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The use of the combined cycle for the generation of electric energy by the gases obtained from the carbonization of wood using

Uso do ciclo combinado para a geração de energia elétrica pelos gases obtidos da carbonização de madeira usando fornos de micro-ondas

El uso del ciclo combinado para la generación de energía eléctrica mediante de los gases obtenidos de la carbonización de madera mediante hornos microondas

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Abstract
The effluents from carbonization or pyrolysis and wood charcoal have aggregated thermal energy and, in conventional charcoal kilns, part of the wood is burned to ignite the burning in the kilns and the effluents generated are dispensed in the atmosphere and in the soil, which causes energy losses and environmental pollution. In this study we seek a clean and sustainable alternative to produce energy, in addition to the search for a system with satisfactory performance in the generation of electric energy. The objective of this study was to evaluate how much electricity can be produced from wood carbonization effluents by ONDATEC technology, using the Brayton and Rankine cycle, also known as Combined Cycle. This method presents a high power generation efficiency, around 50%, compared to other generation systems. A field experiment was carried out from October 21st to 24th, 2010 to determine the calorific value of wood carbonization effluents, using a microwave oven, (condensable and non-condensable gas), in the city of Uberaba -Mg, Brazil. The data generated in this study reveals important information for companies looking for a way to produce clean and renewable electricity from reforestation wood, in addition to the effort to minimize environmental pollution, ensure sustainability in production systems and the growing search for new sources of energy. A complete description of the experiment, including details of the project, is presented in this work.
Keywords: Combined cycle; Carbonization effluents; Sustainable energy; Field experiment; Non-ionizing radiation.

Resumo
Os efluentes da carbonização ou pirólise e o carvão vegetal possuem energia térmica agregada e, nas carvoarias convencionais, parte da madeira é queimada para acender a queima dos fornos e os efluentes gerados são dispensados na atmosfera e no solo, o que provoca perdas de energia e poluição ambiental. Neste estudo buscamos uma alternativa limpa e sustentável para a produção de energia, além da busca por um sistema com desempenho satisfatório na geração de energia elétrica. O objetivo deste estudo foi avaliar a quantidade de eletricidade que pode ser produzida a partir de efluentes da carbonização de madeira pela tecnologia ONDATEC, utilizando o ciclo de Brayton e Rankine, também conhecido como Ciclo Combinado. Este método apresenta uma alta eficiência de geração de energia, em torno de 50%, se comparado a outros sistemas de geração. Um experimento de campo foi realizado de 21 a 24 de outubro de 2010 para determinar o valor calorífico de efluentes da carbonização de madeira, utilizando forno de micro-ondas, (gás condensável e não condensável), na cidade de Uberaba -Mg, Brasil. Dados gerados neste estudo revelam informações importantes para empresas que buscam uma forma de produzir eletricidade limpa e renovável a partir de madeira de reflorestamento, além do esforço para minimizar a poluição ambiental, garantir a sustentabilidade nos sistemas de

produção e a busca crescente por novas fontes de energia. Uma descrição completa do experimento, incluindo detalhes do projeto, é apresentada neste trabalho.
Palavras-chave: Ciclo combinado; Efluentes de carbonização; Energia sustentável; Experimento de campo; Radiação não ionizante.

Resumen
Los efluentes de la carbonización o pirólisis y el carbón vegetal tienen energía térmica agregada y, en los hornos convencionales de carbón vegetal, parte de la madera se quema para encender la combustión en los hornos y los efluentes generados se dispensan a la atmósfera y al suelo, lo que genera energía. pérdidas y contaminación ambiental. En este estudio buscamos una alternativa limpia y sustentable para producir energía, además de la búsqueda de un sistema con desempeño satisfactorio en la generación de energía eléctrica. El objetivo de este estudio fue evaluar cuánta electricidad se puede producir a partir de los efluentes de la carbonización de la madera mediante la tecnología ONDATEC, utilizando el ciclo de Brayton y Rankine, también conocido como ciclo combinado. Este método presenta una alta eficiencia de generación de energía, alrededor del 50%, en comparación con otros sistemas de generación. Se realizó un experimento de campo del 21 al 24 de octubre de 2010 para determinar el valor calorífico de los efluentes de la carbonización de la madera, utilizando un horno microondas, (gas condensable y no condensable), en la ciudad de Uberaba -Mg, Brasil. en este estudio se revela información importante para las empresas que buscan una forma de producir electricidad limpia y renovable a partir de madera de reforestación, además del esfuerzo por minimizar la contaminación ambiental, asegurar la sostenibilidad en los sistemas de producción y la creciente búsqueda de nuevas fuentes de energía. En este trabajo se presenta una descripción completa del experimento, incluidos los detalles del proyecto.
Palabras clave: Ciclo combinado; Efluentes de carbonización; Energía sostenible; Experimento de campo; Radiación no ionizante.

1. Introduction

Considering the increasing demand of electrical supply reported for Anvari et al. (2016), one of the possible generating alternatives is the use of forest biomass, originating valuable forms of energy by different processes, such as thermal, biological, and mechanical (Mohan et al., 2006; Bridgwater, 2012). Discussions about reducing greenhouse gas emissions have led to discussions to mitigate their effects on the climate (Klingenberg et al. 2020). Nevertheless, the use of biomass as an energy source offers significant environmental advantages, Mohan et al. (2006). Thus, forest biomass is one of the most promising strategies for the generation of renewable energy in Brazil (Gomes et al., 2013; Lopes et al., 2016; Welfle, 2017) and, with the use of this biomass to produce charcoal, there is also the possibility of using the carbonization effluents for different purposes, among them the generation of electric energy. According to Westerhof et al. (2011), the oil produced by the charcoal carbonization process has the potential to become an important intermediate energy carrier to produce bio-based chemicals, transport fuels, heat, and electricity.

Carbonization occurs in one action, in which the energy used to burn the wood comes from another source and not from the wood itself, placed in a cavity controlled for the entry of oxygen. Also, according to Payakkawan et al. (2014), biomass carbonization is a process to decompose biomass with heat in the absence of oxygen. Thus, carbonization is a chemical process of incomplete combustion of solid matter, subjected to high heat, which removes hydrogen and oxygen. The product of this chemical reaction involving wood is coal, which is a matter composed mainly of carbon. And in this case, pyrolysis occurs simultaneously, which is the process in which the wood undergoes thermal decomposition when reaching temperatures above 500 ° C in environments without oxygen (Soltes et al., 1981), transforming it into other substances. The complete process delivers coal as the main product, and other gaseous and liquid by-products that have high energy value. Biomass pyrolysis converts wood into gas, liquid and solid, where the percentages of each product are determined by the operational conditions of the process and the characteristics of the biomass used (Pereira et al., 2020).

The average distribution of products and by-products generated by carbonization showed that condensable and non-condensable gases represented almost 70% of the initial wood mass (Rousset et al., 2011). However, the conventional technology to produce industrial coal does not favor the use of gaseous effluents, which are discharged into the environment. According to practical data from the coal industry, on average, one ton of wood is converted into 250 kg of coal and 750 kg of gases. Pig iron is the raw material for steel and its manufacture requires large amounts of carbon that can be found in charcoal or mineral. For the pig iron industry, on average, to produce 1 ton of pig iron, 440 kg of carbon or the equivalent of 630 kg of charcoal are consumed, since in the coal mass there is an average of 70% carbon.

Brazil produced in 2019, with integrated and independent plants, 6.95 million tons of pig iron using charcoal, and consequently consumed approximately 4.37 million tons of charcoal, disregarding losses in production, transportation and in the blast furnace, which together can be around 20% (SINDIFER, 2019). This coal production would generate around 5.3 million tons of bio-oil, which is the net fraction of carbonization gases and 3.57 million tons of non-condensable gas.

Currently, using electricity as a reference with the combined cycle, Brazil could generate the equivalent of 18.74 million MWh of electricity per year if it takes the advantage of the thermal potential of conventional process effluents. The use of products formed during the carbonization of wood would bring several advantages to the industrial sector, such as raising of financial resources aimed at the modernization of coal production techniques and the reduction of the emission of volatile organic compounds, thus minimizing the levels of environmental pollution and the possibility of isolating substances of commercial interest and the development of chemical applications for the fine and polymer industry (Carazza et al., 1993), in addition to the generation of electric energy.

Thus, in line with this context, the present study shows the production of electric energy using the effluents from the carbonization of eucalyptus wood be carried out by means of an industrial oven that uses microwave technology for heat generation. There is potential for microwave technology to be introduced and applied to many other industrial heating processes, which offers unique advantages not achieved with conventional heating (Fernandez et al., 2011). The idea is (1) to explore electric power generation using combustion gases from controlled wood pyrolysis and from the microwave carbonization process, using a combined cycle, which means, having a gas turbine at the same time and a steam turbine to drive electric generators and (2) present a study of mass and energy balance by the combined cycle to verify that this combination has better yields than the individual systems.

2. Methodology

This work was developed using the concept of mass balance, energy balance and the combined cycle for the generation of electrical energy. This type of research can be considered quantitative, as it is a practical part, that is, carried out using an industrial microwave oven with full use of all the baked wood and qualitative, since the condensable gases and non-condensable gases from carbonization, in addition to the analysis of the calorific value of these gases. Therefore, it can be considered as much a work to determine the amount of electric energy production as a laboratory research.

The basic criterion for analyzing the results was to demonstrate a way to take advantage of the gases from wood carbonization and a comparison of performance using the combined cycle with conventional electric power generation systems. The steps of collecting samples of the gases, analyzing the components present in these gases, the mass and energy balances applied to the microwave oven and the yield found for the system are presented in the next sections.

2.1 Development of the micro-wave furnace

The industrial oven used in this study was developed to produce charcoal by carbonization / pyrolysis of wood and in the total recovery of the gaseous and liquid effluents generated in this process, therefore, there will be the possibility of using these compounds for the generation of electric energy. The coal-making process used by ancient civilizations remains almost unchanged today, mainly from the point of view of energy loss, which can reach more than 50% of the energy content of biomass

(Vilela et al., 2014). Carbonization is a process in which the wood is subjected to heating between 300ºC and 500ºC in a closed environment, with total or small exclusion of oxygen (Qiab et al., 2017) and the solid residue, coal, contains about 70% of carbon (FAO, 1985). Some data of the carbonization process is in Table 1.

Table 1: Factors and levels studied in charcoal production and their respective responses.

Test	Independent Variables		Dependent Variables or responses			Yields of products	
	Final temperature	Heating rate	Charcoal yield (wt%)	Fixed carbon yield (wt%)	Fine particles (wt%)	Bio-oil (wt%)	Non-Condensable Gases (wt%)
1	380	0.25	35.53	27.21	11.49	42.64	21.83
2	480	0.25	33.05	28.87	12.21	37.00	29.95
3	380	2.5	32.21	24.49	11.38	40.44	27.35
4	480	2.5	30.22	24.92	15.42	39.51	30.27
5	430	0.25	33.99	26.54	14.87	38.88	27.13
6	430	2.5	32.11	24.49	15.36	38.31	29.58
7	380	1.375	32.81	25.27	12.96	40.44	26.75
8	480	1.375	31.10	24.82	15.15	40.47	28.43
9	430	1.375	31.62	24.43	16.30	40.04	28.86
10	430	1.375	32.74	26.29	16.22	45.30	21.96
11	430	1.375	32.96	25.75	15.67	37.92	29.12

Source: Silva et al. (2019).

The ONDATEC's project was born to initially supply the demand for coal for the manufacture of pig iron, since the manufacture using this technology is faster, produces a coal with superior quality and does not harm the environment and the operators. Carbonization or pyrolysis using microwaves has been explored as a promising technique for converting residues into potentially useful pyrolysis products (Lam et al., 2016; Huang et al., 2016; Salema et al., 2012; Mushtaq et al., 2014; Lam et al., 2016; Lam et al., 2015). The industrial oven used in this analysis is called UPEC-250, developed, designed, and built by ONDATEC - Tecnologia Industrial em Micro-ondas SA (www.ondatec.com). Eucaliptus citriodora is the carbonized wood used in the experiment. The equipment (Fig. 1) is 42 meters long, of which 36 meters are used for the carbonization of wood and the remaining 6 meters are used for pre-cooling the coal. The furnace is fed with 20 cm wood pieces, as illustrated by Fig. 2.

Figure 1: Microwave oven UPEC 250.

Source: Authors.

Figure 2: Feed System UPEC 250.

Source: Authors.

The oven has in its configuration a total of 320 non-ionizing radiation emitting modules (microwaves), with a wood feed capacity of 1000 kg per hour which results in an average production of 250 kg of charcoal per hour, depending on the type and characteristic of the raw material entering the oven. The average residence time of the wood inside the oven is 3 to 4 hours and its internal working temperature is in the range of 400ºC to 500ºC. The system features clean, precise, fast, continuous technology and a good level of automation capable of changing the quality of coal that you want to obtain. Thus, it carries out the continuous carbonization of the wood, seeks the reuse of the carbonization effluents for the generation of electric energy and allows to manage the thermal profile of the oven.

The UPEC 250 ONDATEC oven was assembled in the city of Tietê in the state of São Paulo, Brazil. The oven is fed manually, where the operator loads the feeding system with wooden slugs in the vertical position and after loading, he presses two buttons so that the automatic system unloads the slugs on the conveyor in the same way it was fed. Thus, after delivery, the wooden pieces are transported along the carbonization cavity (Figure 3A) and receive microwave radiation. Much of the carbonization cavity is used for drying and after this process, the wood carbonization begins. At the end of the conveyor belt, there is the unloading sector, where the coal produced is poured into 1 cubic meter containers for cooling, see (Figure 3B) and subsequent packaging in a conventional packaging system. It is noteworthy that the operator has no direct contact with coal production and the environment is free of suspended solids, totally different from conventional coal manufacturing processes.

Figure 3: Side view of the carbonization cavity (A) and front view of the UPEC 250 coal discharge (B).

A B

Source: Authors.

This whole process is carried out in a controlled atmosphere, in which there is no burning of the wood, and this is ideal for producing a combustible gas with high calorific value.

2.2 Carbonization Gases Separation, Collection and Sampling

A gas washer is used to separate the effluents generated in the UPEC-250 ONDATEC® furnace. At the top of the gas washer, the bio-oil (condensable gas) already produced and cooled is sprayed so that the combustion gases, in an upward direction inside the gas washer, can exchange heat with the sprayed bio-oil, in a downward direction. That is inside the gas washer, where the separation of condensable gases (CG) and non-condensable gases (NCG) occurs. The fraction with the lowest volatility, the condensable (CG), comes out from the bottom of the washer and the fraction from the highest volatility (NCG), comes out from the top of the equipment.

The devices needed to perform the CG and NCG analyzes were installed online to the process, next to the chimney. Gas collections and analyzes took place at 4-hour intervals. The system used is represented in Table 2, where three methods were used to determine mass and calorific value. They are calorimetric pump, mass spectrometry and gas chromatography, where each of these methods was used for a specific type of component.

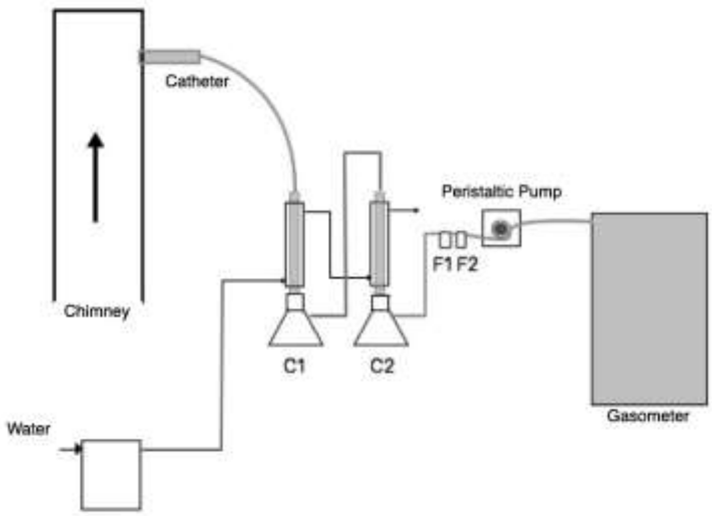
Table 2: Systematic evaluation of the effluents generated by the carbonization of wood in microwave ovens.

	Components				
	Biomass	Charcoal	Non-Condensable gas	Condensable gas	Tar
Calorimetry	3 samples	3 samples	**	***	AC4
Mass spectrometer	---	---	---	AC4	---
Gas chromatography	---	---	AC4	---	---
Weighing	3 samples	3 samples	****	AC4	AC4

* Determination by means of mass balance and calorific powers.
*** Calculation using mass and energy balance.
**** Determination of mass by means of gas chromatography.
AC4 Composite sample every 4 h.
Source: Oliveira et al. (2016).

For gas sampling, a probe was installed in the chimney including some equipment such as: peristaltic pump, filters, erlenmeyers and gasometer (Figure 4). In this system, part of the smoke generated by the carbonization process is collected, with the condensable fraction (Pyroligneous Acid) present in the smoke, collected in the Erlenmeyers C1 and C2, and the non-condensable fraction stored in the gasometer. The residual gases generated in the carbonization process were periodically collected, so that the NCG was analyzed in the plant, by means of gas chromatography coupled with DCT. Thus, it was possible to determine the quantity of each component and the composition of the non-condensable fraction, while the condensable portion was collected and stored for further analysis of its chemical composition, using gas chromatography coupled to a mass spectrometer. The tar was collected through recipients installed at the bottom of the carbonization cavity for further analysis of the PCI with the calorimetric pump.

Figure 4: Sketch of the NCG sampling system.



Source: Authors.

The gas collection system in Figure 4 has been programmed and calibrated for accurate gas collection by conducting 5 sampling sessions. Each sampling session lasted 10 minutes, where this sampling was performed every hour at a rate of 1.5

liter / minute. The gas collected every 4 hours was stored in a gasometer with 60 liters of capacity. The collection and analysis of the gases were carried out in 5 periods of 4 hours each.

Every 4-hour period, a sample of the gas contained in the gasometer was collected using Tedlar bags (Figur 5).

Figure 5: Tedlar bag.

Source: Authors.

To perform the methods of sampling and mass balance, the adapted standard UNFCCC AM0041 version 1 (Mitigation of Methane Emissions in the Wood Carbonization Activity for Charcoal Production) was used. This standard is approved and registered for projects under the Clean Development Mechanism (CDM) of the Climate Convention.

2.3 Analysis of non-condensable gases (NCG), condensable gases (CG) and calculation of calorific value

The analysis of the non-condensed gas was performed using a gas chromatograph coupled to the thermal conductivity detector - TCD, model CG Ultra from Thermo Fisher Scientific®. A gas chromatograph coupled to the mass spectrometer was used to analyze the components of the condensable gas and a calorimetric pump from Ika Works® (model C2000) was used to check the LCP (Lower Calorific Power) of the tar. The analysis have been performed by Ondatec and the School of Agriculture Luiz de Queiroz (ESALQ).

The calorific value of the non-condensed gas was evaluated considering the main components found in this gas, that is, hydrogen (H_2), methane (CH_4) and carbon monoxide (CO). Equation 1 is used to perform the calculation.

$$PCIg = \sum PCIc \ x \ Cc \qquad (1)$$

In equation 1, PCIg is the lower calorific value of the gas (MJ / Kg), PCIc is the lower calorific value of the component (MJ / Kg), and Cc is the concentration of the component in the non-condensable gas (Kg). The potential energy of the gas, in Watt-hours (Wh), is determined by the direct conversion of the lower calorific value, in MJ, and 1MJ is equal to 277.77 Wh according to the conversion factor table of the National Electrical Energy Agency ANEEL (2020).

Based on the results of the chromatography, it was possible to perform the mass balance and estimate the energy balance of the CG and NCG gases generated in the carbonization of the wood. In addition, it was possible to evaluate the production of electricity based on the combined cycle yield.

The following topic presents the research results. It includes the masses of wood, and of the produced charcoal. The gravimetric yield of the generated charcoal, along with the average masses of NCG, and CG are presented. The composition and the calorific value of the NCG and CG gases are also shown. At the end, the calculations of electricity generation and the efficiency factor using the combined cycle are also presented.

3. Results and Discussion

After five carbonization tests, the average mass balance of the process can be performed. Table 3 shows the average mass of wood introduced in the oven and the average production of charcoal. The gravimetric yield of charcoal (η_{cv}), shown in Table 4, was calculated based on the amounts of produced wood and charcoal.

Table 3: Mass of wood introduced in the oven and the produced charcoal UPEC-250 ONDATEC®.

Wood in the oven		Generated solid products	
$Mass_{fed\ wood}$	4172 kg	$Mass_{wet\ charcoal}$	1778 kg
$Mass_{dry\ wood}$	3947 kg	$Mass_{dry\ charcoal}$	1761 kg
Moisture	5,40%	Moisture	1,00%
		$Mass_{tussock}$	103 kg

Source: Authors.

Table 4: Calculation of the gravity yield of the vegetal charcoal inside the oven UPEC-250 ONDATEC®.

	Wet charcoal mass (Kg)	Mass of the dry wood fed in the oven (Kg)	Yield (%)
UPEC-250	1778	3947	45,0

Source: Authors.

Based on tables 3 and 4, it can be noted that the UPEC-250 furnace has a 45% yield for a moisture content in the generated coal of 1%. The mass of tussock, 103kg, is equivalent to the amount of wood removed from the oven that was not transformed into coal, either at the start or at the end of the carbonization process.

3.1 Calculation of Thermal Energy and Lower Calorific Power of Non-Condensable Gas

Table 5 shows the results of the chemical composition of the non-condensable gases by means of gas chromatography analysis. The exposed quantities are average values based on the UPEC 250 unit in line with the wood being introduced in the oven.

Table 5: Average mass of NCG produced in the UPEC 250 oven.

Chemical Composite	Mass NCG (Kg) (percentage)
O_2	37,80 (4,2%)
CO_2	117,32 (12,8%)
H_2	1,70 (0,20%)
N_2	189,87 (20,7%)
CH_4	98,85 (10,8%)
CO	470,29 (51,3%)
TOTAL	915,83 (100%)

Source: Authors.

The main components found in this analysis, which have significant calorific value when compared with the other components found in the NCG, were hydrogen (H_2), methane (CH_4) and carbon monoxide (CO). Based on the mass of the compounds shown in Table 5, and according to the individual lower calorific value of these components, some calculations were performed according to equation 1 to determine the total energy stored in the NCG of the UPEC-250 unit, as shown in Table 6.

Table 6: Lower calorific value of chemical compounds and Total energy stored in the UPEC-250 ONDATEC® NCG.

Chemical Composite	Lower Calorific Power (MJ/Kg)	Stored Energy in MJ
CH_4	50,00	4942,50
CO	9,33	4294,00
H_2	120,00	204,00
Total		9440,50*

* Total stored energy in UPEC-250 NCG.
Source: Authors.

Calculating the NCG PCI of the UPEC-250 unit, according to Eq. (2), below, and considering the total mass of this gas, according to Table 6, we have:

$$PCI_{NCG} = 9440,5 / 915,83 = 10,3 \text{ MJ/Kg} \qquad (2)$$

With the data calculated and using the equivalence between MJ and Wh (MJ / Kg = 0.277 kWh / Kg), the NCG energy potential of the UPEC 250 unit is shown in Table 7.

Table 7: Calculation of the NCG energetic thermal power.

	NCG Lower Calorific (MJ/Kg)	Thermal Energetic Power (KWh/Kg)
UPEC-250	10,3	2,86

Source: Authors.

Based on these calculations, an energy availability of 2.86 kWh is present in the non-condensable gases of the UPEC 250 unit. Finishing the calculations of the lower calorific value and the potential of energy, both non-condensable gases, we can analyze and calculate these same items for condensable gases from the carbonization of wood by microwave technology.

3.2 Calculation of Thermal Energy and Lower Calorific Power of Condensed Gas

Table 8 shows the main components analyzed in the condensable gases, in the UPEC 250 unit. These data were obtained from gas chromatography coupled to the mass spectrometer. It is noteworthy that the calculated values are based on the lower calorific value of the condensed gas, since the bio-oil has water in its composition, that is, this fluid is intrinsically present in the CG.

Table 8: Mass of the main components of the condensable gases of the UPEC-250 unit.

Item	Component	Mass of CG UPEC-250 (Kg)
1	Methanol	50.97
2	Acetone	6.32
3	Methyl Acetate	30.06
4	2.3 - Butanenedione	12.46
5	2 - Butanone	3.50
6	Acetic acid	177.13
7	Acetol	29.23
8	Butanenediol	5.49
9	Furaldehyde	61.76
10	2 - Furanmethanol	14.12
11	2 - Propanone, 1 - hydroxy-acetate	5.82
12	Dimethoxytetrahydrofuran	7.98
13	2 - Methyl, 2 - cyclopentenone	7.31
14	Ethanone, 1- (2 - furanyl)	3.01
15	1-2-Cyclopentanedione	9.80
16	2-Furancarboxialdehyde, 5-methyl	23.91
17	Corilon	23.07
18	p-Cresol	16.29
19	2-Methoxy phenol	34.09
20	4-Methoxy-3-methylphenol	2.83
21	P-Cresol. 2-methoxy	41.00
22	3-Methoxy-1,2-benzenediol	36,02
23	4-Ethyl-2-methoxy phenol	11.48
24	4-Methyl-1,2-benzenediol	4.16
25	2,6-Dimethoxyphenol	61.93
26	1,2,4-Trimethoxybenzene	41,51
27	1,2,3-Trimethoxy-5-methyl-benzene	48.97
28	Tar	238.57
29	Water	227.34
30	Other	139.16
	Total mass (Kg)	1375,29

Source: Morais et al. (2015).

To calculate the lower calorific value of the pyroligneous acid of the UPEC 250 system, the mass balance and the carbonization energy of the process were taken as a basis. And, to calculate the lower calorific power of the tar, the calorimetric pump from Ika Works® (model C2000) was used. These values are presented in Table 9. Based on the mass and energy balance shown in Table 9 and by the equivalence between MJ and Wh, the energetic potential of the condensable gas (CG) of the UPEC 250 are shown in Table 10.

Table 9: Composition of condensable gas (Pyroligneous acid + tar)

U/S = Undetected substances and N / A = Not analyzed.

Gases	Massa (kg)	Energia (MJ)
Alcatrão	238,57	5185
Pyroligneous Ac	770,22	21615
Water	227,34	N/A
U/S	139,16	N/A
Total	1375,29	26800
PCI Report MJ/kg		19,49

Source: Authors.

Table 10: Calculation of the Energetic potential of CG.

	Lower Calorific Power NCG (MJ/Kg)	Thermal Energetic Power (KWh/Kg)
UPEC-250	19,49	5,41

Source: Authors.

Based on the thermal energetic potential of CG and NCG, shown in Tables 7 and 10, it is possible to calculate the electric energy generation potential of the UPEC-250 carbonization effluents using the combined cycle.

3.3 Use of CG and NCG for Electric Power Generation

Considering the average yield of this system of 33% for coal, 40% for condensed gas and 27% for non-condensed gas per ton of wood, and still knowing the energetic potential of the CG and the NCG, one can predict which it would be the generation of electric energy with the carbonization effluents of this system.

Table 11 shows the thermal energetic potentials of the CG and NCG gas according to the production in the UPEC 250 unit.

Table 11: Thermal Energetic Potential of NCG and CG.

Energetic Potential	KWh thermal/Kg
NCG	2,86
CG	5,41

Source: Authors.

Table 12 details the consumption of wood, production of coal and production of effluents in 4 UPEC 250 units, in addition to the electrical consumption of the system. For the presented scenario, the use of four UPEC 250 industrial ovens was considered, that is, 4,000 kg of wood introduced in the oven per hour. For this number of industrial plants, the cost, CAPEX (Capital Expenditure or Investment in Capital Goods), of acquiring the gas turbine and the cost of the steam turbine were considered.

Table 12: Data of the proposed system.

Description	Data	
Number of UPEC 250	4	
Electric consumption of each UPEC 250	0,333 MWh per ton of wood	
Electric consumption of the 4 UPEC 250	1,33 MWh per ton of wood	
Amount of wood fed per each UPEC 250	1 Ton/h	
Total amount of fed wood	4 Ton/h	
Amount of produced coal	33%	1,32 Ton/h
Amount of CG to be produced	40%	1,60 Ton/h
Amount of NCG to be produced	27%	1,08 Ton/h

Source: Authors.

With this data, the amount of electrical generation with the carbonization effluents is calculated. Eq. (3) is used to determine total CG or NCGN production associated with the total wood introduced in the oven and the product yield (CG or NCG). Equation (4) is used to calculate the total thermic potential energy of condensed or non-condensed gas.

$$Production_{index} = (\text{wood introduced in the oven}) * \text{yield (CG or NCG)} \quad (3)$$

$$P_{index} = Production_{index} * (\text{Thermal Potential Energy}) \quad (4)$$

In equations (3) and (4) Index production is the total gas production (CG or NCG). The calculation of the energetic potential of the condensed gas or the non-condensed gas can be performed using Eq. (4), where P_{index} is the energetic potential of the CG or NCG. Thus, the production and potential energy of the CG and NCG are calculated as follows:

$$Production_{CG} = 4 \text{ Ton/h} * 0{,}4 = 1{,}6 \text{ ton/h} \qquad P_{CG} = 1{,}6 * 5{,}41 = 8{,}66 \text{ MWh thermic/h}$$

$$Production_{NCG} = 4 \text{ Ton/h} * 0{,}27 = 1{,}08 \text{ Ton/h} \qquad P_{NCG} = 1{,}08 * 2{,}86 = 3{,}09 \text{ MWh thermic/h}$$

The manufacturer OPRA, based in Hengelo in the Netherlands, develops gas turbines, such as the OP16 model, which has an efficiency of 26% according to the developer and can be fed with both effluents at the same time. Table 13 emphasizes the energy generated.

Table 13: Electric generation with the gas turbine from the manufacturer OPRA.

Description	Values
Turbine yield with CG + NCG (%)	26,00
Energetic potential CG + NCG (MWh thermic/h)	11,75
Electric Generation (MWh electric/h)	3,05

Source: Authors.

As the proposed system is the combined cycle, with the use of the gas turbine cascading with the steam turbine, the thermal energy contained in the exhaust gases of the gas turbine (the thermal 11.74 MWh - 3.05 MWh = 8.68 MWh) is injected into a recovery boiler coupled to a steam turbine with an electric generator. Based on the practical data of this system, the efficiency of this turbogenerator system (recovery boiler and steam turbine) is around 30%. With this, an additional 2.6 MWh can be generated in this process with the thermal 8.68 MWh coming from the OPRA gas turbine, as calculated in Table 14. Adding the electric generations, this combined cycle generates 5.65 MWh for 4 tons of wood introduced in the oven, as shown in Table 15.

Table 14: Electric Generation with the turbogenerator.

Description	Values
Turbogenerator (%)	30,00
Energetic potential (MWh thermic/h)	8,68
Electric Generation (MWh electric/h)	2,60

Source: Authors.

Table 15: Electric Generation – Combined Cycle.

Description	MWh
Electric Generation with the generator driven by a gas turbine	3,05
Electric Generation with the generator driven by a steam turbine	2,60
Total system electric generation	5,65

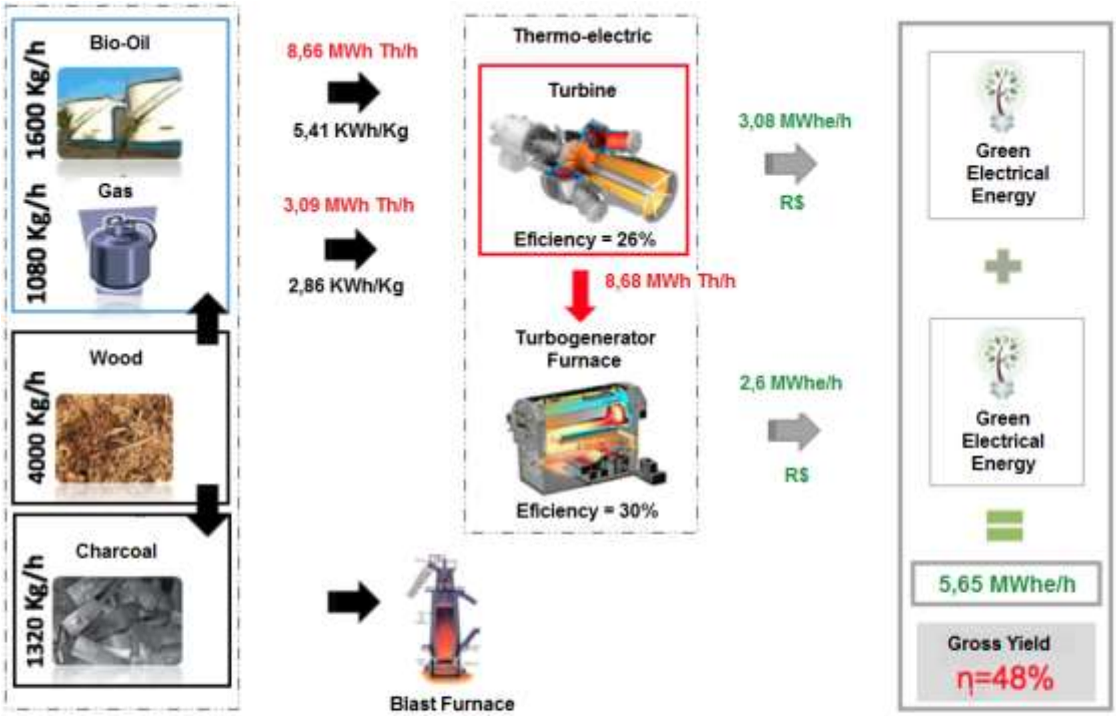
Source: Authors.

Based on the results presented in Table 15, the total electrical energy generated by the proposed combined cycle is 5.65 MWh / h, adding the electrical energy generated by the OPRA gas turbine and the electrical energy generated by the steam turbine. The thermal energy at the outlet of the turbogenerator still contains potential energy and can be used to dry the wood before it is fed into the industrial microwave oven, which increases the efficiency of the carbonization oven. Based on these data, the gross yield of this system is calculated using Eq. 5.

$$\eta = \frac{100 \text{ x Generated electric energy}}{\text{Total thermal energy}} = \frac{100 \text{ x } 5{,}65 \text{ MWh electric}}{11{,}75 \; MWh\ thermic} = 48\ \% \qquad (5)$$

The Figure 6 shows the proposed combined cycle.

Figure 6: Combined cycle with com NCG and CG (Bio-oil).



Source: Authors.

The Figure 6 represents the proposed electricity generation system, that is, the combined cycle. To the left of the figure, you can see the total amount of wood introduced in the oven, as well as the total effluents and coal generated by the UPEC-250 oven. The combined cycle is at the center of the figure, highlighted as thermo-electric, where there is the gas turbine coupled with an electric generator, producing electricity through the CG and NCG and after, the recovery boiler being fed with the combustion gases from the gas turbine. In the recovery boiler, water vapor is generated to move the steam turbine and generate electricity through an electric generator connected to this turbine. To the right of the figure, the sum of electrical energy generated by the electric generators attached to each turbine is shown, as well as the gross performance of the system. The produced coal is used for feeding a blast furnace used to produce pig iron.

4. Conclusion

This study presents a furnace that has an average yield in the production of coal, CG, and NCG, approximately of 33%, 40%, and 27%, respectively. It is also capable of recovering all the effluents generated in carbonization of wood and produce electrical energy with them, taking advantage of the available thermal energy present in these products, converting 11.75 MWh thermal into 5.65 MWh electrical. It demonstrates an efficient system using the combined cycle, because, if the systems are used individually, they will present average yields around 26% or 30%, with the use of the gas turbine or the recovery boiler coupled to a steam turbine, unlike the combined cycle which is 48%, as shown.

With the use of the effluents from the carbonization of wood to produce energy (condensable gases and non-condensable gases), the cost of electric energy that supplies the microwave oven in this carbonization process is compensated and still produces spare electric energy. Just because, with the use of microwave ovens in the manufacture of coal, it is possible to make full use of the effluents - liquid and gaseous - to produce electrical energy. This is a great gain compared to the use of old coal manufacturing technologies, which, on average, 25% of the raw material is used and the remaining 75% is discarded in the atmosphere and in the soil.

Although bio-oil can be easily burned in boilers and with evident advantages over the other fuels, the focus of the analysis was established on a system with higher energy efficiency, which is the combined cycle. Regarding the use of the combined cycle for power generation, we can say that this system proved to be quite adequate, as it uses a turbine specially designed to burn both condensable and non-condensable gases. The exhaust gases from this turbine feed into a recovery boiler generating water vapor for the consequent production of mechanical energy in a steam turbine. In addition, in the combined cycle, the exhaust gas from the recovery boiler can be used in a wood dryer to decrease the moisture of the wood fed to the furnace. Therefore, the result is an increase in the yield of the products generated in the carbonization by the micro- waves.

For future work, it is possible to verify the possibility of using other, more economical techniques to reduce the viscosity of the bio-oil, in addition to reducing the acidity of this liquid. in addition, a study can also be carried out to extract the acetic acid component from the bio-oil, as it is widely used in industry, such as in the manufacture of vinegar, solvent, used in dyeing, perfumery, in the production of vinyl acetate (production of PVA plastic), medicines, among others.

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