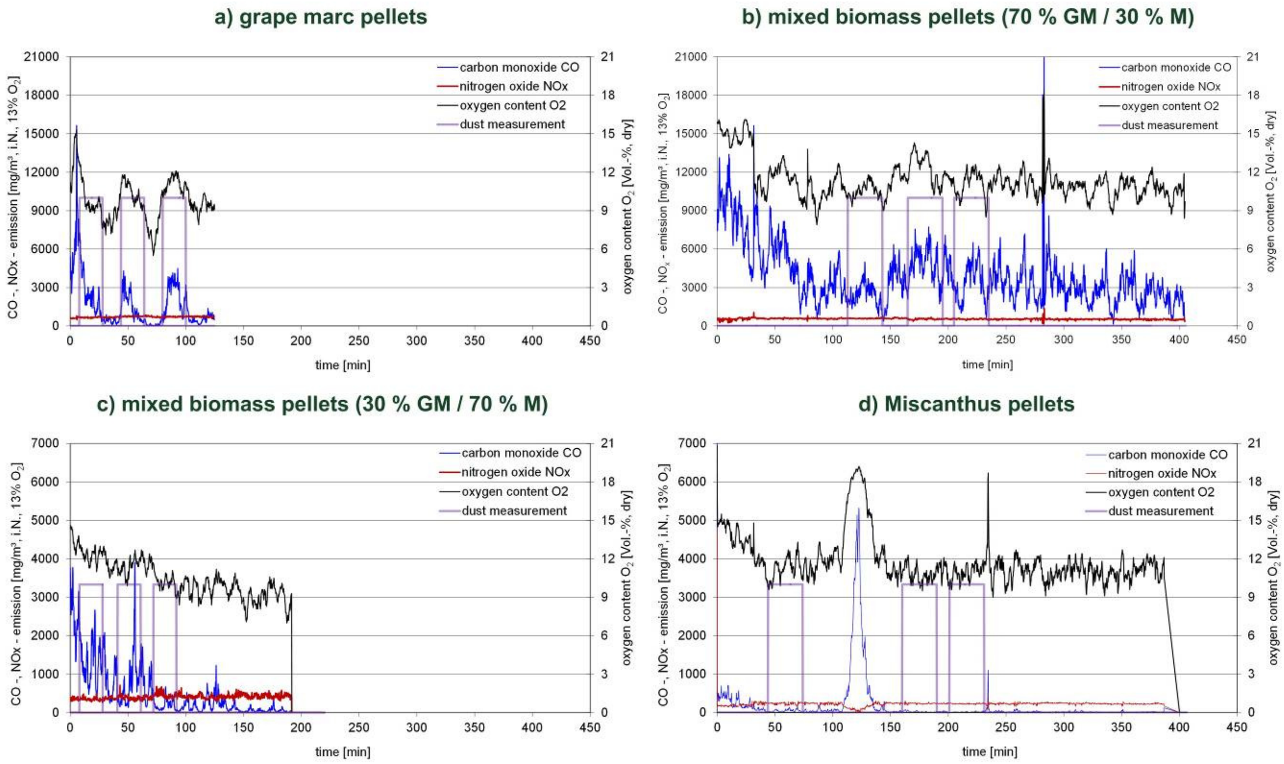

Figure C-1: In the pictures it is shown several parameters over the whole experimental duration.