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BIOFUELS FROM BROOM CLEARINGS: PRODUCTION AND COMBUSTION IN COMMERCIAL BOILERS

Irene Mediavilla[a], Elena Borjabad[a], Miguel J. Fernández[a], Raquel Ramos[a], Paloma Pérez[a], Raquel Bados[a], Juan E. Carrasco[b], Luis S. Esteban[a]

[a] CEDER-CIEMAT, Autovía A-15, salida 56, 42290 Lubia, Soria, Spain
[b] CIEMAT, Avenida Complutense 40, 28040 Madrid, Spain

Abstract

Shrub lands could provide an almost unexplored biomass resource of increasing potential in the EU, particularly in Mediterranean countries. Its collection and transformation into solid biofuels will help to reduce the adverse effects associated with frequent shrub land fires. The objective of this study is to examine the pre-treatment and combustion of biomass obtained from broom plant clearings to assess the feasibility of utilising it as a fuel in commercial combustion applications.

Above ground broom biomass was collected with a harvester-baler machine. Afterwards, in a milling installation and a pilot pelletisation plant two fuels were obtained: 30 mm milled material and pellets, which were used in two commercial grate boilers (40 kWth and 500 kWth). We conclude that biomass from broom clearings could be used to produce solid biofuels for commercial boilers. Milling and pelletisation did not entail difficulties and the pellets could be classified as B (ISO 17225-2:2014). During combustion, no operating problems related to the fuel were observed. However, due to its high potassium content, special attention should be paid to the tendency to produce deposits and to particle emission and it would be advisable to control the working temperature to avoid slag formation in the burner.

1. Introduction

EU climate and decarbonised energy targets rely on a significant increase in the demand for biomass resources. Considering the availability limitations of biomass residues and waste and the uncertainties of biomass production on agricultural land, research into new biomass resources is required and the potential of shrub land stands being an interesting option. Nowadays, this source of biomass is poorly known, since it is frequently considered as secondary natural vegetation when compared to natural or planted tree stands.

1

41 Frequently, shrub lands constitute one of a series of stages of colonisation after the
42 disappearance of tree cover, caused for example by forest fires. In general, shrub formations
43 are mainly understorey vegetation although, in some cases, they may contain varying
44 proportions of tree species, which makes their classification within the different land cover
45 surveying systems even more difficult.
46 The last Global Forest Resources Assessment (FRA 2015) coordinated by the FAO [1], which is
47 estimated to include 88% of the global forest area, considers a category of land called "other
48 wooded land". In most cases it comprises shrub lands and it accounts for 1204 million hectares
49 (9.2% of the global land area).
50 In the EU28, the data from FRA 2015 indicates that "forest land" covers 38% of the land surface
51 (161 million hectares) and "other wooded land" occupies only 4,9% of the land (21 million
52 hectares). However, according to the "Land Use and Cover Area Frame Survey" (LUCAS, 2012)
53 [2], performed every three years by EUROSTAT, shrub lands cover 29 million hectares (6.7% of
54 EU continental territory), reaching 46 million hectares (10.6% of EU continental territory) when
55 the category "grassland with sparse tree/shrub cover" is included. This last figure is quite close
56 to that obtained from Corine Land Cover (CLC, 2012) [3] when the category "scrub and/or
57 herbaceous vegetation associations" is considered, giving a value of 51 million hectares (11.9%
58 of EU continental territory).
59 Within the EU28, the Mediterranean countries support the greatest relative coverage of shrub
60 land. Of the 46 million hectares of shrub land estimated according to LUCAS in the EU28,
61 approximately 21 million (45%) are concentrated in the territories of Greece, Portugal, Spain,
62 Italy, Cyprus and Croatia and about half of this (10.7 million hectares) is located in Spain.
63 However, although the land surface covered by shrubs has been documented in the sources
64 cited, only a few studies of the availability and chemical composition of shrub biomass in
65 Portugal and Spain have been published [4-6].
66 At present, shrub lands usually suffer from lack of management which, together with the
67 abandonment of traditional forestry uses, leads to a forest structure more prone to wildfires [7,
68 8]. In most cases, the uncontrolled concentration of shrubs is frequently the cause of the start
69 and spread of new forest fires in European Mediterranean countries [4, 9, 10]. Thus, about 46-
70 72% of the total forest area burned from 2005 to 2013 in Spain was covered by shrub lands
71 [11]. Fire experts have recommended that the forests, grazing lands and paths need to be
72 cleaned and cleared in order to prevent wildfires [8].
73 Shrub lands could provide an as yet almost unexplored biomass of increasing potential in the
74 EU, particularly in Mediterranean countries, for the production of solid biofuels and this could be
75 expected to contribute to reducing the adverse environmental effects associated with frequent
76 shrub land fires.
77 In this context, one of the goals of the ENERBIOSCRUB LIFE+ project is the mobilisation of
78 new biomass resources through the production of sustainable solid biofuels from the
79 mechanised cleaning of shrub lands with high flammability risk. This paper describes the results
80 obtained in the aforementioned project in the preparation of solid biofuels and their subsequent

81 combustion using broom (*Genista cinerascens* Lange) biomass, in order to assess the feasibility

82 of utilising the new biomass resource as a fuel in commercial combustion appliances.

83

84

85 **2. Materials and methods**

86 2.1 Raw materials

87 The raw material utilised in this study is broom (*Genista cinerascens* Lange) biomass. It is an

88 endemic plant of the centre and west of the Iberian Peninsula (Spain and Portugal) and is very

89 common in shrub lands located at an altitude of 400 to 1,800 m [12]. A map of the distribution of

90 this plant in the Iberian Peninsula can be seen in [13].

91

92 In order to obtain broom (*Genista cinerascens* Lange) biomass, forest clearings were carried

93 out in the ENERBIOSCRUB project. A catchment area of 20 km radius from Las Navas del

94 Marqués (Ávila, Spain) was considered. In this area, 10,633 ha were covered by broom and the

95 above-ground biomass was estimated to be 64,863 t (dry matter). This biomass could be used,

96 inter alia, in a heating network located in the town, where a biomass boiler (1 MW_{th}) is used to

97 provide heating and hot water to three public buildings.

98

99 The broom biomass was collected using a BIOBALER W55 harvester-baler machine. Two

100 pictures of the clearing operations can be seen in Figure 1. Afterwards, the bales were

101 transported to CEDER-CIEMAT and stored for two months in a shed in ambient air conditions in

102 order to reduce their moisture content.

103

104 2.2 Biomass pre-treatment installations

105 2.2.1 Comminution equipment

106 The dry bales were reduced in size by means of a milling installation (Figure 2) that allows the

107 material to be ground from very large sizes, such as tree stumps, big bales, logs, etc., down to

108 fine particles (less than 4 mm) with capacities between 1,000 and 2,000 kg/h. The installation

109 comprises a large pre-shredder (90 kW, slow rotating single-shaft type), a post-grinder (75 kW,

110 swinging hammer type) and an oscillating two deck screening machine.

111

112 2.2.2 Pelletisation plant

113 The facility used in the experiments was a pilot plant (Figure 3) which includes a blending

114 system, a pellet mill and cooling and bagging equipment. The pellet press is a flat die type with

115 500 mm die diameter and 30 kW drive power.

116

117 2.3 Biomass combustion equipment

118 2.3.1 Boilers

119 Two boilers were used for the combustion tests carried out. They were named MG40 and

120 MG500 and they are described below.

3

121 MG40 is a commercial boiler with thermal power between 25 and 40 kW, depending on the
122 biomass fuel used. This boiler, which has been specially designed for agro-fuels has a lateral
123 feeding burner based on a moving grate with a double forward-backward and upward-
124 downward movement. The feed system has been adapted to feed pellets, chips and chopped
125 biomass. Furthermore, the boiler has a fully automatic ash extraction system. The heat
126 exchanger consists of vertical tubes with three smoke passes. Fumes are blown through by a
127 fan which also draws in the primary and the secondary air. The boiler also has a lambda probe
128 located at the flue gas stream which allows the oxygen concentration in the outlet gases to be
129 monitored. This boiler does not have any equipment to remove the particles produced during
130 combustion. The boiler is automatically controlled to ensure low gas emission levels, being
131 classified by its manufacturer as class 3 according to the EN 303-5:1999 standard.
132
133 MG500 is a commercial 500 kW$_{th}$ moving grate boiler, in which primary air is introduced through
134 several holes in the grate, while secondary air enters the furnace through six nozzles. The boiler
135 has a heat exchanger consisting of horizontal tubes with three smoke passes. Combustion air is
136 drawn into the furnace by three fans (one for primary air and two for secondary air) and fumes
137 are blown through by an additional fan. In order to remove particles from exhaust gases, a
138 multi-cyclone unit is used.
139
140 In both the boilers described, operational variables, such as temperatures inside the burner, in
141 the tubes of the heat exchanger and in the chimney, inlet and outlet water temperatures, and
142 water volume flow, are registered on line. Mass fuel flow can be also calculated.
143
144 2.3.2 Process control and emissions measuring equipment
145 Measurement of the gaseous composition of exhaust gases during the combustion tests is
146 carried out with a portable Fourier Transform Infrared (FTIR) Spectroscopy analyser and a
147 zirconium oxide cell for determining the O_2 concentration in the sample gas.
148
149 Continuous monitoring of the particle content in exhaust gases is performed with a system
150 which uses electrodynamic probe electrification technology. The electrical current produced by
151 particles interacting with a grounded rod protruding across the stack is measured and correlated
152 with dust concentration by comparison with the results of an iso-kinetic sample. An automatic
153 iso-kinetic sampler is thus used to measure the particle content in flue gases in certain periods
154 of time.
155
156 2.4 Experimental design
157 2.4.1 Biomass pre-treatment
158 Broom was received as bales and it was milled in two steps:

159 1. Three batches of 10 bales (approximately 3,000 kg/batch) were ground in the pre-shredder
160 using a screen opening of 30 mm. Part of the material obtained was used directly in the
161 combustion tests performed in the MG500 boiler.
162 2. Three batches of 30 mm milled material (approximately 1,500 kg/batch) were fed to the post-
163 grinder, where a screen opening of 4 mm was used. This material was used to produce the
164 pellets utilised in the combustion tests performed in the MG40 boiler.
165
166 At the beginning of the pelletisation test, water and biomass flows fed to the pellet press were
167 modified as the process went on, with the aim of optimising operation of the machine (i.e. stable
168 power demand and low vibration) and obtaining high quality pellets (moisture content < 10%
169 and fines content < 1.0%). When these conditions were reached, it was considered that steady
170 state had been achieved and it was maintained for at least 2 hours. Three tests were carried
171 out, with a specific pelletisation surface of 5.6 cm^2/kW and a die compression pressway of 35
172 mm. These variables are calculated as follows:
173 Specific pelletisation surface: S_p.
174 $S_p = (N \times S_0) / P$
175 where:
176 N: number of die holes covered by the rollers.
177 S_0: surface of one hole. It is calculated with: $S_0 = (\pi \times D^2) / 4$, where D is the diameter of the
178 straight part of the hole (8 mm).
179 P: drive power of the pellet press.
180 Die compression: it is defined as the path between the beginning of the inlet cone and the end
181 of the straight part of the die hole, calculated as l + L in Figure 4.
182
183 The process variables recorded in the milling and pelletisation tests were the specific mass flow
184 (in kg of dry matter per hour and per kW of drive power) and the specific energy (in kWh per t of
185 dry matter). The specific mass flow is calculated as the mass of milled or pelletised material (in
186 kg of dry matter) divided by the time utilised to mill or to pelletise it (in hours) and by the power
187 of the mills (pre-shredder: 90 kW; post-grinder: 75 kW) or the pellet press (30 kW). The specific
188 energy is calculated as the active electric energy demanded by the different items of equipment
189 to mill or to pelletise the material, divided by the mass of material which has been milled or the
190 mass of pellets obtained (in tonnes of dry matter).
191
192 2.4.2 Biomass combustion
193 With the purpose of comparing the behaviour of broom fuels with other commonly used biomass
194 fuels, commercial pellets A1 (according to the ISO 17225-2:2014 standard) and milled pine
195 were used as reference in the combustion tests carried out.
196
197 Preliminary combustion tests were performed in the MG40 and the MG500 boilers with the
198 broom fuels in order to define and adjust the operating conditions with the aim of obtaining the

5

199 lowest emissions. Therefore, adjustment of the boiler parameters was carried out: grate working

200 cycle, O_2 concentration set point for lambda probe, and combustion air distribution between

201 primary and secondary air.

202

203 Afterwards, one combustion test was performed in each boiler with both broom and pine fuels.

204 Each test had a steady state period of 6 hours, working as close as possible to the nominal

205 power of the boiler. The steady state was considered to start at the time in which flue gas

206 temperature did not change more than ± 5 °C in a period of 30 minutes.

207

208 When the combustion tests finished, ash was gathered from different locations, depending on

209 the boiler, and weighed:

210 - MG40: firstly, if slags were observed on the grate, a sample was collected manually and

211 labelled "slag". Afterwards, the rest of the ash in the grate was gathered and, together with the

212 ash from between the furnace and the ash-container extracted with the ash extraction system,

213 this formed the "grate" sample. Next, if sinters were observed inside the tubes of the heat

214 exchanger, a sample was collected manually and labelled "sinter". Lastly, the ash deposited

215 inside the tubes of the heat exchanger was collected using a brush, separating the samples of

216 the 1st and 2nd passes, which were labelled "1st pass tubes" and "2nd pass tubes", respectively.

217 - MG500: firstly, if slags were observed on the grate, a sample was collected manually and

218 labelled "slag". The rest of the ash was extracted with the ash extraction system and, using the

219 quartering method, a sample was collected and labelled "grate". Afterwards, if sinters were

220 observed inside the tubes of the heat exchanger, a sample was collected manually and labelled

221 "sinter". Next, the ash deposited inside the tubes of the heat exchanger was collected using a

222 brush, separating the samples of the 1st, 2nd and 3rd passes, which were labelled "1st pass

223 tubes", "2nd pass tubes" and "3rd pass tubes" respectively. Lastly, all the ash separated from the

224 flue gases with the multi-cyclone unit was collected, to produce the "cyclone" sample.

225

226 The process variables studied in the combustion tests were: thermal power, thermal output,

227 temperatures at different locations in the boiler, emissions (O_2, CO, NO_x, SO_2, HCl, total organic

228 carbon (TOC) and particles), ash deposition velocities and the visual characterisation of the

229 ashes.

230

231 2.5. Analytical procedures

232 The sampling of the milled biomass and the pellets was from moving material (at the outlet of

233 the mill and at the outlet of the bagging bin of the pelletising pilot plant) and 5 samples of 1 dm^3

234 were taken in each test. All the samples were placed in one container to form a combined

235 sample (milled material and pellets separately) which was analysed in the laboratory.

236

237 Regarding the fuels used in the boilers, 10 samples of 1 dm^3 were collected during each

238 combustion test. All the samples (milled material fed to MG500 and pellets fed to MG40

6

239 separately) were placed in one container to form a combined sample which was analysed in the
240 laboratory.
241
242 The laboratory sample was prepared according to the UNE 14780:2011 standard, by means of
243 homogenisation, division, drying and grinding. The analytical tests were performed in the
244 Laboratory of Biomass Characterisation at CEDER-CIEMAT, following the standards shown in
245 Table 1.
246
247 The study of the level of agglomeration of the ash collected inside the boilers after the
248 combustion tests was based on its resistance to being separated by means of particle size
249 distribution analysis. In this methodology, a representative sample of ash by quartering is
250 selected. Its volume must be approximately 1/3 of the sieve volume, using 0.2 m or 0.4 m
251 sieves. Then, a 15-minute sieving process is carried out and samples, collected in the different
252 sieves, are weighed.
253
254
255 **3. Results and discussion**
256 3.1 Biomass pre-treatment
257 3.1.1 Comminution tests
258 Table 2 shows the values of the specific mass flow and the specific energy registered during the
259 milling of broom in the pre-shredder (with 30 mm screen opening) and in the post-grinder (with 4
260 mm screen opening). The moisture content of the milled biomass is also shown.
261
262 As can be seen, the values of the specific mass flow and the specific energy demand are of the
263 same order of magnitude in the three tests performed, both in the pre-shredder and the post-
264 grinder. The differences observed between them could be associated with differences in the
265 moisture content of the biomass milled and with the lack of homogeneity of the bale material.
266
267 Comparing the values of specific energy obtained with some reference studies for wood logs, it
268 can be seen that wood log chippings show an average specific energy demand between 6 and
269 7.2 kWh/t (d.b.) [14], this value being lower than the 11 kWh/t registered to produce 30 mm
270 milled biomass from broom bales. However, it must be taken into account that the final size of
271 the broom is less than the chips considered and the size reduction equipment used is different.
272 On the other hand, the specific energy demand to produce 4 mm milled pine from chips (with
273 14% moisture content and 12.12 mm arithmetic mean diameter) is 48 kWh/t (d.b.) [15], which is
274 similar to the value obtained for mill broom from 30 mm to 4 mm.
275
276 3.1.2 Pelletisation tests
277 The results obtained in the pelletisation tests carried out with 4 mm milled broom can be seen in
278 Table 3. If the values of specific mass flow and specific energy are compared with those

279   identified as optimal during pine sawdust pelletisation in a previous study [16] (6.1 dry kg/h kW

280   and 121 kWh/dry t), it can be observed that the average values calculated in broom tests are

281   very similar to the values recorded with pine sawdust.

282

283   3.1.3 Biofuel characterisation

284   Two different broom fuels were obtained in the pre-treatment tests to be used in subsequent

285   combustion tests: 30 mm milled material and pellets (Figure 5).

286

287   The physical and chemical characterisation of these fuels together with the characterisation of

288   the fuels used as reference in the combustion tests (pine pellets classified as A1 according to

289   the ISO 17225-2:2014 standard and 30 mm milled pine) can be seen in Table 4.

290

291   The broom pellets obtained comply with the limits established in the ISO 17225-2:2014

292   standard for class B pellets.

293

294   Comparing the broom fuels to the reference fuels, it can be seen that the milled broom shows

295   higher bulk density, ash content and fines content than the milled pine used. The calorific

296   values, GCV and NCV, in dry basis, are similar in broom and pine fuels, in spite of their different

297   ash contents. In the ultimate analysis, it can be seen that the nitrogen content in broom is higher

298   than the value analysed in the reference fuels (more than 17 times higher in pellets and more

299   than 10 times higher in milled material), as would be expected, since broom is a leguminous

300   species and is therefore characterised by a high nitrogen fixation capacity, accumulating

301   nitrogen in fine fractions such as leaves or twigs [17]. This fact will have an effect on the NO_x

302   emissions. With regard to sulphur and chlorine content, it can be seen that they are similar in

303   broom and pine fuels. Considering ash composition, we find that the ash of the reference fuels

304   used shows higher Ca content and lower K content than broom fuels, a fact which could explain

305   why sintering is less common with the reference fuels [18].

306

307   3.2 Biomass combustion

308   The fuels obtained in the pre-treatment step were tested and compared to reference fuels in

309   each boiler, using a protocol based on the EN 303-5:2012 standard, as follows:

310   - MG40: one test with broom pellets and one test with commercial A1 pine pellets (used as

311   reference material).

312   - MG500: one test with 30 mm milled broom and one test with 30 mm milled pine (used as

313   reference material).

314

315   During the combustion tests, the two boilers worked without mechanical problems related to the

316   fuels used, each test lasting 6 hours in steady state conditions. Table 5 shows the operating

317   conditions during the combustion tests carried out, where:

8

318 - Heat input refers to the amount of heat per unit time supplied to the furnace by the fuel (based
319 on its net calorific value).
320 - Boiler efficiency is the ratio between the heat transferred to the water per unit time and the
321 heat input.
322 - The variable "T 1st pass tubes" is the temperature registered at the inlet of the 1st pass tubes of
323 the heat exchanger.

324

325 Although the heat input values are of the same order of magnitude with both fuels in each
326 boiler, lower boiler efficiency was obtained with broom fuels, as a result of lower heat transfer to
327 the water during those tests, and related to more severe fouling of the heat exchanger because
328 of ash deposition (see figures in Table 8).

329

330 Table 6 shows the average values of gaseous and particle emissions measured during the
331 steady state of the combustion tests, where it can be observed that broom combustion, using
332 both pellets and milled material, entailed higher emissions of CO, NO_x and particles than the
333 biofuels used as reference (A1 pine pellets and milled pine).

334

335 Taking into account that the combustion tests followed a similar methodology to that used for
336 rated heat output tests in the EN 303-5:2012 standard, the emissions obtained in the MG40
337 boiler (categorised as class 3 according to the EN 303-5:1999 standard) have been compared
338 with the limits established to classify solid fuel heating boilers as class 3 according to this
339 standard. These limits are: 3,000 mg CO/Nm^3 and 150 mg particles/Nm^3, referred to 10%v. of
340 O_2. Both broom and commercial pellets led to CO emissions lower than the established limit.
341 However, particle emission was higher than the limit when broom pellets were used.

342

343 As mentioned above, broom fuels have high nitrogen content compared with pine fuels and
344 consequently, higher NO_x emissions were expected, since the NO_x emission of biomass
345 combustion is mainly conditioned by the content of nitrogen in the biomass [19-23]. European
346 Directive 2015/2193 on the limitation of emissions of certain pollutants into the air from medium
347 combustion plants (1-50 MW) has been taken into account to provide a reference limit for NO_x
348 emissions, in spite of the lower capacity of the boilers considered. The limit for existing
349 installations established by this Directive is 650 mg NO_x/Nm^3 with reference O_2 of 6%. In Table
350 6 the values of NO_x obtained in the tests expressed at the same O_2 reference are shown. It can
351 be observed that the emissions of NO_x obtained during broom combustion did not exceed the
352 limit established by the Directive.
353 With regard to SO_2 emissions, it can be seen that the emissions during broom combustion are
354 lower than those corresponding to pine combustion. These values do not seem to be correlated
355 with the sulphur content of the biomass materials used (see Table 4), which is lower in pine
356 fuels than in broom fuels. However, it is known that alkalis or alkaline earth metals such as
357 sodium, calcium and potassium have the ability to capture sulphur, which has a greater affinity

358 for alkalis than for calcium, as different authors have reported in literature [24-29]. With the aim

359 of explaining the behaviour of broom and pine fuels during combustion, mass balances have

360 been carried out, where the following points have been taken into account:

361 • The total sulphur contained in the biomass has been calculated considering the

362 percentage of sulphur in the biomass (Table 4) and the total quantity of biomass used in

363 each test (by weighing the fuel put into the boiler and the fuel remaining after the tests).

364 • The ash collected on the grate and inside the 1st pass tubes of the heat exchanger has

365 been considered.

366 • The quantity of sulphur retained by the ash has been calculated considering the sulphur

367 content in the collected ash calcined at 550 ºC.

368

369 The results obtained are shown in Table 7, where it can be observed that the percentage of

370 sulphur retained by the ash, calculated as a proportion of the total sulphur contained in the

371 biomass, is higher in broom tests than in pine tests. Furthermore, it must be taken into account

372 that part of the sulphur contained in the biomass will be released with the particles emitted with

373 fumes (levels are higher in broom combustion than in pine combustion, see Table 6), which are

374 mainly dominated by potassium, chlorine and sulphur [30, 31].

375

376 A physical description of the ash gathered from different locations in the boilers after the

377 combustion tests can be seen in Table 8.

378

379 As shown in Table 8, broom combustion entailed the formation of small slags when the MG40

380 boiler was used and agglomerated ash which disintegrated easily in the combustion test with

381 the MG500 boiler; however sintering was not observed in the ash collected inside the tubes of

382 the heat exchanger after any of the combustion tests.

383

384 With the aim of comparing the degree of agglomeration of the ash collected on the grate, its

385 particle size distribution was analysed (see section 2.5). This methodology has proven effective

386 in comparisons of the degree of agglomeration in other studies [32-34]. The results obtained

387 can be seen in Figure 6, where the ash generated on the grate during the combustion test in the

388 MG40 boiler with broom pellets had a higher degree of agglomeration than the ash produced

389 during the test with pine pellets. Thus, 41% of the ash coming from broom pellets had a size

390 larger than 8 mm, compared with 2.5% corresponding to the ash coming from pine pellets. On

391 the other hand, the ash gathered on the grate after tests with milled broom and pine in the

392 MG500 boiler was very similar with regard to its degree of agglomeration, with less than 2% of

393 ash particles larger than 8 mm. The explanation of the formation of small slags when broom

394 pellets were used could be related to the higher temperature registered at the outlet of the grate

395 in the MG40 boiler compared with the temperature in the MG500 boiler when milled material

396 was used.

397

10

398   Table 9 shows the ash deposition velocities in the combustion tests. The deposition pattern

399   depends on different factors: biomass composition, boiler design and operating conditions

400   during combustion (air distribution, air flow, temperatures) [35-42]. With regard to the tests

401   carried out in the MG40 boiler, the high ash deposition velocity inside the 1st pass tubes of the

402   heat exchanger when broom pellets were used is particularly noticeable (more than 3 times

403   higher than the ash deposition velocity obtained with pine pellets). Broom pellet combustion

404   also entailed the highest particle emission (see Table 6).

405

406   In Table 10, the unburnt matter in the ash collected inside the tubes of the heat exchangers

407   after the tests can be seen. This table shows that the proportion of unburnt matter in this ash is

408   higher when the reference biomass materials are used. Therefore, the higher ash deposition

409   velocity and particle emission of broom biofuels compared to pine biofuels are mainly

410   determined by the ash composition and they could be due to the higher content of potassium in

411   the broom biomass (Table 4). This element has been shown to be very important in the

412   deposition of ash and is the major ash forming element in the fine inorganic particulates from

413   residential combustion of biomass [30, 43, 44].

414

415   In order to obtain further information about the different fuels with regard to slagging and ash

416   deposition, a characterisation of the composition of the ash coming from the fuel (at 550 ºC) and

417   the ash collected on the grate and inside the first pass tubes of the heat exchanger (calcined at

418   550 ºC) was performed, using ICP-AES and XRD analysis. The results are shown in Figures 7

419   and 8.

420

421   In the graphs corresponding to the ICP-AES analysis (in the upper part of the Figures), all the

422   elements, with the exception of chlorine, are expressed as oxides and normalised at 100%.

423   Furthermore, the ash composition has been expressed as iron-free, with the aim of avoiding the

424   influence of contamination by metal coming from the tubes of the heat exchanger during the

425   collection of the ash sample. The crystalline compounds detected and semi-quantified using

426   XRD analysis are shown in the lower part of the Figures. These compounds have also been

427   normalised at 100%.

428

429   During the cleaning of the boilers after the combustion tests, the formation of small slags in the

430   combustion of broom pellets was observed (Table 8). However, although the ash collected on

431   the grate after the test with pine pellets was agglomerated, it did not show melting points. This

432   different behaviour was previously predicted taking into account the difference in calcium and

433   potassium content between broom and pine pellets (Table 4). The higher the ratio of alkaline

434   earth oxides to alkaline oxides, the higher the sintering temperature is. Considering the

435   composition of the biomass shown in Figures 7 and 8, it can be seen that the ratio is higher in

436   pine pellets.

437

11

438   With regard to the ash collected inside the first pass tubes of the heat exchanger, it can be

439   observed that, in general, the potassium, chlorine and sulphur content in this ash is higher than

440   that of biomass calcined at 550 ºC. This fact could be due to the deposition of alkaline

441   compounds on the tubes following two mechanisms: direct condensation on the surface of

442   tubes or condensation on particles and subsequent deposition on the surface of tubes by

443   thermophoresis.

444

445   Concerning the ash gathered on the grate, potassium silicates, which are usually compounds

446   with a low melting point, are observed in the tests corresponding to the broom in both boilers

447   and in the test with pine pellets (Figures 7 and 8), where slags or agglomerated ash on the

448   grate were collected (see Table 8). The formation of kalsilite ($KAlSiO_4$) and other complex

449   potassium compounds is a consequence of the chemical reaction between silica and the

450   potassium compounds contained in the biomass (KCl, K_2SO_4 and $CaK_2(CO_3)_2$). Furthermore,

451   the content of potassium silicates in the ash gathered on the grate is higher in the tests carried

452   out in the MG40 boiler. This could be due to the temperature registered at the outlet of the grate

453   of the MG40 boiler being higher than in the MG500 boiler (see Table 5).

454

455   On the other hand, no potassium compounds were detected in the ash sample collected on the

456   grate of the MG500 boiler after the test with milled pine (see Figure 8). Thus, a lower

457   concentration of potassium compounds and silica was detected in milled pine biomass and a

458   lower temperature at the outlet of the grate was registered than the temperatures registered in

459   the MG 40 boiler (Table 5).

460

461

462   **4. Conclusions**

463   Biomass obtained from broom clearings can be used to produce solid biofuels to be utilised in

464   domestic and industrial boilers.

465   Broom bale milling to produce material to be used in boilers (30 mm milling) and to produce 4

466   mm milled material to make pellets does not entail operating problems. Continuous operation of

467   the comminution equipment (slow rotating single-shaft pre-shredder and swinging hammer post-

468   grinder) without blockages was observed.

469   Pelletisation of broom biomass can be carried out without any difficulties, getting specific mass

470   flow and specific energy demand similar to those obtained during pelletisation of pine sawdust

471   in the pilot plant used in this study. The pellets obtained can be classified as B pellets according

472   to the ISO 17225-2:2014 standard.

473   Combustion of 30 mm milled broom and broom pellets did not cause fuel-related operating

474   problems in the tests carried out in this study, although special attention must be paid to the

475   tendency of this biomass to produce ash deposition inside the tubes of the heat exchanger and

476   particle emission (because of its high potassium content). Consequently, particle abatement

477   equipment and more frequent cleaning of the heat exchanger could be required when broom

12

478 fuels are used. With regard to the slagging tendency of broom fuels, although the slags and

479 agglomerated ash produced during the tests have not entailed blockages or unplanned

480 shutdowns, it would be advisable to control the working temperature on the grate to avoid

481 slagging and to study the behaviour of these fuels in the long term.

482 Gaseous emissions during the combustion of broom fuels are lower than the limits defined by

483 the standards referred to in this study. The main factor to be taken into account is NO_x emission,

484 although the values obtained during the tests are lower than the limit established by European

485 Directive 2015/2193 on the limitation of emissions of certain pollutants into the air from medium

486 combustion plants. Although this Directive applies to boilers between 1 and 50 MW_{th}, this value

487 has been taken as a reference.

488 The formation of small slags on the grate of the MG40 boiler is a consequence of the potassium

489 and silicon content in the broom fuel and the high working temperature inside the boiler, which

490 is inherent to its design.

491

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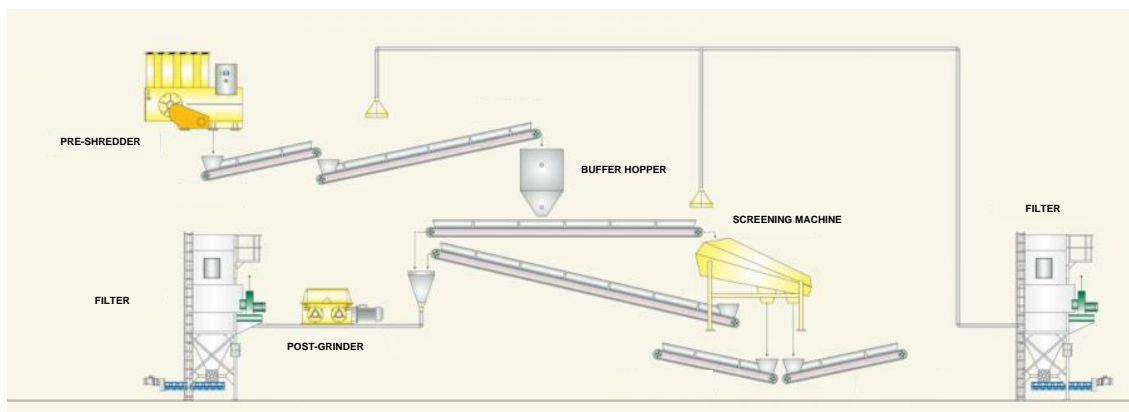
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Acknowledgements

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617 **FIGURES**

618

619 **Figure 1.** Broom clearing in Las Navas del Marqués (Ávila, Spain)
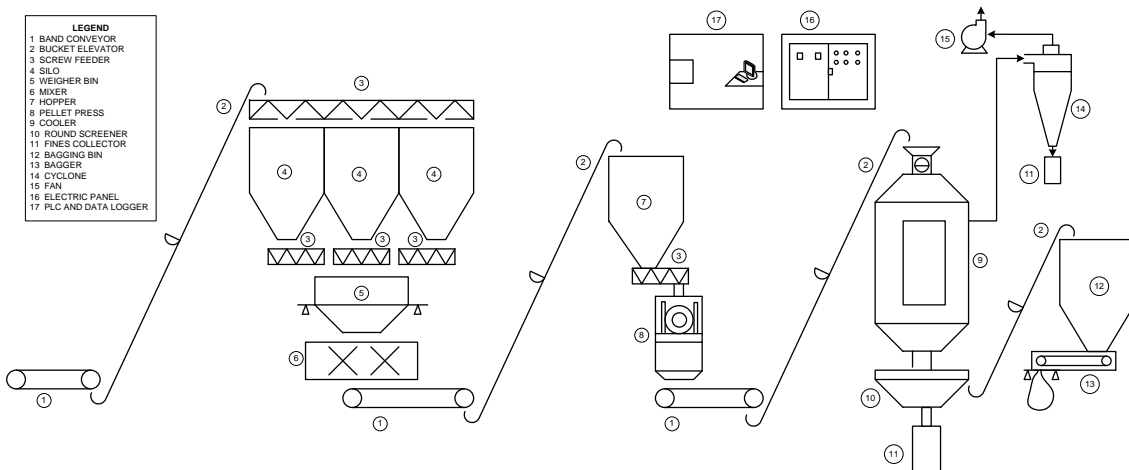
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623 **Figure 2.** Layout of the milling installation used in the tests located at CEDER-CIEMAT (Soria,
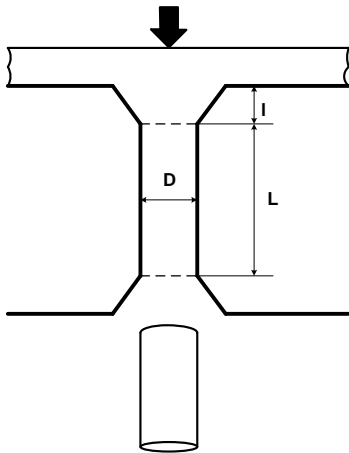624 Spain)

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627 **Figure 3.** Layout of the pelletisation pilot plant used in the tests located at CEDER-CIEMAT
628 (Soria, Spain)

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Figure 4. Schematic representation of a die hole

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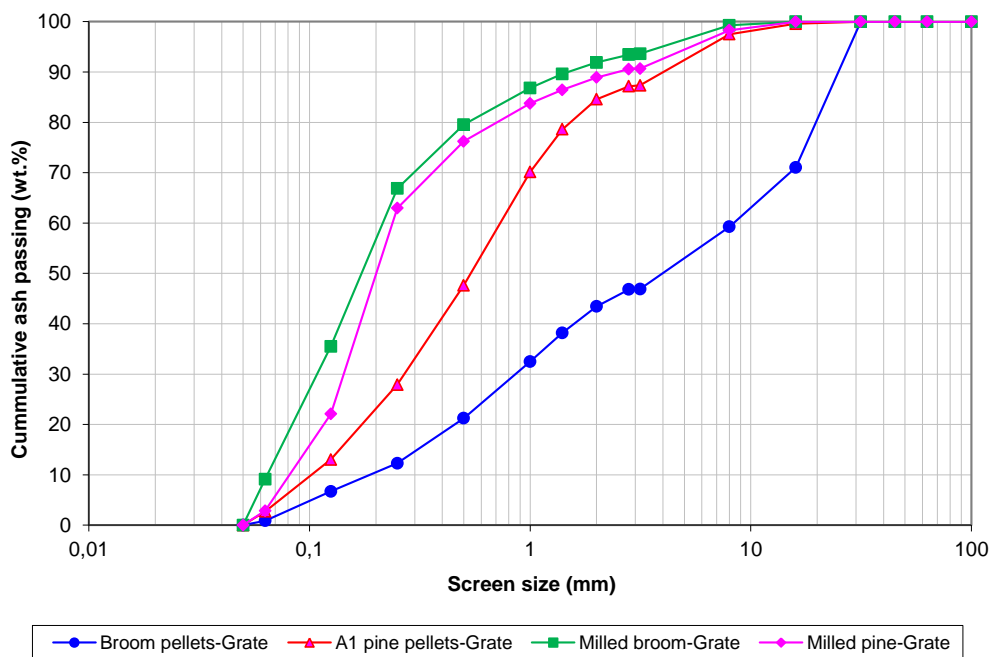
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Figure 5. Broom fuels used in combustion tests: 30 mm milled material (left) and pellets (right)

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Figure 6: Particle size distribution of the ash gathered on the grate after combustion tests in

MG40 and MG500

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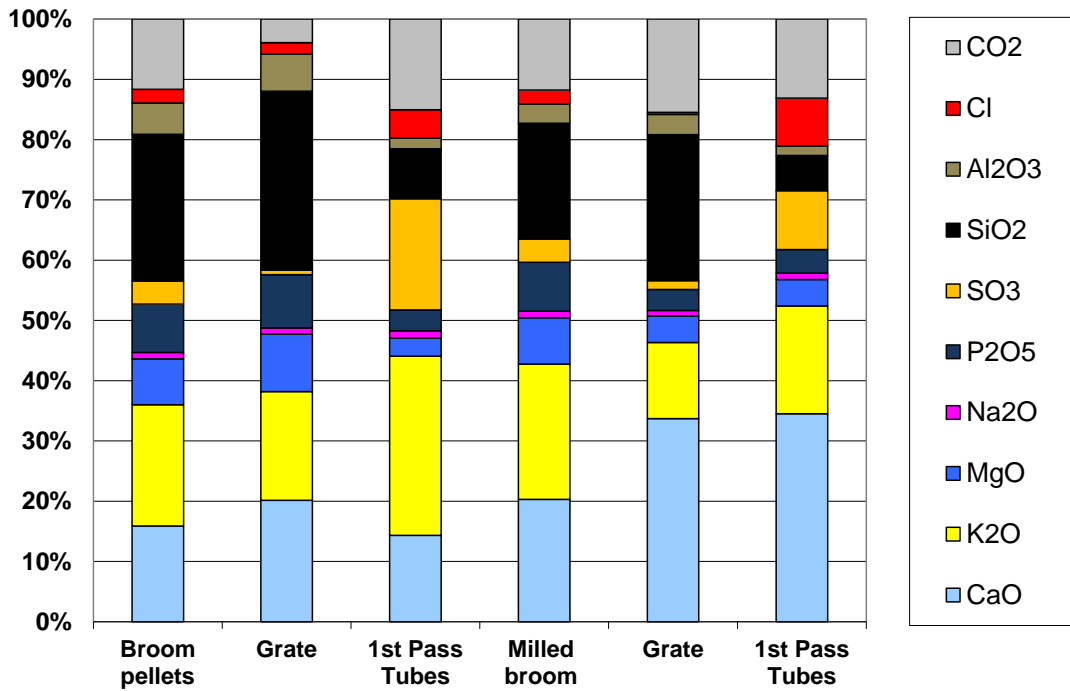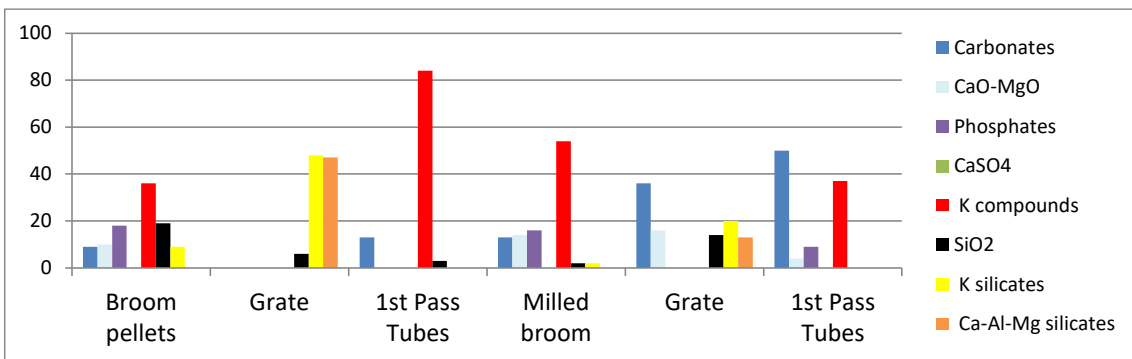
Figure 7: Ash composition of samples collected in broom combustion tests. Elements: upper

figure; Compounds: lower figure.

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649 **Figure 8:** Ash composition of samples collected in pine combustion tests. Elements: upper

650 figure; Compounds: lower figure.

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655   **TABLES**

656   **Table 1:** Analytical methods and standards used in the Laboratory of Biomass Characterisation

657   (CEDER-CIEMAT)

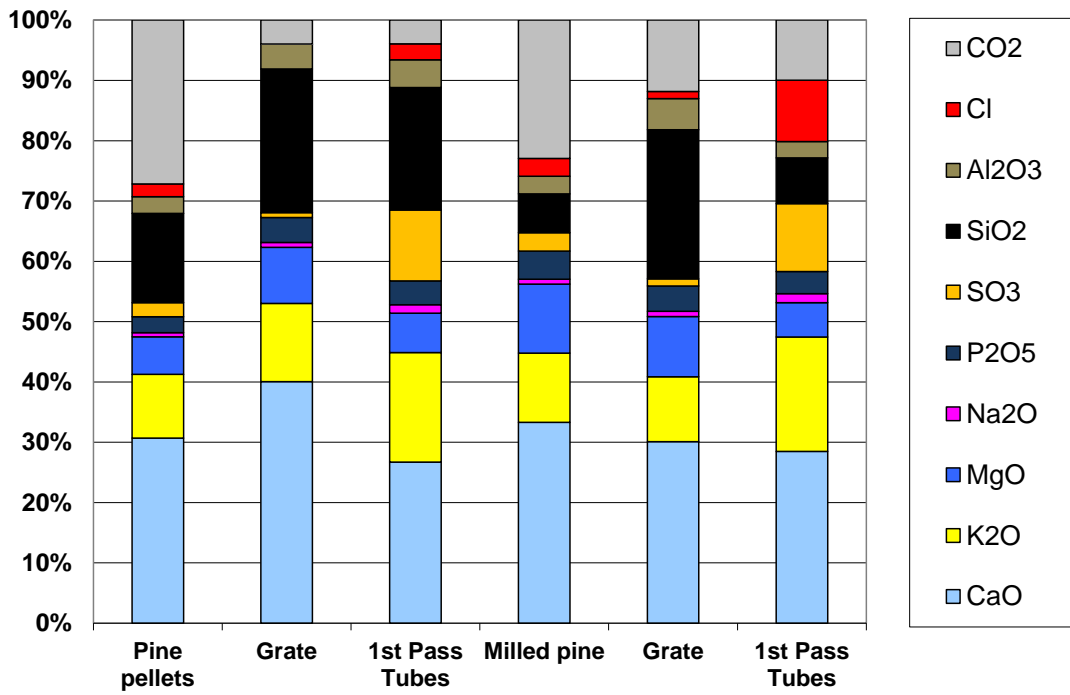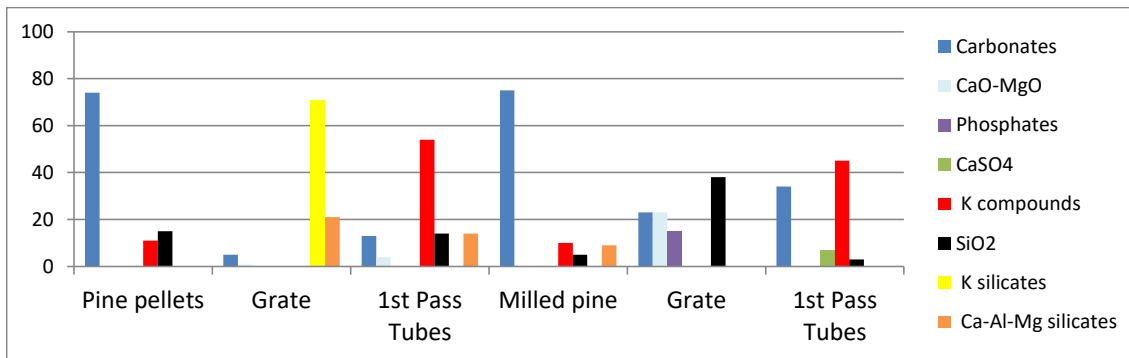| Parameter		Analytical method	Standard
Bulk density		Mass of a known volume	EN 15103
Particle size distribution		Separation into defined size fractions (sieves)	EN 15149-1 and EN 15149-2
Mechanical durability of pellets			EN 15210-2
Length and diameter of pellets			EN 16127
Proximate analysis	Moisture	Drying at 105 ºC	EN 14774-2
	Ash	Calcination at 550 ºC	EN 14775
	Volatile matter	Calcination at 900 ºC	EN 15148
Ultimate analysis	Carbon, Hydrogen and Nitrogen	Elemental analyser equipped with infrared detectors and a thermal conductivity detector	EN 15104
	Sulphur and Chlorine	Ion chromatography after sample combustion	EN 15289
	Chlorine (ash sample)	Calcination at 775 ºC and Eschka method	
Calorific value		Automatic calorimeter	EN 14918
Inorganic elements in ash (calcination at 550 ºC)		Digestion in a microwave furnace and analysis by ICP-AES using a simultaneous spectrometer	EN 15290
Crystalline phases in ash		XRD	

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660 **Table 2:** Results of broom comminution tests

PRE-SHREDDER (30 mm)	Test 1	Test 2	Test 3	Average	Std. dev.	Rel. std. dev. (%)
M (kg/h kW) (d.b.)	15	16	18	16	1.5	9.4
E (kWh/t) (d.b.)	12	12	9.0	10.8	1.6	14.7
Moisture content (wt.%) (w.b.)	15.5	16.5	9.5			
POST-GRINDER (4 mm)						
M (kg/h kW) (d.b.)	9.1	6.3	6.6	7.3	1.5	21.0
E (kWh/t) (d.b.)	48.9	46.9	45.8	47.2	1.6	3.3
Moisture content (wt.%) (w.b.)	7.5	11.2	11.2			

661 M: specific mass flow; E: specific energy; wt.%: weight %; d.b.: dry basis; w.b.: wet basis; Std.

662 dev.: standard deviation; Rel. std. dev.: relative standard deviation

663

664 **Table 3:** Results of the broom pelletisation tests

	Test 1	Test 2	Test 3	Average	sd	%rsd
M (dry kg/h kW)	7.2	5.9	5.0	6.0	1.1	18.3
E (kWh/dry t)	97	118	141	119	22	18.5

665 M: specific mass flow; E: specific energy; sd: standard deviation; %rsd: relative standard

666 deviation (%)

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669   **Table 4:** Physical and chemical characterisation of fuels used in the combustion tests

	Unit	Broom pellets	Milled broom	A1 pine pellets	Milled pine
Diameter	mm	8.1	-	6.0	-
Moisture content	wt.% w.b.	9.6	11.9	6.3	10.2
Bulk density	kg/m^3 WM	620	230	690	170
Mechanical durability	wt.% WM	98.4	-	99.2	-
Fines < 3.15 mm	wt.% WM	0.2	11	0.1	2.4
Calorific values					
GCV	MJ/kg d.b.	20.3	20.4	20.4	20.3
GCV	MJ/kg w.b.	18.3	18.0	19.1	18.3
NCV	MJ/kg d.b.	18.9	19.0	19.1	19.0
NCV	MJ/kg w.b.	16.9	16.5	17.7	16.8
Proximate analysis					
Ash	wt.% d.b.	1.4	1.1	0.5	0.7
Volatile matter	wt.% d.b.	81.1	82.0	84.2	82.2
Ultimate analysis					
Carbon	wt.% d.b.	50.3	50.4	51.4	51.7
Hydrogen	wt.% d.b.	6.3	6.3	6.1	6.0
Nitrogen	wt.% d.b.	0.88	0.91	0.05	0.09
Sulphur	wt.% d.b.	0.04	0.04	0.02	0.03
Chlorine	wt.% d.b.	0.03	0.03	0.01	0.02
Ash composition					
Al	wt.% d.b.	2.6	1.8	1.4	1.5
Ca	wt.% d.b.	11	15	21	23
Fe	wt.% d.b.	1.4	0.84	1.4	0.80
K	wt.% d.b.	15	21	8.6	9.0
Mg	wt.% d.b.	4.3	6.4	3.6	6.6
Na	wt.% d.b.	0.78	0.63	0.48	0.58
P	wt.% d.b.	3.3	4.7	1.1	2.0
Si	wt.% d.b.	11	5.1	6.6	2.9
Trace elements on biomass					
As	wt.% d.b.	< 0.1	n.a.	n.a.	n.a.
Cd	wt.% d.b.	0.17	n.a.	n.a.	n.a.
Cr	wt.% d.b.	< 1	n.a.	n.a.	n.a.
Cu	wt.% d.b.	2.8	n.a.	n.a.	n.a.
Pb	wt.% d.b.	< 1	n.a.	n.a.	n.a.
Hg	wt.% d.b.	0.0050	n.a.	n.a.	n.a.

| Ni | wt.% d.b. | < 1 | n.a. | n.a. | n.a. |
| Zn | wt.% d.b. | 13 | n.a. | n.a. | n.a. |

GCV: gross calorific value; NCV: net calorific value; wt.%: weight %; w.b.: wet basis; WM: wet
matter; d.b.: dry basis; n.a.: not available

Table 5: Operating conditions during the combustion tests

Boiler	Fuel	Heat input (kW)	Boiler efficiency (%)	T 1st pass tubes (°C)	T gas outlet (°C)
MG40	Broom pellets	49	80.3	889	193
MG40	A1 pine pellets	46	95.4	936	178
MG500	Milled broom	424	79.2	606	147
MG500	Milled pine	453	89.5	610	156

Table 6: Emissions during the steady state of the combustion tests. Values referred to dry gas
basis

Emissions	MG40 Broom pellets	MG40 A1 pine pellets	MG500 Milled broom	MG500 Milled pine
O_2 (v.%)	8.0	8.1	8.7	8.8
CO (mg/Nm^3), $O_{2,ref}$: 10%v.	623	295	2102	1558
TOC [1] (mg/Nm^3), $O_{2,ref}$: 10%v.	3.3	1.2	30	43
NO_x [2] (mg/Nm^3), $O_{2,ref}$: 10%v.	388	140	335	126
NO_x [2] (mg/Nm^3), $O_{2,ref}$: 6%v.	529	191	457	172
SO_2 (mg/Nm^3), $O_{2,ref}$: 10%v.	7.0	13	6.2	21
HCl (mg/Nm^3), $O_{2,ref}$: 10%v.	2.9	0.3	0.7	0.2
Particles (mg/Nm^3), $O_{2,ref}$: 10%v.	235	97	148	42

[1]: shown as C; [2]: NO_x: NO + NO_2 shown as NO_2; v.% : volume %; $O_{2,ref}$: reference O_2

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680 **Table 7:** Sulphur balance to the ash collected after the combustion tests

	MG40		MG500	
	Broom pellets	A1 pine pellets	Milled broom	Milled pine
Ratio ash considered: total ash collected (wt.%)	97.8	96.7	78.9	77.5
S retained by the ash (wt.%)	17.2	7.0	21.9	13.4

681 wt.%: weight %

682

683 **Table 8:** Formation of slags and sinters during the combustion tests

Test	Are there agglomerates on the grate?	Description of the ash gathered	Are there sinters inside the tubes?
MG40-Broom pellets	Yes	Small size slags with melting at some points	No
MG40-A1 pine pellets	Yes	Small pieces of agglomerated ash without melting points	No
MG500-Milled broom	Yes	Agglomerated ash with easy disintegration	No
MG500-Milled pine	No	Loose ash	No

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685 **Table 9:** Ash deposition velocities during the combustion tests

Test	Grate (g/h)	1st pass tubes (g/hm^2)	2nd pass tubes (g/hm^2)	3rd pass tubes (g/hm^2)	Cyclone (g/h)
MG40-Broom pellets	85	9.6	2.6	n.a.	n.a.
MG40-A1 pine pellets	24	2.8	1.2	n.a.	n.a.
MG500-Milled broom	1,527	8.5	4.6	7.2	125
MG500-Milled pine	607	5.8	2.4	1.1	139

686 n.a.: not applicable

687

688

689 **Table 10:** Unburnt matter in ash collected inside the tubes of the heat exchanger after the
690 combustion tests

Test	1st pass tubes (wt. %)	2nd pass tubes (wt. %)	3rd pass tubes (wt. %)
MG40-Broom pellets	6.6	9.4	n.a.
MG40-A1 pine pellets	12.5	19.3	n.a.
MG500-Milled broom	14.1	17.4	16.3
MG500-Milled pine	27.8	25.9	19.6

691 wt.%: weight %; n.a.: not applicable