Combustion Behavior of Novel Energy Crops in Domestic Boilers: Poplar and Brassica Experiences

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Abstract In the Mediterranean countries, several reasons promote cultivation of energy crops with respect to other kind of biomass. Specifically, they are expected to enhance the biomass heating opportunities in the energy market. Focused on that goal, Spanish research efforts have involved the evaluation of all the bioenergy chain steps, from fuel production to its transformation into energy in the conversion system. In this work, special emphasis have been placed on the assessment of two crops (*Brassica carinata* and *Populus sp.*) combustion requirements and adaptability level of a novel 250 kW_{th} Spanish grate fired technology to cope with their conversion according acceptable level of gaseous emissions and efficiency. Finally, further research steps, needed to improve the novel fuel conversion system performance, have been presented seeking for a more definite introduction of this heating system in the Spanish bioenergy market.

1 Perspectives of the Energy Crops Use as Biofuels for the Heating Sector in Europe: The Spanish Case

Biomass fuels are one of the most important energy resources. They constitute approximately 14 % of the global primary energy, the fourth largest following coal, oil, and natural gas [1]. In addition, bioenergy is considered to be the

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renewable energy source with the largest unexplored potential in the European Union (EU) [2, 3].

In the last decades, several types of biofuels have been incorporated to the biomass market. Main driving forces to the recent participation of these sources have been related to growing concerns about environmental pollution, especially due to greenhouse gases (GHG), and also those related to fossil fuel supply uncertainties. In addition, limitations concerning biomass availability in specific regions and increasing energy demands have enforced to consider a broad variety of novel sources. It currently involves sources from agro-industrial activities, such as olive oil and almond production, as well as dedicated energy crops, which includes short rotation coppice, perennial grasses and herbaceous species.

With respect to dedicated energy crops, it can be stated that the bioenergy potential contribution of this biomass type is enormous. Taking land availability and projected biomass yield into account, the largest bioenergy potential from the dedicated energy crops will be found in seven of the European Union Member States (Spain, France, Germany, Italy, the United Kingdom, Lithuania and Poland) [4–7]. Specifically, in the Mediterranean countries, energy crops are seen as an attractive alternative to satisfy local energy demands because the possibilities they offer to enhance the local biomass heating opportunities. Moreover, their production is expected to provide collateral benefits to this region, for instance, social sustainability by creating new employment opportunities.

Particularly, in Spain, research efforts for energy production based on dedicated energy crops have mainly been focused on the assessment of inputs and outputs of each chain step involved in the energy crop production processes, from fuel production to its transformation into energy [8]. Emphasis has been placed not only to identify the most suitable fuels adapted to local Mediterranean edapho-climatic conditions but also to learn how to handle and use these materials for heating supply purposes.

Local research in these issues started as part of the "PSE On Cultivos" R&D&I national project carried out between 2005 and 2012. It was defined as singular and strategic project for development, demonstration and viability evaluation of the commercial production of energy from dedicated crops in Spain, in terms of their use for heating, electricity and transport.

With regard to the energy crop application for the domestic heating, this project entailed the assessment of the energy crop properties as well as the development of suitable thermal conversion technology adapted to characteristics of the most promising energy crops produced in Spain.

Concerning the energy crop properties assessment, a complete fuel characterization was done considering both physical and chemical aspects. Energy crops cultivated today can generally be described as "problematic" fuels mainly due to both their high ash content and their composition of ash forming matter in comparison to biofuels used traditionally, such as stemwood based assortments [9–11]. Consequently, a higher tendency to cause fouling, slagging and/or corrosion problems is expected from their thermochemical conversion.

Experiences carried out as part of the "PSE On Cultivos" framework have involved one short rotation coppice, *Populus sp.* (poplar) and one herbaceous *Brassica carinata* (brassica) energy crops, among other raw materials proposed as potential biofuels in the Spanish "PSE On Cultivos" energy schemes.

On the other hand, in order to evaluate the Mediterranean energy crops applicability for heating purposes, a medium biomass grate-fired unit has been developed. The technological features existing in this conversion unit are been based on both previous knowledge from stemwood combustion and specific experimental research carried out with the energy crops assessed as part of the "PSE On Cultivos" domestic heating framework. In spite of grate firing combustion units has been suggested as the most suitable ones to satisfactory thermal conversion of the novel biofuels, significant impacts attributed to fuel quality factors, such as ash content and ash chemical composition, might affect the performance of grate technologies. The intrinsic fuel characteristics might limit the reliability level of the combustion unit, basically affected by type of fuel as well as operation and maintenance of the conversion equipment, among others attributes [12, 13]. Consequently, knowledge of fuel quality influence on the conversion system performance and adaptability level of the novel technology to manage the fuel characteristics was considered of importance as part of the heating generation "PSE On Cultivos" framework.

Based on knowledge acquired by the Spanish experience, the main objective of this chapter is to highlight some important considerations that should be taking into account to satisfactorily convert the more troublesome energy crops for heating purposes. Main characteristics of both the thermal conversion system developed and tested fuels in the "PSE On Cultivos" framework are primarily described. Secondly, an evaluation of the thermal and emission performance during brassica and poplar conversion is presented. Special emphasis is given on analyzing the ash effects on the Spanish fixed-grate system performance, and how to manage them particularly, in terms of practical aspects to take into account for providing high combustion quality. Therefore, research from this work may contribute to identify key factors to consider during grate conversion of the novel crops besides offering useful information to define emission levels or develop reliable conversion units able to cope with the energy crop characteristics.

2 Thermal Conversion of Two Energy Crops for Heating Purposes: Brassica and Poplar Experiences

Knowledge about the dedicated energy crops properties and their conversion requirements to attain a high acceptability level of the final users is limited mainly because of the recent introduction of the novel biofuels into the energy sector. Most of the available information in literature regarding the thermal conversion of dedicated energy crops has been acquired under quite well controlled laboratory conditions, and published full-scale experiences are scarce.

Therefore, gaining knowledge related to the understanding of the combustion behavior of the novel crops is foreseen of relevance for the sustainable development of an energy crop market based on high efficiency, low costs and low environmental impact levels. Considering these aspects, a detailed assessment of combustion experiences carried out for the two energy crops, brassica and poplar, as part of the "PSE On Cultivos" framework, is presented here. Main tested conditions and results are summarized in the following.

2.1 Fuel Properties

A detailed fuel characterization has been carried out to the novel crops. A briefly description of the most significant fuel properties (physical and chemical aspects) will be presented in this section.

The herbaceous energy crop, brassica and the short rotation coppice, poplar, produced as part of the Spanish research project PSE "On Cultivos", were both cultivated and pelletized in Spain. The pelletization plant is located at the Renewable Energy Development Center (CEDER-CIEMAT), in Spain (Lubia, Soria). Biomass raw materials used in the pelletizing process consisted of brassica straw (grains included) and poplar stem (branches, leaves and bark were not included). Pellets had a diameter of 6 mm and a length of 15–20 mm. In Fig. 1, pictures of brassica and poplar raw materials and densified as pellets are showed.

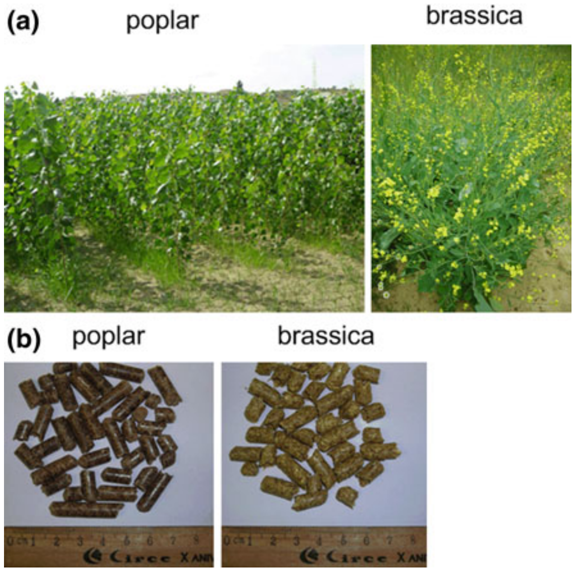

Fig. 1 Brassica and poplar raw materials and densified as pellets

Table 1 Fuel characteristics. Values are given in weight percent dry basis (wt % d.b.) except for heating value, moisture and ultimate analysis, which are given in MJ/kg d.b., weight percent wet basis (wt % w.b.), and dry basis ash free (wt % d.b.a.f), respectively

Parameter		Poplar	Brassica
Calorific value			
Higher heating value, HHV	MJ/kg d.b.	19.49	17.46
Lower heating value, LHV	MJ/kg d.b.	18.13	16.31
Proximate analysis			
Ash content in pellets	wt % d.b.	2.8	10.7
Fixed carbon	wt % d.b.	15.2	18.8
Volatile matter	wt % d.b.	82.0	70.4
Moisture	wt % w.b.	5.0	4.9
Ultimate analysis			
C	wt % d.b.a.f.	50.8	49.7
H	wt % d.b.a.f.	6.1	6.2
N	wt % d.b.a.f.	0.1	1.3
O	wt % d.b.a.f.	42.9	42.2
S	wt % d.b.a.f.	0.16	0.36
Cl	wt % d.b.a.f.	0.02	0.26
Percentage of dry substance in ashes			
SiO_2	wt % d.b.	15	22
Al_2O_3	wt % d.b.	1.7	3.0
CaO	wt % d.b.	37	26
Fe_2O_3	wt % d.b.	0.6	1.2
K_2O	wt % d.b.	8.3	15
MgO	wt % d.b.	4.8	1.7
MnO	wt % d.b.	0.06	0.05
Na_2O	wt % d.b.	0.9	1.6
P_2O_5	wt % d.b.	4.5	6.1
SO_3	wt % d.b.	11	7.3
ZnO	wt % d.b.	0.01	0.08

The main fuel properties of the tested pellets are listed in Table 1. In addition, the ash chemical composition of both fuels, given on a mole of ash-forming element per GJ of dry solid fuel, is provided in Fig. 2.

As shown in Table 1, these two biomass types exhibit a broad variation range of their properties and, consequently, a different combustion behavior is expected for them. According to Table 1, moisture content is rather low and similar between fuels. Based on ash content required for standardized woody pellets defined by the European norm (EN) 303-5 [14] as <0.5 wt % d.b. and by the DINplus standard set at $\leq$0.5 wt % d.b., the energy crops samples are characterized by a larger ash content, and can be generally grouped as ash-rich fuels. The ash condition in these two fuels also affects the V/CF ratio being lower for the herbaceous, and consequently, fuel reactivity differences are expected between them during their thermal conversion.

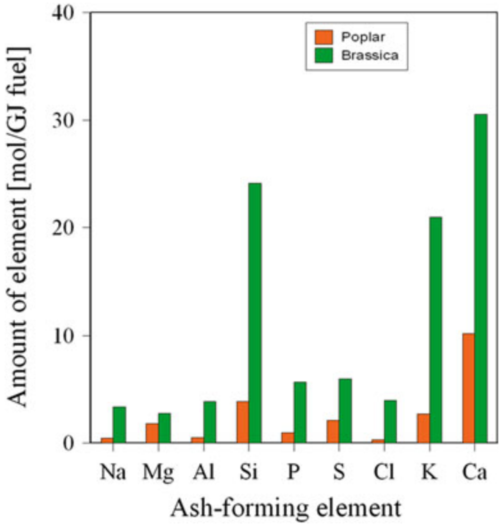

Fig. 2 Brassica and poplar inorganic constituents. Amount of element is calculated based on the LHV of the dry solid fuel. Amount of Cl in ash at 550 °C was assumed as 100 % of the content in fuel obtained by the ultimate analysis

Concerning ultimate analysis, compared on a dry ash free basis, N content for poplar was according to limiting values for the DINplus quality standard set at ≤0.3 wt % d.b. On the contrary, brassica yielded a larger N content, and hence, more significant impacts on the NO_X emission level are expected to this fuel.

In addition, results from the ultimate analysis indicated that brassica depicted the worst condition in terms of other troublesome elements, such as Cl and S. They play an important role on particulate matter and acidic gaseous emissions as well as corrosion phenomenon. With regard to the ash composition, although concentrations vary over quite a broad range, major ash components among fuels are Si, Ca and K. A second group of the ash-forming elements is suggested to be formed by Mg, P and S.

2.2 *Conversion System Characteristics*

As mentioned previously, a 250 kW_{th} (referred to its useful output) grate-fired thermal conversion system (currently, still under development and improvement stages) has been used to perform the combustion tests for the two energy crops, as part of the “PSE On Cultivos” domestic heating framework. The current state of technological advance available in this conversion unit is based on design modifications and improvements aimed to manage the specific combustion properties and ash chemical characteristics of the novel dedicated crops. The work presented here is a part of the development process of this Spanish technology.

The equipment was initially composed of a biomass burner, consisting of six horizontally positioned and separated cast iron grates connected to a horizontal and modular cast iron heat exchanger, which was designed and normally used for gaseous and liquid fuels. The main characteristics of this earlier design, as well as the further improvements carried out on the system to achieve the current state of development of the 250 kW_{th} grate-fired thermal conversion unit can be found elsewhere [15–18].

Combustion experiences performed with the pelletized ash-rich energy crops in the previous designs were considered as preliminary steps for all the improvements defined to the conversion unit presented here. As shown in Fig. 3, the 250 kW_{th} grate-fired thermal conversion system is mainly divided into four zones: burner (I), combustion chamber (II) and two heat exchanger sections (III and IV).

The burner zone is constructed according to the main principles for the combustion of pellets. In this system, fuel feeding (see Fig. 3, 1) is carried out by using a screw with a rotation speed control to provide the optimum adjustment of the fuel flow to the required load condition. The burner consists of two stationary main grates (see Fig. 3, 5). The first, which is located at the upper part of the burner, is divided into four horizontally positioning small steps, resembling a ladder (with nozzles in the riser part), whereas the second is also flat but is longer to ensure complete char burnout. Primary air (see Fig. 3, 2) is provided as under-feed air through each grate.

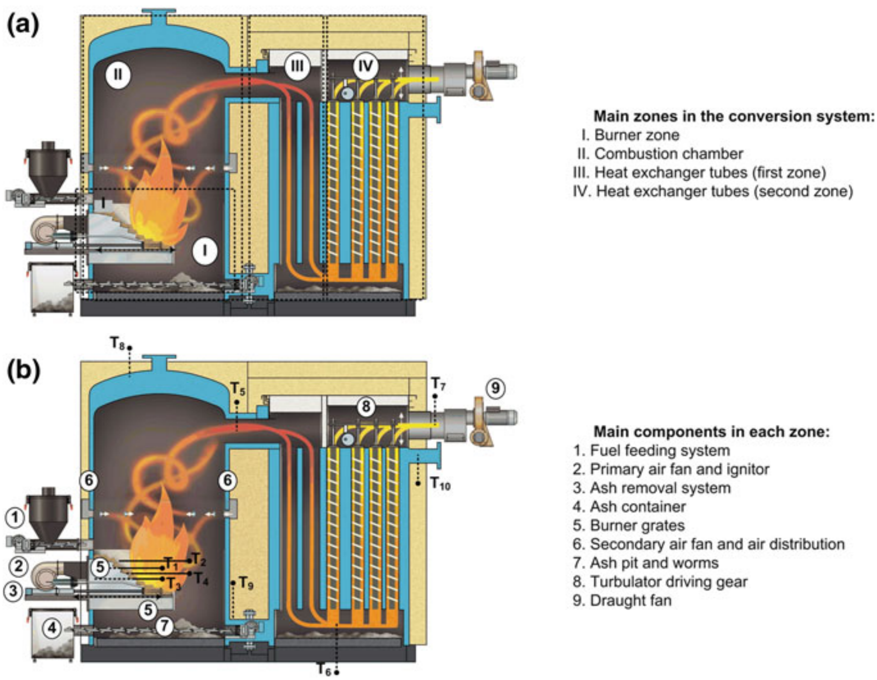

Fig. 3 Schematic figure of the experimental setup. Scheme presents the main zones in the conversion system and the main components in each zone

The air injection nozzle arrangement and their number differ in each grate step in order to supply as much air as possible according to requirements for each thermal transformation process that fuel particles undergoes during combustion over the grate (i.e., heating up, drying, devolatilization and char oxidation phases).

This burner is also designed with an automatic ash removal system (see Fig. 3, 3), which scrapes ashes and other combustion residues away from the second grate and moves them into the ash pit located inside the combustion chamber (see Fig. 3, 7). The ash pusher (on/off) working period (i.e., frequency and duration of the cleaning periods) can be adjusted according to the fuel properties' requirements during continuous operation of the conversion unit. It serves to both guarantee the required time for char combustion and avoid ash accumulation and severe slag and sintering occurrence over the grate.

Bed movement conditions on the grate are also linked to the primary air adjustments. In this manner, an adequate control of the ash pusher working periods and air condition contributes to enhance air–fuel contact over the grate, according to the fuel ash properties under a continuous operation mode of the conversion unit.

In order to facilitate complete mixing, as far as possible, between the air and volatilized matter released from the fuel bed on the grate, secondary air is distributed into the combustion chamber through several nozzles located in a surrounding channel above the grate (see Fig. 3, 6), where secondary air is partially preheated by heat transferred to the boiler walls. Flow adjustments carried out on primary and secondary airs are separately controlled by using frequency meters.

Besides the boiler walls in the combustion chamber, the integrated heat exchanger (see Fig. 3, III and IV) is also water jacketed. Shedding of fly ash deposited on heat exchanging surfaces is also possible as a result of the movement of the automatically controlled up/down turbulators, which are located in the second heat exchanger zone (see Fig. 3, 8). They also contribute to increase the flue gas turbulence and, therefore, the heat transfer rate into the system. Finally, in order to control the amount of air supply and flue gas residence time during their path in the system, the force draught is automatically regulated by a fan equipped with a frequency meter (see Fig. 3, 9).

Temperature was continuously monitored at different locations in the system to gain information about the thermal profile of the unit during combustion. Measuring instruments were placed in the vicinity of the burner grates, in the flue gas channel and in the water steps. Two K-type thermocouples were located at the upper zone of the secondary grate (T_1 and T_2, approximately 24 cm above the longer grate) and other two at the proximity (T_3 and T_4, approximately 6 cm above the longer grate), and three more (T_5, T_6 and T_7) at different positions in the flue gas path through the heat exchanger (see Fig. 3). Three PT 100 were provided, one positioned in the water-in step (T_8) and at two positions in the water-out step (T_9 and T_{10}) (see Fig. 3).

2.3 Combustion Tests in the 250 kW_{th} Spanish Fixed-Grate Technology

As part of the experimental test campaigns, two different type of combustion tests were performed to each fuel, i.e., preliminary and reproducibility tests.

Firstly, preliminary combustion tests were performed to adjust operation conditions to requirements of each fuel. Basically, under the fixed design characteristics of the novel grate technology, adjustments were addressed on four specific combustion parameters: load input, lambda factor, air distribution and pusher working period. The screw feeding frequency used to regulate load input, the working period of the ash pusher for adjusting residence time and air–fuel contact on the grate, the excess air flow as means of lambda factor and the primary/secondary air distribution as means of lambda distribution were considered as the main parameters to be controlled.

Tested conditions were established seeking an output as closer as possible to the nominal value, and for the best performance of the system with regard to unburnt matter (i.e., loss of ignition matter in solid residue and gaseous unburnt quantified as CO concentration), and thermal efficiency. In these tests, combustion quality was defined in terms of CO concentration in flue gases and thermal efficiency. European limits established to standardized high quality woody biofuels by the European standard EN 303-5:1999, and the more restrictive Austrian limits defined by the agreement according to Art.15a B-VG were considered to assess combustion quality obtained during the tests.

In addition, the four combustion parameters aforementioned were also adjusted to avoid the total saturation of the burner section in short test periods by severe sintering and slagging formation over the grate working at as far as possible load input. Nevertheless, main portion of the residues was clearly fused ash to large blocks (see Fig. 4). A more detailed explanation concerning criteria considered to define the operation adjustments carried out to the system can be found elsewhere [19, 20].

Secondly, reproducibility tests were carried out at the selected operating conditions by the preliminary tests. Data was collected for further calculation of combustion performance parameters after a steady-state regime was reached at the fixed operating conditions determined by the preliminary experiments. The concentrations of O_2, CO and NO within the exhaust gas were continuously measured with electrochemical sensors (Flue gas analyzer Testo 350XL), just after the second heat exchanger exit, during all the tests. CO and NO_X concentrations estimated as mg/Nm^3 were normalized at 10 % oxygen in the dry flue gas (d.g.) and their specific emission values were calculated in relation to the energy input in fuels. NO_X emissions were quantified as NO_2 equivalents to be compared to standards limits proposed by the Austrian restriction to other standardized fuels than woody pellets. The European standard EN 303-5:1999 suggests measurement of NO_X emissions although no limits are defined for them yet [14].

After each experiment, solid residues, which remained on the burner grates, and the ones scraped by the pusher into the ash pit were collected. Sintering degree in

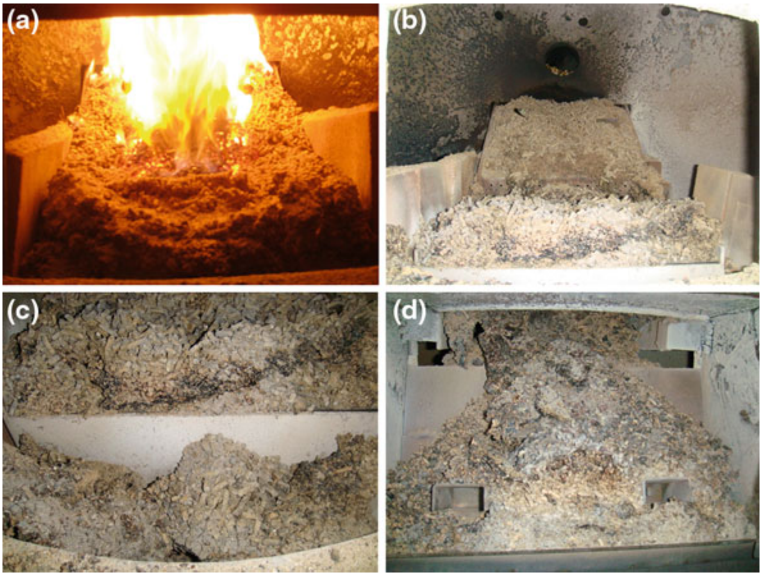

Fig. 4 Bottom Ash accumulated on the grates after brassica combustion experiments

the collected samples was assessed both through visual inspection and by a simple strength test. Unburnt content in solid combustion residues was determined as the difference between 100 % and the ash content obtained from a representative sample of the gathered bottom ash heated at 550 °C according to the standardized method CEN/TS 14775:2004 [21].

2.4 Sampling of Residual Bottom Ash and Sintering Degree Assessment

After each experiment, the solid combustion residues, which remained on the burner grates, and the ones scraped by the pusher into the ash pit were gathered. Sintering degree in the collected samples was assessed both through visual inspection and by a simple strength test.

2.5 Experimental Results During Brassica and Poplar Conversion

Generally, combustion conditions were controlled and relatively stable for each fuel. A summary of results obtained for the four assessed combustion parameters (i.e., load input, lambda factor, air distribution and pusher working period), during the best condition identified to each fuel is presented in Table 2.

Table 2 Operation parameters attained to each fuel maximum load during best condition at stationary combustion phase

Parameter		Poplar	Brassica
Load input	kW_{th}	257	174
Useful output	kW_{th}	230	157
Pusher on (duration)/off (frequency) working period	Adim.	4/100	5/50
Primary lambda	Adim.	0.95 ± 0.01	1.47 ± 0.03
Total lambda, λT	Adim.	1.93 ± 0.09	2.07 ± 0.13

As seen, significant differences with respect to the four selected operating parameters were identified between the crops to manage the fuel properties under the fixed design conditions of the 250 kW_{th} technology tested in this work.

Load input was eventually lowered to the herbaceous compared to the woody crop, up to around 37 % less than the nominal output. This condition was selected as a first measure to control saturation of the burner grates by bottom ashes. Nevertheless, a higher ash removal was also needed to cope with the brassica ash characteristics (total amount of residues and sintering tendency) despite the lower load input used. In general, around 30 % for poplar and up to 50 % for brassica of in-going ash was estimated to be retained as bottom ash inside the burner section and was characterised by a severe slagging degree.

Both frequency and duration of the pusher movements were significantly increased for the herbaceous, up to around 50 % the values applied to poplar. Ash removal adjustments were limited by the carbon burnout control for high combustion quality (i.e., loss of ignition matter was less than 0.01 kg/kg solid residue, d.b.). Because of this condition, partial saturation of the grates could not be avoided. As a result, primary air requirements increased for the herbaceous to minimize the reduction of an effective oxidizer-fuel contact by the ash condition on the grates (quality and quantity).

Concerning combustion quality (CO emissions and thermal efficiency), it was generally according to the Austrian requirements (limits defined by the European norm EN 303-5 are less restrictive). Evolution curves for CO specific emissions and for thermal efficiency at T_7 (temperature in the flue gas at the exit of the conversion system) during all the tested period at maximum load attainable for each fuel are showed in Fig. 5. Comparison of results during the best condition reached to each fuel is presented in Table 3.

Considering Fig. 5, stability of CO emissions and opening degree of the curves were different for the two energy crops. This condition might indicate the higher sensibility of the system during conversion of brassica. As it has been suggested in literature, fuel combustibility is affected by fuel properties, such as ash content and V/CF ration [23–27]. Based on the fuel composition comparison (see Table 1), brassica exhibited the worst fuel quality with regards to these two parameters.

As previously mentioned, ash accumulation on the grates minimizes an effective air to fuel contact. Furthermore, a lower V/CF ratio negatively impacts fuel combustibility. To increase conversion rates of unburnt species, additional air is

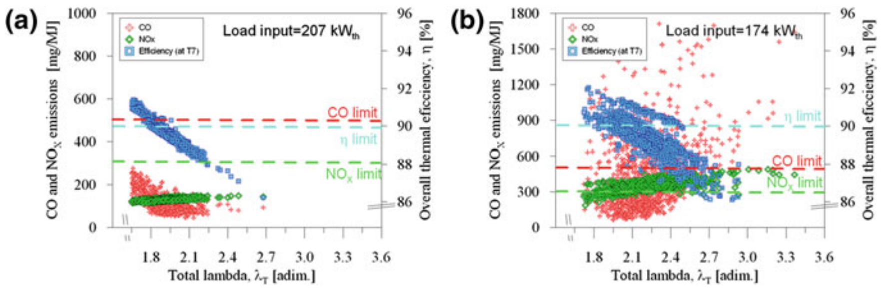

Fig. 5 Evolution curves for CO and NO_X specific emissions and for thermal efficiency at T_7 (temperature in the flue gas at the exit of the conversion system) with regards total lambda factor during all test period at maximum load attainable to each fuel. Limits corresponds to requirements defined by the Austrian law art. 15a B-VG 1994 to CO emissions for high quality stemwood assortments and to NO_X emissions for standardized fuels other than high quality woody biomass [22]

Table 3 Thermal efficiency, gaseous emissions and temperature in the exhaust gases attained to each fuel maximum load during best condition at stationary combustion phase

Parameter		Poplar	Brassica
Oxygen content	O_2 vol % d.g.	10 ± 1	11 ± 1
CO concentration	mg/Nm^3 at 10 % O_2	186 ± 32	285 ± 96
CO concentration	mg/MJ	91 ± 15	138 ± 47
NO_X concentration	mg/MJ	130 ± 3	326 ± 18
Thermal efficiency at T_7	%	89.7 ± 0.4	89.5 ± 0.6
Thermal efficiency at 120 °C	%	92.3 ± 0.4	92.1 ± 0.4
Temperature in the exhaust gases, T_7	°C	155 ± 1	164 ± 1

needed. Consequently, for this fuel, higher amounts of excess air distributed as primary air were demanded (see Table 1). This suggests that the residual ash negatively influenced the combustion performance of the system. The higher the bottom ash amount, the lower the fuel combustibility because of the worsening of air to fuel contact on the grate being necessary to add more primary air to increase combustion rates. Similar effect has been also suggested in literature for several types of ash-rich fuels [23–27]. Nevertheless, an increase of combustion rates has the knock-on effect of increasing slagging occurrence during combustion of the fuels with remarkable ash sintering tendency as brassica (temperature profile in the system was between 850 and 1100 °C). If the fuel ashes exhibit a high sintering tendency, considerably residence time on the high temperature zone subsequently results into their melting. This effect was partially controlled by the ash pusher because of burnout control needs as mentioned previously.

As showed in Table 3, gaseous emissions and thermal efficiency were under the Austrian requirements for the best condition defined by the combustion parameters presented in Table 2 (see also Fig. 5).

Based on data for the best condition attainable to each fuel (see Table 3), CO emission level fulfilled the European norm EN 303-5 requirements set at 1,200 mg/Nm^3 at 10 % O_2 d.g. to the strictest class in terms of thermal efficiency (class 3) for combustion of standardized high quality woody pellets in boilers of nominal output <300 kW_{th}. Results also fulfilled the Austrian limits set at 500 mg/MJ for other standardized non-woody biofuels based on bark, straw, cereals and mixtures (agripellets) fired in automatically boilers up to 400 kW_{th} (CO limit values increase up to 750 mg/MJ at partial load, 30 % nominal heat output) [22].

Thermal efficiency was also according to the EN 303-5 requirements, set at 81 %, and the Austrian limit, set at 90 %.

Under these combustion conditions, NO_X emissions were acceptable and according to the N content in fuels. It has to be considered that the Austrian limit is proposed to other standardized fuels than woody pellets with a nitrogen content $\leq$0.7 wt % d.b [22], which is 60 % lower than nitrogen content found to the herbaceous crop tested in this work. Main differences between the fuels are related to the NO_X formation mechanism. During biomass combustion for heating application, NO_X emissions are mainly formed by oxidation of nitrogen chemically bound in the fuel matrix. Additional NO_X formation routes, such as thermal and prompt NO_X mechanisms, are suggested to have a lesser significant contribution because of temperature profile typically found to biomass heating units [28]. Based on these considerations, NO_X formation during commercial scale combustion has been directly linked to nitrogen content in fuel, although, implemented air conditions, i.e., amount of air supply and distribution can also influence conversion of fuel nitrogen.

3 Future Research Needs Focused on Commercial Heating Application of Energy Crops in the Spanish Bioenergy Market

Taking into account the current conversion unit design and also results from the combustion experiences with the pelletized energy crops presented here, further research lines are identified towards the commercial heating application of this novel fuel type into the Spanish bioenergy market.

In contrast to stemwood based assortments, energy crops are generally more troublesome fuels owing to their higher ash composition and concentration of ash forming and trace elements. A lower thermal efficiency, undesired emissions and unscheduled shut down to required maintenance are counted as the main ash effects. Consequently, combustion technologies should be adapted to manage the energy crop properties not only to provide working periods at high thermal efficiency to the users but also to fulfill European restrictions that have been established to control air pollutants emitted by the heating sector.

Because of significant differences may exist among fuel properties of standardized sources and novel energy crops, established level of emission pollutants might imply one drawback for the crops but also a driving force for research and development. As a first step, specific knowledge of the novel energy crop properties and influence of both design features and operation conditions on their environmental behavior is needed. Consequently, experiences with other dedicated crops are required to gaining a more general knowledge about characteristics of this biofuel type and their specific conversion needs.

Secondly, research efforts have to be addressed on strategies to control or minimize main drawbacks of the novel fuels in terms of possible impacts on design and operation of the existing conversion technologies in the heating market. Based on results obtained to the two crops assessed in this work, brassica and poplar, limitations of the current system design features to manage the ash properties might prevent to burnt fuels with high sintering tendency and high N content.

In addition, control of pollutants resulting from their combustion may adversely impact on the overall conversion system performance. For instance, control of the CO and NO_X followed opposite trends under tested conditions for poplar and brassica being required a trade-off between their emission levels to attain combustion according to the European requirements. Although Fuel-N converted to NO_X greatly depends on N content in fuels, nitrogen oxidation level also increased because of lambda factors used to favor the complete burnout. Based on these conditions, a more detailed study on the air distribution system, regarding the total number of air injection nozzles, their dimensions and their arrangement, can be necessary.

Computational fluid dynamics (CFD) studies may help to provide knowledge about each thermal transformation process which fuel particle undergoes during its path in the combustion unit and, therefore, to improve understanding of the process going on the system. In addition, accordingly to the current state of the technology developed as part of the "PSE On Cultivos" R&D&I framework and results presented in this work, CFD research might have useful contributions to technologic developments. Improvements of the burner and combustion chamber design features (geometries and the air supply system) as well as application of measures, such as flue gas recirculation, might serve as a good option to reduce emissions and to control bed temperature, and hence, sintering occurrence on the grates. It seems that there are two spaces of the Spanish conversion technology to the complexity of the novel fuels are still possible.

On the other hand, an increasing interest on the utilization of biomass fuels in the heating sector may contribute to hugely increase aerosols emissions to air affecting ambient air quality. Exposure to particulate matter, especially fine particulate mode ($PM < 2.5$ μm), is associated with a wide range of diseases, including respiratory infection, lung cancer and bronchus [28–30]. In addition, particulate matter also impacts global climate change. Therefore, sources of these kind of emissions and factors that contribute to their formation have to be controlled. Minimization of these pollutants can be reached by optimization of operation conditions (primary measures), and by incorporation of special equipments (secondary measures), such as filtering systems adapted to the conversion unit, may be an option to fulfil environmental requirements. This kind of study has not been considered in the present work mainly due to this type of research was out of scope in the "PSE On Cultivos" R&D&I framework. However, it is a clear research line that is going to be studied in the framework of projects that are currently being developed in Spain in order to guarantee a sustainable energy crop thermal conversion.

On the other hand, standards are also required to minimize uncertainties related to comparison of raw materials properties from different laboratory data or different producers. There is a greater need for standardized engineering practice in the sampling and analysis of biofuels, as well as in the interpretation of analytical data for biomass fuels. Some protocols have been defined to provide a common basis for analysis. However, due to the huge diversity of biomass sources they are still incomplete with respect to the definition of property evaluations that can or should be applied for each biomass type.

Limiting values presented in standards included here have been developed based on biofuels used traditionally such as stemwood based assortments. Therefore, special attention should be paid to emissions and the risk of deposit effects (for instance, slagging and corrosion inside the boiler) when more troublesome fuels, such as the dedicated energy crops assessed here are combusted.

In many European countries there are neither national quality standards nor good practice guidelines. The reasons of this situation are several, for instance, few raw material available, competitive price of gas natural or inexistent pellets market. In Spain, the National Technical Standardisation Committee on Solid Biofuels (AEN/CTN 164) is working on developing standards for novel opportunity fuels. Considering all aforementioned issues presented here, a sustainable utilization of the novel biofuels may be carried out with high efficiency, low costs and low environmental impacts.

4 Summary and Conclusions

Although still are some questions that have to be solved related to energy crops global sustainability or to their impacts to other markets, energy crops are expected to increase bioenergy contribution in the energy market, especially in areas where other type of less problematic and even less controversial fuels as residual biofuels are not available.

One of sectors in which energy crops production is more interesting is the heating sector since the availability of the usual biofuels employed in this sector (generally stemwood based assortments) seems that is not going to be enough to satisfy the increasing demand and also because the profitability that this market can offer to the whole crop chain is better than the one that other alternatives do. Nevertheless, the thermochemical conversion of these novel fuels shows some drawbacks that have to be overcome before achieving their final introduction in the market. Fuel quality is foreseen as a critical parameter.

Compared to the traditionally used stemwood assortments, conversion of these troublesome fuels might undergo some limitations, in terms of specific design features and operation conditions requirements of the system to attain high quality combustion. A higher tendency to cause ash-related effects, for instance, slagging, fouling and/or corrosion effects as well as undesired particulate emissions is expected from their thermochemical conversion. In this sense, combustion units have to be designed taking into account existing differences that exist among traditional fuels and energy crops, mainly related to their composition and impurities that can accompany them in order to guarantee both efficient thermal performance and low emissions.

Within the framework of the "PSE On Cultivos" R&D&I Spanish project, efforts have been addressed to gain knowledge related to the aforementioned issues. Two energy crops one herbaceous, Brassica carinata, and one short rotation coppice, Populus sp., were selected and their combustion performance assessed in a novel medium scale fixed-grate combustion technology (250 kW_{th}) adapted to the two representative energy crops. In this research, special emphasis has been placed on the assessment of adaptability level of a Spanish combustion technology to cope with the fuel complexity.

Main differences between the two crops properties are not only attributed to results by the proximate and ultimate analyses but also due to the characteristics they exhibit in terms of the ash composition. A higher ash content and sintering tendency among fuels lead to lowering the load input. Nevertheless, a reasonably high load was achieved to the ash-rich energy crops. It corresponded to a load input between 20 and 30 % lower than maximum mean value obtained to the system.

During the fuel conversion, it seems that fuel properties such as ash content and V/CF ration influenced the combustibility of the fuels. Consequently, besides changes on load and pusher working period, air adjustments were also required to achieve good combustion quality during the energy crop conversion.

Concerning air supply, higher amounts of primary air were needed not only to improve combustion quality when ash content and sintering degree tendency increased among the tested fuels because of air passing were blocked, but also to satisfactory convert char proportion in these fuels limiting NO_X emission reduction based on air staging strategies, i.e., non-substoichiometric conditions were kept in the grate area. Nevertheless, NO_X emission level was under the Austrian requirements.

Deviation for brassica was greatly influenced by the Fuel-N content. Although Fuel-N converted to NO_X greatly depends on N content in fuels, nitrogen oxidation level also increased because of lambda factors used to favor the complete gaseous burnout. Therefore, the control of the CO and NO_X opposite trends under tested conditions required a trade-off between their emission levels.

Based on an adequate regulation of these combustion parameters an acceptable level of emissions and thermal efficiency was attainable to each fuel according to requirements established by the European norm EN-303-5 and the Austrian agreement Art.15a B-VG. In general, differences among emissions level from fuels were basically dependent on fuel quality and limitation of the system to cope with the properties of the most troublesome fuel, the herbaceous one.

Considering these results, further improvements steps have been suggested involving design and operational issues of the 250 kW_{th} grate conversion unit. Due to the high variability level expected to the energy crops properties, experiences with other dedicated crops are required to gaining a more general knowledge about characteristics of this biofuel type and their specific conversion requirements.

The results that have been achieved allow to stating that when design and operation considerations are adapted to specific properties of energy crops, both high thermal efficiencies and low emissions (under regulations) will be reached. Although further improvements should be considered in the future, these results are another step on the road to sustainable energy crops pellets final penetration in the market. By attaining this goal, technological requirements to guarantee the energy crop thermochemical conversion in an efficient and cost-effective way can be also identified, and hence, ash-related problems faced by the novel biofuels combustion might be controlled or minimized.

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