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Research paper

Study of biomass applied to a cogeneration system: A steelmaking industry case

Tiago Luís Oliveira [a,*], Paulo Santos Assis [a], Elisângela Martins Leal [b], Jaderson Rodrigues Ilídio [a]

[a] Department of Metallurgical Engineering, School of Mines, Federal University of Ouro Preto, Minas Gerais, Brazil
[b] Department of Control, Automation and Mechanical Engineering, School of Mines, Federal University of Ouro Preto, Minas Gerais, Brazil

HIGHLIGHTS

- A theoretical study of a cogeneration system was carried out.
- The study was applied to an electric arc furnace steelmaking process.
- The ultimate analysis was used to determine the lower calorific value of the biomass materials.
- The study used a Rankine cycle and applied the First Law of Thermodynamics.
- Biomass can replace natural gas in the EAF steelmaking process.

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ABSTRACT

In this paper, a theoretical technical study was carried out using Brazilian available biomass materials (rice husk, coffee husk and elephant grass) compared to natural gas applied to an electric arc furnace (EAF) steelmaking process. Rice and coffee husk are biomass residues from the agriculture while elephant grass (*Pennisetum Purpureum Schum*) is an abundant, fast growing plant, which is used for cattle breeding. The ultimate analysis of the biomass materials was carried out in the research department of a Brazilian Steelmaking Industry. The results of the ultimate analysis were used to determine the lower calorific value and the mass flow rate of the biomass materials used in the cogeneration system. The actual steelmaking process uses natural gas to both improve the "cold spots" inside the furnace and contribute to minimize the use of electrical energy in the heating process. The feasibility study considers a combined heat and power plant (CHP) to generate electricity and heat to the electric arc furnace (EAF) process. This study used the First Law of Thermodynamics to determine the operational parameters of the cogeneration plant considering three cases of different operational parameters in the Rankine cycle. The technical results show that the natural gas consumption and exhaust gas generation were the lowest among the fuels in the three cases analyzed. Regarding the exhaust gases generation, some aspects should be highlighted: the combustion of biomass is considered carbon neutral; the exhaust gases generated may be used to scrap preheat; also, biomass is a renewable fuel in contrast with natural gas, which is a fossil fuel. Thus, an economic analysis, considering only the operational cost of the plant, was conducted exhibiting that elephant grass had the lowest operational cost, accounting for a reduction of about 9% in the second case and 15% in the third case compared to natural gas. Although the biomasses have lower LCV than natural gas, they showed a great promise of their use in the EAF process indicating their feasibility as an excellent alternative for the process of producing iron.

1. Introduction

Steel is essential to the modern world, and its use is critical in enabling man to move towards a sustainable future. In 2012, more than 1.4 billion tons of steel were manufactured, 45% of steel were

* Corresponding author. Tel.: +55 31 8638 0919.
E-mail addresses: tiagoluiscg@yahoo.com.br (T.L. Oliveira), assis@em.ufop.br (P.S. Assis), elisangelamleal@decat.em.ufop.br (E.M. Leal), jaderson.ilidio@yahoo.com.br (J.R. Ilídio).

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Nomenclature

Cp_{fg}	mean specific heat at constant pressure [kJ/kg K]
E_{fuel}	thermal (chemical) power available in the fuel [kW]
h	specific enthalpy [kJ/kg]
ke	kinetic specific energy [kJ/kg]
LCV	lower calorific value [MJ/kg]
m_{fuel}	fuel mass flow rate [kg/s]
m_{steam}	steam mass flow rate [kg/s]
pe	potential specific energy [kJ/kg]
q	specific heat [kJ/kg]
Q_{boiler}	heat input at the boiler [kW]
Q_{cond}	heat transfer from the condenser [kW]
$Q_{process}$	heat transfer to the process [kW]
T	temperature [°C]
w	specific work [kJ/kg]
W_{BOP}	balance of plant electrical power required for the Rankine cycle [kW]
W_{net}	net work output [kW]
$W_{turbine}$	turbine work output [kW]
η_{boiler}	boiler efficiency [−]
η_{cog}	cogeneration efficiency [−]

Abbreviation

BF/BOF	blast furnace/basic oxygen furnace
CHP	combined heat and power
DRI	direct reduction iron
EAF	electric arc furnace
OHF	open hearth furnace
ORC	organic Rankine cycle

produced in China, 28% in the developing regions (excluding China) and 26% in the developed regions. There will be continuing growth in the volume of steel produced, particularly in developing areas such as Latin America, Asia, Africa and the Indian sub-continent, where steel will be vital in raising the welfare of developing societies [55].

According to Arens et al. [3]; nowadays there are four main routes to produce steel. The first route uses blast furnace and basic oxygen furnace (BF/BOF) to produce steel from iron ore. The second route uses scrap as raw material and re-melts it in the Electric Arc Furnace (EAF). The third route is the direct reduction iron (DRI), where iron ore is reduced with the help of gas (usually natural gas) and then it is fed to the EAF. The fourth route is the smelting reduction, which is a technology that produces crude steel from iron ore without the need of coke production as used in the blast furnace. Fig. 1 gives an overview of the steel producing routes.

According to Karali et al. [26]; iron and steel industry is one of the highest energy and emission intensive sectors. Iron and steel sector accounts for about 5% of the total world carbon dioxide (CO_2) emissions. In particular, the blast furnace/basic oxygen furnace route, which uses 13–14 GJ per ton of iron produced, is much more energy intensive than the scrap/electric arc furnace route, which uses 4–6 GJ per ton of iron produced when using 100% scrap. The emissions of about 1.9 tons of CO_2 per ton of steel produced are attributed to this sector [41].

In 2013, more than 30% of steel produced worldwide comes from the Electric Arc Furnace (EAF) process [2]. This process consumes more than 40% of energy, which comes from fossil fuels such as natural gas and coal. Natural gas is used in a dedicated burner during the melting of the charge. The introduction of biomass in steel production is considered a good option to reduce the environmental impact and greenhouse gas emission [14]. Moreover, it can be considered an economical option related to the increasing prices of oil, coal and the market of CO_2 quotes. According to Brandt et al. [9]; enhancing energy efficiency of steel production processes contributes to the reduction of primary energy demand and thereby the achievements of climate protection targets. At steel plants up to 35% of the required energy exhausts via the off-gas channel system, revealing a great potential to increase the total

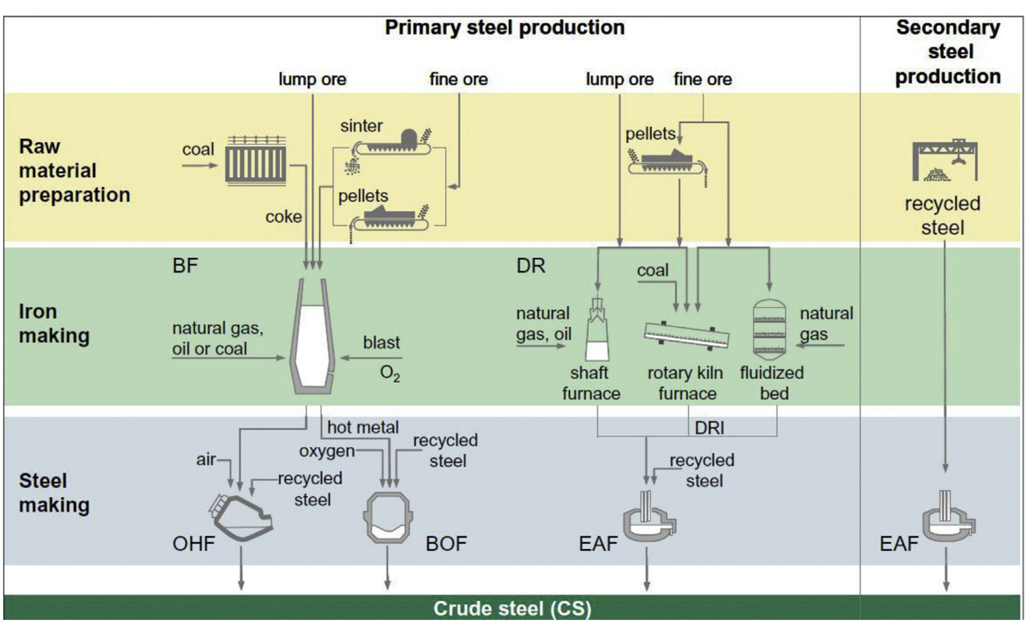

Fig. 1. Overview of steel production routes [55].

energy efficiency. This potential can be used in a cogeneration system or preheating the scrap, for example.

Chen et al. [15] showed scenarios of China steel production until 2050. Fig. 2 displays the model prediction of the total steel production and EAF steel production from 2010 to 2050 in China. The baseline scenario (BP) was set as the penetration rate of energy-saving technologies will reach 75% and 50% for key and non-key producers, respectively, in 2050. Pulverized coal injection will reach the currently advanced level of 180 kg/t. The share of pig iron in EAF will decrease to 15% in 2050. The collection rate will increase to 50% in 2050. Low production (LP) scenario depicts the saturation level of products in each industry will be 10% lower than in the baseline scenario, while the expected lifetime of buildings is 10% longer. The penetration rate of energy saving technologies will reach 50% and 30% (except coke dry quenching and top pressure recovery turbine for key enterprises) for key and non-key producers, respectively, in 2050. The pulverized coal injection will reach 150 kg/t. The high production (HP) scenario describes the saturation level of products in each industry will be 10% higher than in the baseline scenario, while the expected lifetime of buildings is 10% shorter. The penetration rate of energy-saving technologies will reach 90% and 70% for key and non-key producers, respectively, in 2050. The pulverized coal injection will reach the international advanced level of 200 kg/t. The results displayed that the EAF steel production will increase continuously from 62 Mt in 2010 to 254 Mt in 2040, then decrease to some extent to 241 Mt in 2050, with its share in total steel production growing from 9.8% to 45.6%. Steel scrap consumption does not vary widely before 2025 under different scenarios, and will achieve the peak between 2040 and 2050. By 2050, steel scrap consumption will hit 253.0 Mt (HP scenario) and 206.5 Mt (LP scenario), and steel scrap ratio in steel production will reach 411.5 and 498.2 kg/t steel respectively. As a result, EAF steel production will get around the peak during 2035–2045, approximately 20–25 years later than the peak of steel production.

Morfeldt et al. [35] addressed how a global climate target may influence iron and steel production technology deployment and scrap use. They used a global energy system model (ETSAP-TIAM) and developed a Scrap Availability Assessment Model (SAAM) to analyze the relation between steel demand, recycling and the availability of scrap and their implications for steel production technology choices. Steel production using recycled materials has a continuous growth and is likely to be a major route in the long run. But, as the global average of in-use steel stock increases up to the current average stock of the industrialized economies, global steel demand keeps growing and stagnates only after 2050. The European Ultra-Low CO_2 Steel making (ULCOS) initiative aims at reducing CO_2 emissions from steel production (50%) indicates three technology options: (i) carbon capture and storage (CCS) with capture embedded inside in current steel production processes, based either on smelting reduction or direct reduction; (ii) decarbonizing of steel production using hydrogen steelmaking or electrolysis of iron ore; (iii) use of biomass possibly with CCS for negative emissions [6].

Strezov et al. [48]; Yellishetty et al. [56] and Terörde [49] discussed about iron ore and scrap steel reserves, as shown in Fig. 3. While iron ore reserves are limited to the natural distribution and quality of available iron oxides, the availability of scrap used in EAFs is limited to the end of life capacity of various steel products and replacement rates. It is apparent that the fraction of available scrap is less than 1% of the total reserves of iron ore; hence, despite the opposing trend of availability of both resources, iron ore will remain to be the major source for steel production in the next 10 years.

Bioenergy is a renewable and clean energy source that is derived from biomass. It has been attracting great attention these days due to the declining fossil fuel reserves and the ever-increasing greenhouse effects produced through fossil fuel utilization. In Brazil, sugar cane, coffee and rice are cultivated in large scale. In addition, elephant grass (*Pennisetum Purpureum Schum*) is cultivated for cattle breeding. This biomass is a kind of grass with high productivity (30–80 ton/ha/year) and fast growing. Although crops generate high amount of residues, it is narrowly practiced aiming energetic purposes. Farmers and entrepreneurs complain about residues bulkiness, storage difficulties and valuable applicability. In order to answer these complaints and due to their high productivity in a Brazilian agroindustry, rice husk, coffee husk, and elephant grass were considered in the study to fulfill the energy requirements of the EAF process. An interesting characteristic of these biomasses are their reasonable lower calorific value (LCV) and the capacity of being compacted into pellets or briquetted, which permits a significant increase on the lower calorific value and enhances storage and transportation, and the amount of thermal energy that can be potentially recovered.

Yunos et al. [57] studied the use of biomass/agricultural waste as a supplementary fuel along coal in the iron making and steelmaking industry. Also, the use of wood char in iron making has been extensively reviewed by Gupta [19]; Burgess [10] and Del-l'Amico et al. [16]. Charcoal has been used as a reducing agent in open submerged arc furnace for a number of years. Yunos et al. [57]

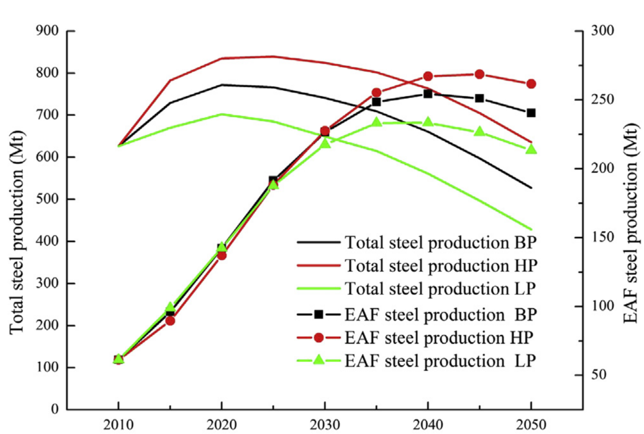

Fig. 2. Modeling results of the total steel production and EAF steel production from 2010 to 2050 in China [15].

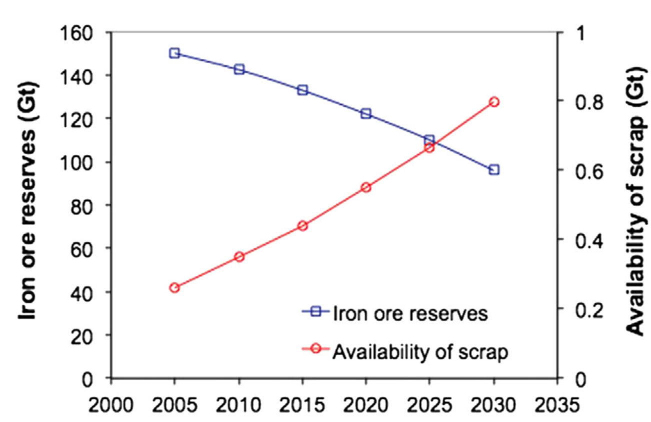

Fig. 3. Iron ore reserves and availability of scrap steel for recycling [48,49,56].

investigated the possibility of utilizing agricultural waste as carbon and energy resource in the electric arc furnace (EAF) steelmaking. Steelmaking requires carbon, which is currently supplied as coal and coke. In conventional EAF steelmaking, the generation of CO leads to slag foaming. During EAF steelmaking, slag foaming shields the arc struck between the electrodes and the bath, thereby reducing the radiation heat losses and improving the efficiency of electrical power input.

In conclusion, steel consumption will peak at around 2020 while EAF process will achieve 50% in the steelmaking process until 2050 [1]. Energy efficiency improvement and structural change will play different roles in near- and long-term CO_2 mitigations and energy consumption. The actual work aimed to evaluate the influence of the biomass use in a power generation system in order to mitigate the effects caused by the greenhouse gases, mainly CO_2. In addition, an evaluation was proposed in how the performance of a cogeneration system using biomass integrated to an EAF steelmaking process influences the power generation and exhaust gases heat recovery applied to its injection into the electric arc furnace.

2. Material and methods

2.1. Electric steelmaking process

According to Jones et al. [25]; the electric arc furnace (EAF) operates as a batch melting process producing batches of molten steel known “heats”. The EAF operating cycle is called the tap-to-tap cycle and is made up of the following operations: Furnace charging, Melting, and Refining, De-slagging, Tapping and Furnace turn-around.

The first step in the production of any heat is to select the grade of steel to be made. The EAF steel mills utilize steel scrap and up to 30 percent of other iron-bearing materials to produce steel. EAF steel plants primarily produce carbon steels as well as alloy and specialty steels. Preparation of the charge bucket is an important operation, to ensure not only proper melt-in chemistry but also good melting conditions. The scrap must be layered in the bucket according to size and density to promote the rapid formation of a liquid pool of steel in the hearth while providing protection for the sidewalls and roof from electric arc radiation.

The melting period is the heart of EAF operations. The EAF has evolved into a highly efficient melting apparatus and modern designs are focused on maximizing the melting capacity of the EAF. Melting is accomplished by supplying energy to the furnace, which can be electrical and/or chemical energy, as can be seen in Fig. 4. Electrical energy is supplied via the graphite electrodes and is usually the largest contributor in melting operations. Scotti [42] explains that scrap melting in the electric furnace takes place almost entirely as a result of the electric arc which is generated between the electrode and the scrap. Therefore, the cost of the finished product is considerably influenced by the prices of the electric energy and the graphite electrodes. According to Çamdali and Tunç [11]; the creation of heat is due to the electric resistance of the metal. To recycle steel, scrap and additives are fed from the top into the furnace and are heated by an electric arc. The temperature of the molten steel can increase up to 1800 °C. Oxygen and other fuel gases are injected in order to accelerate the melting process [3]. Basic chemical reactions in the electric arc furnace are given in Table 1.

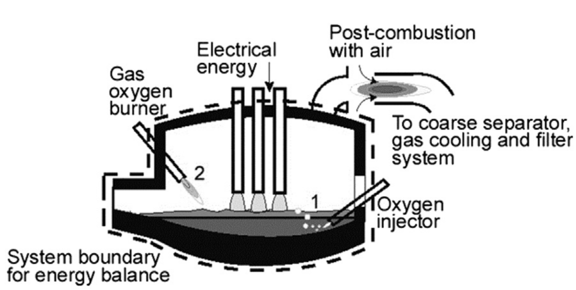

Fig. 4. Electrical energy and chemical energy sources comprising gas burners and oxidation reactions from oxygen injection in the EAF [28].

Chemical energy is supplied via several sources including oxy-fuel burners and oxygen lances. Oxy-fuel burners burn natural gas using oxygen or a blend of oxygen and air. Heat is transferred to the charge by flame radiation and convection by the hot products of combustion and within the charge by conduction. The reaction of oxygen with carbon in the bath produces carbon monoxide, which either burns in the furnace if there is sufficient oxygen, and/or is exhausted through the direct evacuation system where it is burned and conveyed to the pollution control system. Once the final charge is melted, the furnace sidewalls are exposed to intense radiation from the arc. As a result, the voltage must be reduced. Alternatively, creation of a foamy slag will allow the arc to be buried and will protect the furnace shell. In addition, a greater amount of energy will be retained in the slag and is transferred to the bath resulting in greater energy efficiency.

Refining operations in the electric arc furnace have traditionally involved the removal of phosphorus, sulfur, aluminum, silicon, manganese and carbon from the steel. De-slagging operations are carried out to remove impurities from the furnace. During melting and refining operations, some of the undesirable materials within the bath are oxidized and enter the slag phase.

Once the desired steel composition and temperature are achieved in the furnace, the tap-hole is opened, the furnace is tilted, and the steel pours into a ladle for transfer to the next batch operation (usually a ladle furnace or ladle station). During the tapping process, bulk alloy additions are made based on the bath analysis and the desired steel grade. De-oxidizers may be added to the steel to lower the oxygen content prior to further processing. This is commonly referred to as “blocking the heat” or “killing the steel”. Most carbon steel operations aim for minimal slag carry-over. A new slag cover is “built” during tapping.

The theoretical energy consumption to heat and melt one ton of iron from 25 °C to 1600 °C is about 387 kWh. In the early 1960s, furnaces with a capacity of 300–400 kVA/ton were employed. A major development occurred aiming to optimize the melting capacity of these furnaces, having attained the capacity installed of 600–750 kVA/ton up to over 1000 kVA/ton in the Ultra High Power (UHP) furnaces [4]. Fig. 5 illustrates the technological advance occurred from 1965 to 2005. This figure shows the technological

Table 1
Exothermic oxidation reactions and energy released during steel melt refining [28].

	Energy released
Reactions in melt	
$Si + O_2 \rightarrow SiO_2$	8.94 kWh/kg Si
$Mn + O \rightarrow MnO$	1.93 kWh/kg Mn
$2Cr + 1.5O_2 \rightarrow Cr_2O_3$	3.05 kWh/kg Cr
$2Fe + 1.5O_2 \rightarrow Fe_2O_3$	2.05 kWh/kg Fe
$Fe + 0.5O_2 \rightarrow FeO$	1.32 kWh/kg Fe
$C + 0.5O_2 \rightarrow CO$	2.55 kWh/kg C
$2Al + 1.5O_2 \rightarrow Al_2O_3$	5.29 kWh/kg Al
$Mo + O_2 \rightarrow MoO_2$	1.70 kWh/kg Mo
$S + O_2 \rightarrow SO_2$	2.75 kWh/kg S
$2 P + 2.5O_2 \rightarrow P_2O_5$	5.54 kWh/kg P
Reactions in gas phase	
$C + O_2 \rightarrow CO_2$	9.10 kWh/kg C

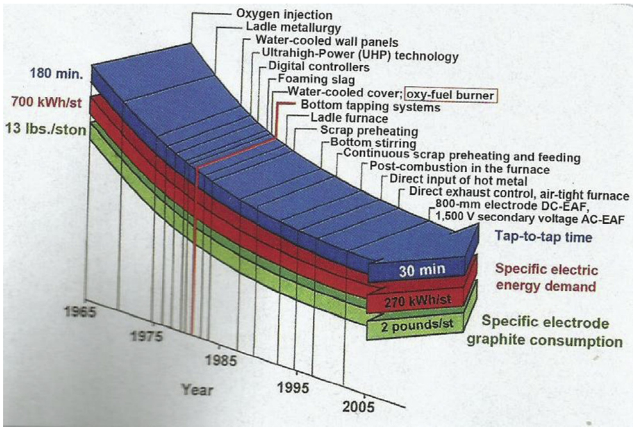

Fig. 5. Technological advances in the iron process [4].

advances such as oxygen injection, metallurgy ladle modifications, cooled panels, ultra-high-power technology, foamy slag, ladle furnace, preheating scrap, post-combustion control and exhaust system. For example, with the use of these technological advances, there was a reduction in the:

- specific energy consumption of about 52.3% (from 630 kWh/ton to 300 kWh/ton);
- running time of about 80% (from 180 min to 30 min);
- specific consumption of the electrode of about 85% (from 6.5 kg/ton to 1 kg/ton).

Kirschen et al. [28] developed a model of the EAF melting process applying a mass and energy balance. Fig. 6 shows the Sankey diagram of the results. The model was applied to industrial EAFs in steel industry charged with scrap or with mixes of scrap and direct reduction iron. The results showed a close agreement of the process parameters of sixteen electric arc furnaces and the sensitivity analysis indicated the importance of efficient foaming slag operation in EAF steelmaking.

The determination of the total energy input into an EAF is complex because energy is supplied to the EAF from multiple sources: Electrical energy as well as chemical energy that is released from the combustion of natural gas, liquefied petroleum gas or oil, and due to the oxidation of elements in the melt during refining, for example C, Si, Al, Fe, Cr, and Mn. The latter energy contribution is not only dependent on the oxygen input but also on the chemical composition of the raw steel melt and slag. The electrical energy requirements of EAF steel plants are in the range of 350–550 kWh/ton. Decreasing the mean electrical energy requirement and decreasing the mean specific natural gas consumption (i.e. 21 m^3/ton in 1991 to 10 m^3/ton in 2008) correlated with an increased specific oxygen consumption (i.e. 24 m^3/ton to 35 m^3/ton, respectively) [4].

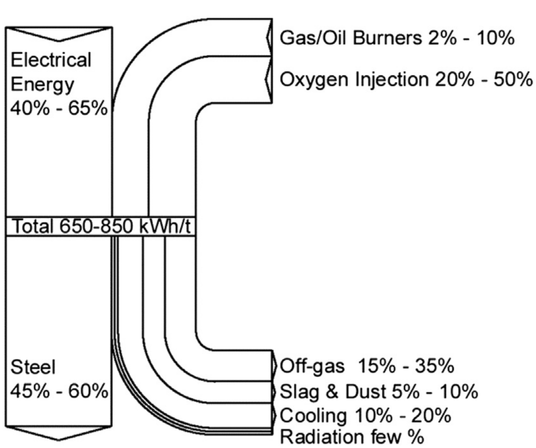

Fig. 6. Sankey diagram of an EAF process [28].

2.2. Biomass selection and characterization

Fossil fuels, including primarily coal, oil and natural gas, are considered to be non-renewable sources of energy considering the rate of their formation (millions of years) and consumption. Burning fossil fuels releases net carbon dioxide (CO_2) to the atmosphere. By contrast, biomass is a renewable resource and considered to be CO_2 neutral as the CO_2 released during combustion will be re-captured by the regrowth of the biomass. In addition, the lower emission of environmentally detrimental gases, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), during the combustion of biomass also plays a positive role in reducing global acid rain formation [24,33,58].

According to CONAB [13]; rice production in Brazil during 2012/2013 was 11.8 million of tons, the largest producer is the state of Rio Grande do Sul, accounting for 67.1% of the Brazilian national production. The planned production for the harvest 2020/2021 is 13.7 million of tons, which indicates the great potential of biomass energy. Approximately 22% of rice is constituted of husks, which accounts for more than 2.5 million of tons of rice husk produced in 2010/2011.

Coffee took an essential part of the Brazilian history. The plant, originally from Ethiopia, was first brought to Brazil by some French settlers who established in the state of Pará in the early 18th century. Brazil is the largest producer of coffee in the world, controlling more than 30% of the international production. The exports of coffee from the 2011/2012 harvest invoiced USD 7841 billion, a 5.6% increase compared to 2010. Around 10% of all the coffee exported was the Arabica type, followed by the Robusta variety with 5%. According to CONAB [12]; coffee production in Brazil in 2013 was of 3.0 million of tons. Minas Gerais state, located in Southeast Brazil, is the leader producer and exporter of coffee, accounting for 1.6 million of tons produced. The processing of one ton of coffee generates approximately 0.2 tons of coffee husks. The majority of small-scale farmers employ part of this residue direct on soil, aiming protection against erosion and fertilization.

Elephant grass is a plant species native to Africa with growth rates as high as 40 tons of dry biomass per hectare annual [54]. Over a century ago, the plant was also introduced to South America and Australia as forage for livestock. Elephant grass requires very little supplementary nutrients for growth and can be harvested up to four times a year, which makes this plant prospective for energy usage [37].

The chemical energy stored in biomass can be extracted through combustion to produce energy that can be used as heat or power. Sustainable managed biomass resources are considered green because they are renewable and do not contribute to global warming. Carbon dioxide generated from the combustion of biomass is consumed as plants regrow, so that as long as the resource is sustainable managed, the net contribution of carbon dioxide to the atmosphere is zero [31]. Combustion is a complex phenomenon involving simultaneous coupled heat and mass transfer with chemical reaction and fluid flow. Its prediction for the purposes of design and control requires knowledge of fuel properties and the manner in which these properties influence the outcome of the combustion process [24].

Table 2
Ultimate analysis of the biomass materials [51] and energy information of each biomass in briquettes form [5,36].

Element	Molar mass [kg/kmol]	Elephant grass	Rice husk	Coffee husk
		Ultimate analysis [%mass]	Ultimate analysis [%mass]	Ultimate analysis [%mass]
Carbon (C)	12.011	38.6	35.40	43.30
Hydrogen (H)	1.008	5.16	5.23	5.28
Oxygen (O)	15.999	36.9	38.39	40.00
Nitrogen (N)	14.007	1.47	0.66	2.04
Sulfur (S)	32.065	0.19	0.12	0.24
LCV [MJ/kg] in natural form	–	13.96	12.72	15.56
LCV [MJ/kg] in briquette form	–	17.10	15.90	20.01
Specific mass [kg/m^3] in briquette form	–	580	650	1300
Cost [US$/kg][a]	–	0.10	0.15	0.23

[a] Considering 1 US$ equal to 2 BR$.

Thus, the ultimate analyses of rice and coffee husks and elephant grass (napier grass) were carried out by the research and development department of USIMINAS[1] and are given in Table 2. The materials were homogenized, apportioned, crushed, pulverized and separated by grain size according to the European Standard EN 14780 [45] (Solid biofuels: sample preparation). Once prepared, the samples were subjected to ultimate chemical analysis using the standards EN 15104 [46] and EN 15289 [47]. In order to determine the lower calorific value (LCV) of each biomass, the Mendeleev formula was used, which can be written as [52]:

$$LCV = 339.13 \times C + 1029.95 \times H - 108.85 \times (O - S) - 25.12 \times W \ \ [kJ/kg] \tag{1}$$

where: C, H, O, S and W are the amounts, in percent, of carbon, hydrogen, oxygen, volatile sulfur, and water, respectively, in the total working weight of the fuel. The direct application of biomasses for cooking and heating occurs mainly in developing countries and involves more than 2.5 billion people worldwide [22]. Nevertheless, the process of drying, grinding and compressing the biomass before combustion is mostly used in European countries. This paper considers the conversion of the Brazilian residues into briquettes. Table 2 exhibits the energy information of each biomass in briquette form. The LCV of the biomass materials in briquette form is higher than in the natural from due to the lower moisture content of the biomass in briquette form. Natural gas is used to compare the performance of the biomasses. Its composition and energy information is displayed in Table 3.

2.3. Cogeneration system

Cogeneration or Combined Heat and Power (CHP) is defined as the sequential generation of two different forms of useful energy from a single primary energy source, typically mechanical energy and thermal energy. Cogeneration provides a wide range of technologies for application in various domains of economic activities. The overall efficiency of energy use in cogeneration mode can be up to 85 percent and above in some cases. According to Hammond and Norman [20]; all heating processes result in a surplus of heat energy at the end of the process. This surplus thermal energy source can, in certain cases, be recovered and utilized to fulfill an existing energy demand. Using surplus heat in this manner would replace conventional energy sources (in the case of EAF, natural gas or coal), and so reduce both energy costs and associated emissions. Heat recovery is commonly practiced in manufacturing, especially in energy-intensive industries, although it is thought that considerable potential still exists.

[1] Usiminas is one of the largest producers of steel in the Americas, with major steel mills in Brazil with a total capacity of 9.5 million metric tons of steel per year. The company accounts for 28% of total steel output in Brazil. Usiminas has an installed capacity of producing 9.5 million tons of crude steel. The company also operates in the logistics sector through a stake in logistic company MRS Logística.

Table 3
Natural gas volume composition and energy information [18].

Brazilian states	Volume composition [%]						LCV [MJ/Sm^3]
	Methane (CH_4)	Ethane (C_2H_6)	Propane (C_3H_8)	Butane and higher	Carbon dioxide (CO_2)	Nitrogen (N_2)	
Rio de Janeiro	89.44	6.7	2.26	0.46	0.34	0.8	39.16
Bahia	88.56	9.17	0.42	–	0.65	1.2	38.14
Alagoas	76.90	10.1	5.8	1.67	1.15	2.02	41.61
Rio Grande do Norte	83.48	11	0.41	–	1.95	3.16	37.47
Espírito Santo	84.8	8.9	3.0	0.9	0.3	1.58	40.13
Ceará	76.05	8.0	7.0	4.3	1.08	1.53	44.34

Cogeneration systems are normally classified according to the sequence of energy use and the operating schemes adopted. A cogeneration system can be classified as either a topping or a bottoming cycle on the basis of the sequence of energy use. In a topping cycle, the fuel supplied is used to first produce power and then thermal energy, which is the by-product of the cycle and is used to satisfy process heat or other thermal requirements.

Losowska [32] studied two cases involving cogeneration plant and steel recycling mil. Biomass based CHP system applied to a Polish steel plant was analyzed, implementing a concept of emergy in the country bio and fossil fuel-based systems. The goal of the emergy analysis of a specific product or service is to determine the solar energy which is required in a direct or indirect way to allow a system to produce product or service. Emergy principle states that the emergy of renewable energy, nonrenewable resources, products or services is determined by the energy required to make them. The study was divided into four main steps: (i) Process description and emergy system diagram; (ii) list of inputs and raw data; (iii) transformity values and (iv) emergy tables. The case study used a biomass based cogeneration plant of the existing plant in Forssa, Finland. Plant description, equipment type and main characteristics were taken from the report of Kirjavainen et al. [27]. Forssa cogeneration plant involves a steam cycle of 17 MW of electrical power output, 48 MW of heat output, and 72 MW of heat input as wood residues (LCV of 19.31 MJ/kg). The cogeneration plant has an efficiency of about 90%.

Born and Granderath [7] discussed about the heat recovery in EAF steel plants proposing that steam generation can be the best means of recovering heat using a combination of partial evaporation of cooling water circulating around the off-gas duct and a heat recovery boiler for secondary recovery when temperatures drop below 600 °C. Forni et al. [17] evaluated the heat recovery from a reheating furnace, employed in the rolling mill process. A direct exchange scheme has been employed, in which an organic Rankine cycle (ORC) power-block was provided with a heat exchanger to transfer the thermal power of the exhaust gas directly to the working fluid, avoiding the intermediate loop with the heat carrier. The results showed that this solution was feasible for not too big ORC sizes (lower than 1 MW electric), because, for big ORCs, the volume of the working fluid to be used is too high.

According to MetalPass [34]; most cogeneration operations in the steel industry of the USA use conventional systems (steam boiler and steam turbines). Integrated steel plants produce significant levels of off-gases (coke oven gas, blast furnace gas, and basic oxygen furnace gas). Specially adapted turbines have been developed that can burn these low-calorific-value gases. Electric arc furnace steelmaking facilities have low demand for steam; about 90% of cogeneration occurs in integrated facilities. The cogeneration technology used in steel industry accounts for seven establishments with steam turbines supplied by heat from high temperature processes and twenty four establishments with steam turbines supplied by bed boilers.

According to Jones et al. [25]; the melting process takes a theoretical minimum of 300 kWh/ton. In addition, it is necessary to provide heat above the melting point, which requires an additional energy for typical tap temperature needs. The total theoretical energy required in the process usually lies in the range of 330–370 kWh/ton. However, EAF steelmaking is only 55–65% efficient and as a result, the total equivalent energy input is usually in the range of 500–680 kWh/ton for most modern operations.

An alternative to reduce the consumption of electricity is the scrap preheating through exhaust gases from the EAF process. According to Schmitt [43]; using the heat content of the waste gas to scrap preheating can result in recovering and offsetting the electrical energy requirements of the process. The behavior of the scrap preheating and its heat content seems to be linear. For example, the heat content in equivalent kWh/ton of scrap preheated to 150 °C is 22 kWh/ton while to 540 °C, this value is 81 kWh/ton. The advantages of scrap preheating include increased productivity, removal of moisture from scrap, reduce electrode consumption and reduce refractory consumption. Nowadays, there are several scrap preheating systems as shown in Table 4. Fig. 7 shows a scheme of preheating of scrap in a scrap bucket.

The cogeneration system proposed for this study consists mainly of a biomass boiler, steam turbine and condenser, as shown in Fig. 8. It is a cogeneration topping cycle where the exhausted gases are used as heating source in the electric arc furnace or to preheat the scrap. Through the biomass briquettes combustion in a boiler, superheated steam is produced and feed into a steam turbine. The electricity produced is used to supply the EAF electricity demand. The exhaust gases can also be used to increase the temperature of the cold spots in the EAF process by direct injection, producing better and cheaper steel. This method has some advantages such as the use of a low cost material, energy potential, and the use of a renewable source.

2.4. Thermodynamic analysis of the cogeneration system

According to Wark and Richards [53]; the thermal efficiency of a power cycle is maximized if all the energy supplied from a source occurs at the maximum possible temperature and all the energy rejected to a sink occurs at the lowest possible temperature.

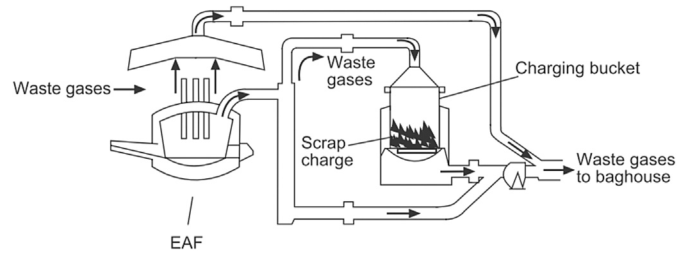

Fig. 7. Schematic diagram of scrap preheating in a bucket [25].

The cogeneration system operates in a Rankine cycle. The basic ideal Rankine cycle consists of (i) isentropic compression in a pump, (ii) constant pressure energy addition by heat transfer in a boiler-superheater, (iii) isentropic expansion in a turbine and (iv) constant pressure energy removal by heat transfer from a condenser. After the saturated steam leaves the boiler, the fluid passes through another energy input section, a superheater. The heat transfer process of superheating leads to a higher temperature at the turbine inlet without increasing the maximum pressure in the cycle. Based on Carnot engine analysis, superheating would be expecting to increase the thermal efficiency and alleviating the moisture problem in the turbine exit [53].

Expressions for the work and heat interactions in the Rankine Cycle are found by applying the steady-flow energy equation on a unit-mass basis [53]:

$$q + w = \Delta h + \Delta ke + \Delta pe \tag{2}$$

To each separate piece of equipment. If we neglect kinetic (ke) and potential (pe) energy changes, the basic steady state energy equation for each process reduces to ($q + w = h_{out} - h_{in}$). The heat input at the boiler (Q_{boiler}) is [53]:

$$Q_{boiler} = m_{steam}\left(h_{out,steam} - h_{in,water}\right) \tag{3}$$

where: m_{steam} is the mass flow rate of steam produced at the boiler [kg/s], $h_{out,\ steam}$ is the enthalpy of the steam at the boiler exit [kJ/kg], and $h_{in,water}$ is the enthalpy of the water at the boiler entrance [kJ/kg].

In this paper, the heat input at the boiler is given by the conversion of biomasses or natural gas as the fuel in the burner. When a fuel is burned, chemical energy is released in form of heat. The amount of heat released by a unit of fuel is its calorific value. The product of the lower calorific value (LCV) by the mass flow rate of fuel (m_{fuel}) gives the thermal energy available in the cycle [24]:

$$E_{fuel} = m_{fuel} LCV \tag{4}$$

Boiler efficiency (η_{boiler}) relates energy output to energy input, usually in percentage terms [44]:

Table 4
Characteristics between electric steelmaking furnaces [29].

Characteristics	Conventional EAF	Consteel	Finger shaft	EPC
Power off	Scrap basket 12–14 min	Continuous charge 6–8 min	Scrap basket/fingers 12–14 min	Continuous charge 6–8 min
Preheating	No	Low efficiency	Medium efficiency	High efficiency
Energy consumption	400 kWh/ton	360 kWh/ton	335 kWh/ton	290 kWh/ton
Gas consumption	6 Nm^3/ton	3 Nm^3/ton	6 Nm^3/ton	3 Nm^3/ton
Scrap limitation	Yes	Yes	Yes	No
Metallic yield	0	0.50%	1%	1%
Burners required	Yes	No	Yes	No
Dust removal system	100%	100%	70%	50%

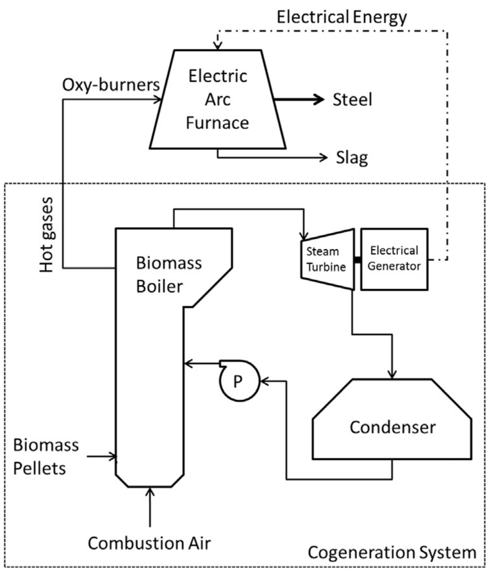

Fig. 8. Proposed combined generation of electrical and thermal energy for the EAF process.

$$\eta_{boiler} = \frac{\text{Heat exported in steam}}{\text{Heat provided by the fuel}} = \frac{Q_{boiler}}{E_{fuel}} \tag{5}$$

The heat exported in steam is calculated using the steam tables, from knowledge of the feed water temperature [°C], the pressure at which steam is exported [kPa] and the steam flow rate [kg/s]. The turbine work output may be written as [53]:

$$W_{turbine} = m_{steam}(h_{in} - h_{out}) \tag{6}$$

In addition, the heat transfer from the condenser is [53]:

$$Q_{cond} = m_{steam}(h_{out} - h_{in}) \tag{7}$$

The cogeneration system thermal efficiency is the ratio of all the useful energy extracted from the system (electrical and process heat) to the energy of the fuel input. Thus [53]:

$$\eta_{cog} = \frac{W_{net} + Q_{process}}{E_{fuel}} = \frac{(W_{turb} - W_{BOP}) + Q_{process}}{E_{fuel}} \tag{8}$$

where: W_{BOP} is the balance of plant electrical power required for the Rankine cycle (includes the pump electrical requirements) and $Q_{process}$ is the heat content in the flue gas of the boiler, used in the EAF process, which can be written as [44]:

$$Q_{process} = m_{fg}Cp_{fg}(T_{out,boiler} - T_{out,process}) \tag{9}$$

where: m_{fg} is the mass flow rate of flue gas [kg/s], Cp_{fg} is the mean specific heat at constant pressure [kJ/kg K] between boiler exit temperature ($T_{out,\ boiler}$) and process exit temperature ($T_{out,\ process}$).

3. Results and discussion

The following considerations and assumptions were made for the energy analyses presented herein:

- Steady state in all cycle equipment [53];
- Dry air with volumetric composition of 79% of nitrogen and 21% of oxygen [50];
- Air excess for biomass combustion of 30% and for natural gas combustion of 5% [38].
- Electrical power produced by the cogeneration system of 500 kW (as shown in section Cogeneration System), which is the total equivalent energy input for 1 ton of hot metal per hour produced in the EAF steelmaking process;
- Cogeneration system operation in electrical parity;
- Biomass and natural gas boiler steam parameters and steam turbine isentropic efficiency given by Table 5.

Fig. 9 displays the results of the mass flow rate of each fuel (elephant grass, rice husk, coffee husk and natural gas) in the cogeneration system using the boiler steam parameters (Table 5) and the energy required for 1 ton of hot metal produced in the EAF steelmaking process.

Fig. 9 shows the consumption of the biomass materials and natural gas in the cogeneration system. The calculation of mass flow rate came from the First Law of Thermodynamics, equations showed in Section 2.4 (thermodynamic analysis of the cogeneration system). For example, elephant grass in briquette form has a LCV of 17.1 MJ/kg and it is burned with air in excess (7.3 kg_{air}/kg_{fuel}) in a grate fired boiler. From the data of Table 5 – case 1, and using the First Law of Thermodynamics (Mollier diagram), it is found an enthalpy difference of 3042.76 kJ/kg in the working fluid through the boiler. With the steam mass flow rate of 0.63 kg/s and from the Equations (3)–(5), for example, one can observe an elephant grass mass flow rate of 0.53 ton/h. This mass flow rate is the quantity of briquettes in mass to supply the net electricity demand of 1 ton of hot metal (500 kWe) produced in the Rankine Cycle.

The electrical power produced by the cogeneration system is the total equivalent energy input for one ton of hot metal produced in the EAF steelmaking process. Fig. 9 displays that the natural gas consumption is the lowest in the three cases and also exhibits small variations related to them. This behavior was expected because the percentage difference of the lower calorific value of each fuel. Elephant grass has 36.3% of the calorific value of natural gas as rice and coffee husks have 34.1% and 42.6%, respectively. However, biomass has advantages from an environmental viewpoint with respect to natural gas, since the combustion of biomass is considered carbon neutral. Thus, an economic analysis of the process may show other advantages of using biomass. Another advantage that can be commented is the replacement of electricity produced via fossil fuel for electricity produced via renewable fuel. However, the use of biomass in cogeneration, in accordance with Table 2, produces sulfur compounds which can produce hot metal with non-standard chemical composition. In this scenario, the best option is to use biomass to produce electricity to the EAF process and heat (from the boiler exhaust gases) to scrap preheating, in accordance of Table 4 and Fig. 7.

Fig. 10 shows the results of thermal energy available in the boiler exhaust gases, which can be used into EAF process to preheating the scrap or injecting in the metallic charge. In this paper, the injection of exhaust gases in the metallic charge is not considered. Fig. 10 exhibits that the use of biomass provides a greater amount of exhaust gas than natural gas due to the difference of lower heating

Table 5
Boiler steam parameters for biomass and natural gas and turbine isentropic efficiency [23,40].

	Pressure [kPa]	Temperature [°C]	Boiler efficiency	Turbine efficiency
Biomass (case 1)	4200	420	75%	75%
Natural gas (case 1)			90%	89%
Biomass (case 2)	6500	520	85%	80%
Natural gas (case 2)			90%	89%
Biomass (case 3)	10,000	540	91%	86%
Natural gas (case 3)			90%	89%

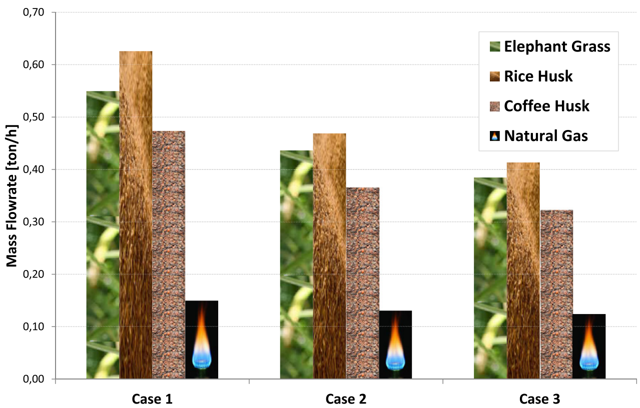

Fig. 9. Results of mass flow rate of the cogeneration system using biomasses and natural gas as the fuel.

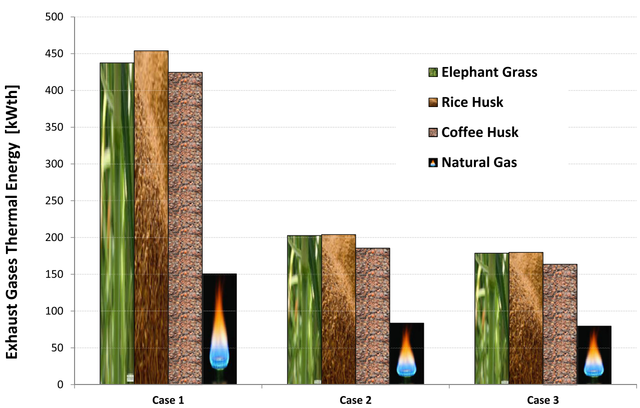

Fig. 10. Results of thermal energy available for cogeneration system.

value of the fuels. For example, the LCV of elephant grass and natural gas is 17.1 MJ/kg and 47 MJ/kg, respectively. There is more thermal energy available due to the increased exhaust gas mass flow rate in the case of biomass. In each case, there are differences in equipment efficiencies among fuels, as shown in Table 5. Therefore, the use of biomass in the cogeneration system is suitable for preheating scrap regardless of the equipment efficiency.

The economic analysis was performed according to the biomass and natural gas consumption showed in Fig. 9 and considering only the operational costs of the plant. The analysis was done considering one ton of steel produced in one hour. The cost of biomass briquettes is given by Table 2. The cost of natural gas considered was 0.30 US$/

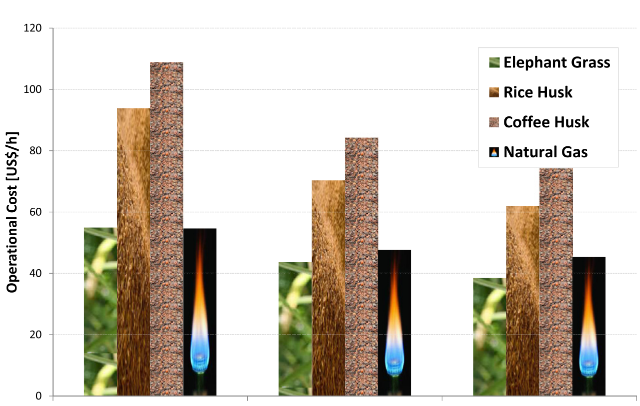

Fig. 11. Results of operational cost among cases and fuels.

Sm^3 [39]. The operational cost was calculated by multiplying the amount of the fuel used in one hour by its cost, i.e., for one ton of hot metal produced in the industry. So, the results of operational cost are given by Fig. 11. This figure shows that elephant grass has the lowest operational cost. Although the biomasses have lower LCV than natural gas, they have environmental benefits that make them an excellent alternative for the process of producing iron.

4. Conclusions

The steel industry has faced several challenges during the years. There has always been an aspiration towards higher economic profitability for the system. The energy crises caused a dramatic rise in energy costs, which led to an increased awareness in energy conservation. In recent years, climate change issues have become more important for the industry. On the other hand, the Brazilian strategy for agricultural expansion has been providing a potential raw material for use in this industrial segment. In this paper, a feasibility study was carried out using Brazilian available biomass materials (rice husk, coffee husk and elephant grass) compared to natural gas. Rice and coffee husk are biomass residues from the agriculture while elephant grass is an abundant, fast growing plant. Three cases were proposed with differences in the equipment efficiencies (commercial efficiencies) and the cogeneration system was theoretical analyzed using the First Law of Thermodynamics and the equivalent commercial energy input for one ton of hot metal produced in the EAF steelmaking process. The energy comparison study showed that natural gas fuel consumption is the lowest in the three cases and also exhibits small variations related to them. An economic analysis was done using the results of the energy consumption in each case and the Brazilian commercial fuel price, showing that elephant grass had the lowest operational cost. Although natural gas is the fuel used in the steelmaking process, biomass has advantages from an environmental viewpoint since the combustion of biomass is considered carbon neutral. They demonstrate an excellent alternative for the process of producing iron.

Also, some benefits of using biomass can be summarized as:

- Help in the reduction process of iron mineral due to the production of carbon monoxide (CO);
- Foaming of slag;
- Improvements of wear of the refractory and electrodes;
- Heating of cold spots inside the EAF process;
- Reduction of the running time (tap to tap);
- Reduction of electricity costs;
- Reduction of the need for natural gas into the EAF process.

Moreover, the use of biomass cogeneration system allows the recovery of thermal energy in the boiler exhaust gases to preheating scrap. This alternative can bring some benefits such as increased productivity, removal of moisture from reduced electrode, and reduced refractory. All of these advantages can help improve the competitiveness of individual steel plants and reduce the natural gas consumption by the use of biomass.

Suggestions for future work include the scale-up of the cogeneration system to meet the electricity and thermal demands of the steelmaking process, and the second law of thermodynamics analysis for the steelmaking and cogeneration system.

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