Results of the combustion test campaigns

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Contents

1 Introduction and Objectives

Currently BIOMASUD PLUS fuels like olive stones are widely used for heating purposes in the domestic sector. Others, like, vineyard and olive tree pruning pellets are scarcely applied, but they represent a significant, untapped biomass potential in Mediterranean regions. This fuel potential is of increasing interest for the market since the prices for BIOMASUD PLUS fuels in Mediterranean regions are expected to be lower than the prices for wood pellets.

This Deliverable Report is related to Task 5.3 of the BIOMASUD PLUS project, *Characterization of selected biofuels combustion in commercial stoves and boilers*, which was dedicated to the determination of the efficiencies, gaseous and particulate emissions during combustion of selected BIOMASUD fuels in state-of-the-art residential heating stoves and boilers. The main objective was to find out if current residential combustion equipment is suitable for the utilisation of such biomass assortments.

Therefore, lab-tests have been performed at BIOS, CIEMAT and CERTH under well controlled conditions and utilizing common procedures. One stove and one boiler have been tested at each site. The detailed objectives were:

- Performance of test runs by BIOS, CIEMAT and CERTH under well controlled conditions and utilizing common procedures.
- Test of one stove and one boiler per partner
  - capacity range of the stoves: up to 10 kW_{th}
  - capacity range of the boilers: between 20 and 120 kW_{th}
- Elaboration of common testing protocols as well as procedures for result collection, evaluation and reporting.
- Determination of the efficiencies, gaseous and particulate emissions during combustion of selected BIOMASUD PLUS fuels in stoves and boilers.
- Evaluation of the test runs with respect to operation stability, thermal efficiency, gaseous and particulate emissions.

2 Methodology

At the beginning, the BIOMASUD PLUS fuels to be tested within Task 5.3 have been selected. Then the stoves and boilers have been selected and in parallel, a common test run procedure as well as test run protocols have been worked out. According to that subsequently the test runs have been performed.

2.1 Fuel selection

According to the conclusions of Task 5.1, *Selection of the BIOMASUD biofuels for combustion tests*, the following fuels have been agreed to be utilized during the test runs.

- Olive stones (OS),
- Olive tree prunings (OTP), in the form of pellets and,
- Vineyard prunings (VYP), also in the form of pellets.

To assure that at the different test stands comparable fuel qualities are applied, the fuels for all test runs have been purchased and prepared by CIEMAT and distributed to BIOS and CERTH.

2.2 Stove and boiler selection

The results of Task 5.2, *State of the art of the combustion devices for the selected biofuels*, have revealed that there are not sufficient boilers and stoves certified for BIOMASUD PLUS fuels available in Greece (CERTH), Spain (CIEMAT) and Austria (BIOS). However, it would also be very interesting to test conventional wood chip and wood pellet combustion devices with the new fuels in order to find out if they are suitable for BIOMASUD PLUS fuels or if major adaptations are needed. Therefore, it has been decided by BIOS, CIEMAT, CERTH and the project coordinator to test, both, regarding BIOMASUD PLUS fuels certified and not certified devices. Moreover, it was decided to extend the capacity range of the stoves to be tested to more than 10 kW_{th}. Based on these adapted framework conditions the stoves and boilers have been selected. A detailed description of these heating devices is presented in section 3.

2.3 Elaboration of a common test run methodology

A test stand set-up according to according to EN 14785 for stoves and according to EN 303-5 for boilers has been selected. Schemes of the respective test stand arrangements are presented in Figure 1.

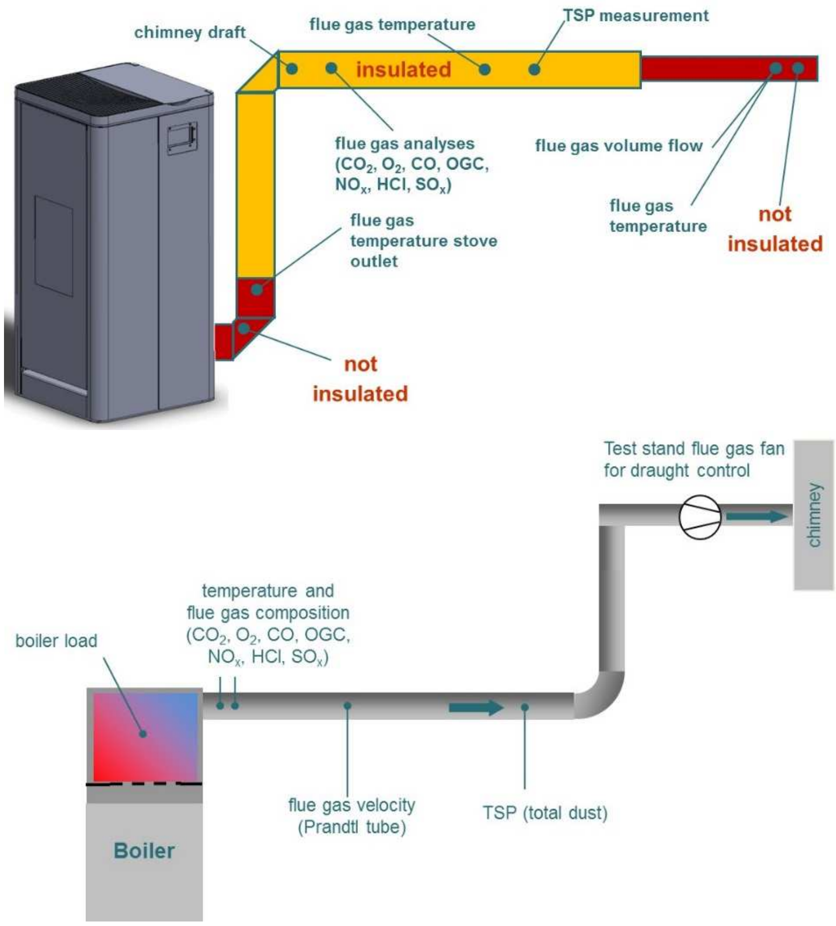

Figure 1: Scheme of the test stand set-up for stove testing (above) and boiler testing (below)
Explanations: TSP … total suspended particulate matter; OGC … organic gaseous compounds

Each boiler/stove was at first taken in operation with wood pellets or wood chips as fuel in order to check its functionality and to get familiar with the device and its control system. During these tests it has also been checked if the emission values according to the respective certification of the stove/boiler are achieved. Then first tests with the respective BIOMASUD PLUS fuel have been performed in order to adjust the control settings to the fuel characteristics. After appropriate settings had been found, test runs at full and partial load have been carried out. For each load case tests at stable and representative operation over at least 6 hours have been performed. During these test runs a comprehensive sampling and measurement program has been performed. Results of the following measurements are presented in this report.

- Discontinuous measurements and sampling
  - Fuel properties (representative samples were taken along each test)
  - Grate ash sampling and analyses
  - Mass of fuel supplied
  - Total particle emissions (at least 3 measurements)
  - SO_x and HCl emission measurements
  - Ambient temperature
  - Air pressure
- Continuous measurements
  - Heat output (only for boilers - water feed and return temperature, water flow)
  - Flue gas temperature at boiler/stove outlet
  - Gaseous emissions (O_2 and / or CO_2, CO, NO_x, OGC)
  - Combustion air flow
  - Flue gas flow

The measurement techniques/devices listed in Table 1 have been applied.

Table 1: Measurement techniques applied by BIOS, CERTH and CIEMAT

Explanations: OGC … organic gaseous compounds

Parameter	Partner	Device
O_2, CO, CO_2, NO	BIOS	NGA 2000, Emerson (ND-IR and paramagnetic sensors), sampling time: 2 sec.
	CIEMAT	Gasmet DX4000 (FT-IR); sampling time: 5 sec.
	CERTH	Ansyco DX400 (FT-IR); sampling time: 5 sec.
OGC	BIOS, CIEMAT, CERTH	FID (flame ionization detector)
HCl, SO_x (SO_2+SO_3)	BIOS, CIEMAT, CERTH	Discontinuous sampling according to EN 14791 (SO_x) and EN 1911 (HCl)
TSP (total dust)	BIOS, CIEMAT, CERTH	Filter method according to ISO 9096 and EN 13284

Chemical analyses of the fuels have been performed applying the methods described in Deliverable Report D3.2, *Selected biofuels characterization results and quality assessment report*.

In Figure 2 a picture of the test stand at CIEMAT taken during the test runs with the stove is presented. Similar configurations were used at the test stands at BIOS, CERTH and CIEMAT.

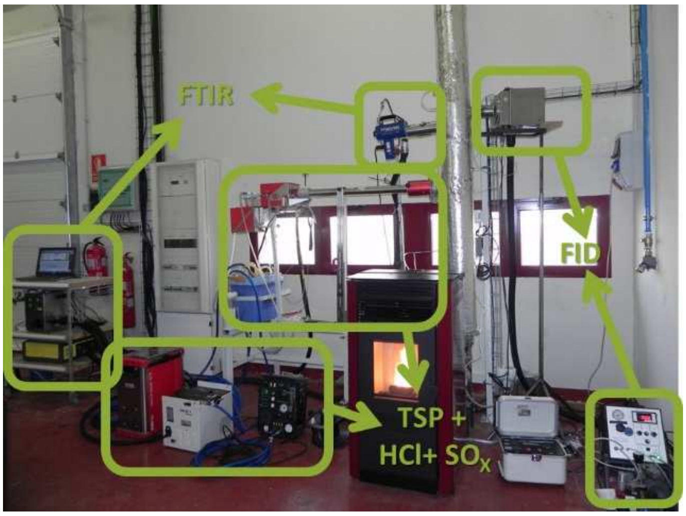

Figure 2: Picture of the test stand at CIEMAT

3 Description of the stoves and boilers tested

Three pellet stoves and three boiler systems have been selected for the performance of the test runs. In the following the main characteristics of these appliances are listed and some relevant data are compared in Table 2 and Table 3.

The stove tested at CIEMAT (in the following referred to as *Stove/CIEMAT*) is produced by a Spanish manufacturer. It has a nominal thermal power of 10.4 kW. The thermal efficiency (according to the manufacturer) amounts to 89% during operation with EN ISO 17225-2 class 1 wood pellets. Heat transfer is realised by radiation to the surrounding and by convection to the ambient and two additional rooms. The stove is based on a rotating grate technology with an automated de-ashing of the grate into an ash box situated below the grate. Combustion air is supplied through the grate (primary air) and above the fuel bed via the window purge air flow. The stove has an automated combustion control system. The stove is designed for the combustion of EN ISO 17225-2 class 1 wood pellets. However, it has already been tested by the manufacturer with olive stones and fuels with high ash contents.

The stove tested at CERTH (in the following referred to as *Stove/CERTH*) is produced by an Italian manufacturer. In contrast with the other two stoves tested, it is equipped with a water jacket. It's nominal heating capacity amounts to 21.2 kW, whereby 18.4 kW are transferred to heating water and 2.8 kW are released by radiation to the surrounding (during nominal load operation). The thermal efficiency (according to the manufacturer) amounts to 88% during operation with EN ISO 17225-2 class 1 wood pellets. It is based on a fixed grate technology, which demands for a periodic manual removal of the ashes from the grate. Combustion air is supplied through the grate (primary air) and above the fuel bed via the window purge air flow. The stove has an automated combustion and load control system. The stove is designed for the combustion of EN ISO 17225-2 class 1 wood pellets. To our knowledge, no other fuels have been tested in this stove yet.

The stove tested at BIOS (in the following referred to as *Stove/BIOS*) is produced by an Austrian manufacturer. It has a nominal thermal power of 10.0 kW. The thermal efficiency (according to the manufacturer) amounts to 90% during operation with EN ISO 17225-2 class 1 wood pellets. Heat transfer is realised by radiation to the surrounding. The stove is based on a rotating grate technology with an automated deashing of the grate into an ash box situated below the grate. Combustion air is supplied through the grate (primary air), via secondary air injection nozzles above the fuel bed and into the combustion chamber via the window purge air flow. The stove has an automated combustion control system. The stove is designed for the combustion of EN ISO 17225-2 class 1 wood pellets. To our knowledge, no other fuels have been tested in this stove yet.

When comparing the three stoves tested the main similarities resp. differences are:

- All stoves are based on a staged combustion concept with primary combustion air and window purge air. *Stove/BIOS* additionally has a secondary air injection.
- While *Stove/CIEMAT* and *Stove/BIOS* are equipped with rotating grates with automated de-ashing, *Stove/CERTH* has a fixed grate, which demands for manual de-ashing.
- All stoves are equipped with automatic control systems.
- While for *Stove/CIEMAT* and *Stove/BIOS* heat release to the room is realised via radiation, *Stove/CERTH* is equipped with a water jacket. *Stove/CIEMAT* supplies also heat with a convective fan to the ambient and to two additional rooms.

Table 2: Main characteristics of the stoves tested

Explanations: *) according to the manufacturer during operation with EN ISO 17225-2 class 1 wood pellets

		Stove/CIEMAT	***Stove/CERTH***	***Stove/BIOS***
Nominal thermal capacity	kW	10.4	21.2 18.4 to water cycle 2.8 to the room	10
Thermal efficiency*)	%	89	88	90
Dimensions (length/height/width	mm	535 x 1070 x 515	820 x 2200 x 820	660 x 550 x 1200
Weight	kg	125	200	200
Diameter of chimney connection	mm	80	80	100
Fuel feeding to the fuel bed		from above	from above	from above
Grate technology		rotating grate	fixed grate	rotating grate
De-ashing of the grate		automatic	manual	automatic
Combustion air flows		primary air and window air	primary air and window air	primary air, secondary air and window air
Control systems		automatic combustion control	automatic combustion and load control	automatic combustion control

The boiler tested at CIEMAT (in the following referred to as *Boiler/CIEMAT*) is produced by a Spanish manufacturer. The overall nominal thermal power amounts to 25 kW. The thermal efficiency (according to the manufacturer) amounts to 95% during operation with EN ISO 17225-2 class 1 wood pellets. The boiler is based on an underfeed stoker combustion technology with a moving grate (automated de-ashing of the grate). Combustion air is supplied through the grate (primary air) and above the fuel bed into the main combustion chamber (secondary air). The hot water boiler is equipped with an automated cleaning system. Combustion and load control is realised by an automated control system. The boiler is designed for the combustion of EN ISO 17225-2 class 1 wood pellets and it is certified as class 5, according to EN 303-5:2012, for that fuel. Moreover, it has already been tested by the manufacturer with olive stones and fuels with high ash contents.

The boiler tested at CERTH (in the following referred to as *Boiler/CERTH*) is produced by a Greek manufacturer. The nominal thermal power amounts to 28 kW. The thermal efficiency (according to the manufacturer) amounts to 80% during operation with EN ISO 17225-2 class 1 wood pellets. The boiler is based on an underfeed stoker combustion technology with a fixed grate (demands for manual de-ashing of the grate). Combustion air is supplied through the grate (primary air) and above the fuel bed into the main combustion chamber (secondary air). Process control has to be done manually. The boiler is designed for the combustion of EN ISO 17225-2 class 1 wood pellets. However, it has already been tested by the manufacturer with ash rich fuels. In general, the boiler design is rather simple; the manufacturer claims conformity with the requirements of class 3, according to EN 303-5.

The boiler tested at BIOS (in the following referred to as *Boiler/BIOS*) is produced by an Austrian manufacturer. The overall nominal thermal power of the boiler amounts to 40 kW. The thermal efficiency (according to the manufacturer) amounts to 95% during operation with EN ISO 17225-2 class 1 wood pellets. The fuel is inserted horizontally and burned on a moving grate (automated de-ashing of the grate). Combustion air is supplied through the grate (primary air) and above the fuel bed into the secondary combustion zone (secondary air). The hot water boiler is equipped with an automated mechanical cleaning system. Combustion and load control is realised by an automated control system. The boiler is designed for the combustion of EN ISO 17225-2 class 1 wood pellets and wood chips and it is certified as class 5 according to EN 303-5:2012 for these biomass fuels. It is also certified for the utilisation of olive stones.

When comparing the three boilers tested the main similarities resp. differences are:

- All boilers are based on a staged combustion concept with primary and secondary combustion air injection.
- While the boilers *Boiler/CIEMAT* and *Boiler/BIOS* are equipped with moving grates with automated de-ashing, *Boiler/CERTH* has a fixed grate, which demands for manual de-ashing.
- *Boiler/CIEMAT* and *Boiler/BIOS* are equipped with automatic boiler cleaning systems.
- *Boiler/CIEMAT* and *Boiler/BIOS* are equipped with automatic control systems.
- *Boiler/CERTH* is based on a rather simple technology (compared with the two others) with a low degree of automation and is consequently the by far cheapest solution tested.

Table 3: Main characteristics of the boilers tested

Explanations: *) according to the manufacturer during operation with EN ISO 17225-2 class 1 wood pellets

		Boiler/CIEMAT	***Boiler/CERTH***	***Boiler/BIOS***
Nominal thermal capacity	kW	25	28	40
Thermal efficiency*)	%	95	80	95
Dimensions (length/height/width	mm	850 x 1465 x 1295	820 x 2200 x 1200	2120 x 1420 x 1590
Weight	kg	550	225	980
Diameter of chimney connection	mm	150	180	150
Fuel feeding to the fuel bed		underfed stoker	underfed stoker	horizontal screw
Grate technology		moving grate	fixed grate	moving grate
De-ashing of the grate		automated	manual	automated
Boiler cleaning		automated	manual	automated
Combustion air flows		primary air and secondary air	primary air and secondary air	primary air and secondary air
Control systems		automated combustion and load control	manual	automated combustion and load control
Certification class acc. to EN 303-5		5	3	5

4 Characterisation of the fuels applied

The BIOMASUD PLUS fuels applied during the test runs have been distributed by CIEMAT. CIEMAT has purchased the fuels from Spanish manufacturers and eventually has produced them from raw materials when required (pellets from olive tree and vineyard prunings). At CIEMAT, CERTH and BIOS the different fuels finally applied during the test runs have been analysed regarding relevant parameters. In the following, relevant results of these analyses are presented and, where appropriate, the results are compared with the guiding values for quality criteria for BIOMASUD PLUS fuels, stated in Deliverable Report D3.3, *Quality classification of the solid biofuels to be considered in the biofuels extended BIOMASUD label*.

4.1 Olive stones (OS)

In Table 4 the results of chemical analyses of the olive stones utilised during the combustion test runs at CERTH, CIEMAT and BIOS are presented and compared with guiding values for quality criteria regarding BIOMASUD PLUS fuels as established within Deliverable Report D3.3.

Table 4: Results of the chemical analyses of olive stone samples performed at CIEMAT, CERTH and BIOS

Explanations: d.b. … dry basis; w.b. … wet basis; n.d. not determined

		BIOS (stove and boiler)	Stove CIEMAT	Boiler CIEMAT	Stove CERTH	Boiler CERTH	Criteria acc. to D3.3 - class A2
Moisture content	wt% w.b.	11.60	10.60	8.90	11.3	12.0	≤12.0
Ash content	wt% d.b.	1.06	0.80	0.80	1.0	0.9	≤1.0
Gross calorific value	MJ/kg d.b.	20.16	20.17	20.26	19.95	20.18	
Net calorific value	MJ/kg w.b.	16.38	16.62	17.06	15.99	16.14	≥15.7
Bulk density	kg/m³	760	750.0	840.0	740	750	≥700
C	wt% d.b.	50.41	50.00	51.00	52.43	51.66	
H	wt% d.b.	5.92	5.90	6.00	7.44	6.93	
N	wt% d.b.	0.11	0.25	0.17	0.28	0.89	≤0.4
S	mg/kg d.b.	144	120	120	300	400	≤400
Cl	mg/kg d.b.	280	220	220	400	200	≤400
Al	mg/kg d.b.	64	22	24	30	33	
Ca	mg/kg d.b.	1,990	1,280	1,200	1,516	3,161	
Fe	mg/kg d.b.	65	21	19	17	123	
K	mg/kg d.b.	2,270	1,840	1,520	2,436	2,835	
Mg	mg/kg d.b.	332	120	112	114	71	
Mn	mg/kg d.b.	6	4	3	6	6	
Na	mg/kg d.b.	16	12	10	279	15	
P	mg/kg d.b.	71	66	66	n.d.	n.d.	
Si	mg/kg d.b.	226	88.	69	98	139	
Fuel index							
(Si+P+K)/(Ca+Mg+Al)	mol/mol	1.02	1.26	1.11	1.54	0.95	

At project start a Round Robin regarding the performance of fuel analyses has been performed within WP3. When considering the deviation ranges of the results gained from CIEMAT, CERTH and BIOS as well as typical deviations due to fuel inhomogeneity, the analyses results of the different samples are in acceptable agreement. Therefore, it can be stated that the olive stones utilised at the three testing sites are well comparable.

With the exception of the ash content, the composition of the fuel fulfils the class A2 standard defined within Deliverable Report D3.3 for residential utilisation of olive stones. The sample analysed at BIOS, which shows a slightly higher ash content, would satisfy the demands regarding class B (<1.3 wt% d.b.).

The molar ratio of (Si+P+K)/(Ca+Mg+Al) can be used as an indicator for ash melting properties of biomass fuels. With increasing value of this index the ash melting temperatures decrease. With values between 1.0 and 1.5 no significant problems with slagging have to be expected.

It has to be mentioned that olive stones show, compared with wood pellets, about 3 to 5 times higher K contents. Since K is the most relevant element regarding the formation of fine particulate emissions, increased dust emissions compared to pellet combustion have to be expected.

4.2 Olive tree pruning (OTP) pellets

In Table 5 the results of chemical analyses of the olive tree pruning pellets utilised during the combustion test runs at CERTH, CIEMAT and BIOS are presented and compared with guiding values for quality criteria regarding BIOMASUD PLUS fuels as established within Deliverable Report D3.3.

Table 5: Results of the chemical analyses of olive tree pruning pellet samples performed at CIEMAT, CERTH and BIOS

Explanations: d.b. … dry basis; w.b. … wet basis; n.d. not determined

		BIOS (stove and boiler)	Stove CIEMAT	Boiler CIEMAT	Stove CERTH	Boiler CERTH	Criteria acc. to D3.3 - class B
Moisture content	wt% w.b.	8.40	8.20	8.60	8.6	7.9	≤10
Ash content	wt% d.b.	4.37	4.20	4.90	5.0	4.8	≤2
Gross calorific value	MJ/kg d.b.	19.69	19.50	19.61	18.80	18.90	
Net calorific value	MJ/kg w.b.	16.61	16.48	16.52	15.66	15.93	≥15
Bulk density	kg/m³	580	590.0	580.0	610	610	
C	wt% d.b.	48.33	49.50	48.80	49.25	49.75	
H	wt% d.b.	6.04	6.10	6.00	6.72	6.44	
N	wt% d.b.	0.54	0.61	0.77	0.68	1.33	≤1
S	mg/kg d.b.	662	560	650	700	700	
Cl	mg/kg d.b.	249	210	220	400	200	≤300
Al	mg/kg d.b.	299	310	343	200	270	≤500
Ca	mg/kg d.b.	11,800	11,760	12,740	17,179	17,924	
Fe	mg/kg d.b.	227	197	240	181	374	
K	mg/kg d.b.	4,040	3,318	3,822	5,922	5,342	
Mg	mg/kg d.b.	820	882	882	1,127	941	
Mn	mg/kg d.b.	25	19	21	19	24	
Na	mg/kg d.b.	95	126	127	390	97	
P	mg/kg d.b.	553	546	686	n.d	n.d	
Si	mg/kg d.b.	1,750	1,512	2,499	1,504	1,057	
Fuel index							
(Si+P+K)/(Ca+Mg+Al)	mol/mol	0.50	0.26	0.28	0.43	0.23	

When considering the deviation ranges of the results gained from CIEMAT, CERTH and BIOS within the aforementioned Round Robin as well as typical deviations due to fuel inhomogeneity, the analyses results of the different samples are in acceptable agreement. Therefore, it can be stated that the olive tree pruning pellets utilised at the three testing sites are well comparable. In Deliverable Report D3.3 it is stated that olive tree pruning pellets devoid of OTP leaf fractions could be suitable for residential combustion, meeting the ash, nitrogen, Cl and S contents of class B of ISO 17225-2:2014. However, in Table 5 the ash content exceeded by more than two times the class B limit. Moreover, the N-contents are very high.

With values equal and below 0.5, the ash melting index (molar ratio of (Si+P+K)/(Ca+Mg+Al) indicates rather high ash melting temperatures. Because of the very high K contents of the fuel (about 8 times of the K content of class A1 wood pellets) significantly elevated particulate emissions have to be expected. Moreover, the N-content of the olive tree prunings is, compared with wood pellets, very high, which is expected to result in significantly increased NO_x emissions.

4.3 Vineyard pruning (VYP) pellets

In Table 6 the results of chemical analyses of the vineyard pruning pellets utilised during the combustion test runs at CERTH, CIEMAT and BIOS are presented. In Deliverable Report D3.3 it is stated that vineyard pellets are not suitable for residential combustion and therefore no guiding values have been defined for this fuel.

The analyses results of the different samples are in acceptable agreement. Therefore, it can be stated that the vineyard pruning pellets utilised at the three testing sites are well comparable. However, as already reported for olive tree pruning pellets, the ash, K and N contents of these fuel assortments are very high and therefore, elevated emissions during combustion in residential stoves and boilers have to be expected

With values equal and below 0.53, the ash melting index (molar ratio of (Si+P+K)/(Ca+Mg+Al) however, indicates rather high ash melting temperatures and therefore, vineyard pruning pellets are not supposed to cause significant problems with ash melting and slag formation during combustion.

Table 6: Results of the chemical analyses of vineyard pruning pellet samples performed at CIEMAT, CERTH and BIOS

Explanations: d.b. … dry basis; w.b. … wet basis; n.d. not determined

		BIOS (stove and boiler)	Stove CIEMAT	Boiler CIEMAT	Stove CERTH	Boiler CERTH
Moisture content	wt% w.b.	8.60	9.50	11.20	8.0	8.8
Ash content	wt% d.b.	5.46	4.20	4.40	5.0	4.9
Gross calorific value	MJ/kg d.b.	19.04	18.92	19.06	18.98	18.76
Net calorific value	MJ/kg w.b.	16.03	15.71	15.63	15.93	15.68
Bulk density	kg/m³	610	630.0	620.0	610	640
C	wt% d.b.	47.47	48.60	47.50	49.13	47.26
H	wt% d.b.	5.77	6.00	5.70	6.68	6.10
N	wt% d.b.	0.51	0.53	0.70	0.81	1.41
S	mg/kg d.b.	603	480	430.0	700	500
Cl	mg/kg d.b.	196	140	140.0	300	200
Al	mg/kg d.b.	184	205	171.6	167	161
Ca	mg/kg d.b.	13,900	12,180	11,880.0	19,801	24,209
Fe	mg/kg d.b.	243	163	127.6	252	292
K	mg/kg d.b.	5,360	5,460	4,400.0	5,433	6,398
Mg	mg/kg d.b.	1,290	1,848	1,408.0	1,413	1,227
Mn	mg/kg d.b.	19	18	14.5	22	17
Na	mg/kg d.b.	39	79	79.2	144	73
P	mg/kg d.b.	792	924	704.0	n.d.	n.d.
Si	mg/kg d.b.	2,130	1,932	1,716	1,324	971
Fuel index						
(Si+P+K)/(Ca+Mg+Al)	mol/mol	0.53	0.37	0.32	0.33	0.30

4.4 Fuel characterisation – summary

Summing up, it can be stated that for each fuel, the compositions of the three batches used at the three testing sites are well comparable.

From a combustion technology related perspective the olive stones can be assessed as a fuel, which should be applicable in residential-scale stoves and boilers.

The olive tree pruning pellets and the vineyard pruning pellets however show comparably high N, K and ash contents, which represent a real challenge regarding efficient and low emission combustion in residential appliances. In comparison to class A1 wood pellet combustion elevated particulate emissions (due to the high ash and K contents) and NO_x emissions (due to the high N contents) have to be expected. Moreover, the high ash contents may lead to problems with an appropriate air flow through the fuel bed that could cause CO rich streaks which result in elevated CO emissions. Regarding ash melting related problems (slag formation on the grate) however, the pruning pellets can be assessed as rather unproblematic.

5 Results of the test runs

5.1 Plant operation in general

In the following relevant experiences made during the test runs regarding general plant operation related aspects are separately summarised for the test runs with the stoves and the boilers.

5.1.1 Stoves

Plant operation

Fuel feeding: No problems occurred for the different BIOMASUD PLUS fuels tested as the fuels were used in granular (OS) or pelletised (OTP/VYP) form. The feeding systems of the different stoves (pellet stoves) are already designed for the related bulk and energy densities.

Combustion control: The stoves have been operated at typical process conditions regarding excess air ratios, chimney draft, flue gas fan speed and air distribution. No relevant combustion control related problems occurred during the test runs.

Ash related problems

Ash melting/slagging: No problems with ash melting or slagging on the grate and in the combustion chamber were observed.

De-ashing: The ash contents of OTP and VYP (up to 5.5 wt% d.b.) were very high compared to class A1 wood pellets (0.5 wt% d.b.). OTP and VYP pellets partly keep their shape during combustion due to their high ash contents and therefore a high volume ash consisting of "ash pellets" results (see also Figure 3). This leads to a fast growing ash bed on the grate. Therefore, a self-cleaning (moving) grate is necessary for a continuous de-ashing. Systems with fixed grates and manual de-ashing (as *Stove/CERTH*) are not suitable as the quick build-up of the ash bed disturbs the combustion in the fuel bed.

Cleaning of heat exchanger surfaces: The BIOMASUD PLUS fuels tested caused increased ash and aerosol deposits in the combustion chamber and on heat exchanger surfaces that may have a negative impact on the heat exchange and therefore have to be periodically manually removed. Significantly more frequent manual cleaning is needed than for wood pellet utilisation.

Vision panel (window): Severe aerosol depositions of the vision panel (window) occurred for *Stove/CERTH* and *Stove/BIOS* during operation with OTP and VYP pellets, which partly blocked the view on the flame. This is an undesired effect for stoves since flame visibility is an important customer need (see Figure 4). The fact that this effect did not occur for *Stove/CIEMAT* was most probably due to the high excess air ratios applied during the test runs with this stove (see section 5.3).

5.1.2 Boilers

Plant operation

Fuel feeding: No problems occurred for the different BIOMASUD PLUS fuels tested as the fuels are used in granular (OS) or pelletised (OTP/VYP) form. The feeding systems of the different pellet boilers tested are designed for such fuel shapes and bulk densities as well as the related energy densities.

Combustion control: The automated combustion control system of *Boiler/CIEMAT* and *Boiler/BIOS* have been adjusted to the utilisation of the fuels applied. Therefore, slight changes regarding e.g. grate movements and de-ashing intervals were needed. The basis control concept however, remained unchanged. No relevant combustion or load control related problems occurred during the test runs.

Ash related problems

Ash melting/slagging: No problems with ash melting or slagging on the grates and in the combustion chambers were observed.

De-ashing of the grate: The high ash contents of OTP and VYP can lead to ash accumulations on the grate. Also the ash boxes had to be emptied more often compared to the operation with class A1 wood pellets. A boiler concept with manual de-ashing of the grate (*Boiler/CERTH*) turned out to be not suitable for long-term operation.

Cleaning of heat exchanger surfaces: The BIOMASUD PLUS fuels, especially OTP and VYP pellets, caused increased ash and aerosol deposits on the heat exchanger surfaces that may have a negative effect on the heat exchange and therefore have to be periodically removed. Thus, an automatic cleaning system of the heat exchanger surfaces is recommended for the operation with BIOMASUD PLUS fuels (as it was installed at *Boiler/CIEMAT* and *Boiler/BIOS*).

Figure 3: Ash box of *Stove/BIOS* after test runs with OTP - OTP and VYP pellets keep their shape during combustion due to their high ash contents

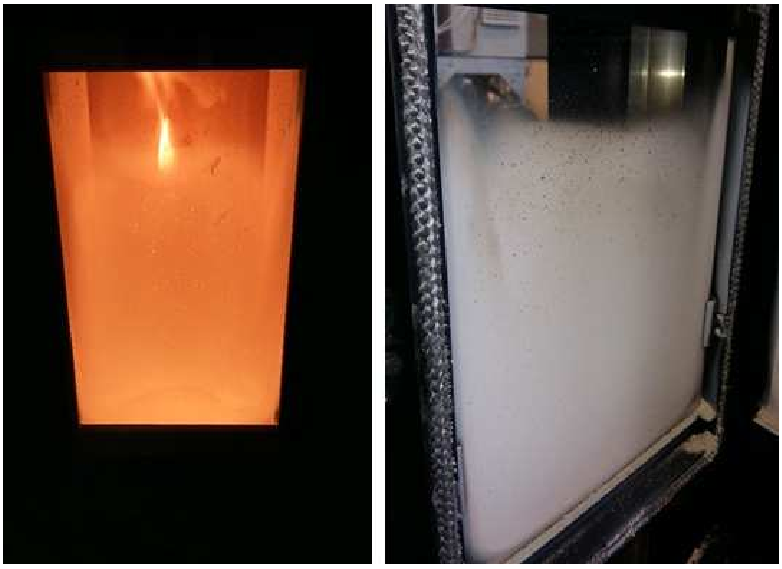

Figure 4: Vision panel of *Stove/BIOS* after a test run with OTP pellets

5.2 Emissions

5.2.1 Stoves

The results of the test runs at full and partial load operation performed with olive stones, olive tree pruning pellets and vineyard pruning pellets are presented in Table 7 to Table 9. The data represent mean values and standard deviations over the whole operation period of at least 6 hours.

Moreover, in these tables emission limit values according to the Ecodesign Directive are mentioned. This Directive (Directive 2009/125/EC) establishes a framework to set mandatory ecological requirements for energy-using and energy-related products sold in all 28 Member States. The Commission Regulation (EU) 2015/1185 of 24 April 2015 implementing *Directive 2009/125/EC of the European Parliament and of the Council with regard to Ecodesign requirements for solid fuel local space heaters* contains the emission limit values for stoves, which will be compulsory from 2022 on. These limit values have to be kept at nominal load operation. The regulation shall not apply to non-woody biomass combustion. This aspect leaves out some biomass fuels, including olive stones. However, it also foresees the category *other suitable fuels*, which may be applied to olive stones. Moreover, the regulation applies to olive tree and vineyard pruning pellets, since they can be considered as "woody biomass", but the ash content of OTP and VYP is generally much higher than the class limits established in the regulation for that biomass fuel category. Despite of this, the requirements of the Ecodesign Directive have been taken as the reference for characterization of emissions of the selected, both, stoves and boilers.

Table 7: Emissions measured during the test runs with olive stones and comparison with limit values according to the Ecodesign Directive

Explanations: emissions related to dry flue gas and 13 vol% O_2; OGC … organic gaseous compounds; NO_x calculated as NO_2; FL … full load; PL … partial load; TSP … total suspended particulate matter = total dust; mean/s …mean value and standard deviation over the testing period; *) limit value according to the Ecodesign Directive for wood pellets; **) limit value according to the eco-Design Directive for *other fuels that can be used.*

		Stove / CIEMAT		Stove / CERTH		Stove / BIOS		Eco-Desgn Directive	
		FL	PL	FL	PL	FL	PL	WP *)	Other **)
CO [mg/Nm³]	mean	965	1.416	786	2.616	56	410	300	1.500
	s	*476*	*379*	*438*	*1.516*	*10*	*151*		
NO_x [mg/Nm³]	mean	199	150	234	174	171	136	200	200
	s	*17*	*24*	*24*	*34*	*6*	*10*		
OGC [mg/Nm³]	mean	10	n.a.	7	39	8	19	60	120
	s	*5*	*n.a.*	*2*	*21*	*3*	*8*		
TSP [mg/Nm³]	mean	63	85	51	102	18	10	20	40
	s	*2*	*7*	*8*	*22*	*1*	*1*		

As Table 7 shows, for all parameters except for NO_x the full load emissions are lower than the partial load emissions. Decreasing NO_x emissions with decreasing load are a well known phenomenon in small-scale combustion plants which is partly supported by the fact that increased CO emissions during partial load lead to a certain NO_x-emission reduction.

The *Stove/BIOS* was able to keep all emission limit values applicable for wood pellets according to the Ecodesign Directive while the stoves tested at CIEMAT and CERTH showed exceedances regarding CO and TSP and the *Stove/CERTH* also exceeded the NO_x emission limit value.

In Table 8 the result for the combustion trials with olive tree pruning pellets are presented. As discussed in section 4.2, the olive tree pruning pellets showed 4.2 to 5.0 wt% d.b. ash contents which exceeded the targeted fuel quality of the BIOMASUD PLUS A qualities, which are recommended for small-scale combustion devices. Fuel with such high ash contents quickly form a high ash bed on the grate, which partly disturbs primary air distribution and gas flow through the fuel bed. This effect is more pronounced for fixed grates. CO-rich streaks, which cannot be fully oxidised with the secondary combustion air, are one consequence. Accordingly, the stoves with the moving grates show lower CO emissions than the *Stove/CERTH* (fixed grate system). Moreover, the high ash content and the high K content of OTP pellets leads to significantly increased TSP emissions (10 to 15 times of the limit value) and the comparably high N-contents of the fuel lead to elevated NO_x emissions (about double value of the emission limit value).

Consequently, at full load operation all three stoves showed exceedances regarding all limiting values listed in Table 8 except OGC. In case of CO, further adaptations of the grate and fuel bed region as well as improvements regarding air staging may reduce the emissions below the limit value and regarding TSP, the application of an electrostatic precipitator would be an option to reduce dust emissions. With respect to NO_x emissions however, primary measures will not be sufficient to gain the 50% reduction needed and secondary measures for NO_x emission reduction for stoves have not been developed yet

Table 8: Emissions measured during the test runs with olive tree pruning pellets and comparison with limit values according to the Ecodesign Directive

Explanations: emissions related to dry flue gas and 13 vol% O_2; OGC … organic gaseous compounds; NO_x calculated as NO_2; FL … full load; PL … partial load; TSP … total suspended particulate matter = total dust; mean/s … mean value and standard deviation over the testing period; *) limit value according to the Ecodesign Directive for wood pellets

		Stove / CIEMAT		Stove / CERTH		Stove / BIOS		Eco-Design WP *)
		FL	PL	FL	PL	FL	PL	
CO [mg/Nm³]	mean	1.895	2.007	3.479	6.314	614	2.109	300
	s	*1.020*	*1.239*	*1.398*	*1.774*	*668*	*2.114*	
NO_x [mg/Nm³]	mean	430	321	385	313	419	401	200
	s	*46*	*70*	*47*	*36*	*43*	*51*	
OGC [mg/Nm³]	mean	n.a.	n.a.	22	72	14	93	60
	s	*n.a.*	*n.a.*	*13*	*40*	*24*	*129*	
TSP [mg/Nm³]	mean	295	950	254	340	194	141	20
	s	*9*	*90*	*57*	*36*	*2*	*2*	

Regarding vineyard pruning pellets (see Table 9), in general the same results as for the olive tree prunings have been achieved. The high ash content leads to problems with gas phase burnout (i.e. high CO emissions). Also the PM and NO_x emissions exceed the limit values by more than 11 times for TSP and 1.5 to 2 times for NO_x.

Table 9: Emissions measured during the test runs with vineyard pruning pellets and comparison with limit values according to the Ecodesign Directive

Explanations: emissions related to dry flue gas and 13 vol% O_2; OGC … organic gaseous compounds; NO_x calculated as NO_2; FL … full load; PL … partial load; TSP … total suspended particulate matter = total dust; mean/s … mean value and standard deviation over the testing period; *) limit value according to the Ecodesign Directive for wood pellets

		Stove / CIEMAT		Stove / CERTH		Stove / BIOS		Eco-Design WP *)
		FL	PL	FL	PL	FL	PL	
CO [mg/Nm³]	mean	2.134	3.080	4.384	8.310	525	1.678	300
	s	*908*	*1.669*	*1.787*	*1.706*	*398*	*1.151*	
NO_x [mg/Nm³]	mean	403	292	344	273	299	270	200
	s	*45*	*61*	*52*	*37*	*35*	*39*	
OGC [mg/Nm³]	mean	24	160	31	111	15	50	60
	s	*40*	*237*	*22*	*36*	*24*	*46*	
TSP [mg/Nm³]	mean	269	216	287	441	228	96	20
	s	*19*	*18*	*97*	*21*	*10*	*11*	

5.2.2 Boilers

The results of the test runs at full and partial load operation performed with olive stones, olive tree prunings and vineyard prunings are presented in Table 10 to Table 12. The data represent mean values and standard deviations over the whole operation period of at least 6 hours.

Moreover, in these tables emission limit values according to the Ecodesign Directive are mentioned. The *Commission Regulation (EU) 2015/1189 of 28 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to eco-design requirements for solid fuel boilers* contains the respective emission limit values. It will be compulsory from 2020 on. The regulation shall not apply to non-woody biomass combustion, however, it is expected that during a review in 2022 also non-wood fuels will be included. Therefore, the results for olive stones are here also assessed against the Ecodesign emission limit values for wood fuels.

Within the Ecodesign Directive, the emission limit values for boilers are expressed as seasonal emission limits. The seasonal emissions (E_s) are calculated based on the nominal ($E_{s,n}$) and partial load ($E_{s,p}$) emissions according to the following formula: $E_s = 0.85 \times E_{s,p} + 0.15 \times E_{s,n.}$

The emission data gained from the test runs with olive stones, which are presented in Table 10, reveal significant differences between the boilers tested at CIEMAT and BIOS compared with the low-cost boiler model tested by CERTH. The simple technology of this boiler makes it not suitable for challenging new biomass fuels. All emission limit values (with the exception of NO_x) are significantly exceeded by the *Boiler/CERTH*. The comparably low NO_x emissions thereby are mainly an effect of the high CO emissions.

The other two boilers both show slight exceedances regarding NO_x emissions. While *Boiler/CIEMAT* was able to keep the seasonal emission limit for TSP, *Boiler/BIOS* exceeded it by about 50%. Even if the boilers tested at BIOS and CIEMAT showed acceptably low CO and OGC emissions during full load operation, the increased CO and OGC emissions during partial load as well as the 85% weighing of partial load within the calculation of the seasonal emissions lead to exceedances of the seasonal emission limit values regarding CO and OGC. The implementation of some measures, which improve the partial load operation, may help to keep the emission limit values regarding CO, OGC and TSP. By improving the air staging strategy, it seems also to be realistic to reduce the NO_x-emissions to values below the emission limit value for these two boilers.

Table 10: Emissions measured during the test runs with olive stones and comparison with limit values according to the Ecodesign Directive

<u>Explanations:</u> emissions related to dry flue gas and 10 vol% O_2; OGC … organic gaseous compounds; NO_x calculated as NO_2; FL … full load; PL … partial load; E_s …. seasonal emission = $0.85 \times E_{PL} + 0,15 \times E_{FL}$; TSP … total suspended particulate matter = total dust; mean/s … mean value and standard deviation over the testing period; Ecodesign … seasonal emission limit value according to the Ecodesign Directive

			Boiler / CIEMAT			Boiler / CERTH			Bioler / BIOS			Eco-
			FL	PL	seasonal	FL	PL	seasonal	FL	PL	seasonal	Design
CO	[mg/Nm³]	mean	143	1.507	1.302	4.668	7.612	7.170	189	1.256	1.096	600
		s	*63*	*912*		*512*	*806*		*154*	*805*		
NO_x	[mg/Nm³]	mean	271	230	236	182	135	142	235	204	209	200
		s	*10*	*28*		*20*	*17*		*10*	*19*		
OGC	[mg/Nm³]	mean	2	22	19	65	136	125	1	33	28	20
		s	*1*	*20*		*24*	*62*		*1*	*23*		
TSP	[mg/Nm³]	mean	25	11	13	169	132	137	124	57	67	40
		s	*6*	*3*		*43*	*28*		*3*	*10*		

Also regarding the results of the test runs with olive tree pruning pellets (Table 11), significant technological differences between the three boilers tested are noticed. Again, with the simple technology of the *Boiler/CERTH* an operation at acceptable emissions cannot be achieved. The seasonal CO emissions of this boiler for instance amount to about 10 times of the limit value of the Ecodesign Directive and the OGC emissions are doubled in comparison with the limit value. Also the other two boilers show exceedances of the CO emission limit value (1 resp. 1.5 times higher for the *Boiler/BIOS* and the *Boiler/CIEMAT*). *Boiler/CIEMAT* can keep the OGC emission limit while *Boiler/BIOS* exceeds it mainly due the dominant influence of the partial load operation emissions on the seasonal emissions.

As expected, due to the high ash and especially K-contents of OTP, the particulate matter emissions significantly exceed the emission limit value with OTP pellets, which makes the application of an electrostatic precipitator for PM emission control indispensable. However, as already reported for the stove test runs, the most relevant emission related problem are the high NO_x emissions, which are caused by the comparably high fuel-N content. All three boilers tested exceed the limit vale by about 1.5 times. An optimisation of the combustion conditions (improved air staging for NO_x emission reduction) cannot be expected to be efficient enough to reduce the NO_x emissions below the limit value and secondary measures for NO_x emission control in small-scale biomass boilers so far do not exist. Therefore, the high N-content of the OTP pellets with a chemical composition as the assortment tested must be assessed as a K.O criterion regarding their utilisation in small-scale appliances.

Table 11: Emissions measured during the test runs with olive tree pruning pellets and comparison with limit values according to the Ecodesign Directive

Explanations: emissions related to dry flue gas and 10 vol% O_2; OGC … organic gaseous compounds; NO_x calculated as NO_2; FL … full load; PL … partial load; E_S …. Seasonal emission = 0.85 × E_{PL} + 0,15 × E_{FL}; TSP … total suspended particulate matter = total dust; mean/s … mean value and standard deviation over the testing period; Ecodesign … seasonal emission limit value according to the Ecodesign Directive

			Boiler / CIEMAT			Boiler / CERTH			Bioler / BIOS			Eco-Design
			FL	PL	seasonal	FL	PL	seasonal	FL	PL	seasonal	
CO	[mg/Nm³]	mean	1.480	1.705	1.671	7.803	5.653	5.976	989	1.125	1.105	600
		s	*435*	*758*		*938*	*946*		*725*	*969*		
NO_x	[mg/Nm³]	mean	526	504	507	650	486	511	531	493	499	200
		s	*36*	*33*		*38*	*30*		*51*	*47*		
OGC	[mg/Nm³]	mean	12	12	12	82	41	47	2	30	26	20
		s	*6*	*4*		*18*	*12*		*3*	*22*		
TSP	[mg/Nm³]	mean	111	89	93	665	301	355	253	115	136	40
		s	*6*	*4*		*170*	*69*		*10*	*16*		

In Table 12 the results of the test runs with the vineyard pruning pellets are summarised. The evaluation of the data generally shows the same trends as discussed before regarding olive tree pruning pellets. Elevated CO and OGC emissions may be reduced by appropriate modifications/ optimisations of the grate system and the combustion concept. The too high particulate emissions can be controlled with an electrostatic precipitator. However, no state-of-the-art primary or secondary emission control measures are presently available for the small capacity range, to reduce the too high NO_x emissions to values below the limit value.

Table 12: Emissions measured during the test runs with vineyard pruning pellets and comparison with limit values according to the Ecodesign Directive

Explanations: emissions related to dry flue gas and 10 vol% O_2; OGC … organic gaseous compounds; NO_x calculated as NO_2; FL … full load; PL … partial load; E_S …. Seasonal emission = $0.85 \times E_{PL} + 0.15 \times E_{FL}$; TSP … total suspended particulate matter = total dust; mean/s … mean value and standard deviation over the testing period; Ecodesign … seasonal emission limit value according to the Ecodesign Directive

			Boiler / CIEMAT			Boiler / CERTH			Bioler / BIOS			Eco-Design
			FL	PL	seasonal	FL	PL	seasonal	FL	PL	seasonal	
CO	[mg/Nm³]	mean	3.396	3.223	3.249	11.614	8.632	9.080	984	1.771	1.653	600
		s	*611*	*1.796*		*1.096*	*1.587*		*631*	*2.309*		
NO_x	[mg/Nm³]	mean	515	430	443	410	363	370	570	526	533	200
		s	*30*	*36*		*35*	*34*		*46*	*52*		
OGC	[mg/Nm³]	mean	26	25	25	209	97	114	1	25	22	20
		s	*10*	*12*		*35*	*31*		*2*	*43*		
TSP	[mg/Nm³]	mean	145	94	101	702	416	459	281	100	127	40
		s	*9*	*5*		*152*	*119*		*11*	*27*		

5.3 Efficiencies

In Table 13 the thermal efficiencies determined during the test runs with the different stoves are presented and compared with efficiency data for the utilisation of class-A1 wood pellets in the same stove (manufacturer data). During full load operation *Stove/BIOS* and *Stove/CERTH* achieved 2.7 to 4.5% (absolute) lower efficiencies compared to wood pellet combustion. No significant differences between the three BIOMASUD PLUS fuels tested can be identified. The reason for the lower efficiencies is most probably related to the somewhat higher oxygen contents of the flue gas and the slightly elevated flue gas temperatures at stove outlet in comparison to wood pellet combustion.

Stove/CIEMAT however, showed for olive stones an 11% and for both pruning pellets an up to 20% decrease of the efficiency in comparison with wood pellet combustion. In this case, the very high oxygen content of the flue gas is the parameter responsible for the decreased efficiency. This however, can be compensated by an appropriate adjustment of the process control.

Table 13: Thermal efficiencies, oxygen contents in the flue gas and flue gas temperatures at stove outlet achieved during the test runs with stoves

Explanations: Eff. … thermal efficiency based on the NCV of the fuel; O_2 … average O_2 content of the flue gas in vol% d.b.; T FG … average flue gas temperature at stove outlet; *) according to manufacturer data; n.a. … no data available

	Stove/CIEMAT			*Stove/CERTH*			*Stove/BIOS*		
	Eff.	O_2	T FG	Eff.	O_2	T FG	Eff.	O_2	T FG
Full load operation									
Wood pellets *)	89.0	n.a.	n.a.	88.0	n.a.	n.a.	90.0	n.a.	n.a.
Olive stones	78.1	13.9	232	84.4	8.1	164	87.3	9.3	208
Olive tree pruning pellets	68.7	16.5	204	83.5	8.3	186	85.8	10.7	208
Vineyard pruning pellets	69.7	16.3	212	84.2	7.2	198	88.3	9.0	202
Partial load operation									
Wood pellets *)	85.0	n.a.	n.a.	76.9	n.a.	n.a.	94.0	n.a.	n.a.
Olive stones	81.3	17.3	123	74.4	13.1	81	91.9	11.4	125
Olive tree pruning pellets	70.4	18.9	93	73.0	12.8	77	90.8	12.6	123
Vineyard pruning pellets	78.5	18.5	96	76.2	13.4	72	93.1	10.1	121

For partial load operation, the data in Table 13 show about the same trends as the full load operation data. Consequently, by a reduction of the excess air (lower lambda) during combustion of olive stones, olive tree pruning pellets and vineyard pruning pellets the same high thermal efficiencies shall be reachable in all stoves tested as for wood pellet combustion.

In Table 14 the thermal efficiencies, determined during the test runs with the different boilers, are presented and compared with efficiency data for the utilisation of class-A1 wood pellets (manufacturer data). During full load operation, *Boiler/BIOS* and *Boiler/CIEMAT* achieved only slightly lower thermal efficiencies (0.8 to 2.2%) than during wood pellet combustion. For partial load operation the differences are even lower with the exception of the test runs with vineyard pruning pellets at the *Boiler/CIEMAT*, where the efficiency was about 1.6% lower than during wood pellet combustion. Therefore, it can be concluded that for these two boilers oxygen contents in the flue gas and flue gas temperatures, which are well comparable with those during wood pellet combustion, could be achieved. Regarding the low flue gas temperatures achieved, the automated heat exchanger cleaning systems seemed to work well and thus, no significant effects of fouling on efficiency were detected.

Not only regarding emissions (see section 5.2.2) but also regarding the efficiencies, the simple concept of *Boiler/CERTH* shows a weaker performance compared with wood pellet combustion but also compared with the other two boilers. During full load operation, the efficiencies are between 3.4% (olive stones) and 15.4% (olive tree prunings) lower than for wood pellet combustion. The reason therefore are mainly the significantly higher oxygen contents in the flue gas. For partial load operation, the efficiencies for the pruning pellets are only slightly below the wood pellet performance data and for olive stones, *Boiler/CERTH* even showed a higher efficiency compared to wood pellet combustion.

Table 14: Thermal efficiencies, oxygen contents in the flue gas and flue gas temperatures at boiler outlet achieved during test runs with boilers.

Explanations: Eff. … thermal efficiency based on the NCV of the fuel; O_2 … average O_2 content of the flue gas in vol% d.b.; T FG … average flue gas temperature at stove outlet; *) according to manufacturer data

	Boiler/CIEMAT			*Boiler/CERTH*			*Boiler/BIOS*		
	Eff.	O2	T FG	Eff.	O2	T FG	Eff.	O2	T FG
	Full load operation								
Wood pellets *)	95.0	n.a.	n.a.	80.0	n.a.	n.a.	95.0	n.a.	n.a.
Olive stones	93.6	7.3	52.9	76.6	12.4	220	93.1	6.5	118
Olive tree pruning pellets	94.3	6.7	54.0	64.6	15.7	226	92.8	6.6	113
Vineyard pruning pellets	94.2	6.6	55.2	69.6	15.0	221	93.1	5.6	113
	Partial load operation								
Wood pellets *)	90.9	n.a.	n.a.	65.0	n.a.	n.a.	90.3	n.a.	n.a.
Olive stones	87.5	10.8	44.2	70.3	15.5	125	90.2	8.9	75
Olive tree pruning pellets	87.1	10.4	41.7	64.7	16.9	131	89.9	9.7	79
Vineyard pruning pellets	85.6	10.2	40.8	62.0	17.6	127	88.7	5.6	77

5.4 HCl and SO_2 emissions

HCl and SO_2 emissions are not concerned by any emission limit within the small capacity range, however, these acidic gases may have a negative impact on corrosion issues, especially on low-temperature corrosion. Therefore, these two parameters were also determined during the test runs. The HCl and SO_2 emission detected during the combustion of the three test runs fuels generally were on a comparably low level. This is an expected result since in all fuels tested a significant K-surplus over S and Cl is given. Therefore, S and Cl released to the gas phase during combustion, can react in the gas phase with K-compounds forming KCl and K_2SO_4 which subsequently condense during the cooling of the flue gas and form fine particulate emissions.

During the test runs with the stoves, the HCl emissions were generally below 20 mg/Nm³ and the SO_2 emissions below 12 mg/Nm³ (related to dry flue gas and 13 vol% O_2). During the test runs with the boilers, HCl emissions below 12 mg/Nm³ and SO_2 emissions below 33 mg/Nm³ (related to dry flue gas and 13 vol% O_2). These concentration levels of acidic components are not expected to cause significantly enhanced problems with low temperature corrosion in the boilers and stoves compared with wood pellet combustion.

5.5 Grate ash burnout

For vineyard prunings and olive tree prunings, generally an acceptable ash burnout with organic carbon contents of the grate ashes below 5 wt% (d.b.) could be achieved during all test runs (boilers and stove tests). Regarding olive stones however, increased organic carbon contents were measured in the grate ashes of the boilers and the stoves reaching levels of up to 75 wt% (d.b.). This is mainly caused by the small particle size of the olive stones and the comparably low ash content. Even smaller amounts of unburned fuel particles in the grate ash therefore can lead to elevated organic carbon contents, which underlines the need for a grate concept with small air supply openings and an adapted ash burnout control in order to prevent fuel particles from being de-ashed before burnout took place.

6 Summary and conclusions

Test runs with olive stones, vineyard pruning pellets and olive tree pruning pellets have been performed with three different market available stoves and three different market available residential boilers at CIEMAT, CERTH and BIOS. The evaluation of process and emission data as well as of operation experiences made during these test runs should be applied to assess whether present market available stove and boiler technologies are suitable for the utilisation of these selected Mediterranean fuels.

In general, it must be stated that the olive stones applied fulfilled the proposed quality criteria to gain an A2 label within the BIOMASUD certification scheme, which means that, according to the opinion of the consortium, they should be applicable for residential-scale combustion devices. The olive tree pruning pellets and the vineyard pruning pellets assortments tested however, showed significantly increased ash and nitrogen contents. According to the fuel quality criteria for these biomass fuel assortments, which have been worked out within the project and published within Deliverable Report D3.3, they are not suitable for residential heating systems. This preliminary assessment based on fuel quality criteria has been confirmed by the test runs performed.

Utilisation of the selected BIOMASUD PLUS fuels in stoves

Regarding the general operation of the stoves no problems occurred. Since the stoves were designed for wood pellet combustion, which are in terms of bulk density and energy density well comparable with the test run fuels, as expected no problems with the fuel feeding occurred. Especially when utilising ash rich fuels like the olive tree and vineyard pruning pellets, there is always a concern regarding operational problems due to ash melting on the grate. However, for all three fuels tested, no problems with slag-formation occurred. Consequently, with all stove technologies tested a continuous operation has been possible.

Two of the three stoves tested were based on moving grate concepts with automated de-ashing while one stove was based on a fixed grate with manual de-ashing. It turned out that the latter was not suitable for a long-term operation with both types of pruning pellets, since too frequent de-ashing was needed due to the high ash contents of these fuels. Consequently, only systems with automated de-ashing of the grate are suitable for ash rich fuels such as prunings. However, for these ash rich fuels also the ash box must be emptied by the user much more often than during wood pellet combustion. Regarding olive stones this problem does not exist due to the significantly lower ash content.

Moreover, the high K-contents of the olive tree and the vineyard pruning pellets led to increased fine particle formation and deposition of such particles on the vision panels (window). Within short operation periods (some hours) the window was almost fully covered with ash deposits and had to be manually cleaned. This is a highly undesired effect since an undisturbed view on the flame, which was not given anymore, is a typical user need of stove owners. With olive stones, these problems did not occur.

Consequently, from a user-need perspective, olive stones are an alternative to wood pellets. Even if a problem-free stove operation with olive tree and vineyard pruning pellets was possible, increased efforts for window cleaning and emptying the ash box significantly reduce user comfort and therefore, from a user point of view, these fuels are not a suitable alternative.

Also regarding emissions, it was found that olive stones are suitable for application in pellet stoves. With olive stones, CO, OGC and NO_x emissions below or close to the limit values according to the EU Ecodesign Directive could be achieved with all three stoves. Only regarding dust emissions the limit value was exceeded. This, however, could be overcome by some adaptations of the combustion air distribution and the grate concepts. Regarding the latter, a better adjustment of the air supply openings and the de-ashing strategy to the small particle size of olive stones is needed since it turned out, that partly unburned fuel particles lead to up to 75% organic carbon contents in the grate ash. Moreover, the test runs revealed that the thermal efficiencies of the stoves were lower when utilising olive stones instead of wood pellets. Since the reason therefore mainly were higher oxygen contents in the flue gas during olive stone combustion, an optimisation of the process control towards lower excess air ratios can increase the efficiencies to the same level as for wood pellet combustion.

Olive tree and vineyard pruning pellets turned out as not suitable for an application in stoves as they exceeded the emission limit values for almost all relevant parameters in all stoves tested significantly. Too high CO and OGC emissions could to a certain extent be reduced by an adaptation of the grate and the fuel bed zone with respect to fuels with high ash contents. The significantly increased dust emissions however may only be reduced by the application of a filter (electrostatic precipitator). The most significant problem are the high NO_x emissions determined for these two fuel assortments at all three stoves tested, which exceeded the limit values according to the Ecodesign Directive by more than 100%. Even by fully utilising the emission reduction potentials of primary NO_x emission reduction measures (i.e. application of advanced air staging concepts) it cannot be expected that the emission limits of the Ecodesign Directive can be kept. OTP pellets without leaves, with low ash and nitrogen contents, have not been used for testing.

Utilisation of the selected BIOMASUD PLUS fuels in boilers

Most of the issues discussed for stoves, also apply for the utilisation of the BIOMASUD PLUS fuels tested in conventional wood pellet und wood chip boilers.

Generally, no problems with fuel feeding, general plant operation and ash melting on the grates were detected. Continuous operation could be achieved with all three fuels without major problems. Also regarding boilers it turned out that fixed grate systems with manual de-ashing are not suitable for the ash rich olive tree and vineyard pruning pellets, as very frequent manual de-ashing was needed.

According to the results of the test runs, olive stones are suitable for pellet and wood chip boilers with moving grate systems and/or automated de-ashing, but some minor adaptations/optimisations are needed. Even if the CO and OGC emissions at full load operation were very low, elevated partial load emissions caused seasonal emission factors, which exceeded the Ecodesign emission limits. This problem however, can be overcome by a better adjustment of the process control system to partial load operation with olive stones. The results gained from the test runs with the *Boiler/CIEMAT* showed that also the dust emission limit value can be kept without the application of any secondary emission reduction technology. NO_x emission limits were slightly exceeded, but with a better adjustment of the air supply strategy also this problem should in future be controllable. Regarding the thermal efficiencies, only slightly lower values have been achieved than during wood pellet combustion.

Regarding the utilisation of olive tree and vineyard pruning pellets in principle the same key-problems as during the test runs with the stoves occurred. While elevated CO emissions may be reduced by a better adaptation of the process control system, the dust emission limit can only be kept by application of electrostatic precipitators. However, the much too high NO_x emissions (2 to 2.5-fold of the limit value according to Ecodesign) cannot be achieved by applying primary measures only and secondary measures for NO_x emission reduction have not been developed yet for residential biomass boilers.

Summing up, it can be concluded that olive stones are suitable for application in present pellet stove as well as pellet and wood chip boiler technologies, even though some adaptations respectively optimisations are needed to keep all emission limits set in the Ecodesign Directive, which will in future be the most relevant regulation. On the other side, the qualities of olive tree and vineyard pruning pellets utilised within the combustion tests are not suitable for residential stoves and boilers. The main problems are the too high dust and NO_x emissions. However, qualities of these assortments, which show lower ash and N-contents, could be suitable for application in residential heating appliances which are adapted towards the utilisation of fuels with higher ash contents than wood pellets.