

1 Influencing factors on NO_X emission level
2 during grate conversion of three pelletized
3 energy crops

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10 ABSTRACT:

11 NO_X emission behavior of three different pelletized energy crops, a herbaceous one,
12 *Brassica carinata*, a short rotation coppice, *Populus sp.*, and a blend of them, was
13 assessed under fixed grate combustion conditions. Measurements of NO_X emissions
14 were done at combustion conditions that yielded both thermal efficiency and CO
15 emissions according to the European norm (EN 305-5:2012), and results compared to
16 limits established by the Austrian deviations. Based on the experimental data, Fuel-NO_X
17 was identified as the main formation mechanism. NO_X results fulfilled the Austrian
18 restrictions except during combustion of brassica, which exhibited the highest Fuel-N
19 content. Based on the experimental data, an opposite relation was determined between

1 specific NO_x emissions and Fuel-N conversion ratio obtained between the N-rich and
2 N-lean fuels tested. The influence of the air supply (amount and distribution) on the
3 NO_x formation was also noticeable. In general, higher proportion of air increased the
4 specific NO_x emissions and the Fuel-N conversion ratio. Possibilities to control NO_x
5 emissions by air staging were rather limited, particularly, during combustion of brassica
6 and the blend because of their peculiarities as ash-rich fuels with high slag formation
7 risk. For achieving appropriate conversion of these fuels, primary air requirements
8 substantially increased. Due to limitations found during the energy crops conversion,
9 efforts to achieve reduction level of NO_x emissions identified here for the troublesome
10 fuels tested should be mainly focused on a properly design of the air supply system and
11 the grate temperature control as well as on conditioning of Fuel-N content by blending.
12 Keywords: energy crops, biomass, ash, nitrogen emissions, grate combustion, air
13 pollutants.

14 1 INTRODUCTION

15 In last decades, growing interest towards greenhouse gases (GHG) reduction goals
16 and supply uncertainties related to fossil fuels have enforced to seeking for novel
17 biofuel streams, sometimes defined as “opportunity or alternative sources” [1, 2]. In
18 Mediterranean countries like Spain, these non-traditional and emergent biofuel sources
19 may involve residual biomass from agro-industrial activities, such as olive oil and
20 almond production, as well as dedicated energy crops [3-5]. Particularly, energy crops
21 are foreseen as an attractive option because of the advantages they offer to produce local
22 energy sources, to cover heating demands and to provide collateral benefits, for
23 instance, social sustainability by creating new employment opportunities.

24 Despite the aforementioned advantages, fuel quality of energy crops is seen as a
25 critical parameter to enhance their potential participation in the European energy mix.

1 Energy crops generally exhibit a larger proportion of troublesome elements compared to
2 standardized wood products. This condition is not only attributed to specific growing
3 needs of these novel fuels but also as a consequence of factors related to their
4 production, which may lead to a high variability of the fuel properties in spite of using
5 the same variety [6, 7].

6 Fuel composition has a notorious effect during combustion. Inorganic matter may
7 affect burning characteristics of the biomass fuels [8-12], and cause several ash-related
8 problems that negatively impact on the conversion system operation [13, 14], its
9 maintenance needs and air quality [15-17]. Organic components may also cause adverse
10 effects during biofuel conversion. Particularly, energy crops may exhibit higher
11 nitrogen content than stemwood assortments [7, 18]. During biomass combustion,
12 oxidation of nitrogen chemically bound in the fuel matrix (Fuel-N) results into nitrogen
13 oxides (NO_x) formation, mostly nitric oxide (NO) with smaller amounts of nitrogen
14 dioxide (NO_2), which are finally emitted as gaseous atmospheric pollutants [13, 19-23].
15 In addition to this phenomenon, commonly denoted as “Fuel- NO_x ” mechanism, NO_x
16 formation can be also linked to mechanisms associated to conversion of atmospheric
17 nitrogen at high temperatures, usually above 1300 °C (“Thermal- NO_x ”) or to reaction of
18 fuel derived radicals with atmospheric nitrogen (“Prompt- NO_x ”) [19-21]. Particularly,
19 NO_x emissions are mainly formed by the Fuel- NO_x mechanism in commercial scale
20 heating systems [13, 14, 20, 23-25].

21 Generally, the role that Fuel-N content plays on the NO_x formation during
22 combustion has resulted to be substantial in most of research experiences up to date [13,
23 23, 26]. Contribution of fuel properties, others than Fuel-N content, such as moisture
24 [24, 27, 28], fuel particle size [24, 27, 28] and volatile matter content [25] has been also
25 identified. Recently, influence of the ash characteristics has been indicated during

1 conversion of novel biofuel streams [13, 14, 29].

2 Characteristics of the conversion unit, which involves design features and operating
3 conditions, such as temperature [22, 30], residence time [23, 31, 32] and stoichiometry
4 of the combustion process [24, 27, 28], have been also suggested as influencing factors
5 on the NO_x formation. Concerning the latter, due to the oxidation phase carried out by
6 the Fuel-NO_x mechanism, specific air requirements for combustion (amount and
7 distribution of air supplied) substantially influence the fuel nitrogen conversion [13, 20,
8 33, 34]. Consequently, air staging strategies has been, up to now, the most suggested
9 alternative to control NO_x emissions by primary measures during commercial scale
10 grate combustion [27, 35-38].

11 Due to NO_x emissions produced during biofuel combustion lead to significant
12 environmental impacts, several projects are currently in progress for solid biofuel
13 standardization in Europe. Particularly in Austria, restrictive NO_x emission thresholds
14 have been developed for standardized woody and non-woody biofuels combustion [39,
15 40]. Restrictions on NO_x emission levels might imply one drawback for the potential
16 use of novel energy crops in the European heating sector. These alternative fuels may
17 exhibit differences with regard to fuel properties and emission level demanded for
18 standardized fuels. Among other fuel distinctions, nitrogen content of the alternative
19 biofuels is typically higher than standardized woody fuels. Therefore, gaining
20 knowledge concerning NO_x emission behavior during the combustion of novel energy
21 crops will provide useful information for attaining emissions under the European limits.

22 As an initial objective of this research, NO_x emission behavior of two varieties of
23 energy crops cultivated in Spain, a herbaceous energy crop, *Brassica carinata*, and a
24 short rotation coppice, *Populus sp.*, and a blend of them, densified as pellets, was
25 assessed during grate conversion in a 250 kW_{th} fixed-grate combustion unit. Emphasis

1 was specially placed on elucidating influencing factors on the NO_x emission level at
2 combustion conditions that satisfy CO emissions and thermal efficiency according to
3 the current European requirements. Particularly, efforts were focused on the
4 comprehension of the Fuel-N content and stoichiometry applied during combustion.
5 Existing NO_x restrictions in standards have been considered as reference values to
6 identify deviations. Finally, possibilities for achieving reductions on NO_x emission
7 level resulted during the combustion experiences presented here have been explored.

8

9 2 MATERIALS AND METHODS

10 2.1 Fuels

11 Two varieties of energy crops of current interest in the Mediterranean area were tested
12 in this study; a herbaceous energy crop, *Brassica carinata* (brassica), and a short
13 rotation coppice, *Populus sp.* (poplar). A blend (pop_{50%}-br_{50%}) of the two previously
14 mentioned species was pelletized in the proportion of 50 weight % wet basis (wt%,
15 w.b.) and tested. The raw materials used for the blend corresponded to different stocks
16 than the ones used for both brassica and poplar pellets. Crops were cultivated and
17 pelletized in Spain. Pellets were composed by particles around 4 mm screen and
18 dimensions were a diameter of 6 mm and a length of 15–20 mm. Standardized wood
19 pellets with DINplus certification were also tested and considered as a reference fuel.
20 Main fuel properties of the four tested pellets are presented in Tables 1 and 2. As
21 indicated, important variations were found in terms of the ash characteristics and among
22 results of the proximate and ultimate analyzes. Minimum quality requirements set for
23 DINplus certification, ÖNORM standards available in Austria for non-wood biomass
24 fuels as energy grains, and the ones defined by the European standardization EN 14961-
25 2 [41] for short rotation coppice and EN 14961-6 [42] for herbaceous biomass and

1 blends, all of them included in Table 1, were considered as reference values for
2 assessing the fuel properties. In general, the pelletized energy crops studied in this work
3 fulfill Class B specifications set for each fuel type. Exceptions were found for the three
4 fuels in terms of sulphur (S) content and for brassica and the blend with regard to the
5 ash content. However, the three energy crop samples are characterized by an important
6 amount of ash compared to limit set for DINplus certification. Therefore, they can be
7 denoted as ash-rich fuels. Particularly, ash content for brassica was around 21 times
8 higher than limiting values required for the DINplus certification and 7% higher than
9 the EN 14961-6 Class B, the one with the highest ash content limit. The blend had more
10 significant ash content than the one which could be expected by blending the pure
11 species in the proportion of 50 wt% w.b. As represented in Figure 1, there was a higher
12 concentration of aluminum (Al), iron (Fe) and silicon (Si) in pop_{50%}-br_{50%}. The
13 occurrence of these ash constituents is assumed to result from a contamination of the
14 biomass, possibly soil constituents added as extraneous components during the
15 procurement stages.

16 Based on the proximate analysis, lower values of the volatile matter to fixed carbon
17 ratio (VM/FC ratio) were found in brassica and the blend compared to the woody pellets
18 (poplar and DINplus), and consequently, fuel reactivity differences could be anticipated
19 among fuels. This condition is also expected by the stoichiometric air to fuel ratio
20 (SAR) results. As presented in Table 1, this ratio is relatively similar among crops,
21 however, the lowest value corresponded to DINplus. Based on these two parameters
22 (VM/FC ratio and SAR), air requirements might increase during combustion of the
23 three pelletized energy crops compared to the reference fuel.

24 Concerning Fuel-N content, results for the woody pellets were according to limiting
25 values for DINplus certification, the highest restriction, so these fuels can be denoted as

1 N-lean fuels. On the contrary, brassica and the blend exhibited a significant N-content,
2 and consequently, they can be called as N-rich fuels. Therefore, NO_x emissions are
3 expected to be higher during combustion of these two crops.

4 With regard to results from the ash composition analyze, as seen in Figure 1 and
5 Table 2, concentration of the ash-forming elements vary over a rather quite broad range.
6 Considering results from previous works carried out with brassica and poplar [43, 44],
7 the major ash components: silicon (Si), calcium (Ca), potassium (K), magnesium (Mg),
8 phosphorus (P) and sulfur (S), play an important role on the ash transformation
9 mechanisms. Comparison of the four tested fuels in this work by the alkali index
10 suggests slag and fouling formation risk during the crops conversion. Typically,
11 slagging formation can affect proper operation of grate combustion system, whereas
12 fouling effects mainly lead to the worsening of heat transfer efficiency [13, 29, 45, 46].

13 2.2 Conversion system characteristics

14 A prototype of a biomass grate-fired unit of nominal useful output 250 kW_{th},
15 primarily adapted for the conversion of ash-rich fuels, has been used to evaluate the
16 applicability of the three pelletized energy crops types for heating purposes. This
17 technology has been initially developed as part of a Spanish national research project
18 focused on the energy crop utilization for domestic heating.

19 As presented in Figure 2, the conversion system used in the experimental part of this
20 work is mainly divided into four zones: burner (I), combustion chamber (II) and two
21 heat exchanger sections (III and IV). Due to a general description of the conversion
22 system can be found in a previous work [44], detailed information about zones I and II
23 is basically provided here because these two zones play an important role during fuel
24 conversion.

25 The burner (24 cm height) is placed inside the combustion chamber (internal

1 dimensions: 75 cm diameter and 148 cm height) and consists of two stationary main
2 grates (see Figure 2, 5) with several holes for air supply. The first grate, which is
3 located at the upper part of the burner, is composed by four horizontally positioning
4 small steps, resembling a ladder (with the openings in the riser part). The second one,
5 which is positioned at the end of the last step, is also flat but longer to facilitate
6 complete char burnout.

7 An integrated automatic ash removal system (see Figures 2, 3) helps the scraping of
8 the ashes and other combustion residues away from the second grate to be finally
9 accumulated into the ash pit located inside the combustion chamber and below the
10 burner (see Figure 2, 7).

11 Combustion air is supplied by two different fans. Primary air (see Figure 2, 2) is
12 provided as underfeed air through each burner grate. Secondary air (see Figure 2, 6)
13 passes through an annular air supply channel surrounding the water-cooled combustion
14 chamber to be finally distributed into the secondary combustion zone by ten holes
15 placed at the combustion chamber walls. This configuration allows a radial secondary
16 air injection (see Figure 2, 6). The annular channel is located approximately 24 cm
17 above the burner and 48 cm below of the internal combustion chamber roof (148 cm
18 height). Knowledge of the flow field resulted inside the combustion chamber was
19 gained by an analysis of the fluid-dynamics based on a set of CFD simulations applied
20 to this combustion unit prototype [47]. The simulations showed that an important down-
21 flow of secondary air towards the grates is created as a result of the current holes
22 arrangement for introducing secondary air and the combustion chamber geometry.

23 Gases from combustion chamber pass through two pirotubular heat exchanger
24 sections. One consists of four firetubes whereas the second is constituted by thirty
25 firetubes with turbulators for both increasing heat transfer rates and cleaning the internal

1 tubes surface by mechanical removal of deposits.

2 2.3 Experimental setup

3 A schematic view of the experimental setup used is illustrated in Figure 3. Several
4 combustion parameters were measured and operating conditions were controlled and
5 adjusted with the conversion unit data logging system. Data were recorded every 15 s.

6 Pellets were manually loaded into a pellet hopper and fed into the combustion
7 chamber by an automatically controlled horizontal screw feeder with a rotation speed
8 control. The ash pusher on/off working period (frequency and duration of the ash
9 removal) was adjusted according to the specific fuel requirements during a continuous
10 operation mode of the conversion unit.

11 Primary and secondary air flows were continuously measured using annubar tubes
12 according to the standard UNE 100-212:1990 [48]. An air velocity meter
13 (VELOCICALC 8350; accuracy: ± 2.5 % of reading) was also used during the tests.
14 Adjustments on the primary and secondary air flows rates were separately controlled by
15 using two different frequency meters. The force draught was automatically regulated by
16 a fan (see Figure 2, 9) equipped with a frequency meter.

17 Temperature measuring instruments were positioned in the vicinity of the burner
18 grates, in the flue gas path and in the water steps to gain detailed information about the
19 temperature profile inside the system. Two K-type thermocouples (± 2.5 °C) were
20 located at the top (T_1 and T_2) and another two at the bottom (T_3 and T_4) of the fuel bed
21 on the second grate and three (T_5 , T_6 and T_7) at different positions in the flue gas path
22 through the heat exchanger (see Figure 2). Three PT100 were also provided, one
23 positioned in the water-in step (T_8) and the rest at two positions in the water-out step (T_9
24 and T_{10}), see Figure 2.

25 The concentrations of O_2 (accuracy: ± 0.2 vol %), CO (accuracy: $\pm 0.5\%$ measured

1 value, m.v., given as ppm) and NO (accuracy: $\pm 5\%$ m.v., given as ppm) within the
2 exhaust gas were continuously measured during all the tests with electrochemical
3 sensors (Flue gas analyzer Testo 350XL), just after the second heat exchanger exit. Flue
4 gas and ambient temperatures were also measured by the gas analyzer (accuracy: $\pm 5\%$
5 m.v., given as $^{\circ}\text{C}$). An auto zeroing mechanism of the equipment was automatically
6 executed every hour during the measurements. Data was recorded every 10 s.

7 2.4 Combustion tests

8 In general, four operating periods were distinguished for each experiment based on
9 the conversion unit control algorithm: start-up, stabilization, stationary combustion and
10 cooling of the system. The start-up period consisted of automatically controlled pellets
11 ignition and air supply to achieve the preset flue gas temperature corresponding to this
12 period. This stage lasted approximately 30 min. Once it was attained, load input was
13 steeply increased in order to gradually reach stabilization of combustion conditions at
14 the selected load input for the test. Each load increment was kept constant at least 20
15 min. In general, the stabilization period needed at least 2 h. A stationary combustion
16 regime at the maximum load condition defined for the test was kept a minimum time of
17 2 h before stopping the fuel feeding and cooling the system, which required
18 approximately 1 h. In general, total operation time involving start-up, stabilization,
19 stationary combustion and cooling of the system was around 6-8 h.

20 Firstly, preliminary tests were performed to define adjustments on operation
21 conditions required for an appropriate conversion of each fuel type at the $250 \text{ kW}_{\text{th}}$
22 combustion unit. In the experiments, this condition was checked with regard to thermal
23 efficiency and unburnt matter. The latter was defined here as loss of ignition matter in
24 solid combustion residues and gaseous unburnt quantified as CO concentration in flue
25 gases. Restrictions set by the EN 303-5:2012 were used as reference values for CO

1 emissions and thermal efficiency (see section 2.6). Control of the above mentioned
2 parameters was important to ensure that NO_x measurements were representative for
3 what may be expected under normal and efficient running conditions.

4 During the preliminary tests, some difficulties were found to attain nominal output.
5 This fact was mainly attributed to limitations of the refrigeration equipments during the
6 DINplus test. For the rest of the fuels, limitations were mostly related to the specific
7 fuel properties, particularly the ash attributes, and suitability level of the system to
8 manage them. To cope with these issues, the relevant and modified parameters
9 considered were: load input, ash pusher working periods, air supply and its distribution.
10 Each fuel demanded different adjustments on these parameters. Emphasis was placed on
11 achieving an useful output as closer to nominal value as possible. Criteria applied for
12 selecting the appropriate adjustment corresponding to each fuel case are described in
13 section 3.1. Once operating conditions were defined for each fuel case, additional tests
14 were carried out to verify reproducibility of results. During reproducibility tests
15 different air staging degrees were tested after achieving stationary combustion stage at
16 the maximum load input defined during the preliminary tests for each fuel case. In this
17 work, total lambda distribution with respect to primary air, $(\lambda_T - \lambda_s)/\lambda_T$, was varied in the
18 range around 55-85%. Each tested air condition was kept without variation over at least
19 20 min of stable operation.

20 2.5 Quantification of combustion parameters

21 During all the experiment (the four operating periods described in section 2.4), data
22 was collected for further calculation of several combustion parameters. Statistical
23 analysis was considered to determine the mean and standard deviation corresponding to
24 each parameter.

25 Solid combustion residues, which remained on the burner grates and the ones scraped

1 by the pusher into the ash pit, were collected after concluding each combustion
2 experiment. Samples were qualitatively assessed in terms of sintering and slagging
3 tendency by visual inspections and by a simple strength test, following the methodology
4 described in previous works [43, 44]. Loss of ignition matter in solid combustion
5 residues was determined according to the standardized method CEN/TS 14775:2004
6 [49].

7 Combustion thermal efficiency, η , was calculated by the indirect method, which
8 considers energy inputs and outputs linked to the conversion system, and defined at flue
9 gas temperature. A mass and energy balance was performed considering measured data.
10 Total energy input was estimated as energy in fuel and air fed to the conversion unit.
11 Energy outputs included energy in unburnt matter and in flue gases. Heat losses from
12 the system walls were considered negligible due to the existing insulation and excluded
13 from calculations.

14 Combustion thermal efficiency was determined by using the following equations:

$$15 \quad \eta_{\text{LHV}} = 100 \times [(H_{\text{fuel}} + H_{\text{air}}) - (H_{\text{gases}} + H_{\text{unburnt gases}} + H_{\text{solid residue}})] / (H_{\text{fuel}} + H_{\text{air}}) \quad (1)$$

16 where:

17 η_{LHV} (%), is the thermal efficiency of the system regarding $\text{LHV}_{\text{p (a.r.)}}$.

18 H_{fuel} (kW), is the energy input per time unit in fuel sample at the feeding conditions.

19 H_{air} (kW), is the energy input per time unit in total wet air at the feeding conditions.

20 H_{gases} (kW), is the energy output per time unit of sensible heat in flue gases evaluated at
21 T_7 (see Figures 2 and 3).

22 $H_{\text{unburnt gases}}$ (kW), is the energy output per time unit in unburnt gas at the exit of the
23 conversion system.

24 $H_{\text{solid residue}}$ (kW), is the energy output per time unit in the solid residue at the exit of the
25 conversion system.

1 Energy input in fuel sample included the term $m_{\text{fuel}} \times \text{LHV}_p \text{ (a.r.)}$ (kW); where m_{fuel}
2 (kg/s), is the mass flow of the fuel sample fed into the system and $\text{LHV}_p \text{ (a.r.)}$ (kJ/kg) is
3 its lower heating value as received. Mass flow of the fuel sample was quantified by the
4 total amount of pellet loaded into the hopper and the corresponding consuming time.

5 H_{air} involves energy content of wet air at the feeding conditions and the mass flow of
6 total wet air calculated by a mass balance considering concentration of O_2 measured at
7 the flue gas exit.

8 In order to quantify the energy losses the following equations were used:

9
$$H_{\text{gases}} = \Sigma H_{\text{gas}} \text{ (2)}$$

10
$$H_{\text{unburnt gases}} = m_{\text{fuel}} \times m_{\text{CO}} \times P_{\text{CO}} \text{ (3)}$$

11
$$H_{\text{solid residue}} = H_{\text{ash}} + H_{\text{unburnt solid}} \text{ (4)}$$

12 where H_{gas} (kW) refers to sensible heat in each gas component (CO , CO_2 , N_2 , O_2 , H_2O ,
13 SO_2) at the exit of the conversion system, m_{CO} (kg/h) is the amount of CO produced
14 during combustion of 1 kg of fuel sample, P_{CO} (kJ/kg CO) is the energy of combustion
15 of CO per 1 kg of gaseous unburnt (assumed as CO), H_{ash} (kW) is the sensible energy in
16 ash produced during combustion and $H_{\text{unburnt solid}}$ (kW) is the energy of combustion of
17 loss of ignition matter (assumed as solid carbon) in bottom ash gathered after
18 combustion.

19 Total energy input was quantified as the sum of H_{fuel} and H_{air} . The useful output was
20 calculated from the energy conservation law applied to the system. It was determined as
21 the difference between the total energy input and heat losses in gases, H_{gases} , in unburnt
22 gas, $H_{\text{unburnt gases}}$, and in solid residue, $H_{\text{solid residue}}$.

23 Furthermore, three lambda factors were determined. Total lambda (λ_T) was calculated
24 based on O_2 concentration measured at the exit of the conversion system and the
25 stoichiometric air required (SAR, see Table 1) by each fuel. Therefore, it was calculated

1 according to the following equation:

$$2 \quad \lambda_T = (a/f)_{\text{real}} / (a/f)_{\text{stoich.}} = A_{\text{real}} / A_{\text{stoich.}} \quad (5)$$

3 where λ_T refers to the total lambda used, $(a/f)_{\text{real}}$ is the actual air to fuel ratio, $(a/f)_{\text{stoich.}}$ is
4 defined as the stoichiometric one for the same conditions, A_{real} (m^3/h) is the actual air
5 introduced in the conversion system and $A_{\text{stoich.}}$ (m^3/h) is the stoichiometric air
6 necessary to burn 1 kg of the fuel sample.

7 The air staging degree considered for each fuel test is based on lambda ratios applied
8 in the primary and secondary combustion zones inside the combustion chamber, namely
9 lambdas for the primary, λ_p , and the secondary air supply, λ_s . They were estimated on
10 the basis of primary and secondary air flow measurements (see section 2.2). Based on
11 air measurements carried out in the tested unit prior to the combustion process,
12 accounting air in-leakage is believed to be originated from the burner zone and the
13 surroundings of the fuel feeding system. Occurrence of surrounding air in-leakage into
14 the system due to non-air tightness, denoted as delta total lambda ($\Delta\lambda_T$), was calculated
15 by the difference between λ_T and $(\lambda_p + \lambda_s)$. Primary lambda and total lambda distribution
16 with respect to primary air were further corrected considering the air in-leakage, and
17 therefore, were quantified as $(\lambda_T - \lambda_s)$ and $(\lambda_T - \lambda_s)/\lambda_T$, respectively.

18 2.6 Conversion of the fuel nitrogen

19 The degree of conversion of the Fuel-N to NO_X (i.e., $\text{NO}_X/\text{Fuel-N}$ conversion ratio)
20 was also estimated. It was quantified considering N content in each biofuel load input
21 and N that exists in NO_X emissions (measured as NO), both estimated as NO_2
22 equivalents, according to the following equation:

$$23 \quad \text{NO}_X/\text{Fuel-N conversion ratio} = 100 \times [\text{N}_{\text{flue gas (as NO}_2)}] / [\text{N}_{\text{fuel sample (as NO}_2)}] \quad (6)$$

24 2.7 Threshold values for thermal efficiency and emissions

25 Due to the recent interest towards the use of alternative biofuels in Europe, the

1 standard EN 303-5:2012 [50] has been recently updated to include both standardized
2 woody and non-woody biomass produced according to the EN 14961 series
3 requirements. This European standard can be used to test boilers of nominal output of
4 up to 500 kW_{th} and categorizes them into three classes. Class 5 is the strictest one. This
5 standard defines limits for thermal efficiency and emissions of CO, C_XH_Y and
6 particulate matter, and suggests measurement of NO_X emissions although no limits are
7 established for them yet.

8 Particularly in Austria, more restrictive threshold values have been set for the
9 combustion of both standardized high quality woody fuels and non-woody biofuels
10 produced according to ÖNORM standards [39]. The Austrian agreement,
11 Art 15a B-VG:2010 [40], refers to specific commercial heating system characteristics of
12 nominal heat output of up to 400 kW_{th} firing the standardized biofuels, and specifies
13 limits to thermal efficiency and emissions of CO, NO_X, C_XH_Y and particulate matter.
14 These restrictions are also referred in the EN 303-5:2012 as deviations from Austria
15 [50].

16 In this work, experimental results were compared with the permissible limits for
17 thermal efficiency and CO and NO_X emissions established by the previously mentioned
18 standard restrictions. A summary of limiting values is presented in Table 3.

19 CO and NO concentrations measured as ppm were reported as mg/Nm³ standardized
20 to a dry flue gas basis (d.g.) at 10% oxygen to be compared with limits set by the
21 EN 303-5:2012. NO_X emissions were quantified as equivalent NO₂ according to the
22 procedure defined by the European standard EN 303-5:2012. CO and NO_X specific
23 emission values were calculated in relation to the energy input in fuels (LHV_{p (a.r.)}) to
24 be compared with the Art. 15a B-VG:2010 restrictions.

25

3 RESULTS

3.1 Operating conditions

In Table 4, a summary of operating conditions and temperature profile of the system applied for attaining best results in terms of CO and efficiency corresponding for each fuel test is presented as mean values with their standard deviations. Conditions correspond to data collected during the reproducibility tests after achieving a stationary combustion regime at the maximum load input defined for each fuel case.

Results comparison in terms of load input indicates important differences, up to 30%, among the four fuel type tested. According to Table 4, the blend showed an intermediate condition between poplar and brassica, which depicted the lowest value. These results were mostly related to the ash condition on the grates and suitability of the tested technology to manage the ash attributes. During the preliminary experiments, the ash condition exacerbated an appropriate fuel conversion in the primary combustion zone. Accordingly, unscheduled shutdowns and substantial level of unburnt matter could not be avoided. Based on the qualitative assessment of the ash collected after the four reproducibility tests, around 30% up to 60% of in-going ash was estimated to be retained as bottom ash. Poplar yielded the lowest proportion. For brassica and the blend tests, a significant amount of these solid residues was found as large blocks of highly sintered ash, approximately, 30% and 54% of in-going ash, respectively. Degree of hardness in poplar gathered ash was considerably lower. For poplar test, highly sintered ash represented only 9% of in-going ash. These results were in agreement to expectations, based on the fuel properties assessment (see section 2.1) and data presented in previous works [43, 44]. Variation of load input serves to control thickness of the bed layer and heat rate produced in the grate section. Therefore, adjustments on this parameter were used as a first measure to improve combustion conditions on the

1 grate while controlling undesired ash softening and burner grate saturation by ashes,
2 particularly, during combustion of the ash-rich fuels with high slag formation risk,
3 brassica and the blend.

4 Besides the lower load input used, variations on the pusher cleaning periods were also
5 required to control undesired accumulation of high sintering tendency ash over the hot
6 grate blocking primary air inlets. Adjustments on the cleaning frequency and duration
7 were carried out to all the tests but they were significantly increased to the more
8 troublesome fuels. Removal frequency used for the two herbaceous fuels was up to 50%
9 higher than the one applied for the others (see Table 4). Nevertheless, partial saturation
10 of the grates could not be avoided because maximum removal adjustments were limited
11 by control of solid unburnt matter. During the cleaning periods, it was noticeable that
12 each movement of the ash pusher caused short term peaks on O₂ and CO concentrations.
13 Fluctuations were detected by the flue gas analyzer. This effect was more evident for
14 the more troublesome fuels, when high removal conditions were applied. Accordingly,
15 the pusher movements were linked to perturbation of the gaseous emissions, which also
16 limited adjustments on the cleaning periods.

17 Concerning air supply and distribution indicated in Table 4, results show that oxidant
18 conditions in the primary combustion zone were needed for all the four fuel cases, with
19 a total lambda close to 2. As indicated, the primary lambda was more significant during
20 brassica and the blend tests in that order, which corresponded to around 28% and 24%
21 higher than values applied for the reference fuel DINplus. For poplar, the primary
22 lambda represented an increment of around 2% with respect to DINplus values.

23 During the preliminary tests, these parameters were primarily varied based on results
24 from the fuel characterization, basically information by SAR and VM/CF ratios
25 included in Table 1. Further addition of primary air was needed to enhance the air-fuel

1 contact and mixture because of the ash effect on blocking air inlets. This addition was
2 done with caution, especially during combustion of the ash-rich fuels with high slag
3 formation risk, brassica and the blend. Increasing primary air not only enhances burning
4 rates but also may lead to undesired softening of ashes by the increment of combustion
5 temperature. As mentioned previously, melting of ashes could not be completely
6 avoided. The observed ash condition resulted by formation of low ash melting residues
7 retained in the hot grates. Temperature reached during the brassica test was around 1200
8 °C (see Table 4), which according to literature [51, 52] is in the range where brassica
9 ashes are expected to melt (~ 780-1280 °C).

10 3.2 Thermal efficiency and unburnt matter

11 A summary of the best condition achieved with each fuel at maximum load during
12 stationary combustion regime is presented in Table 5. As indicated, high burnout of the
13 solid residues was attained despite the generally large differences within fuel properties.
14 Loss of ignition matter in collected residues after combustion was lower than 0.01 kg/kg
15 solid residue, d.b (see Table 5).

16 Thermal efficiency and CO emissions results were rather acceptable compared to the
17 EN 303-5:2012 and the Austrian restrictions. Some considerations have to be taken into
18 account for the comparison based on the standard EN 303-5:2012. Restrictions set by
19 the EN 303-5:2012 are specific to systems working at nominal conditions [50]. For all
20 of the tests, the best attainable condition corresponded to an useful output lower than the
21 nominal one defined for this system, which is based on firing standardized woody fuels.
22 During pop_{50%}-br_{50%} and brassica conversion, useful output resulted to be around 30%
23 and 40% lower than the nominal value, respectively. For the woody fuels, it was rather
24 close to nominal values, only 8% and 12% lower for poplar and DINplus, respectively.
25 As mentioned in section 2.3, during the DINplus test output values were mainly linked

1 to limitations of the cooling system whereas for the rest of the fuels output was affected
2 by the specific fuel properties and the capability of the system to manage them. Due to
3 grate fired units generally have better combustion behavior working at nominal
4 conditions, it can be assumed that combustion quality was rather adjusted to limits set
5 by the EN 303-5:2012.

6 3.3 NO_x emissions

7 According to results presented in Table 5, NO_x emissions significantly differ among
8 fuels. Considering the fuel reference case, specific NO_x emissions for the pelletized
9 energy crops increased up to more than 4 times. In general terms, the lower values
10 corresponded to the N-lean fuels (DINplus and poplar) and the higher ones to the N-rich
11 fuels (pop_{50%}-br_{50%} and brassica). Results satisfied the Austrian requirements but one
12 exception was found for brassica. For this fuel, specific NO_x emissions were around
13 13% higher than the Austrian limit set for the standardized non-woody fuels.

14 3.4 Fuel-N conversion

15 According to Table 5, Fuel-N conversion was rather similar between the N-rich fuels
16 and in a comparable range between the N-lean fuels. Poplar test yielded the highest
17 conversion. The lowest NO_x/Fuel-N ratio values achieved during brassica and the blend
18 corresponded to around 75% lower than results attained for the reference case DINplus.

19

20 4 DISCUSSIONS

21 4.1 General remarks about fuel conversion and NO_x emissions

22 Based on results attained in this work, a broad variability and heterogeneity of the
23 fuels properties has been a key conditioning factor for selecting operating conditions
24 during each fuel test. Achieving the best results with respect to unburnt matter and
25 thermal efficiency implied different fuel demands in terms of load input, ash removal

1 and air conditions. Considering experimental data and restriction limits set by the
2 European norms, it can be stated that NO_x measurements were representative values of
3 the expected ones under normal and efficient operation of the system.

4 Focused on the aim of this work, in this section, attention is given to the
5 comprehension of main influencing parameters on the NO_x formation during the energy
6 crops conversion. This assessment has been particularly focused on elucidating the role
7 of Fuel-N content and air stoichiometry.

8 4.2 Fuel-N content influence

9 In Figures 5-a and -b, evolution of specific NO_x emissions with regard to the range of
10 air conditions tested in this work at the preset maximum load for each fuel test is
11 compared. According to these figures, at constant lambda but higher Fuel-N content, the
12 NO_x emissions increased. Furthermore, for a Fuel-N content of around 14 times higher
13 than one for the woody reference fuel, the NO_x emissions values exceeding the Austrian
14 restrictions. Based on the experimental data, the effect of Fuel-N content on the NO_x
15 emission behavior was evident. The observed behavior for NO_x emissions support
16 expectations posed on the Fuel- NO_x mechanism as the main source of NO_x formation
17 during conversion of the crops at the tested conditions here.

18 Besides the effect observed in terms of the Fuel-N variations, temperature profile in
19 the system was lower than conditions needed to thermal NO_x formation mechanism. As
20 depicted in Table 2, temperature profile in the system was generally around 850-1100
21 °C for all the study cases. Fuel- NO_x mechanism has been extensively reported to be
22 predominant at this temperature range and type of grate technology [13, 21, 27, 53].
23 Therefore, it is assumed that oxidation of fuel-bound nitrogen has certainly been the
24 main source of NO_x formation under conversion conditions tested in this work.

25 Additional information about NO_x formation for the crop tested here is gained by

1 comparison of the $\text{NO}_x/\text{Fuel-N}$ conversion ratios, which is illustrated in Figures 6-a and
2 -b. At constant lambda, the N-rich fuels (the ones with the highest specific NO_x
3 emissions) exhibited the lowest $\text{NO}_x/\text{Fuel-N}$ conversion ratio. As expected, the opposite
4 relation was observed for the N-lean fuels. Tendencies observed between each Fuel-N
5 category can be explained by the Fuel- NO_x mechanism.

6 According to the simplified reaction scheme for the Fuel-N conversion paths
7 illustrated in Figure 7, during combustion process, Fuel-N is distributed between the
8 volatiles and the solid char matrix [20, 22]. Available N in both volatiles and the solid
9 char matrix can be oxidized to form NO.

10 With regard to the volatile fraction, the light N compounds NH_3 and HCN have been
11 extensively suggested as the main NO_x precursors [20, 26, 54]. Measurement of NH_3
12 and HCN was out of the scope of the present work. However, information in literature
13 found for poplar supports that NH_3 and HCN are the main NO_x precursors [26]. It was
14 also reported that they exhibited similar contribution to NO_x formation [26].

15 Based on the Fuel- NO_x mechanism, reduction of nitrogen oxides can be achieved by
16 further reaction among NO and the volatiles NH_3 and HCN to subsequently form N_2 .
17 This reaction path depends on the combined effect of Fuel-N concentration and
18 stoichiometry, but is mostly promoted by high concentration of volatile nitrogen
19 compounds [20, 22]. Considering Fuel-N content differences among fuels, at constant
20 lambda, more nitrogen was available for the oxidation mechanism during combustion of
21 the N-rich fuel group and, consequently, a higher level of specific NO_x emissions
22 resulted for them. Furthermore, NO_x reduction paths were also favored for this fuel
23 type. Higher availability of NO_x precursors and NO_x emissions for the N-rich fuels
24 tests contributed to the lower conversion rates achieved for the N-rich fuel category. On

1 the other hand, for the N-lean group, oxidation reaction to form NO is favored instead
2 of the NO reduction because of the lower concentration of volatile N-species.

3 As illustrated in Figure 7, NO_x reduction may also occur by char and NO interactions.
4 It is a complex process affected by a variety of factors involving several fuel and
5 technology parameters and is not completely understood yet [20, 55]. It is believed that
6 the NO-char reaction is affected by physical structure and chemical composition of char
7 [55]. Concerning the latter, an important catalytic effect is mainly attributed to
8 concentration of potassium; however, its effect is very temperature dependent because
9 of the formation of K-silicates [55, 56]. As indicated in section 3.1, a high level of
10 sintered ash occurred for the energy crops, particularly, for brassica and the blend.
11 Based on results from XRD and SEM-EDS analyses carried out in previous works for
12 brassica and poplar bottom ash [43, 44], K/Ca-silicates were identified as the main ash
13 components. Accordingly, it is assumed that char reduction paths were not significant
14 under conditions tested here. NO_x reduction by the NO-char reaction was presumably
15 inhibited by slagging/sintering occurrence in bottom ash mainly constituted by K-
16 silicates. It has been suggested that occurrence of these compounds at temperature
17 above 800 °C considerably decrease the catalytic effect of K and, consequently, the rate
18 of NO-char reaction is rather limited [55, 56].

19 Based on the above explanations, huge differences observed among the two groups in
20 terms of NO_x/Fuel-N conversion and specific NO_x emissions are explained. Reactions
21 paths by the Fuel-NO_x mechanism also explain differences with regard to the
22 NO_x/Fuel-N conversion ratio observed between fuels within each category (see Figure
23 6). For the N-lean group, Fuel-N content in poplar increased 25% compared to
24 DINplus, which resulted into a higher conversion level for the woody crop. For the N-
25 rich fuels, the NO_x/Fuel-N conversion ratio was rather similar despite Fuel-N content

1 for the blend was approximately 38% lower than the brassica one (compared on a d.b.
2 or d.a.f. because of similar ash content in fuels). Considering the NO_x reduction paths
3 proposed by the Fuel-NO_x mechanism and the experimental data, it appears that
4 concentration of volatile species during the blend test was high enough to favor a
5 significant reduction of NO_x emissions despite the lower Fuel-N content for the blend
6 compared to brassica. Accordingly, it seems that proportion of brassica applied for the
7 blend is rather acceptable to promote the use of N-rich local sources without exceeding
8 NO_x restrictions.

9 4.3 Effects of the air supply

10 As introduced, besides fuel properties, operating conditions may exhibit an important
11 role on the NO_x formation. As it has been extensively reported [16, 19, 20, 24], NO_x
12 behavior is substantially affected by air stoichiometry. Due to the oxidation phase
13 carried out by the Fuel-NO_x formation mechanism, despite of being NO_x emissions
14 strongly dependent on Fuel-N content, they are also affected by the air supply and its
15 distribution [20, 33, 34]. Considering the four NO_x evolution curves with respect to
16 total lambda illustrated in Figure 4, results indicate that the best condition based on the
17 CO emissions and thermal efficiency limited operation at the lowest NO_x concentration.
18 This opposite relation demanded a trade-off between the fulfillment of restrictions for
19 CO emissions and thermal efficiency and the ones for NO_x emissions.

20 According to Table 4, total lambda used for poplar and DINplus was similar to the
21 expected ones in grate conversion, which are typically found around 1.5-2 [21].
22 However, to attain the best results for thermal efficiency and CO emissions, a
23 substantial amount of primary air was required for all of the four study cases. For the
24 reference case DINplus primary lambda used exceeded up to around 76% the proposed
25 substoichiometric condition to apply a deep air staged combustion (i.e., primary lambda

1 around 0.7-0.95 [21, 24, 30, 38, 57]). Considering the primary lambda increment
2 attained for the reference case with regard to proposed values in literature, it seems that
3 the achievement of substoichiometric condition in the primary combustion zone was
4 limited by the current combustion chamber design and air configuration. As mentioned
5 in section 2.2., strong recirculation zones appear close to the combustion chamber walls
6 as a result of down-flow of secondary air [47]. The region of recirculation zones
7 increases the residence time of combustion gases in areas characterized by high
8 temperatures and low oxygen concentration. Consequently, the CO conversion to CO₂ is
9 inhibited. To improve CO conversion higher amounts of primary air were applied even
10 during combustion tests with the reference fuel.

11 Concerning brassica and the blend, total lambda reported in Table 4 was slightly
12 higher than values proposed in literature, and increased up to around 11% the total
13 lambda used for the reference fuel. It was mainly distributed as primary air and resulted
14 to be around up to 28% higher than the primary lambda used for DINplus. The more
15 troublesome fuels in terms of ash attributes demanded a higher primary lambda ratio.
16 As explained in section 3.1, additional demands of primary lambda for the pelletized
17 energy crops compared to the reference case were mostly related to fuel properties
18 differences, particularly in terms of the ash attributes of the pelletized energy crops. Air
19 condition in the primary combustion zone was needed to overcome the ash effect on
20 blocking air inlets and mixing worsened by the sintering and slagging occurrence on the
21 fuel bed. Similar strategies have been reported in literature when burning similar type of
22 troublesome fuels (ash-rich biofuels with an unfavorable ash softening tendency) [8, 13,
23 17, 29].

24 Effects of different air staging degrees on the NO_x behavior are illustrated in Figures
25 5 and 6. According to these figures, at constant Fuel-N content, lambda increments in

1 both total and primary distribution contributed to higher both NO_x emissions and
2 $\text{NO}_x/\text{Fuel-N}$ conversion ratio. It is clear that the Fuel-N oxidation level raised for each
3 fuel to form more NO, while higher amount of air was supplied, which is in agreement
4 with the expected behavior by the Fuel- NO_x formation mechanism, as mentioned in the
5 previous section. Based on Figure 5, comparison of the slopes at constant Fuel-N
6 content indicates that the air effect was more significant for the N-rich fuels and,
7 particularly, during the brassica test, as expected by literature [20, 24, 29]. Furthermore,
8 it can be seen from Figures 5-a and 6-a that evolution curves for the blend and for
9 brassica show a maximum point of NO_x emission and $\text{NO}_x/\text{Fuel-N}$ conversion rates. It
10 occurs close to a total lambda of around 2.9 and 3.0 for the blend and for brassica,
11 respectively. For this condition, total lambda distribution with respect to primary
12 lambda was around 0.8 for both fuels.

13 One explanation for this maximum point is found on the residence time achieved
14 during the tests inside the combustion chamber. It was roughly calculated based on the
15 total flue gas flow at the exit of the system (determined by a mass balance at the tested
16 conditions) and the combustion chamber geometry. Residence time values
17 corresponding for the best condition in terms of thermal efficiency and unburnt matter
18 achieved for each fuel case are given in Table 4. As depicted, results were similar
19 among each Fuel-N category, close to 0.7 s for the woody fuels and around 1 s for the
20 more troublesome ones. Residence time for the maximum point in Figures 5-a and 6-a
21 during the blend and brassica tests was around 0.85 s and 0.95 s, respectively. Based on
22 literature [31, 32], by prolonging the residence time in the primary zone the NO
23 emission is reduced. This tendency was also observed for results from this work when
24 the evolution of Fuel-N conversion ratio was plotted with respect to the residence time

1 calculated. Consequently, the maximum point observed for the N-rich fuels represented
2 the maximum oxidation level.

3 Due to air condition may affect temperature profile on the grates and this parameter
4 may affect NO_x behavior, temperatures measured inside the combustion chamber were
5 compared with regard to lambda distribution (see Figure 8). As depicted, temperature
6 profile was generally constant for all the primary air proportions tested during the four
7 study cases. The highest values were achieved during brassica test. In this case, bed
8 temperature relatively increased from 900-1200 °C for brassica when primary air
9 proportion increased from 0.7 up to around 0.85. Based on the evolution of temperature
10 profile (Figure 8) and the conversion rates illustrated in Figure 6, it seems that the bed
11 temperature effect on NO_x emissions and conversion rates was not significant for the N-
12 rich fuels. For the N-lean fuels, a clear contribution is also not evident. Similar results
13 have been indicated in literature for the temperature range considered here [23, 30, 57].
14 However, it has been reported for grate combustion that at high concentration of NO
15 and NO_x precursors reduction rate of NO is faster above 800 °C [22], although required
16 temperature might be lower at high concentration of oxygen and volatile N forms [31,
17 55]. Based on results from this work, further investigations need to be carried out at
18 different temperatures in order to be able to provide a deeper analysis about the effect of
19 this parameter.

20 4.4 Comparison with other technologies

21 As mentioned in previous sections, the ash characteristics of the tested herbaceous
22 crops in terms of amount and melting behavior limited the grate performance and
23 consequently, air staging possibilities to control NO_x emissions. Consequently, despite
24 primary and secondary airs are separately controlled in the tested unit, the potential
25 reduction on NO_x conversion rates by air staging could not be satisfactorily quantified.

1 To estimate potential benefits of air staging, results derived from the best condition
2 attained to all tested fuels indicated in Table 4 were compared to staged combustion
3 experiences available in literature and performed for different fuels during grate
4 conversion in commercial units (see Figure 9). A potential fit was used to represent
5 $\text{NO}_x/\text{Fuel-N}$ ratio variation by N-content in fuels, according to literature [24, 29, 58].
6 Firstly, it can be observed that the $\text{NO}_x/\text{Fuel-N}$ ratio exhibit a clear tendency to increase
7 when the total amount of excess air supplied and primary lambda were higher at
8 constant Fuel-N content, as previously assessed for the experimental data (section 4.3)
9 and suggested by literature [19, 20, 24]. Secondly, based on comparison of two slagging
10 risky fuels with similar Fuel-N and ash attributes (ash content and melting tendencies),
11 the blend and straw, it is expected that a potential NO_x conversion reduction of around
12 67% could be attained for the blend if a deep air staging is achieved (i.e., primary
13 lambda 0.8-0.95). Although further studies have to be performed to confirm this
14 assumption, a high potential for NO_x reduction is foreseen if a deep air staging
15 combustion is applied for the energy crop conversion.

16 4.5 Alternatives for NO_x reduction

17 The assessment of influencing factors on the NO_x emissions behavior has provided
18 useful information for achieving further NO_x reduction. As result of the dominant Fuel-
19 NO_x formation mechanism assumed here, main actions to be applied on controlling
20 NO_x emissions are linked to technology and fuel properties issues. Seeking an
21 appropriate fuel conversion with minimum NO_x emission level, possibilities for
22 overcoming detected limitations in terms of technology and fuel properties are explored
23 in this section.

24 Concerning technology, opportunities are foreseen in terms of the current system
25 design and control of the process. Based on the experimental data, the current system

1 design showed limitations to achieve the proposed substoichiometric condition for a
2 deep air staging, with both the reference fuel case and the energy crops.

3 As indicated in section 4.3, primary lambda used for the reference case DINplus
4 exceeded up to approximately 75% the suggested stoichiometric condition in literature
5 (i.e., 1.23 vs 0.7-0.95). It suggest that for achieving a deep air staging an improved
6 combustion chamber design should provide at least a potential reduction of 30% the
7 primary lambda applied in this work without exacerbating level of unburnt matter,
8 efficiency and NO_x emissions obtained here. The achievement of a deeper air staging
9 offer several advantages. It provides a longer residence time, which has been identified
10 of advantageous for lowering NO_x emissions. It also serves to control temperature in
11 the primary combustion zone, which is of importance for troublesome fuels in terms of
12 ash melting behavior. Furthermore, lowering the amount of air supplied also limits the
13 entrainment of ash in flue gases, which reduces deposits accumulation on heat
14 exchanger sections and particulate emissions.

15 Focused on reducing the share of primary air, influence of leakage air (see values for
16 delta total lambda in Table 4) should be avoided by an improved sealing of the fuel
17 supply but, particularly, undesired effects attributed to the current secondary air
18 configuration should be controlled. An appropriate secondary air configuration should
19 be evaluated in terms of angle of air injection, number of nozzles, separation between
20 primary-secondary combustion zone and enlarging the combustion chamber by
21 experimental campaigns or numerical simulations. The latter represents a useful
22 approach complementary to the experimental analysis for suggesting possible
23 modifications of geometrical configurations [59]. A CFD analysis of the current
24 combustion unit design has been performed to advance on these issues [47].

1 Concerning control of the process, results have indicated that grate temperature
2 should be keep in the range 800 °C-1000 °C when firing high slag formation risk fuels.
3 Operation of the grate combustion unit was affected by existing facilities to control
4 grate temperature or to remove ashes and therefore, control of lambda (total and
5 distribution) in a narrow range was required. During combustion of the Fuel-N and ash-
6 rich fuels with high slag formation risk temperature control may lead not only to limit
7 undesired melting of ash but also may favor the NO_x reduction paths because of a
8 temperature window has been reported around to 800 °C-950 °C [22, 31, 55]. Existing
9 limitations in terms of temperature control might be overcome by applying a deep air
10 staging, as mentioned previously. Flue gas recirculation seems to be also a helpful tool
11 to control bed temperature, minimizing the excess air applied to obtain a high burnout
12 and avoiding undesired effects of softening of ashes and NO_x formation [37, 60]. To
13 maintain a high temperature profile for gaseous unburnt, an efficient preheat of
14 secondary air should be also provided.

15 Concerning the fuel properties, based on all the results presented in this work, it
16 seems that the fulfillment of the threshold values for NO_x emission may be limited for
17 pure brassica, or similar fuels. In this work, it has been evaluated that besides the higher
18 Fuel-N content in this fuel the behavior of ash accumulated on grates lead to an
19 important troublesome character for this fuel. Accordingly, the use of this alternative
20 source might demand to consider possibilities for conditioning its Fuel-N content by
21 blending or as a last option, avoid burning this type of fuels. Adding 50% of poplar to
22 brassica resulted into a blend with Fuel-N content reduced up to around 38% the one in
23 the herbaceous. Then, after the blend combustion test, a reduction of around 40% the
24 NO_x emission level attained to brassica test was identified. Therefore, fuel blending is

1 suggested as a potential alternative to increase contribution of local energy sources,
2 such as energy crops, and to control their NO_x emission behavior.

3 4 5 CONCLUSIONS

5 This paper has discussed influencing factors on NO_x emission performance of three
6 pelletized energy crops, one herbaceous, brassica, one short rotation coppice, poplar,
7 and a blend in the proportion of 50 wt% w.b. brassica and poplar. Fuels were burnt in a
8 250 kW_{th} grate fired thermal conversion system initially adapted to ash-rich fuel
9 properties. Due to pelletized condition of fuels, main differences considered of
10 importance for this work were found in terms of the Fuel-N content, the VM/FC ratio
11 and the ash attributes. The more complex tested crops were ash-rich fuels with
12 considerable sintering tendency and exhibited a high N-content.

13 In general, CO emissions and thermal efficiency attained for the tested fuels fulfilled
14 the requirements defined by the standard EN 303-5:2012. Different operating conditions
15 had to be implemented among fuels to achieve the best results on CO emissions and
16 thermal efficiency. It was mostly dependent on fuel properties, particularly, the ash
17 attributes and limitations of the system to cope with the ash-related effects.
18 Accordingly, conversion of the ash-rich fuels with high slag formation risk (brassica
19 and the blend) demanded specific conditions which differed substantially of the ones
20 implemented during combustion of the woody fuels.

21 Based on the experimental data, the Fuel-NO_x formation mechanism was the most
22 important one. The NO emissions increased when Fuel-N was higher but the increments
23 were not proportional to the Fuel-N content. NO_x emissions satisfied restrictions
24 defined by the Austrian agreement, although one exception was found for brassica. For
25 this fuel, nitrogen content was around 14 times higher the one for the woody reference

1 fuel. Furthermore, an opposite relation was observed for the specific NO_x emissions and
2 the NO_x/Fuel-N conversion rates obtained for the two Fuel-N groups tested here, the N-
3 rich ones (brassica and the blend), and the N-lean ones (poplar and DIN plus).

4 As expected by the Fuel-NO_x formation mechanism, air conditions used to enhance a
5 complete burnout also had a substantial influence on the NO_x emissions behavior. For
6 all the fuel tested, increments on oxidant conditions at constant Fuel-N content
7 increased the NO_x emission level. Accordingly, NO_x emission behavior was also
8 dependent on the combustion stoichiometry.

9 Control of NO_x emission by applying a deep air staged combustion was limited
10 during the experiments. A substantial proportion of primary air was implemented as
11 consequence of limitations attributed to the combustion chamber design of the tested
12 technology and the ash attributes of the pelletized energy crops, particularly the ones
13 with high tendency to form slag. Due to the characteristics of the troublesome fuels and
14 the technology tested in this work, special attention has to be placed on attaining a
15 better control of grate temperature and air amount and its distribution. In addition, based
16 on NO_x emissions results achieved for pop_{50%}- br_{50%}, blending of raw materials might be
17 evaluated as an option to fulfill European restrictions in terms of NO_x emissions as well
18 as to promote the use of local biofuels, although measures leading to a rigorous control
19 of the production process have to be also considered.

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Figure Caption 1

Figure 1. Main ash-forming elements in fuel samples. Amount of element is calculated based on the higher heating value given for each fuel in Table 1. Values in parenthesis correspond to the ash content in fuels given in wt% d.b.

Figure 2. Main components of the conversion system.

Figure Caption 3

Figure 3. Experimental set-up schematic diagram.

Figure Caption 4

Figure 4. Evolution curves for CO and NO_x specific emissions with respect to lambda during combustion operating period at maximum load attained to each fuel case. Emission limits corresponds to requirements defined by the Austrian law art. 15a B-VG [40, 50]. Emissions of NO_x are presented as NO₂ (NO₂ equivalent).

Figure Caption 5

Figure 5. Evolution of specific NOX emissions with respect to lambda during combustion operating period at maximum load attained to each fuel case. Emission limits corresponds to requirements defined by the Austrian law art. 15a B-VG [40, 50]. Values in parenthesis correspond to the N-content in fuels given in wt% d.b.

Figure Caption 6

Figure 6. NO_x/Fuel-N ratio variations with respect to lambda during combustion operating period at maximum load attained to each fuel case. Values in parenthesis correspond to the N-content in fuels given in wt% d.b.

Figure Caption 7

Figure 7. Simplified schematic description for the Fuel-N conversion paths based on literature [20, 29, 55]. Main products related to each step are indicated.

Figure Caption 8

Figure 8. Evolution curves for thermal profile inside the combustion chamber with respect to lambda distribution during stationary combustion operating period at maximum load attained to each fuel.

Figure Caption 9

Figure 9. Influence of Fuel-N content on mean values of the ratio $\text{NO}_x/\text{Fuel-N}$. Mean values corresponding to the best condition during stationary combustion phase obtained to each fuel combustion test are depicted in this figure. Additional data is obtained from literature: samples 5-8 from reference [61] and samples 9-12 from reference [29].

Figure 1
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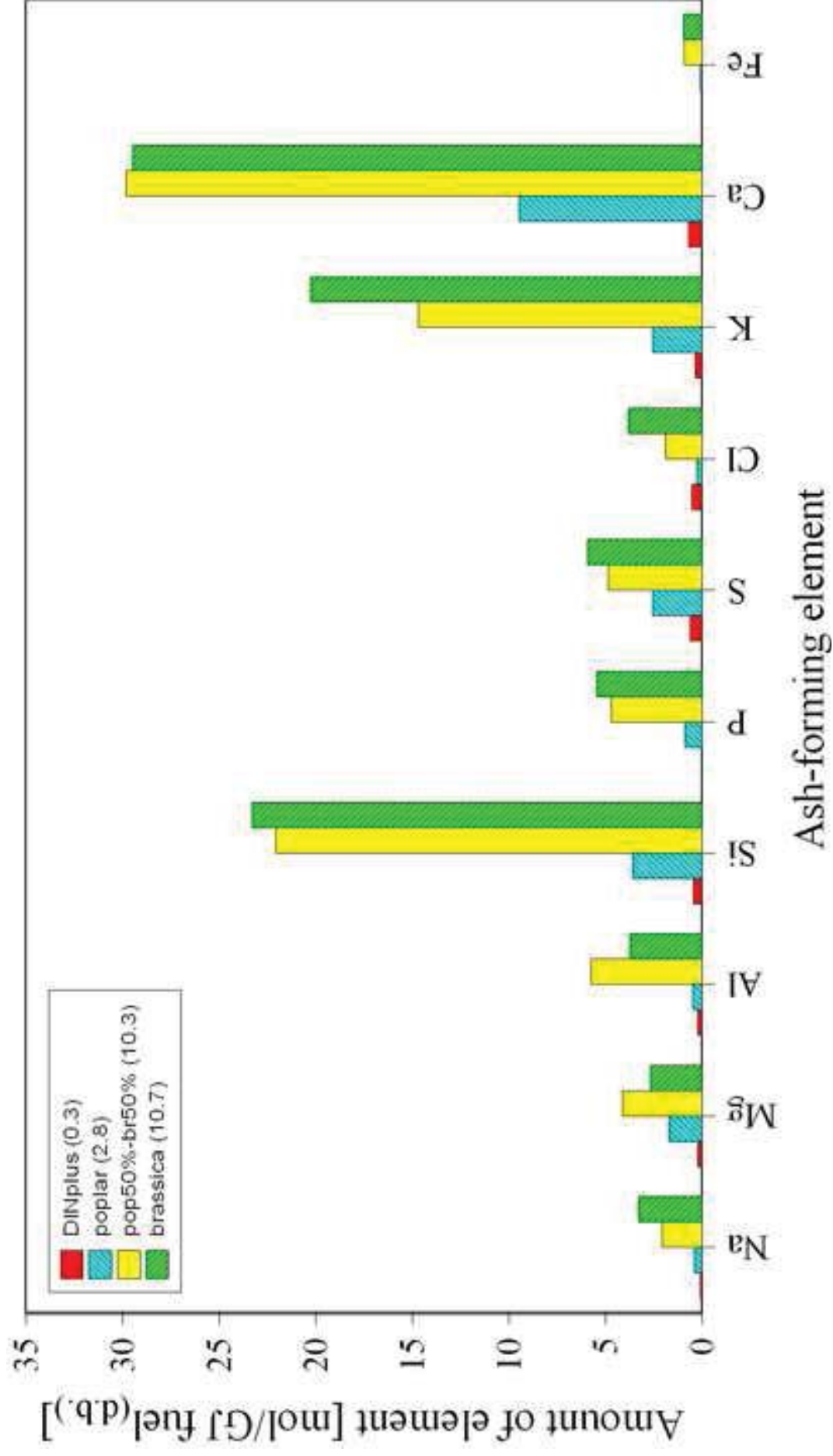
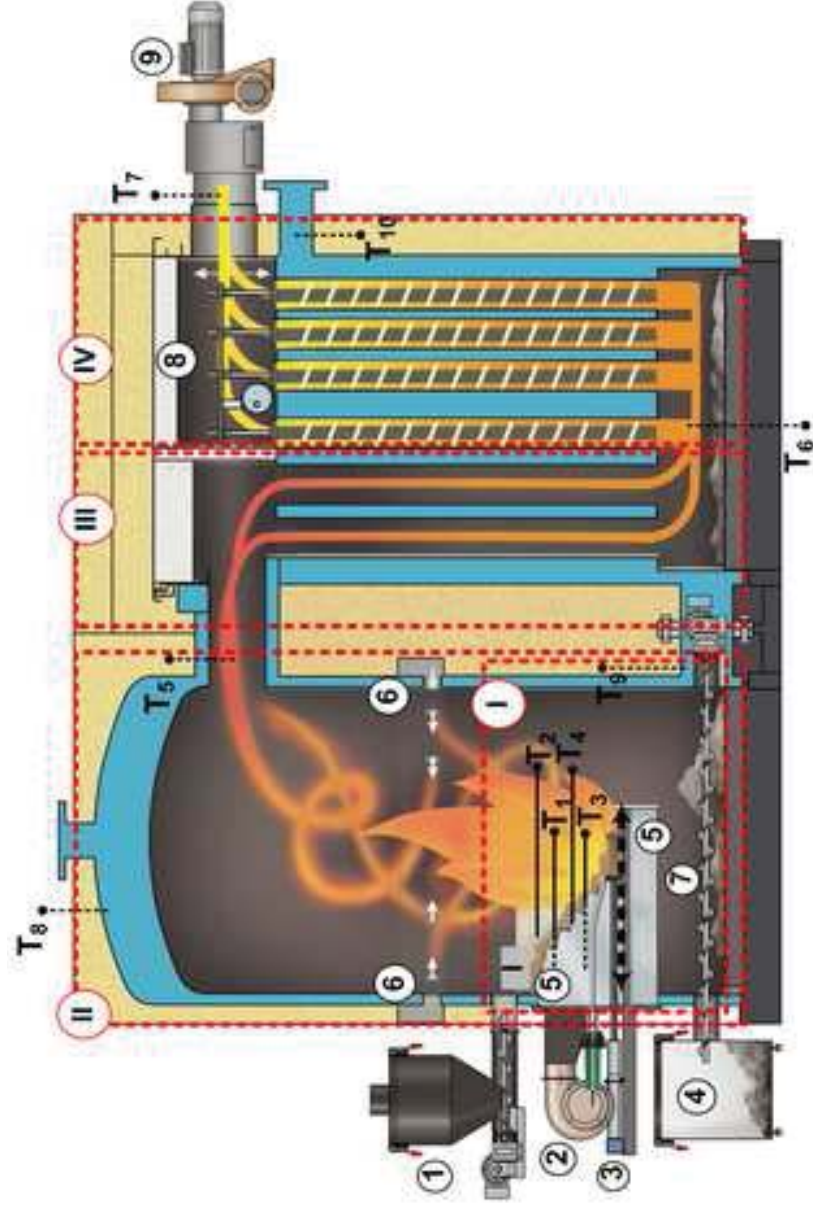


Figure 2
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Legend:

Main zones in the conversion system:

- I. Burner zone
- II. Combustion chamber
- III. Heat exchanger tubes (first zone)
- IV. Heat exchanger tubes (second zone)

Main components in each zone:

- 1. Fuel feeding system
- 2. Primary air fan and ignitor
- 3. Ash removal system
- 4. Ash container
- 5. Burner grates
- 6. Secondary air fan and air distribution
- 7. Ash pit and worms
- 8. Turbulator driving gear
- 9. Draught fan

Figure 3
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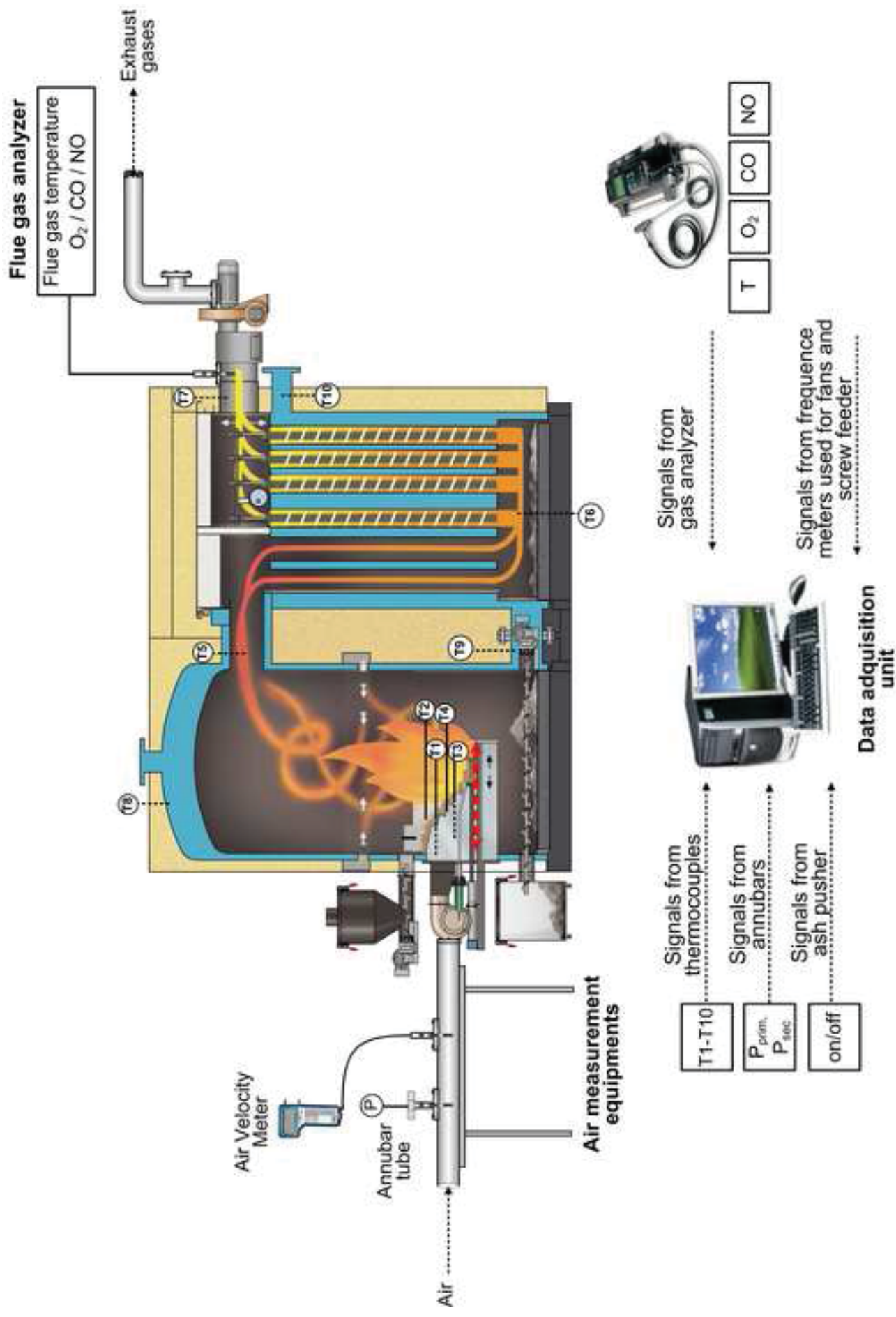


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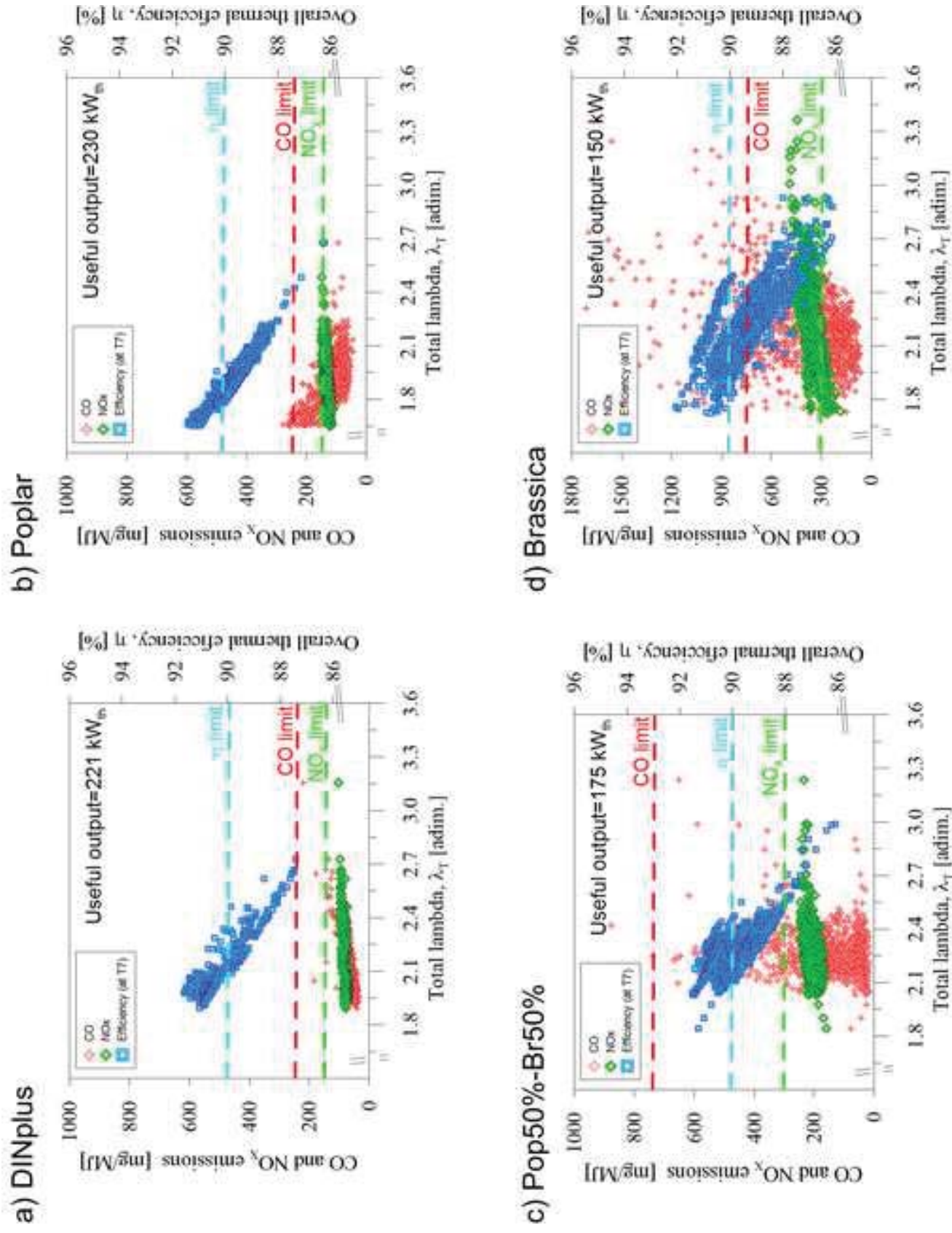


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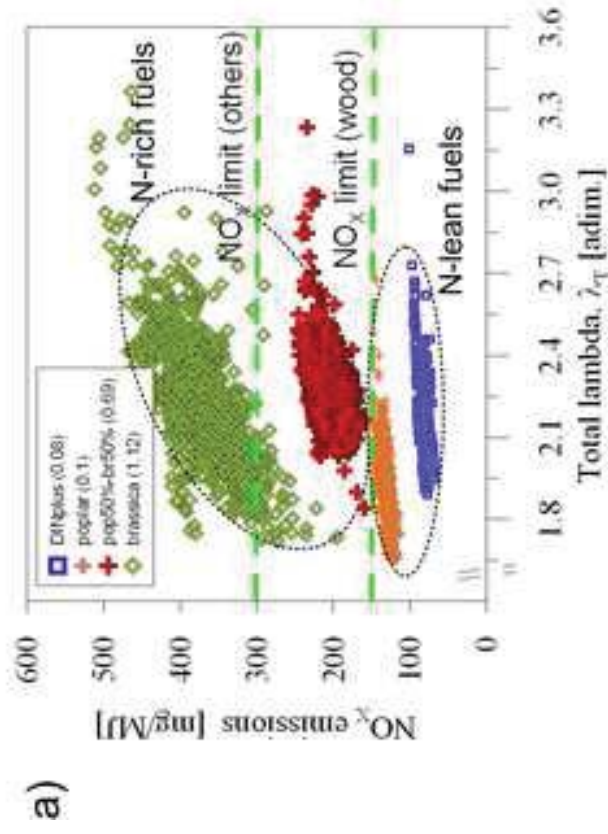
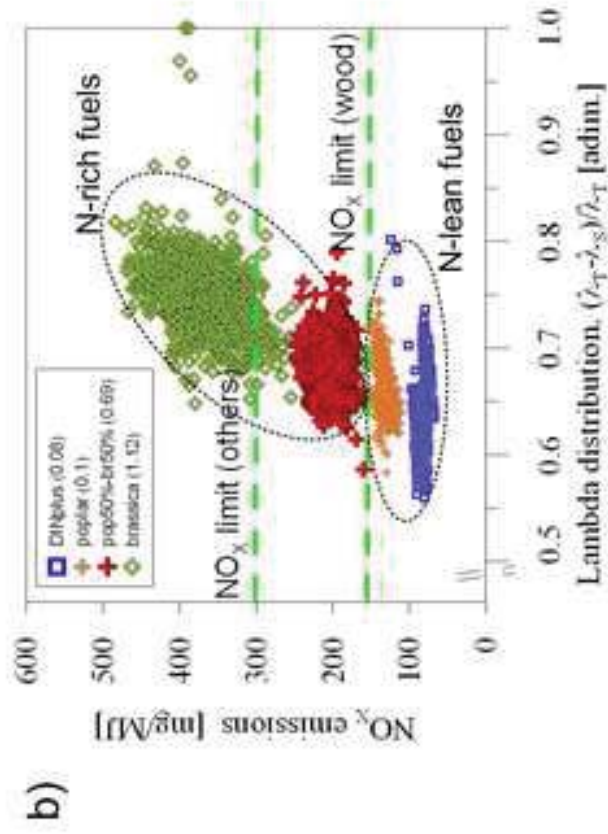


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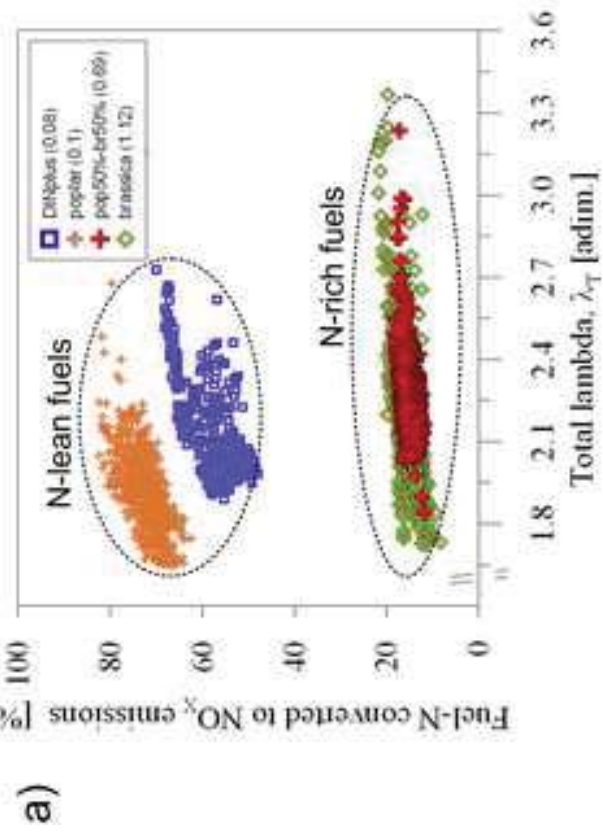
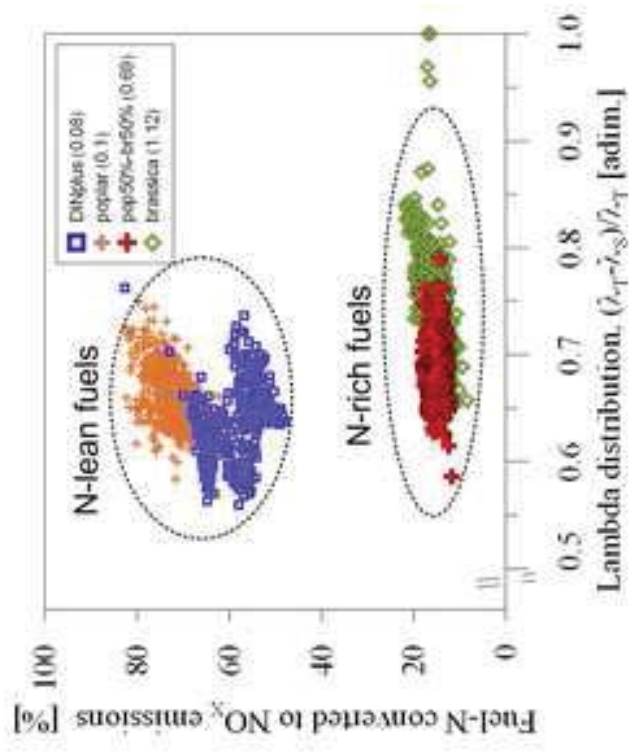
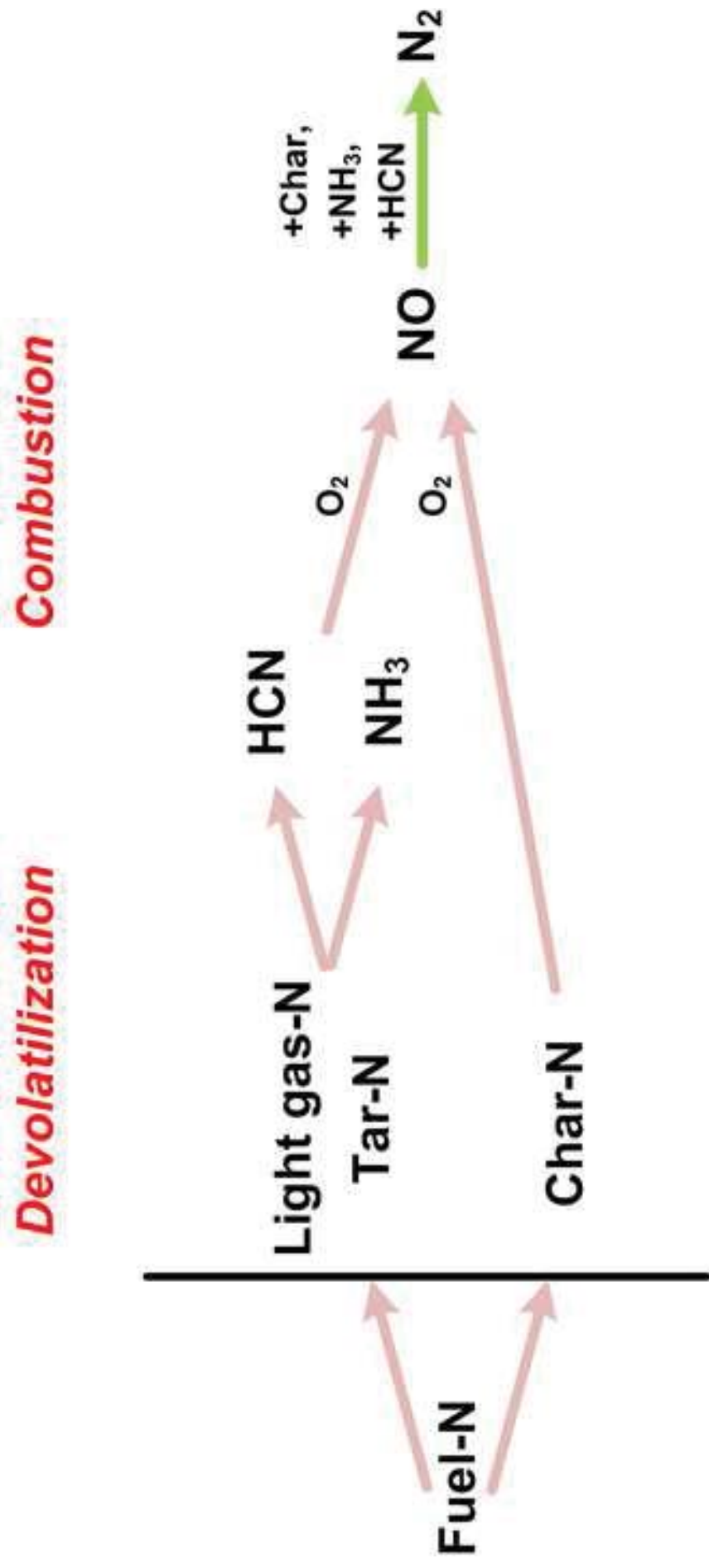


Figure 7
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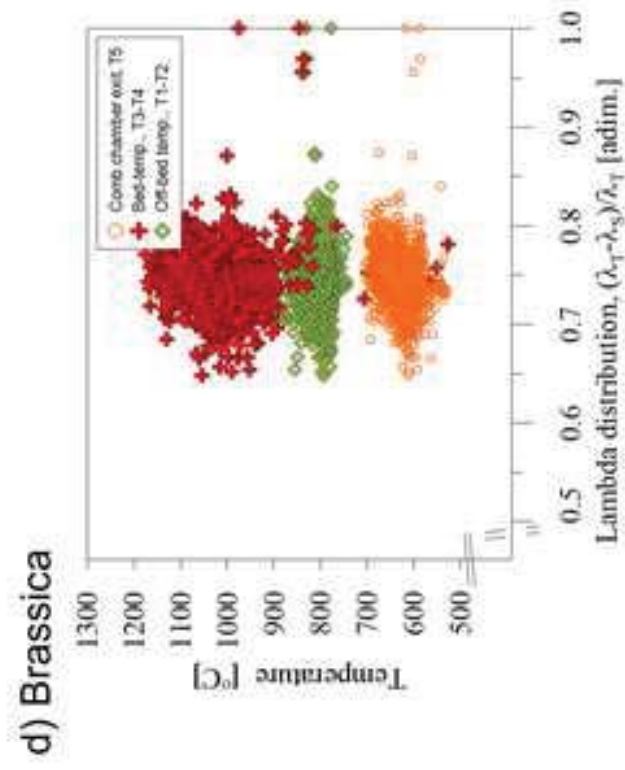
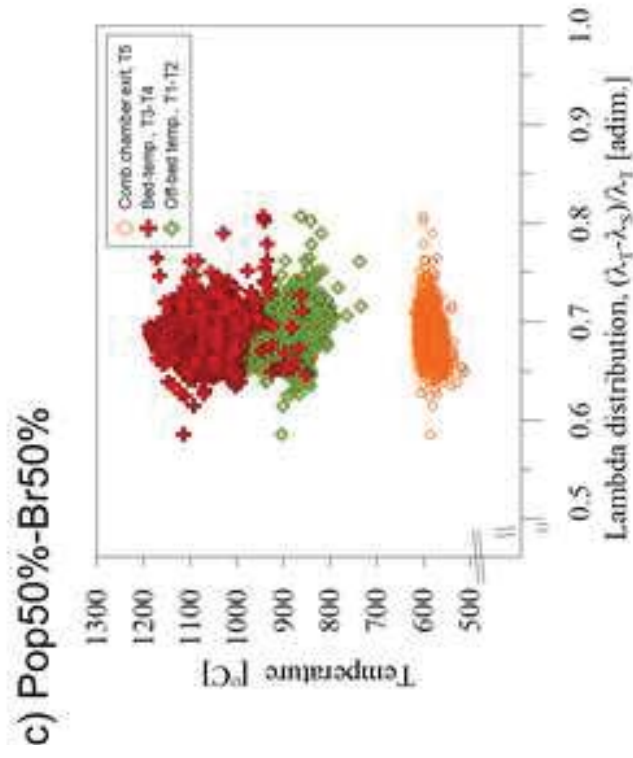
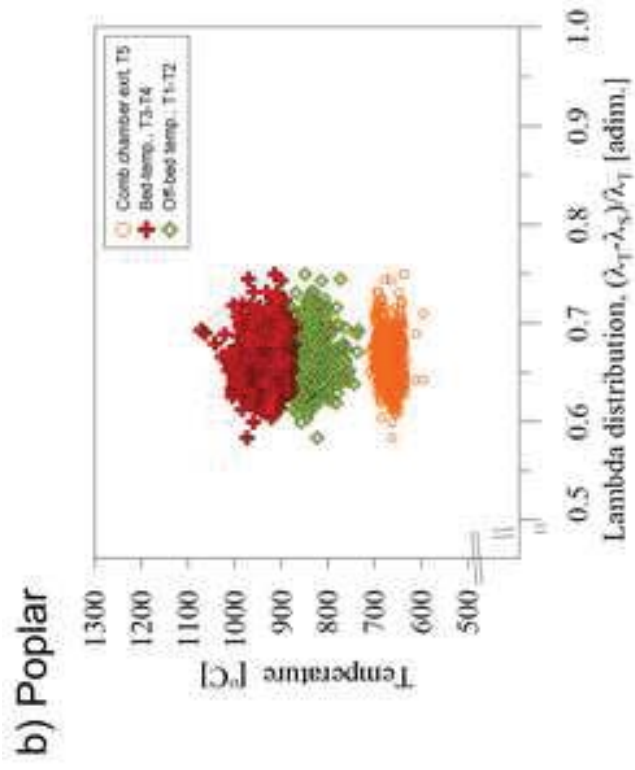
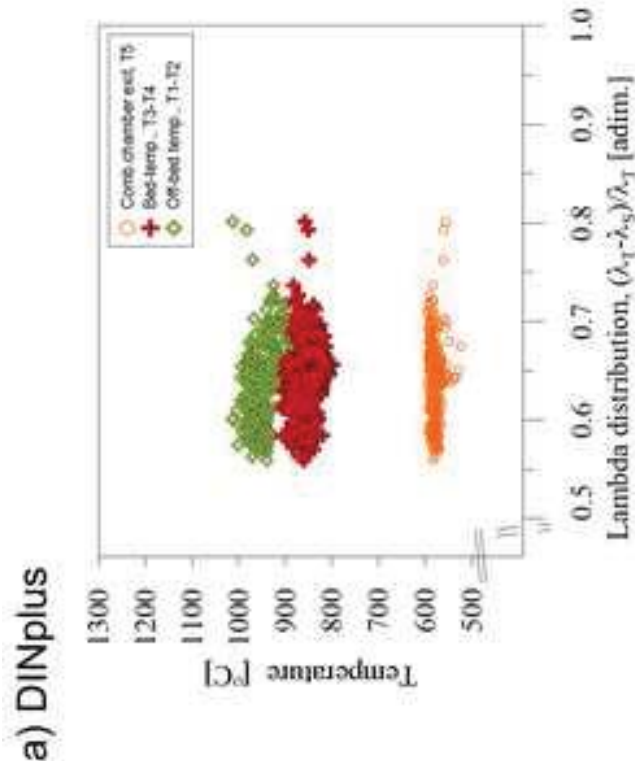


Figure 9
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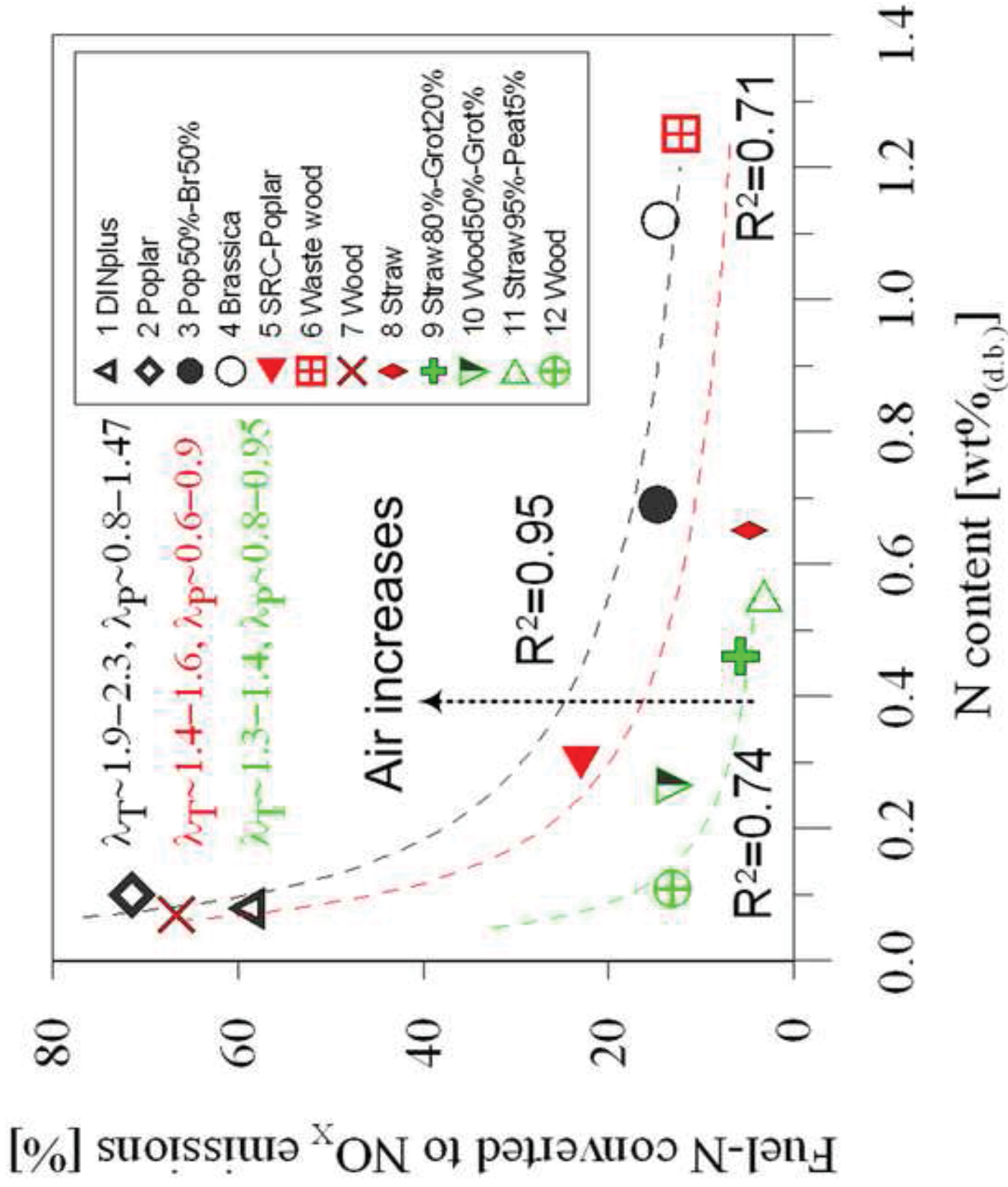


Table 1. Fuel characteristics and product standard requirements

Parameter	European standards				Studied fuels		
	DINplus certification	ÖNORM M 7139 energy grains	EN 14961-2 Woody biomass (Short rotation coppice)	EN 14961-6 Herbaceous biomass, fruit biomass, blends and mixtures	DINplus	poplar	pop _{50%} -br _{50%}
			Class A2	Class B	Class A	Class B	
Calorific value ^a							
Higher heating value, HHV _v	MJ/kg d.b.				20.1	19.49	17.90
Lower heating value, LHV _p	MJ/kg d.b.	≥ 18			18.85	18.13	16.63
Lower heating value, LHV _p (a.r.)	MJ/kg w.b.		16.3 - 19	16 - 19	17.58	16.38	14.58
Proximate analysis ^b							
Ash content in pellets at 550 °C	wt% d.b.	≤ 0.5	≤ 1.5	≤ 3	≤ 5	≤ 10	0.3
Fixed carbon, FC ^c	wt% d.b.				16.5	15.2	15.3
Volatile matter, VM	wt% d.b.				83.2	82.0	74.4
Moisture	wt% w.b.	≤ 10	≤ 10	≤ 10	5.4	5.0	4.9
Ultimate analysis ^d							
C	wt% d.b.				50.57	49.36	44.95
H	wt% d.b.				5.93	5.9	5.55
N	wt% d.b.	≤ 0.3	≤ 0.5	≤ 1.0	0.08	0.1	0.69
N	wt% d.a.f.				0.08	0.1	0.77
O ^e	wt% d.b.				43.13	41.66	38.09
S	wt% d.b.	≤ 0.04	≤ 0.03	≤ 0.04	0.0	0.16	0.28
Cl	wt% d.b.	≤ 0.02	≤ 0.02	≤ 0.03	0.0	0.02	0.12
Indices							
Volatile matter/Fixed carbon ratio, VM/FC	Adim.				5.04	5.39	4.86
Stoichiometric air to fuel ratio, SAR	kg wet air/MJ fuel				0.3218	0.3393	0.3344

a. Values are given in Megajoules per kilogram, dry basis (MJ/kg, db). HHV_v is determined at volume constant and LHV_p at constant pressure. Lower

heating value as received, $LHV_{p(a.r.)}$, (MJ/kg w.b) is also included.

b. Values are given in weight percent, dry basis (wt% d.b.), except for moisture given in weight percent wet basis (wt% w.b.).

c. Calculated by balance.

d. Values are given in ash free, dry basis (wt% d.a.f).

Table 2

Table 2. Composition of fuel ash at 550 °C.

Parameter		DINplus	poplar	pop _{50%} - br _{50%}	brassica
Percentage of dry substance in ashes ^a					
Na ₂ O	wt% d.b.	2.1	0.9	1.1	1.6
MgO	wt% d.b.	5.9	4.8	2.9	1.7
Al ₂ O ₃	wt% d.b.	8.8	1.7	5.1	3.0
SiO ₂	wt% d.b.	19	15	23	22
P ₂ O ₅	wt% d.b.	2.1	4.5	5.8	6.1
SO ₃	wt% d.b.	3.6	11	5.6	7.3
K ₂ O	wt% d.b.	12	8.3	12	15
CaO	wt% d.b.	26	37	29	26
Fe ₂ O ₃	wt% d.b.	3.2	0.6	1.3	1.2
Alkali index ^b	kg alkali metals/GJ fuel	0.02	0.13	0.76	1.06

a. Values are given in g oxide/100 g ash in dry basis (d.b.) for all parameters.

b. Values of (0.17-0.34) kg alkali metals/GJ fuel suggest probably occurrence of slagging and fouling. Above 0.34 kg alkali metals/GJ fuel, the ash effects certainly occur. This ratio is based on the HHV_v given for each fuel in Table 1 [16].

Table 3

Table 3. Limiting values for automatically loaded combustion system firing biofuels.

Document	Nominal heat output, kW _{th} (PN)	Biofuel type	Boiler class	CO	NO _x	Efficiency, % (η)	
European Norm (EN) 303-5:2012	150 < PN ≤ 500	Standardized woody and non-woody fuels	Class 3	1200 mg/Nm ³ ^b	---	PN>300 kW _{th}	82%
			Class 4	1000 mg/Nm ³ ^b		PN>100 kW _{th}	84%
			Class 5	500 mg/Nm ³ ^b		PN>100 kW _{th}	89%
Austrian agreement (15a B-VG)	200 < PN ≤ 400	Standardized woody fuels ^a	No apply	250 mg/MJ ^c	150 mg/MJ ^d	PN>200 kW _{th} (automatically loaded)	90%
		Other standardized wooden fuels ^a					
		Other standardized biofuels ^a		500 mg/MJ ^c	300 mg/MJ		

a. Fuels should fulfill fuel quality requirements by the standards ÖNORM [39].

b. Limit related to 10% O₂. Automatic boiler class 3 is the strictest class of this standard [50].

c. During partial load operation at 30% of nominal heat output CO limit increases up to 50% [50].

d. Future requirements (1.1.2015) are expected to be set at 100 mg/MJ [50].

Table 4

Table 4. Set of operating parameters and temperature profile reached during the best condition attainable to each fuel at maximum load and stationary combustion phase.^a

Parameter		brassica	pop _{50%} -br _{50%}	poplar	DINplus
Operation conditions					
Total energy input (dry basis)	kW _{th}	168.2 ± 0.1	194.9 ± 0.1	256.6 ± 0.1	244.3 ± 0.2
Load input (based on dry fuel)	kW _{th}	167	192	255	242
Useful output (at T ₇)	kW _{th}	149.8 ± 0.9	174.5 ± 0.4	230 ± 1	220.7 ± 1.1
Pusher on/off working period	Adim.	5/50	5/50	4/100	4/100
Total lambda, λ _T	Adim.	2.07 ± 0.13	2.27 ± 0.07	1.93 ± 0.09	2.04 ± 0.12
Delta total lambda, Δλ _T	Adim.	0.11 ± 0.13	0.40 ± 0.07	0.31 ± 0.10	0.44 ± 0.12
Primary lambda, λ _T - λ _S	Adim.	1.57 ± 0.13	1.53 ± 0.09	1.26 ± 0.11	1.23 ± 0.12
Lambda distribution (with respect to primary air), (λ _T - λ _S)/λ _T	%	76	68	65	60
Temperature profile					
Burner mean T ₁ - T ₄	°C	1015 ± 154	1029 ± 78	880 ± 53	915 ± 50
Burner minimum T ₁ - T ₄	°C	771	917	765	770
Burner maximum T ₁ - T ₄	°C	1232	1202	1012	1001
Off-bed temperature, T ₁ and T ₂	°C	803 ± 14	970 ± 38	840 ± 38	958 ± 18
Bed temperature, T ₃ and T ₄	°C	1122 ± 38	1087 ± 63	920 ± 23	872 ± 31
Temperature at the exit of the combustion chamber, T ₅	°C	668 ± 16	593 ± 5	657 ± 7	583 ± 6
Temperature in the exhaust gases, T ₇	°C	155 ± 1	148 ± 1	164 ± 1	155 ± 1
Residence time inside combustion chamber, τ	s	1.03 ± 0.01	0.9 ± 1.5	0.712 ± 0.006	0.749 ± 0.008
a. Average values are given with standards deviations.					

Table 5

Table 5. Thermal efficiency, unburnt matter and NO_x results for the best condition attainable to each fuel during stationary combustion phase at maximum load.^a

Parameter		brassica	pop _{50%} -br _{50%}	poplar	DINplus
Flue gas composition and solid unburnt matter					
O ₂	vol% d.g.	10.9 ± 0.6	11.8 ± 0.3	10.2 ± 0.5	10.7 ± 0.6
CO ^b	mg/Nm ³ (10% O ₂ d.g.)	285 ± 96 (500)	202 ± 114 (500)	186 ± 32 (500)	117 ± 25 (500)
NO _x ^c	mg/Nm ³ (10% O ₂ d.g.)	672 ± 37	418 ± 42	266 ± 7	176 ± 6
Loss of ignition matter in solid residue	kg/kg solid residue	0.0071	0.0064	0.0088	0.0044
Specific gaseous emissions and thermal efficiency					
CO ^d	mg/MJ	144 ± 49 (500 ^d /750 ^e)	96 ± 54 (500 ^d /750 ^e)	91 ± 15 (250 ^d /500 ^e)	54 ± 11 (250 ^d /500 ^e)
NO _x ^f	mg/MJ	340 ± 19 (300)	200 ± 20 (300)	129 ± 3 (150)	82 ± 3 (150)
Thermal efficiency at T ₇ , η_{T7} ^g	%	89.1 ± 0.6	89.5 ± 0.2	89.7 ± 0.4	90.3 ± 0.5
NO_x/ Fuel-N ratio	%	14.5 ± 0.8	14.6 ± 1.5	71.4 ± 1.9	58.7 ± 1.9

a. Average values are given with standards deviations.

b. Reference value according to the European norm EN 303-5:2012, for the strictest category, Class 5 [50].

c. Evaluated as NO₂ according to the European norm EN 303-5:2012 [50].

d. Reference value according to the Austrian Art.15a B-VG restrictions.

e. CO limit increases up to 50% during partial load operation at 30% of nominal heat output [50].

f. Reference values according to the Art.15a B-VG restrictions [50].

g. Thermal efficiency limit according to the European norm EN 303-5:2012, Class 5 is set at 89% [50]. The Austrian requirements are set at 90%.