ENERGY RECOVERY FROM CHARCOALPRODUCTION IN BRAZIL: CASE STUDY

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Abstract. *Brazil is the largest world charcoal producer thanks to its use in the pig iron industry, the second world exporter. Most of this charcoal comes from the slow pyrolysis of eucalyptus wood produced in reforestation farms. Generally, the carbonization technology of Brazilian big companies comprises the use of a batch process using large auto-thermal brick kilns, based on the Missouri kiln technology. Unfortunately, the residual gases produced by this process, which states for more than 30% of wood energy, are wasted, decreasing the air quality and producing a negative environmental and social impact. This work assess the possibility to recovery this energy to produce electricity, and issues the topics related to the use of a very lean gas fuel, which varies its composition over time, and the lack of water to be used as cooling mean for the thermodynamic cycles in the eucalyptus farms. Results, based on a case study, shows that 25,5% of the initial wood energy can be recovered for power generation using a cluster batch system. The use of a steam power plant coupled with an air-cooled condenser showed a electricity potential of 0,8 to 1* MWh_e *per ton of charcoal produced, recovering from 5,6 to 6,6% of initial wood energy content. This system is able to offset the global warming up to 2,60 tCO2eq. per ton of dry charcoal produced, considering the methane abatement present in the pyrolysis gas and the electricity export to the Brazilian electrical system.*

Keywords*: Energy Recovery, Charcoal, Biochar, Slow Pyrolysis, Global Warming*

2. INTRODUCTION

The steel industry is an important CO_2 emitter and is therefore being called to mitigate climate change, by reducing the Green House Gases (GHG) of its on production processes and funding the infrastructure of a new low-carbon economy. The steel production, based on the use of mineral coal coke, generates about 11% of global anthropogenic CO_2 emissions annually (Shimaoka, et al., 2016) what can be partially mitigate by the usage of carbon-neutral charcoal sourced from sustainable forests and other biomass feedstock (Suopajärviaet al., 2013). On average, around 2.2 t of CO_2 is emitted for every t of crude steel produced in the world (IPCC, 2014).

In historic times, the iron industry initially developed based on local proximity of forests to supply the charcoal for the production of pig iron (primary iron) in the first's blast furnaces. Early in the 18th century, the cheaper and less labor-intensive coal coke quickly replaced its use. Brazil was the only country still capable to produce charcoal cheap enough to compete locally with coke. Historically, this was possible due to a conjunction of local factors, like plentiful reserves of iron ore, high availability of wood, low-cost workforce and the lack of good quality coal to produce coke.

Nowadays, Brazil is the second larger exporter of pig iron, losing only to Russia, but is the only one that can produce the so-called "green pig iron" in large scale, based on the use of renewable charcoal, instead of coal coke, originated form planted and renewable forests (Nogueira et al., 2009). In addition, the quality of the pig iron produced with charcoal is higher because it contains little amounts of sulfur, allowing the steel industry to command attractive prices, producing about 8 million tons of pig iron using charcoal, 25% of national production, and generating an income of US$ 2.1 billion per year. About 40% of this pig iron is exported to other countries (MME, 2015).

Currently, this is only possible due to the high productivity of eucalyptus wood from cloned trees, which makes this activity economically feasible and environmentally friendly, also being an important factor of social inclusion, requiring intensive hand-labor, being, therefore a major generator of jobs. While using charcoal as thermo-reducer instead of coke, the pig iron industry triples its capacity to generate jobs in establishment and maintenance of forests, as well as in the production of charcoal (Sindifer, 2012; CGEE, 2014). As well, when charcoal originates from planted forests, it is possible to obtain carbon credits as Certificated Emissions Reduction (CERs) under de Clean Development Mechanism (CDM) (Plantar, 2006; Sonter et al., 2015).

The Brazilian production of green pig iron is concentrated in two regions, Minas Gerais State (Southeast), Carajás (East Amazonas) and Maranhão States. The State of Minas Gerais houses 80% of cold pig iron plants (independent producers). Brazil had 5,56 million hectares of planted eucalyptus forests in 2014, using about 15% to produce charcoal for the steel sector (IBA, 2015). However, the potential is much bigger, according to Piketty et al. (2009) the country has 77 million hectares of land potentially available for plantations that would feed a charcoal supply-chain to the steel industry.

Unfortunately, in the past, the quick growth in demand for charcoal has generated pressure on the Brazilian native forests, causing emission of greenhouse gases and loss of biodiversity. Later on, the use of native forests were gradually replaced by planted forests and nowadays only part of charcoal is still from native wood. In 2014, 81% of the wood involved in charcoal production derived from planted trees (IBA, 2015). Significant efforts from environmental groups, the establishment of regulations and certification procedures are working together to control the use of native woods, and were able to decrease rapidly its use in recent years (Arimaa et al. 2014). Today, the Brazilian pig iron industry has committed to finally changing its ways. Minas Gerais passed a law that prohibits charcoal collection of native forests by 2018. In 2012, all seven pig iron companies in the Brazilian state of Maranhão signed an agreement not to source wood charcoal that comes from forest destruction. According to Keenan et al. (2015), the net rate of forest loss has significantly declined in Brazil between 2010 and 2015, and now is only 40% of the rate in the 1990s.

Still, the process of charcoal production in Brazil is undeveloped and inefficient. The renewable charcoal is produce by the slow pyrolysis of planted biomass (charring), which produces charcoal, a cheap and high quality renewable biofuel, and condensable and non-condensable gases emitted directly into atmosphere, decreasing air quality and wasting a source of renewable energy. These gases represent about 30 to 50% of the initial energy content of the wood (Miranda et al., 2013). For the Brazilian context, it is estimated that 4 million toe are wasted annually in the country in the form of carbonization gases. Besides, these gases contain reactive compounds, such as carbon monoxide, methane and PAHs that can be harmful to the local workers and communities (Gomesa and Encarnação, 2012).

Usually, the small manufactures of charcoal uses poorly mechanized masonry kilns highly dependent on human labor. The big companies generally use big mechanized auto thermal rectangular kilns, based on the Missouri kiln technology, capable to produce up to 200 t of charcoal monthly.

Today, several Brazilian charcoal industries are concerned with the environmental constrains related to the pyrolysis gases and are investing in the development of afterburners to control emissions of the carbonization system and evaluating the best way to benefit from its energy, including options like wood drying, self sustain kilns and electricity generation. Although, this study focus only on the energy recovery of the carbonization gases through its burning, using the heat generated to produce power, based on a case study, the carbonization unit of Plantar Siderúrgica S.A located in Itacambira, north of Minas Gerais State.

These gases can be used to produce heat and power in thermodynamic cycles like Organic Rankine Cyle (ORC), Steam Cycles or Externally Fired Gas turbines (EFGT). Brazil has already EFGT an experiment in course at the city of Martinho Campos (Minas Gerais State) with a 100 kW micro turbine that uses the gases produced by charcoal kilns similar to the ones evaluated in this study.

3. CASE STUDY

The charcoal comes from a eucalyptus farm located in a transition area between the Cerrado and the Caatinga ecoregions. It has an average elevation of 1100 m above sea level, an annual rainfall of 917 mm, and 22.4 °C of mean temperature. The total farm area is 36,092 hectares, of which 38% are in environmental protection regime, with wildlife corridors and legal reserve, surpassing the Brazilian environmental laws. Today, there are 20,488 hectares of planted eucalyptus forests with 3x3 m planting distance, generating a wood with average basic density of 0.48 g/cm³, and a charcoal with 22.2% of volatile content, 0.8% ash and 77.0% fixed carbon (mass percentages, dry basis), using eucalyptus hybrid clones "urograndis". The farm produces about 705,000 cubic meters of eucalyptus per year; however, this amount may vary according to farm productivity subject to climatic variations, especially the rainfall. Charcoal productivity is about 130,000 metric tons per year.

On average, the wood has an HHV of 19,2 MJ/kg and an initial moisture of 50-55% (wet basis) after the harvesting, which is naturally dried to 30 to 20% in the field. The Charcoal has a HHV of 31,5 MJ/kg and a moisture of 3,8%.

The wood is conveyed to a central Carbonization Unit (CU) with 120 self-sustaining batch reactors (named as rectangular kilns), capable to carbonize 200 tons of wood per cycle each one. In each unit, the complete carbonization cycle last 12 to 18 days, and comprises three stages: loading and unloading (1-2 days), pyrolysis (4-6 days), and cooling down (8-12 days). The kilns have an average mass yield of 30 to 35% (dry basis), considering the relation between the dry carbonaceous residues (charcoal) output and the total dry wood input.

3. ENERGY POTENCTIAL

While charcoal is a high-energy-density material, the slow pyrolysis gas is a low-energy-density product with LHV below 6 MJ/kg (Laird et al., 2009). Therefore it has been neglected as a valuable source, with few studies focused on its application (Crombie and Mašek, 2014; Lee et al., 2014; Miranda et al., 2013; Adrados et al., 2013; Fagernäs et al., 2012), which is even rare in the field of traditional charcoal making with focus on electricity production or biomass drying.

The charcoaling gases are made of Condensable Gases (CG) and Non-Condensable Gases (NCG) fractions. The condensable part is a mix of water, soluble light hydrocarbons (like Methanol, Acetic Acid and Furfural) and insoluble heavy tars. The NCG comprises combustibles such as CH_4, CO and H_2, and non-combustibles like CO_2 and air. The precise composition present in the mixture will depend on the feedstock as well as the final temperature and heating rate of pyrolysis (Antal et al., 1996).

Other issue related to the gases potential arises from instability in the availability of energy, associated with two characteristics. First, its constitution changes over time, going from an initial low-energy phase with high water content, to a later phase with an energy-rich gas following the carbonization phases: pre-heating, drying and pyrolysis. Second, in the batch cycle the kiln needs to be cooled to avoid the charcoal spontaneous combustion, unloaded and loaded with fresh wood, stages where there is no gas production. To overcome this instability several charcoal kilns can be operated in sequence, in a cluster system, in order to stabilize the energy output (Miranda et al., 2013).

To evaluate the energy potential of the carbonization gases in situ analysis were performed to measure its composition, temperature and flow. The Integrated Laboratories of Chemistry, Pulp and Energy from the University of São Paulo were responsible for the analysis. All procedures were conducted in accordance with the UNFCCC standard AM0041 version 1: "Mitigation of Methane Emissions in the Wood Carbonization Activity for Charcoal Production", an approved and registered standard for CDM projects under the climate change convention.

The average combustible gas production of a rectangular kiln is shown in Tab. 1. Fig.1 displays the gases production during the entire carbonization process, excluding the air content.

Table 1. Average composition of the carbonization gases produced in the rectangular kiln.

	First 60 hours				Second 60 hours			
	Mean	Max	Min	RSD[1]	Mean	Max	Min	RSD[1]
Air	72.9%	85.5%	63.5%	4.9%	71.0%	79.1%	63.1%	4.8%
CO_2	0.1%	0.1%	0.0%	0.0%	0.2%	0.4%	0.1%	0.1%
H2	9.3%	10.1%	8.5%	0.4%	10.8%	12.5%	9.4%	0.9%
CO	2.7%	5.5%	1.2%	1.0%	4.4%	6.0%	3.3%	0.8%
CH_4	0.4%	0.6%	0.3%	0.1%	0.9%	1.3%	0.6%	0.1%
CG[2]	14.7%	22.4%	4.4%	4.3%	12.6%	22.2%	5.9%	4.0%

Values in mass fractions / [1] Relative Standard Deviation / [2] Condensable Gases

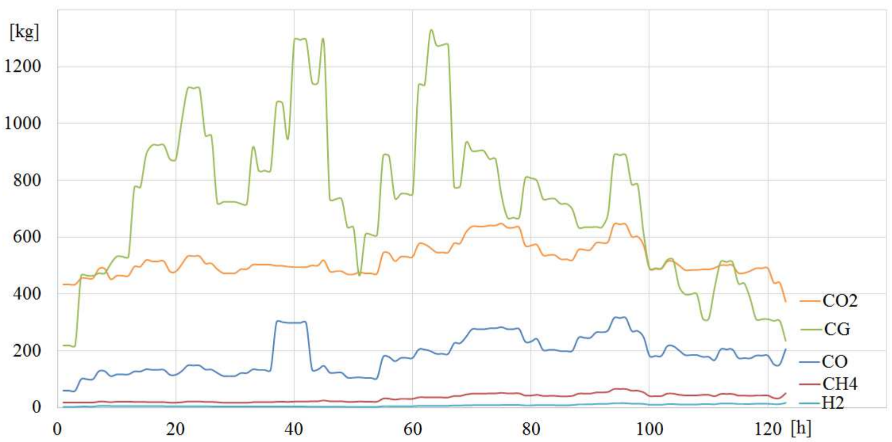

Figure 1. Gases average emission behavior during the carbonization process.

As can be notice, the gases includes major amounts of air, CO_2, and condensable gases which comprises around 85% of water, 1,4 % of heavy tars and the reminder light hydrocarbons like Methanol (about 1%). This means that this is a very lean fuel in such a degree that it can show difficulty to burn, mainly in the initial stages of the carbonization where the concentration of combustible gases (CH_4, H_2, CO) are lower. To reach the lean flammability limit two strategies are used, pre-heating the gases, and mixing it with rich gases form other kilns that are in an advanced stage of carbonization, producing a richer fuel. Today, the combination of these strategies are able to burn it, but this technology is still under development, and steps forward need to be taken to reach a commercial stage, capable to burn the gas efficiently and in the long-run.

Due to its great size, the carbonization process inside the kiln is not homogenous. Therefore, occurrences like drying, combustion and pyrolysis happen simultaneously, generating a nonlinear gas production but with a tendency to produce a better gas along the process, notable after the half time of carbonization, about 60 hours.

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The enthalpy and heat capacity at constant pressure for the standard state in terms of polynomial equations were used to estimate the non-condensable gases calorific value and energy content. For that, the NASA polynomial formula and parameters was adopted (McBride et al., 1993). For the condensable gases, the Joback and Reid predictive method was applied (Joback and Reid, 1987). The average flow and calorific value of the gases during the carbonization is shown in Tab. 2 and Fig. 2.

Table 2. Average flow and calorific value of the carbonization gases produced in the rectangular kiln.

		First 60 hours				Second 60 hours			
		Mean	Max	Min	RSD	Mean	Max	Min	RSD
Flow $_{NCG}$	kg/h	4498	4808	4364	78	4384	4480	3754	99
Flow $_{CG}$	kg/h	786	1294	219	261	646	1276	235	242
HHV	kJ/kg	1110	1572	566	223	1589	2136	1278	202
LHV	kJ/kg	1035	1481	526	211	1713	2305	1388	217

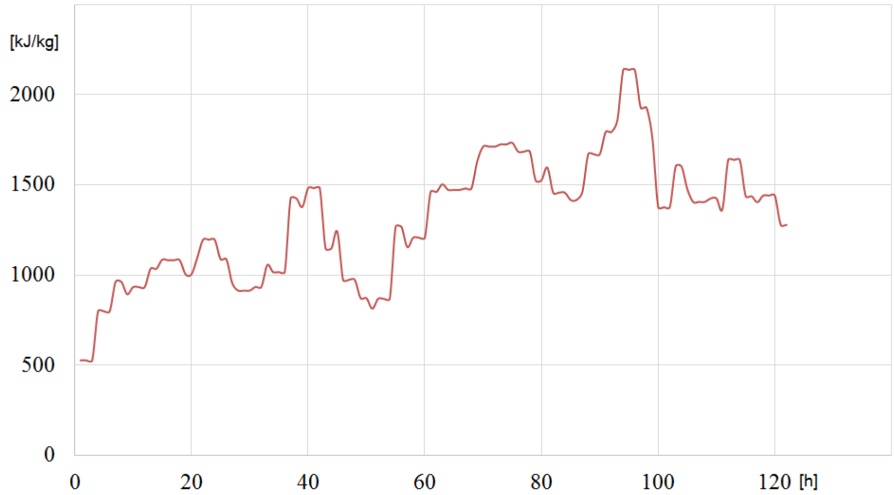

Figure 2. Average carbonization gases LHV behavior during the carbonization process in the rectangular kiln.

To assure a constant energy flow to the generator set, the kilns operation need to be set up into a cluster system. So the continuous use of 120 kilns was take into consideration. These kilns had their cycles adjusted in order to maintain as far as possible a constant energy flow at the entrance of the central burner or boiler. Figure 3 displays the idea of the cluster-operating scheme.

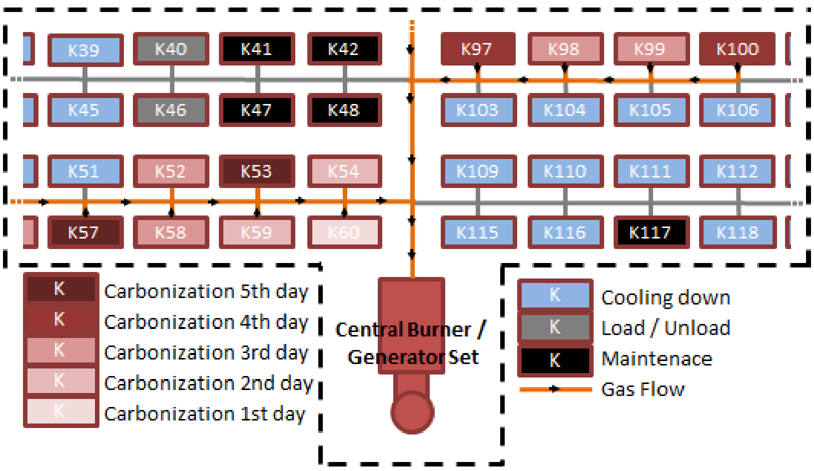

Figure 3. Rectangular kilns operation in cluster.

In Figure 3, can be observed that the kilns are in different stages, and only the ones in carbonization are able to send gases to the generator set. The others, which are in cooling or in maintenance, will be able to produce gas only when these stages are completed.

The calculations were performed in a software tool developed in Excel®/VBA, which calculates the thermal power of the cluster according to the kilns operation sequence and gas production. The program uses data on the gases generated by the cluster, each hour, to calculate automatically the necessary information for the study, such as LHV and thermal power available. Hence, the program performs the enthalpy balance between the reagents and products of combustion, considering the excess air, gases inlet temperature, the temperature of the combustion air flow, and other factors.

The tool enable to find the available power of the cluster based on the evaluation of different operation sequences, defining the one capable to guarantee the smallest power standard relative deviance. For that, it was considered that the kilns are identical and have the exactly same gases output and carbonization time. The analysis results are shown in Tab. 3 and Fig. 3.

Table 3. Average kiln cluster energy potential and characteristics during the cycle operation.

Mean Power	65265 kWt	Mean Flow	49,7 kg/s
Minimum Power	63472 kWt	Δt Kilns	3,6 h
Maximum Power	67647 kWt	Mean LHV	1312 kJ/kg
RSD	697 kWt	Mean HHV	1412 kJ/kg

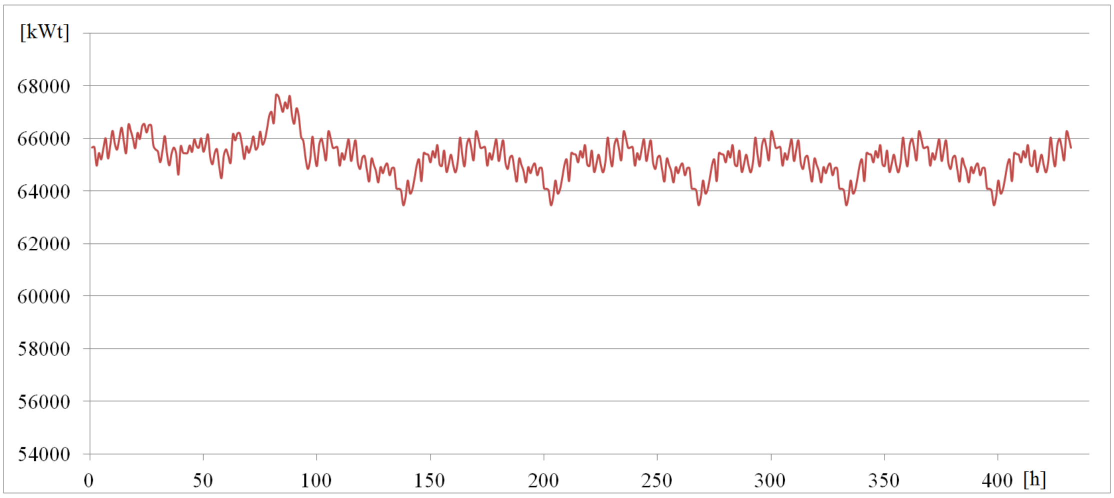

Figure 4. Estimated kiln cluster available thermal power during the cycle operation.

As the kilns are set to have the same behavior, the minimum power RSD occurs when the kilns are set up to ignite with 3,6 hours' time delay between then, exactly the cluster time (432 hours or 18 days) divided by the number of kilns in operation (120).

As shown in Tab. 3, the cluster thermal power varies from 63 to 65 MWt. However, in the development of a thermoelectric project, generally, should be ensured that the generator set can receive one hundred percent its required thermal power, which normally assures a better economic feasibility. Thus, a thermal power available of 57,125 MWt was considered, based on the minimum 63 MWt and allowing for a 10% security margin, adopted to account for kilns that can be out of the cluster synchronism or in maintenance, considering the historical kilns usage for the past 8 years and the burner efficiency. This power output means that about 25,5% of the wood energy input can be available for electricity generation in a thermodynamic cycle (Based on the wood HHV).

During the cluster operation cycle 5.515 t of dry charcoal will be produced using 18.128 t of dry wood, and 450 t of Methane will be burned, considering a 90% burning efficiency as stated above. The methane come from a biogenic source and has a global warming potential of 25 (IPCC, 2007), so the average global warming potential reduction that arises from the charcoaling gas burning is 2,05 $tCO_{2eq.}$ per t of produced charcoal.

4. CYCLE MODELLING

Assure of the available power, the use of a convectional steam Rankine cycle was initially preferred, but other thermodynamic cycles will be evaluated during the course of this research, like the ORC and the EFGT. Technologies such as the internal combustion (IC) engines and the direct-fired gas turbines do not couple the use of a lean fuel like the carbonization gas (Miranda et al., 2013). As there is no availability of water for cooling the thermodynamic cycle in the carbonization unit, the use of a air-cooled condenser with direct steam condensation was chosen, due to its greater efficiency (Milman and Anan 'ev, 2016).

The disadvantage of this system is in the air condenser fan power consumption, and the increased pressure at the turbine steam outlet, factors that can diminish the cycle efficiency at an average of 3 to 10% over the conventional water cooled condenser. Approximately, at every 1 psi (~ 7 kPa) of pressure increase about 0.5% efficiency in the turbine is lost (Tang et al., 2013). Furthermore, the costs related to air condensation system may be 5 to 10% higher compared to the conventional water system. However, the use of such solution has grown worldwide due to factors such as water scarcity and high fuel transportation cost, for example, China now produces over 100 GWe with this technology (Maulbetsch and DiFilippo, 2006).

The cycle was modeled using GateCycle™ v. 5.51.0.r, which is a General Electric software able to predict design and off-design performance of power plants. To estimate the air fan power consumption, the air cooled condenser model of Hudson Products Coorporation was used (Hudson, 2016).

Modeling was performed for two scenarios of pressure and temperature at the steam turbine inlet, 22 bar / 300 ° C, 45 bar / 450, considering the Brazilian market availability for this power range. Figure 5 shows the cycle developed at GateCycle.

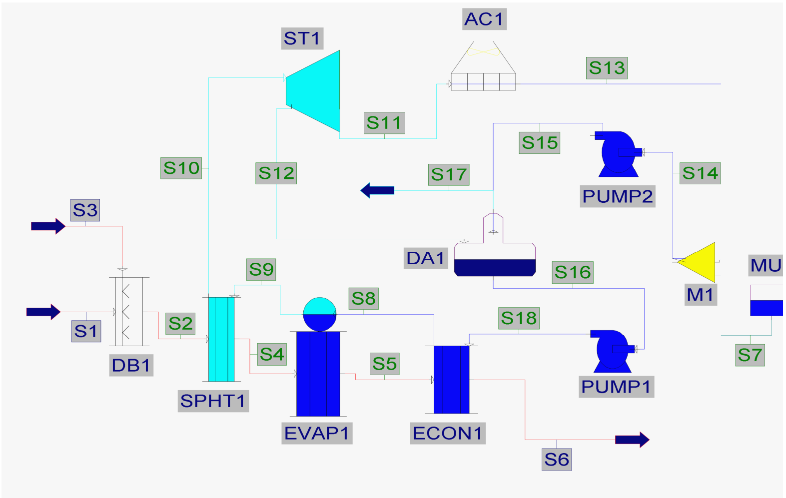

Figure 1. Modeling of the steam Rankine cycle in GateCycle.

The main parameters and assumptions in the modeling can be found below (Gadhamshetty et al., 2006;.. Rupeshkumar et Al., 2010; Srinivas et Al., 2010;. Lora and Nascimento, 2004). Table 4 shows the simulation results.

1 - Atmospheric condition is taken as 24,5 °C and 89.072 kPa (local conditions);
2 - The air condenser pressure is 15 kPa and the deaerator is 137.9 kPa;
3 - The isentropic efficiency of the steam turbine is 82%;
4 - The isentropic efficiency of the pumps is 70%;
5 - The efficiency of the generator is 96%;
6 - Boiler efficiency is 85%;

Table 4. Modeling results of Steam Rankine Cycle with an air-cooled condenser.

Case	Parameters P bar	T °C	Electrical Efficiency %	Gross Power MW	Net Power MW	Fan Power Consumption kW	Pump Power Consumption kW	Generator Loss kW	Steam Flow kg/s
1	45	450	24,0	14,7	13,7	302	116	586	17,5
2	22	300	20,4	12,5	11,6	328	63	501	29,5

The cycle efficiency ranged from 20,4 to 24%. The choice of the pressure and temperature parameters at the turbine inlet, and consequently the efficiency, will depend on a technical and economic analysis, which must take into account the availability of on-site equipment, capital costs, investment costs and O&M. Considering a capacity factor of 90% at the steam power plant (Rupeshkumar et al., 2010), it will be produced on average 4510 to 5715 MWh of electricity in the cluster cycle time (18 days), or 0,818 to 1,036 MWh_e per ton of charcoal produced. This means that 7% of the wood energy can be recovered in the form of electricity, from a first law perspective energy balance. According to MCT (2016), the Brazilian electric system produce about 0,5317 tCO2eq/MWh in 2015. Adding to the GWP reduction thought methane burning, as calculated in the previous section, the carbonization gas burning coupled with electricity production can offset 2,48 to 2,60 tCO_{2eq}. per t of charcoal produced.

5. CONCLUSIONS

Besides being one of the fewer options to directly reduce the green house gas production of the iron production chain, the green pig iron industry can be well improved by the energetic use of carbonization gases produced in the wood pyrolysis. This can offer many benefits including commercial opportunities, employment diversification and increased incomes in rural areas for charcoal producers, as well as reduction of greenhouse gases emissions and renewable energy capacity.

In this work, a cluster system with 120 carbonization batch reactors was assessed. It was found that 25.5% of the wood energy content could be available to be used for power production or other energetic uses. The methane burned in the cluster can offset the global warming by means of 2,04 tCO_{2eq}. per ton of dry charcoal produced.

To convert the charcoaling gas energy into electricity a conventional steam Rankine cycle coupled with an air-cooled condenser was taken as primary option. The system showed an electrical efficiency between 20 to 24% (depending on the steam parameters at the turbine inlet), being capable to produce 0,818 to 1,036 MWh, and increasing the GWP reduction to 2,40 to 2,50 tCO_{2eq}. per ton of dry charcoal produced, considering the electricity export to the Brazilian electrical system.

Many poor regions in the World, that uses charcoal for cooking and heating, suffer from deficit on electricity access, and could benefit from this kind of technology. For that, small-scale energy conversion technology fitted for the pyrolysis gas utilization must be accessed in future researches on this field. Besides a technological comparison, a life cycle analysis should be performed in the future to evaluate the charcoal production chain and the energetic use of its byproducts.

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7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

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