Gasification as possible technological solution for driftwood management in bodies of waters

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Abstract. This work studies the possibility of the thermochemical conversion, through gasification, of wood waste that accumulates along river bodies. Thanks to the startup SEADS (Sea Defense Solutions), tree branches were collected from the Lamone river (province of Ravenna - IT) in various conservation states. The wood wastes were pre-treated through a chipping process to make them suitable for chemical/physical analyses and subsequent gasification process using the All Power Labs Power Pallet 30 (PP30) commercial micro-gasifier. The elemental analysis show how the wood material undergoes a certain chemical degradation due to weathering, which leads to an HHV of 18.76 MJ/kg, lower than virgin biomass. The gasification process was firstly simulated through a numerical method that gave positive outputs: syngas with a higher heating value of 4.61 MJ/kg and a gasification efficiency of 63.03%. A subsequent gasification test was used to validate the numerical model that was also used to estimate the electrical (18.91%) and thermal (25.21%) efficiency of a cogeneration power plant, powered by the PP30 gasification reactor.

1. Introduction

The deposit of driftwood in the course of rivers represents a significant problem as it can lead to the modification of the river path by increasing the erosion of the embankments and increasing the risk of flooding when these go to occlude the free passage under the span of the bridges [1,2].

The startup Sea Defense Solutions (SEADS) [3] has developed floating physical barriers that divert the path of river debris until they are conveyed to one or more collection points. The barriers have the ability to intercept materials with different densities, ranging from plastics to wood residues that frequently run through rivers following periods of floods.

The study stems from the desire of SEADS to investigate the possibility of exploiting the material, mainly wood, accumulated by the barriers. For this purpose, 50 kg of residues were collected from the Lamone river in the province of Ravenna (Italy), composed almost exclusively of woody biomass in a different state of conservation, and an experimental campaign was conducted to evaluate their thermochemical conversion through the process of gasification.

The woody biomass was first separated from the fraction of plastics present (< 1 %w/w), then shredded using a commercial wood chipper to reach a size compatible with the All Power Labs Power Pallet 30 (PP30) [4] micro scale gasification power plant used in this study. The chipped biomass was

sifted to eliminate the fine fraction <5 mm which would generate bridging and ash melting phenomena in the gasification reactor and analyses of moisture content, ash content and elemental composition were carried out on the biomass samples to calculate the higher heating value and evaluate the conservation state. Through a thermodynamic equilibrium model it was simulated the gasification process by identifying the higher heating value of the gas, the gasification efficiency, the tar content and it was also possible to simulate the overall electrical and thermal efficiency of a CHP (combined heat and power) power plant powered by the PP30 reactor and fed with the collected driftwood.

An experimental campaign was carried out using a modified version of the PP30 and the composition of the syngas produced was measured by means of a micro-GC to experimentally estimate the higher heating value of the syngas and the gasification efficiency validating the results of the numerical model.

A preliminary cost/benefit analysis was also carried out to estimate the economic feasibility of the gasification of drift-wood residues in a medium-scale gasification power plant.

2. Materials and Methods

This section describes the different phases of the analysis and testing process of the biomass under investigation.

2.1. Biomass pre-treatments

The gasification power plant PP30 used in this work can operate with woodchips with a maximum length of 30 mm and, for this reason, the "as-received" biomass was chipped using a Green Technik portable chipper model CIP800 (Figure 1) capable of shredding branches up to 60 mm in diameter.

Figure 1. Portable woodchipper Green Technik CIP800

Figure 2. Modified operating conditions

During chipping operation, a continuous and persistent clogging of the chipper was observed at the level of the discharge throat identified by point A of Figure 1. The phenomenon is probably attributable to two factors:

- The wood from river bodies is weakened by chemical/physical degradation and, part of it, tends to be reduced to dust or small flakes;

- its reduced density, combined with the reduced size of the flakes obtained, lower the momentum of the chips, often making the aerodynamic friction forces prevail and shorten the throw of the wood chipper.

This behavior forced the modification of the operating conditions of the machine (Figure 2), leading to the removal of the discharge conveyor (B in Figure 1) and the support feet, reducing the angle of discharge of the wood chips from expel.

The obtained wood chips were then subjected to sifting with a 5x5 mm mesh sieve to reduce the finer fraction, not suitable for gasification in the Power Pallet.

2.2. Biomass characterization

The characterization of the biomass takes place following 3 different steps: the water content of the material is investigated, the elementary analysis is obtained and the quantity of ash present is measured. The analysis of the water content of the biomass was obtained by heating each biomass sample in a stove for 24 hours at 105 ° C (method ASTM E1756 - 08 (2015)). The ash content of the different biomass samples was performed by calcination in an oven at 600 ° C for 6 hours (method ASTM E1755 - 01 (2015)) preceded by complete drying.

The elemental analysis was carried out using a CHSN-O analyzer that allows to calculate the carbon, hydrogen, nitrogen and sulfur content in the dried biomass. The oxygen content is calculated by difference, while the empirical equation of Channiwala and Parikh [5] (Eq. 1) is used to calculate the higher heating value (on a dry basis).

$$HHV_{biomass,db} = 349.1\,C + 1178.3\,H + 100.5\,S - 103.4\,O - 15.1\,N - 21.1\,ASH \quad (1)$$

2.3. Numerical simulation of the gasification process

The numerical model used to simulate the entire gasification process is adapted from [16,17,18] following the method reported by Jarungthammachote and Dutta [6]. The block diagram representing the functioning of the algorithm is shown in the Figure 3.

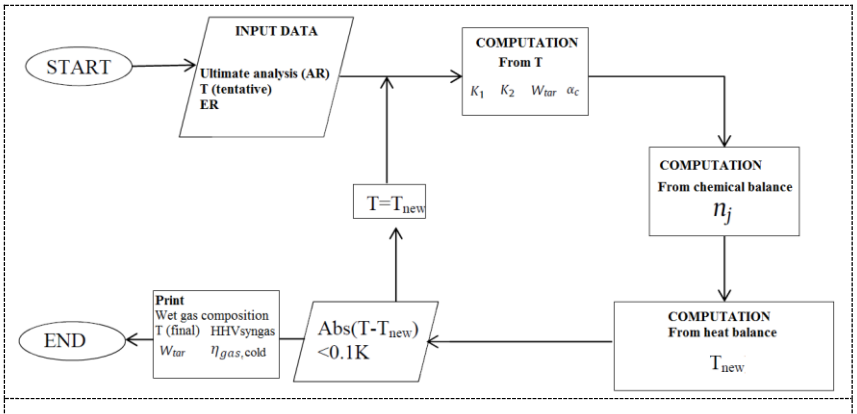

Figure 3. Solution algorithm,

The algorithm was implemented in Phyton™ software environment in order to estimate the following outputs:

- syngas molar composition x_i [% mol/mol];

- syngas higher heating value HHV_{syngas} [MJ/Nm^3] using Eq. 2 and considering the syngas as ideal gas;
- cold gas efficiency $\eta_{gas,cold}$ [%] using Eq. 3;
- tar volumetric production rate v_{tar} [g/Nm^3] using Eq. 4 considering the syngas as ideal gas.

$$HHV_{syngas} = x_{H_2} HHV_{H_2} + x_{CO} HHV_{CO} + x_{CH_4} HHV_{CH_4} \quad (2)$$

$$\eta_{gas,cold} = \frac{HHV_{syngas} v_{syngas}}{HHV_{bio} M_{bio}} \quad (3)$$

$$v_{tar} = \frac{n_{tar} M_{tar}}{v_{syngas}} \quad (4)$$

Through the cold gas efficiency and equations 5 and 6 it is also possible to estimate the overall electrical ($\eta_{el,ovr}$) and thermal ($\eta_{th,ovr}$) efficiency of a CHP power plant powered by the PP30 gasification reactor.

$$\eta_{el,ovr} = \eta_{gas,cold} * \eta_{el,CHP} \quad (5)$$

$$\eta_{th,ovr} = \eta_{gas,cold} * \eta_{th,CHP} \quad (6)$$

where $\eta_{el,CHP}$ and $\eta_{th,CHP}$ are respectively considered equal to 30% and 40% which are usual values for CHP powered by internal combustion engines.

2.4. Description of the gasification facility

To evaluate the gasification performance of the woody residues under investigation, the coarse fraction of the wood chips obtained from already dry branches was used to feed a full-scale commercial gasifier of 30 kg/h nominal biomass flowrate, which correspond approximately to a maximum syngas production of 75 Nm^3/h. The gasification plant used is the gas-making skid of the Power Pallet 30 biomass cogenerator (Figure 4) and is composed of a conical hopper (1) into which the biomass is manually loaded, a feed screw (2) controlled by a magnetic level sensor that automatically feeds the gasification reactor (3) in which the biomass is mainly converted into syngas and char. The char left over from incomplete combustion is discharged into a gastight container which can only be emptied at the end of the test. The syngas produced is conveyed to a cyclone separator (4), on the bottom of which the coarser fraction of the dust suspended in the gaseous stream is deposited. Once it leaves the cyclone, the syngas is directed to a torch where it is burned after being mixed with air (5).

Unlike the commercial version of the PP30, this prototype works under positive pressure and the gasifying agent (ambient air) is pumped into the reactor by means of a 230 VAC side channel blower as described in [7]. The gas cooling system [8] used to lower the syngas temperature and make it suitable for combustion in internal combustion engines [9], the filtration stage composed of polyester filter bags or char candles [10] and the engine for heat and power generation were not connected and used for this test.

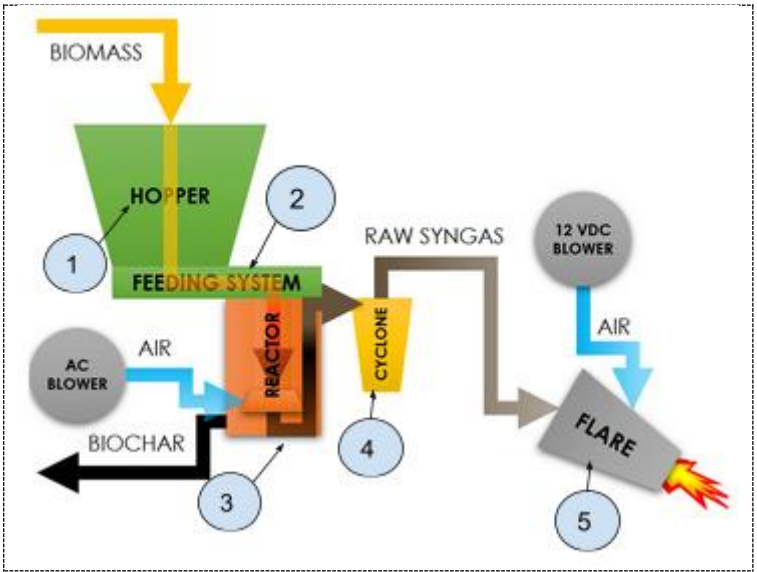

Figure 4. Operating scheme of the Power Pallet 30.

2.4.1. Gasification efficiency. The gasification efficiency is a parameter that indicates how much of the chemical energy contained in the starting biomass is transferred, again as chemical energy, in the syngas produced.

$$\eta_{gas,cold} = \frac{m'_{gas} \cdot HHV_{gas}}{m'_{bio} \cdot HHV_{bio}} \quad (7)$$

where m' indicates the mass flow rate of biomass (bio) and syngas produced (gas) while HHV are respectively the higher heating values of biomass (bio) and syngas (gas). Following the equation, during the efficiency test it is necessary to measure the amount of incoming biomass and the amount of gas generated at the same time. The heating value of the syngas was calculated by measuring its composition using the Pollution MicroGC gas chromatograph. The flowrate of syngas produced was calculated starting from the flowrate of combustion air entering the reactor, measured by means of a calibrated orifice meter. The correlation is shown in the equation below and is based on the conservation of nitrogen gas between the reactor inlet and outlet.

$$m'_{gas} = m'_{\text{air}} \cdot \frac{0.781}{x_{N2_{gas}}} \quad (8)$$

2.4.2. Syngas quality.

The measurement of the impurities contained in the syngas was conducted following a simplified version of the Tar Sampling Guideline [11] in which the gas is drawn from the operating power plant at a predetermined flow rate and sent to a series of impinge flasks containing acetone. The flasks, immersed in a water and glycol bath maintained at a temperature of about -15 ° C, collect the particulate matter, the condensation of water vapor and most of the tars contained in the syngas produced by the gasifier. At the end of the sampling, the acetone is filtered with Whatman 7 μm filters and distilled to separate the tars with a boiling point higher than acetone. The condensate is then dried in an oven at 105°C for 24 hours. Gravimetrically, the quantity of particulate matter and tars collected during sampling is

obtained, which divided by the volume of sampled gas returns the average value of impurities present in the syngas.

3. Results

3.1. Biomass pre-treatment

Three different biomass samples were chipped with the modified machine:

- 1_dry: obtained from the collection of dry branches along the river;
- 1_wet: obtained by immersing some dry branches in water before chipping for about 30 minutes;
- 2_wet: branches collected from the river and chipped still wet.

Figures 5 a, b and c show the images of the wood chips obtained from the three qualities mentioned above.

1_dry	1_wet	2_wet

Figure 5. Woodchips samples.

All the biomass samples were successfully chipped but only the 1_dry was selected for the subsequent sifting process, due to the larger available quantity. The sifting process led to the separation of the coarse part of the woodchips that represent the 38% w/w of the total, while the finer part (< 5 mm) is the remaining 62 % w/w. In Figure 6 a picture of the coarse and fine samples is shown.

1_dry	1_dry - coarse	1_dry - fine

Figure 6. Result of the sifting process.

3.2. Biomass characterization

Table 1 shows the moisture values of the different biomass samples following the same nomenclature used in the previous paragraph. The water content is expressed as a mass / mass ratio on a wet basis, i.e. 1 kg of wood chips as it is at 8.9% humidity contains 0.089 kg of water.

Table 1. water content of the different biomass samples

Sample	Moisture %wt_wb
1_dry	8.9%
1_dry – fine	9.2%
1_dry – coarse	9.8%
1_wet	20.6%
2_wet	43.8%

The moisture content of the sample 1_dry was found to be suitable for gasification tests without the need for further drying treatments, showing how the natural drying process could be sufficient for the purpose of energy conversion. The difference between the fine and coarse fractions is mainly due to the inhomogeneity of the chipped material rather than to the size analyzed. The sample 1_wet, immersed in water for about 30 minutes before chipping, has double humidity compared to its non-immersed counterpart (1_dry) and can be critical for most gasification plants on the market that often accept wood chips with humidity <10%. This qualitative test indicates how the absorption of water by the dry branches collected at the river's edge is quite sudden, although probably localized to the outermost portions of the branches. It is also advisable to evaluate the natural drying process following this treatment in order to decide the type of storage of the harvested material. The wood collected from the river and still wet (2_wet) have a moisture content very close to that of the fresh cut wood (which can reach up to 60%). This material must be necessarily dried before its thermochemical conversion through combustion or gasification. Table 2 shows the ash content of the different biomass samples.

Table 2. Ash content of the different biomass samples

Sample	Ash %wt
1_dry	1.3%
1_dry – fine	1.9%
1_dry – coarse	7.5%

The ash content of the wood chips as it is and of the coarse fraction would seem low enough to make the biomass suitable for thermochemical conversion processes. However, it should be noted the high ash content of the fine fraction, which could negatively affect the conversion processes increasing the risk of producing ash melting phenomena in the hottest areas of the gasification reactor. For this reason and due to the inhomogeneity of the samples analyzed, it is precautionary to consider only the coarse fraction of the wood chips suitable for gasification with the Power Pallet 30. Table 3 shows the result of the elemental analysis carried out on the woodchips suitable for the gasification process in the Power Pallet 30.

The values of the higher heating value are slightly below the literature references for biomass from conifers or broad-leaved trees, which on average are between 19 and 21 MJ / kg. In particular, the carbon value is on average 5 percentage points lower than the data available in the literature, suggesting a possible degradation of the material due to its conservation in an unprotected environment.

Table 3. Elemental analyses of the as received (1_dry) and coarse fraction of the woodchips

Sample	N_{db} [%]	C_{db} [%]	H_{db} [%]	S_{db} [%]	HHV_{db} [MJ/kg]
1_dry	0.36	45.25	6.07	0	18.07
1_dry – coarse	0.38	45.95	6.33	0	18.76

3.3. Output of the numerical model

The results of the model for the gasification of the sample *1_dry – coarse* are shown in Table 4. In the calculations, a value of ER = 0.3 typical of fixed bed gasifiers was set, a first attempt temperature of 900 K, an electrical efficiency of the cogenerator of 30 % and a thermal efficiency of the cogenerator of 40% were used.

Table 4. Outputs of the numerical model.

Average reaction temperature	1062	[°C]
Percentage of H_2 in the syngas	16.56	[% vol.]
Percentage of H_2O in the syngas	15.73	[% vol.]
Percentage of CO in the syngas	19.78	[% vol.]
Percentage of CO_2 in the syngas	8.79	[% vol.]
Percentage of CH_4 in the syngas	0.016	[% vol.]
Percentage of N_2 in the syngas	39.11	[% vol.]
HHV of the syngas	4.614	[MJ/kg]
Cold gas efficiency $\eta_{gas,cold}$	63.03	[%]
Tar content v_{tar}	7.29	[g/Nm^3]

The calculated electrical and thermal overall efficiency of a biomass cogeneration plant fed with such residues resulted respectively 18.91 % and 25.21 %.

3.4. Gasification test results

In this section the results of the efficiency calculation and syngas quality measured during the gasification test with the *1_dry – coarse* biomass sample are shown.

3.4.1. Gasification efficiency

The results of the gas chromatography and the calculation of the higher heating value are shown in Table 5.

Table 5. Syngas composition. Concentration in mol/mol.

	CO_2	CO	N_2	CH_4	H_2	O_2	HHV [MJ Nm^{-3}]
Sampling 1	11.0%	17.4%	46.1%	2.9%	12.3%	3.8%	
Sampling 2	8.6%	19.0%	47.5%	2.0%	11.9%	3.6%	
Average value @ 0% O_2	**11.9%**	**22.1%**	**40.0%**	**3.0%**	**14.7%**	**0%**	**5.86**

The gasification test was conducted with an average biomass flow rate equal to 9.8 kg/h which generated an average syngas flow rate equal to 18.7 Nm^3/h. The resulting average efficiency was 61.4%, in line with the analytical model. In Figure 8 is reported the test setup.

Figure 7. PP30 prototype during the gasification efficiency test.

3.4.2. Syngas quality.

Table 6 shows the particulate matter and tar content of the syngas generated during the gasification test. The values are not suitable for a direct use of the gas in internal combustion engines which require a maximum content of tar of 30 mg/Nm^3 and a maximum content of particulate matter between 50 and 100 mg/Nm^3 [12]. In particular, tars can condensate over the mechanical components of the engine (e.g. throttle body, intake valves …) and block their movement [13,14,15].

Table 6. ash content of the different biomass samples	
Particulate matter (> 7 μm)	0.452 g/Nm^3
Tars	6.491 g/Nm^3

A gas clean-up system is then required for power generation purpose.

3.5. Cost/benefit analysis of a medium-scale gasification power plant

From the simulations and experimental tests, the preliminary economic analysis was carried out for the evaluation of the feasibility of a 200 kW_e (the upper limit for downdraft-type gasifiers [20,21]) gasification power plant powered wood chips collected from river bodies. The scenario considered the co-production of 400kW_{th} of thermal power deriving from the recovery of heat from the engine cooling system and from the exhaust gases. The analysis carried out considers to self-consume all the electricity produced, while, for the share of thermal energy, it was considered to use 50% for drying the biomass and the remaining 50% was considered to be self-consumed. It was also considered to operate the plant for 6000 hours/year in order to take into account the downtime for maintenance. The cost of the system (CAPEX) was estimated at 5000 €/kW while the operating costs (OPEX) were assumed to be 0.05 €/kWh [22]. The remaining parameters are summarized in Table 7 and the graph in Figure 8 shows the trend of the net present value on a monthly basis for 20 years. A sensitivity analysis was conducted on the price of electricity and heat; data susceptible to even significant variations. Table 8 shows the payback time calculated as the cost of electricity and heat changes.

Table 7. Input and output data of the economic analysis.

Input		
Electrical power output	200	kW
Thermal power output	400	kW
Hours of operation per year	6000	hours/year
Cost of the electrical energy	0.2	€/kWh
Cost of the thermal energy	0.069	€/kWh
Cost of the biomass fuel	0.03	€/kg
Biomass consumption	1	kg/kWh
Capital expenditure per unit of power	5000	€/kW
Operational expenditure per unit of energy	0.05	€/kWh
Site operation and maintenance cost	30000	€/year
Output		
Annual electricity production	1200000	kWh/year
Annual heat production	2400000	kWh/year
Revenues from electrical energy	240000	€/year
Revenues from thermal energy	82800	€/year
Biomass consumption per year	1200000	kg/year
Biomass cost per year	36000	€/year
Operational expenditure per year	90000	€/year
Capital expenditure	1000000	€

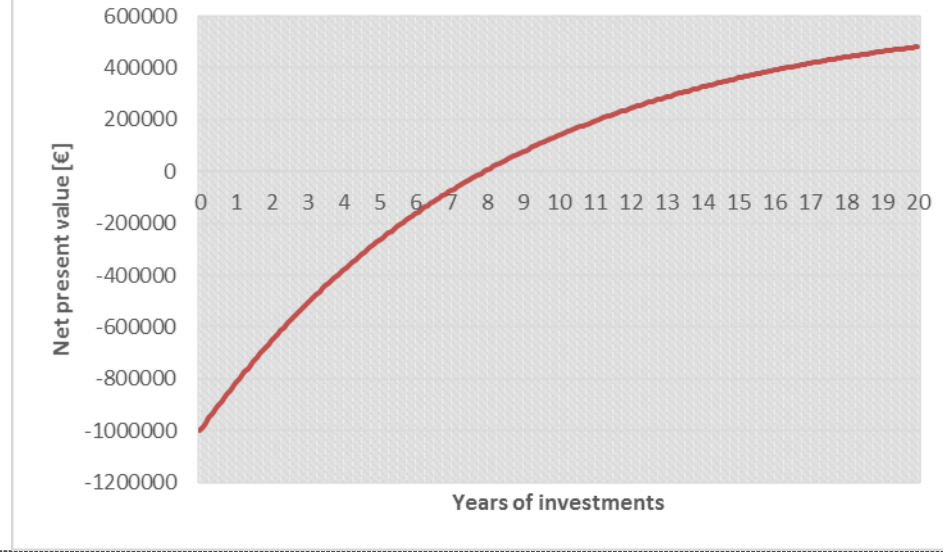

Figure 8. Net present value of the 200 kW power plant considered in the baseline scenario.

Table 8. Sensitivity analysis on the variation of the energy price for the electrical and thermal outputs. The table shows the years necessary for the return on investment. The baseline scenario is highlighted in green and corresponds to a payback time of 8 years.

		Thermal energy cost [€/kWh]										
		0.035	**0.041**	**0.048**	**0.055**	**0.062**	**0.069**	**0.076**	**0.083**	**0.090**	**0.097**	**0.104**
Electrical energy cost [€/kWh]	**0.10**	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D
	0.12	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D	19.4	15.8
	0.14	#N/D	#N/D	#N/D	#N/D	#N/D	#N/D	19.9	16.1	13.8	12.1	10.8
	0.16	#N/D	#N/D	#N/D	#N/D	16.4	13.9	12.3	10.9	9.9	9.1	8.4
	0.18	#N/D	16.8	14.2	12.4	11.1	10.0	9.2	8.5	7.9	7.4	6.9
	0.20	12.6	11.2	10.2	9.3	8.6	8.0	7.4	7.0	6.6	6.3	5.9
	0.22	9.3	8.7	8.0	7.5	7.0	6.7	6.3	6.0	5.7	5.4	5.2
	0.24	7.5	7.1	6.7	6.3	6.0	5.7	5.4	5.2	5.0	4.8	4.6
	0.26	6.3	6.0	5.8	5.5	5.3	5.0	4.8	4.6	4.4	4.3	4.2
	0.28	5.5	5.3	5.0	4.8	4.7	4.5	4.3	4.2	4.0	3.9	3.8
	0.30	4.8	4.7	4.5	4.3	4.2	4.0	3.9	3.8	3.7	3.6	3.5

4. Conclusions

The work demonstrates how it is technically possible to recover the residual biomass that is deposited along the river bodies for energy purposes following a gasification process. Analyses of moisture content, ash content and elemental composition of the biomass returned a higher heating value of 18.76 MJ/kg_{db} slightly lower if compared to the values of virgin conifers and broad-leaved trees (19-21

MJ/kg_{db}). What has been noted from the analyses is a loss of 5% of the carbon content compared to reference value of well-preserved biomass, which confirms the partial degradation of the wood residues due to weathering.

Through a thermodynamic equilibrium model it was possible to simulate the gasification process calculating the higher heating value of the gas (4.614 MJ/kg), the estimated gasification efficiency (63.03 %) and the electrical (18.91 %) and thermal (25.21 %) overall efficiency of a biomass cogeneration plant fed with such residues. Through an experimental campaign with the PP30 the composition of the syngas produced was measured by means of a micro-GC to experimentally estimate the higher heating value of the syngas (4.51 MJ/kg), confirming the result of the numerical method. The average gasification efficiency measured in the experimental campaign was 61.4% and it validates the overall performance of the CHP power plant simulated in the numerical model. The economic analysis conducted on a $200kW_e$ plant provided payback times in line with other renewable energy plants. The scenarios analyzed as the price of energy changes suggest payback times that can be reduced to just over 3 years considering a 50% increase in the price of energy compared to the considered baseline. Further advantages could lie in the commercialization of the biochar that is naturally produced by the gasification plant: a material which is increasingly conquering market shares in the world of carbon credits.

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