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Electricity from wood: a wood quality and energy efficiency approach to small scale pyro-gasification

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Abstract

The global demand for renewable energy in the last years is facing innovations like the co-generation of electricity and heat from wooden industrial residues and biomass. Wood gasification is a very promising technique for conversion of wood chemical energy into thermal energy and into electricity. A new generation of small scale, moderately priced and easy to install pyro-gasification plants became available on the market, being an opportunity for the SMEs. These systems are also characterized by a remarkable operational easiness and great versatility in the type of used biomass, which can range from industrial residues (sawdust, wood chips...) to biomass of forestry and non-forestry origin. This study performed an extensive testing of a small size pyro-gasification plant capable of producing 30 kW of electricity and 30 kW of thermal energy, both net to enter in the network of GSE (Energy Services Manager) via the feed-in tariff and in a small district heating network or other uses. The process of pyro-gasification is analyzed in its entirety by a characterization of input biomass, pyro-gasification process monitoring, analysis of the quality of the produced syngas, characterization of residues due to the process (washing water smoke, charcoal...) and verification of the total efficiency. The electric efficiency of the system, from hardwood to syngas to electricity is quantified in being 12 %.

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*Keywords:*wood quality; biomass; pyro-gasification; syngas; emissions; efficiency; VOC.

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1. Introduction

The global demand for renewable energy in the last years is facing innovations like the co-generation of electricity and heat from wooden industrial residues and biomass. Wood combustion and gasification are the main processes of converting the wood chemical energy into thermal energy (Proto, Zimbalatti, Abenavoli, Bernardi & Benalia, 2014). There are many differences among the two processes, in particular in terms of complexity of the technologies used, efficiency, volatile emissions and impact on ecosystems (Zimbalatti & Proto, 2009; Proto & Zimbalatti, 2015). For both processes the generation of electricity is readily feasible, and the electrical energy can be used for both on site (off-grid) or on-grid consumption(Moneti, Delfanti, Marucci, Bedini, Gambella, Proto & Gallucci, 2015). In the last few years small-scale pyro-gasification plants have become available on the market. These systems are moderately priced, readily available and distinguished by a remarkable ease of use and maintenance and a great versatility in the type of biomass power, which can range from wood chips to refuse-derived fuel (from municipal solid waste) as well as manure from livestock (Bhattacharya, Mizanur Rahman Siddique & Hoang-Luong Pham, 2009; Dornburg & Faaij 2001; Bridgwater et al., 2002; Senneca, 2007).Gasification shows interesting advantages versus other technologies (Bridgwater et al., 2002, Quaak et al., 1999, Basu, 2006), particularly related to the urban-forest or urban-rural contexts, where coexist both the availability of biomass and the energy need. This paper summarizes the research of experimental monitoring on a small-scale pyro-gasification plant, producing up to 30 kW of electrical power and 30 kW of thermal energy. The plant accepts a wide variety of biomasses, being tolerant with low-quality (dusty, wet...) biomasses. The plant was located in the province of Modena – Italy, and the analysis were conducted in the years 2013 and 2014 for a total of 5 measurements sessions lasted about 4 hours each. The engine is equipped with anexhaust gas heat exchanger; the planttotal heat recovery is fair, compared to other systems. This is motivated by a precise business strategy of reducing plant costs by under-exploiting the thermal energy. Heat was used for residential purposes, while the electrical energy was provided to the national enterprise “GSE” (Energy Services Manager). The whole pyro-gasification process was analyzed thorough the characterization of biomass inputs, thorough the real-time syngas monitoring and analysis, together with the control of volatile emissions, the characterization of waste products (washing water fumes, charcoal ...) and the electrical efficiency (Mathieu & Dubuisson, 2002;Puig-Arnavat, Joan Carles& Coronas, 2010; Jenkins, Baxter, Miles Jr, & Miles, 1998).

2. Materials and methods

2.1. Moisture content of biomass and biochar

The moisture content of the input biomass (fir and chestnut wood chips, straw, other agricultural-based fuels such as manure) and the by-product biochar were measured following the European Norm (EN) test method EN 14774-2: 2005: drying in an oven at 105 ° C (± 2 ° C) and weighed with a precision balance (0.1 g). Water mass is reported in reference to the wood wet mass. The 6 biomass samples are constituted of 10 portions each, sampled from the stockpile with a shovel.

2.2. Heavy metals content

The chemical elements present in the fuels were measured by XRF spectrometry (ED-XRF or X-Ray Fluorescence Energy Dispersion). This technology allowed on-site analyzes of the chemical elements with atomic number higher than 12 (magnesium)with good precision and speed. The instrument was an X-MET 5100 Oxford Instruments in-deep tested and optimized (Negri & Fellin, 2013; Fellin, Negri & Zanuttini, 2013 a, b, c; Fellin, 2014) for the use on wooden materials. The X-ray tube was energized with voltage of 45 kV and current of 40 µA. The measurement time of 60 s provided a limit of quantification of the elements compatible with rapid screening for the detection of possible contamination by heavy metals in the biomass, together with the detection of some light elements (e.g. Cl or Ca, with minimum quantification levels of 20000 mg/kg and 300 mg/kg,respectively). Three replica XRF measurements were performed on the 6 types of biomass samples.

2.3. pH, solid residues and moisture of the fumes wash liquid

The fumes wash liquid, functional to the scrubber syngas cleaner, was characterized by pH, solid residues and moisture content measurements. Liquid specimens were taken at about two hours interval while gasifier was fully operational. pH measurements were made with a pH meter laboratory with a resolution of pH 0.01. The measurement of the dry (and therefore the moisture) content of the liquid was performed according to the test methods EN 12880: 2002 and EN 15934: 2012. One sample of liquid was taken per time. Liquids were mixed thoroughly before measurements and three repetitions were performed for each specimen.

2.4. Syngas production, tVOC atmospheric emissions and plant parameters

The process of pyro-gasification was monitored through the log of real-time parameters such as fan speeds (for blowing in and suction from the reactor), temperature and pressure of the gasification chamber, etc. The real time chemical composition of the produced syngas was used for the calculation of its calorific value and therefore for the total efficiency of the biomass-syngas energy conversion. The syngas chemical composition was performed through a MRU Vario Plus syngas analyzer. The sampling point was on the syngas upstream in between the gasifier and the engine. The analysis gas line was filtered to remove impurities through an oil bubbler and cotton filters, and it was not heated. Plant parameters and operational values (such as gasifier pressure and temperature, ongoing processes, biomass loading, intake air pressure...) were logged together with the syngas chemical composition. The measures of the tVOC in atmosphere were made via a photoionization analyzer (Phockeck) running in continuous mode, averaging readings every 10 s.

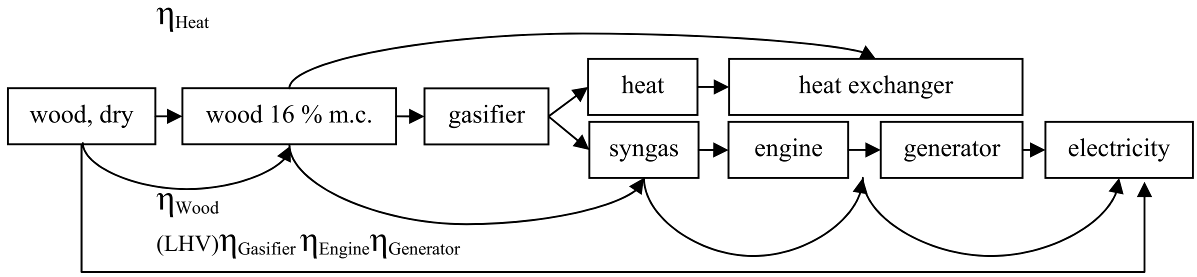
2.5. Calculation of the efficiency

The verification of electricity produced, the calculation of the partial efficiency syngas-electricity and the total efficiency biomass-electricity were carried out. The total efficiency of a gasification system (η_{Tot}) is the sum of electric and heat efficiencies. Electric efficiency is the product of the efficiencies of each production step (Figure 1). The gasification system, at time of writing, lacked in thermal and electrical power monitoring system, therefore nominal values has been accounted.Similarly, the efficiency of both engine and generator has been calculatedas one, on the basis of the datasheet.The electric self-consuming has not been considered. The total efficiency of the whole production cycle wastherefore calculated on the basis of experimental and technical data. The energy input was calculated using the hourly consumption of biomass (60 kg/h) and its calorific value (related to wood specie and moisture content (16 %), Hartmann, 2012). The chemical composition of the produced syngas was then used for the modelization of its lower heat value (LHV), by combining the ideal gas law and gas volume and LHV ratios according to the follow equation:

$$PCItot = \frac{O2g}{massgass} \times 10.5 + \frac{H2g}{massgass} \times 120 + \frac{CH4g}{massgass} \times 50 \qquad (1)$$

Where:
O2g= mass of O_2 in syngas, given by O2g = (P/1013,25)*O2%/100/(0,08205784*(T+273,14))*31,9988
CO2g= mass of CO_2 in syngas, given by CO2g=(P/1013,25)*CO2%/100/(0,08205784*(T +273,14))*44,0095
COg= mass of CO in syngas, given by COg=(P/1013,25)*CO%/100/(0,08205784*(T +273,14))*28,0101
H2g= mass of H_2 in syngas, given by H2g=(P/1013,25)*H2%/100/(0,08205784*(T +273,14))*2,0159
CH4g = mass of CH_4 in syngas, given by CH4g=(P/1013,25)*CH4%/100/(0,08205784*(T +273,14))*16,0425
N2g= mass of N_2 in syngas, given by N2g=(P/1013,25)*N2%/100/(0,08205784*(T +273,14))*28,02
P = syngas pressure, in mbar
T = syngas temperature, in °C
O2%, CO2%, CO%, H2%, CH4%, N2% = syngas composition, percentage on volume, from analyzer
massgas = total of the gas mass = O2g+CO2g+COg+H2g+CH4g+N2g.

By measuring the syngas flow per hour it was possible to calculate the energy output of the gasifier. Finally, the theoretical calculation of the efficiency of the heat engine and generator fueled by syngas was performed, based on the data provided by the manufacturer of an overall efficiency of 17.9 %. The total efficiency is referred to a hardwood biomass at 16 %of moisture content (m.c.), typical for the considered open air stockpile.



$$\eta_{Electric} = \eta_{Wood} \times \eta_{Gasifier} \times \eta_{Engine} \times \eta_{Generator}$$

$$\eta_{Tot} = \eta_{Electric} + \eta_{Heat}$$

Fig. 1. Gassification schematic steps and related efficiencies.

3. Results and discussion

3.1. Moisture content of biomass and biochar

The wood chips had a moisture content varying among 15 and 22%. There is an evident increasing of chips moisture content as deep is the sampling point in the chips pile. The surface wood chips are obviously exposed to air and dry faster than the ones placed at few tens of centimeters in depth, which were found to have greater moisture content. The manure was found to have very high moisture content (81%) and a drying process is therefore required prior to gasification.

3.2. Heavy metals content

The results of the elemental analyses in wood chips and manure highlighted the absence of heavy metals. Some measures showed a presence of iron, perhaps due by contamination of wood chips with silo storage tank or due to the transport. The oligo-elemental analysis showed no concern for heavy metals, and all detected elements are in normal concentrations. The data are presented in Table 1.

Table 1. Elementary chemical composition of biomass (of elements with atomic mass >Mg).

Specimen name	Chemical element concentration		Ca	Mn	Fe	Cu	Zn	Sr
Wood chips from conveyor belt	mean	mg/kg	16995	137	688	38	121	73
	st. dev.	mg/kg	2444	13	64	7	16	8
	cov	%	14	10	9	19	13	11
Manure	mean	mg/kg	2622	38	n.d.	9	18	31
	st. dev.	mg/kg	1354	33	-	2	5	9
	cov	%	52	85	-	22	29	30
Wood chips from container (surface)	mean	mg/kg	5091	47	893	n.d.	28	35
	st. dev.	mg/kg	2010	22	214	-	10	3
	cov	%	39	46	24	-	35	7
Wood chips from container (30 cm depth)	mean	mg/kg	6176	48	735	n.d.	24	30
	st. dev.	mg/kg	2981	25	10	-	10	10
	cov	%	48	52	1	-	43	32
Wood chips from pile 1	mean	mg/kg	9378	128	841	n.d.	31	51
	st. dev.	mg/kg	2263	62	-	-	4	33
	cov	%	24	49	-	-	14	66
Wood chips from pile 2	mean	mg/kg	4563	47	-	n.d.	12	27
	st. dev.	mg/kg	2928	21	-	-	3	13
	cov	%	64	44	-	-	24	47

3.3. pH, solid residues and moisture of the fumes wash liquid

The fumes wash liquid resulted to be moderately acidic, with a tendency to decrease the pH in function of the gasifier operational time. The details in Table 2.

Table 2. Characteristics of washing water fumes: pH, dry and moisture contents.

Washing water fumes specimen	pH	Dry content [%]	st. dev. [%]	cov [%]	Moisture content [%]	st. dev. [%]	cov [%]
n° 1, taken at 11:10	4.23	0.1	0.01	5.2	99.9	0.01	0
n° 2, taken at 13:20	4.28	0.1	0.04	40.4	99.9	0.04	0
n° 3, taken at 15:20	3.90	0.2	0	1.9	99.8	0	0
n° 4, taken at 18:00	3.96	0.2	0.05	28.5	99.8	0.05	0

3.4. Syngas production, tVOC atmospheric emissions and plant parameters

In the test session reported in this paper and presented in Figure 2 and in Table 3 the gasifier was in fully working order and run smoothly without obvious technical problems. It is possible to identify four different phases: ignition, biomass loads, full power, powering off. We will focus on the biomass loads, on the full power and the two phases together, indicated as “session mean”. During the biomass loads, there is an opening of the gasification chamber for feeding wood chips, a supply of oxygen and an inevitableLHV drop. During the full power phase the LVH is pretty stable, reaching a peak of 4.5 MJ/kg. Analyzing the whole session mean (ignition and powering off excluded, in order to simulate a long-working period) the produced syngas LHV fluctuated in between 1.8 and 4.5 MJ/kg. The syngas LHV of the analyzed session resulted to be slightly lower than the manufacture specification. However, the major issue which causes the LHV drop isunder technical revision and a new biomass feed system is going to be installed.

Table 3. Syngas production LHV performances.

gasifier status	time		unit	**LHV CO**	**LHV H2**	**LHV CH4**	**LHV total**
biomass loads	12:20-12:53 13:19-13:39 15:05-1546 1748-18:10	mean	MJ/kg	1.9	1.0	0.6	3.5
		st. dev.	MJ/kg	0.5	0.2	0.1	0.7
		cov	%	27.9	17.8	17.8	20.6
		min.	MJ/kg	0.6	0.6	0.4	1.8
		max.	MJ/kg	2.7	1.2	0.8	4.4
full power	11:54-12:20 12:53-13:19 13:39-15:05 1546:1748	mean	MJ/kg	2.4	1.1	0.7	4.2
		st. dev.	MJ/kg	0.2	0.1	0.0	0.2
		cov	%	7.5	6.8	6.8	3.7
		min.	MJ/kg	2.0	1.0	0.6	3.7
		max.	MJ/kg	2.7	1.2	0.8	4.5
session mean	11:54-18:10	mean	MJ/kg	2.3	1.0	0.7	4.0
		st. dev.	MJ/kg	0.4	0.1	0.1	0.5
		cov	%	17.5	11.9	12.4	13.1
		min.	MJ/kg	0.6	0.6	0.4	1.8
		max.	MJ/kg	2.7	1.2	0.8	4.5

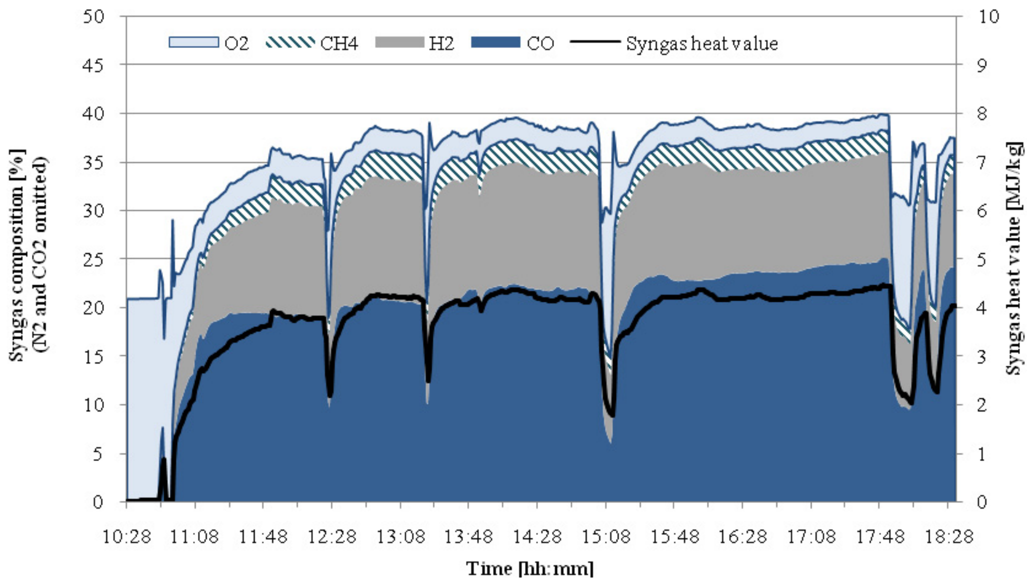


Fig. 2. Syngas production performances.

The tVOC emissions showed a trend with medium to high concentrations emissions throughout the duration of the tests, ranging from 100 to 800 ppb. Many and varied are the operations performed on the gasifier and apparently none major operation/process was univocally responsible to the increase in VOC emissions into the atmosphere.

Large oscillations in values can be caused by the presence of wind. The details are presented in Figure 3.

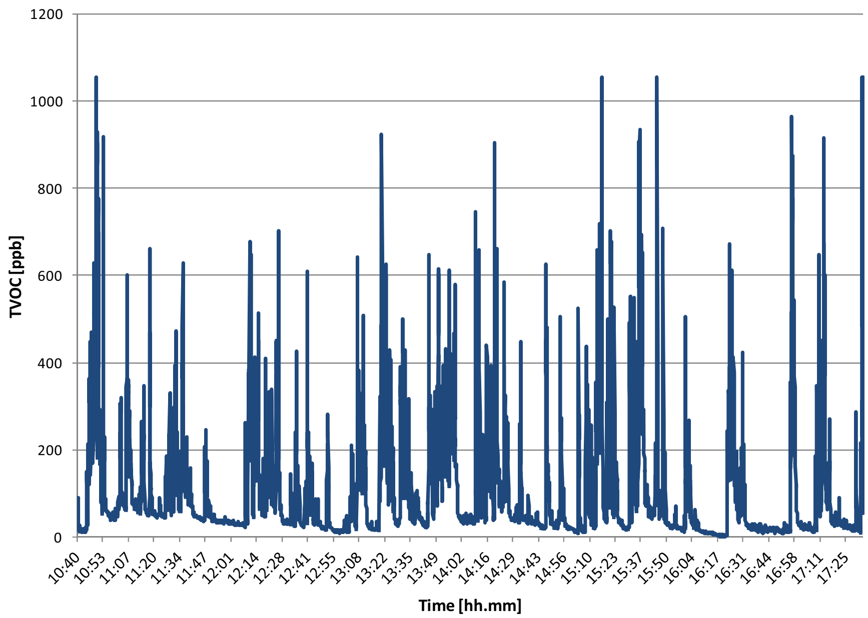


Fig.3. Total volatile organic compounds measured at a distance of 10 m from the plant.

3.5. Evaluation of the efficiency

The energy efficiency between the biomass and the production of syngas is found to be 72 %; the overall electric efficiency is 12 %, calculated in between the energy stocked in biomass and the production of electrical energy. The efficiency of the engine and generator phase is 18 %,thethermal efficiency is 12 % (both nominal values provided by the manufacturer).The total efficiency of the pyro-gasification plant is 24 %. The details are presented in Table 4.

Table 4. Evaluation of the performance: syngas and electrical production from biomass.

Gasification phase	Heat value		Energy produced in 1 h	efficiency calculated on wood at 16% m.c.	
	MJ/kg	kWh/kg	kWh	η	
1, Oak wood, 16 % m. c.	15.1	4.2	252	1 (theoretical)	η wood
2, syngas	4.5	1.2	168	0.67	η gasifier
3, engine/generator (calculated)	-	-	*30*	*0.18*	*η eng* η gen (calculated)*
	Wood to electricity total efficiency			*0.12*	η electric
4, heat exchanger	-	-	30	0.12	η heat
	Wood to electricity total efficiency			*0.24*	*η tot (calculated)*

4. Conclusion

The characterization of the different types of biomass resulted in a moisture content generally suitable for burning/gasification (15 ÷ 22%). The manure fuel had a very high moisture content. A further drying of biomass can significantly contribute to improve the overall efficiency of the gasifier.

The biomass did not show any presence of heavy metal content.It was possible to identify a modest iron contamination, probably caused by the transport and/or storage of the biomass, which were not considered to be a danger to human health nor for the gasification plant.

The pH of the washing waters was moderately acid.The dry content is very low (0.1%).

The heat value of produced syngas was 3.5 to 4.5 MJ/kg (about 4.1 ÷ 5.3 MJ/Nm^3). It is evident a drop in LHV during the biomass feed phase; this technical issues should be solved in a prompt upgrade of the plant.

The volatile organic compounds emissions were occasionally moderate to high.

The overall efficiency in converting biomass to electricity is 12 %, lower than other gasification plants (Caputo et al., 2005). However, the studied plant is capable of using a wide variety of biomasses and it may be an optimal choice for a mid-size farm or wood SME.

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