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TECHNO-ECONOMIC ANALYSIS OF TORREFACTION, DRYING AND BRIQUETTING OF EUCALYPTUS FOR ENERGY GENERATION

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Abstract. *With the increasing need for renewable energy sources due to possible fossil fuel scarcity in a near future and due to the pollution caused by these fuels, which degrade the environment, there is a need to look for alternatives. The torrefaction of eucalyptus is a soft pyrolysis treatment (thermal treatment) with temperatures up to 300°C that has a positive influence on energy generation when logistics and combustion efficiency are taken into consideration. The main benefits of this process are the increase in energy density, which lowers transport costs and the resulting properties that are more suitable for storage. The purpose of this paper is to assess the techno-economic feasibility of the torrefaction, briquetting and drying processes used prior to the transport by trains to the power plants. Calculations based on data obtained from related literature and companies have been made for the assessment. The results indicated that the most economical scenario in the climate conditions of the city of Aratu is the one using torrified eucalyptus briquettes for distances greater than about 240 km and solar dried eucalyptus for smaller distances. For the climate conditions of the city of São Desidério the most economical scenario is the one using torrified eucalyptus briquettes for distances greater than about 295 km and solar dried eucalyptus for smaller distances.*

Keywords: *Biomass, Eucalyptus, Torrefaction, Briquetting, Drying*.

1. INTRODUCTION

Lignocellulosic biomasses such as eucalyptus are being used as a renewable alternative for energy generation due to the recent climate changes and possible running out of fossil fuels in a near future. They are composed of natural carbohydrate polymers like lignin, cellulose, hemicellulose and small amounts of other substances. As all the carbon released in the combustion process of biomass was absorbed by photosynthesis, so the carbon emissions can be considered almost null. However, this energy source is not free of drawbacks because of its low energy density, poor grindability, high humidity, hygroscopic nature, heterogeneity and high oxygen content (Bach et al., 2015).

Some conversion processes can be used to minimize these issues. According to Basu (2010), the torrefaction process is a soft pyrolysis usually in the temperature range of 230 to 300°C in the absence of oxygen. It improves the energy density, the hygroscopic nature of the fuel and reduces the ratios of oxygen to carbon and hydrogen to carbon, so that the properties of the biomass become similar to those of coal. The hemicellulose suffers depolymerization and consequently the biomass becomes frail acquiring better grindability properties. The densification is another process used to improve biomass properties that can occur as pelletizing or briquetting. It consists in the application of a mechanical force to compress the biomass into solid particles of uniform size such as briquettes, pellets, and logs (Chen et al., 2015).

Solar drying and oven drying are other processes analyzed in this work. According to Denig et al. (2000) the drying of wood has as the primary objective the production of a useful product, minimizing quality losses. According to Verma et al. (2016) raw biomass used for bio-fuel production may contain up to *60* to *70 %* moisture content, even though biomass with a moisture content between *55* and *65 %* can sustain combustion, the optimum moisture content is between *10* and *15 %* (Gebreegziabher et al., 2013).

These improvements reduce the transportation costs from the conversion facilities to the power plants because more energy in the form of biomass can be transported as it becomes energy denser. The combustion efficiency also increases because of the decrease in humidity. Therefore, even though the conversion processes increase monetary and energetic costs, they can make the use of biomass for energy generation more profitable.

The goal of this article is the assessment of the cost reduction in biomass storage and transportation by trains and the change in combustion efficiencies caused by the conversion processes. The fuel examined was the eucalyptus, a tree from Indonesia and Australia which has found proper soil and climatic conditions in Brazil where it has faster growth than in other regions and a high productivity (ABRAF, 2011). In Brazil there are about *5.1* million hectares of eucalyptus forest (ABRAF, 2013), of which *1.8* million are feedstock for the paper and cellulose industry, which accounts for *81.2 %* of the planted forests in this sector (ABRAF, 2011).

Brazil has a relatively small railroad network as it is more focused on road transportation, which is a problem because road transportation is more expensive than rail transportation. The transport matrix in Brazil is composed *62.7%* by road networks, *21.7%* by railways, *3.8%* by canal/rivers and *0.1%* by airways (ILOS, 2010).

Contributions to this subject include a regression analysis made by Gonzales et al., (2013) that indicated that the costs of transportation of densified biomass are influenced by the transport distance, cargo volume, used transport mode and destination, among others. According to Gonzales et al., (2013) the size of railroads and the easy access make rail transport more suitable than ships for large-volume and long-distance cargoes. A timeline system was developed by Hahn (2014) to obtain close to optimal solutions for scale transport media problems. Manzone et al. (2013) has analyzed the costs and energy consumption of different vehicles used in the transportation of biomass. A model of transportation of biomass was developed by Golecha et al. (2015) in which the road network and the density of production vary with the radius of transport. Roni et al. (2014) argues about the benefits of using railways to transport biomass. Among them are lower greenhouse gas emissions and greater safety than on highways.

Models for the biofuel supply chain and for plant location planning are presented in some recent works (Eksioglu et al., 2009, Parker et al., 2010, Bai et al., 2011, Kim et al., 2011, Papapostolou et al., 2011. Miao et al. (2012) reviews the implications of the use of different modes of transport in managing the logistics and supply chain of various types of energy crops. A summary of the processes and costs involved in the collection of lignocellulosic biomass, processing and delivery to biofuel plants was made by Miao et al. (2013). Cundiff et al. (1997), Huang et al. (2010), Kim et al. (2011), Chen et al. (2012) and Gebreslassie et al. (2012) have made stochastic lease-transport models to identify the effects of uncertainty on the performance of the biofuels supply chain. Transport analysis studies using lignocellulosic biomass were made by Searcy et al. (2007), Ileleji et al, (2010) and Judd et al. (2011). An analysis of the cost of trucking to densified biomass when in the form of pellets, packages and cubs was made by some studies (Badger et al., 2006; Rogers et al., 2009). The studies of Mahmudi et al. (2006), Searcy et al. (2007), Bonilla et al. (2009), Sokhansanj et al. (2009), Ileleji et al. (2010) and Judd et al. (2011) discuss the biomass rail transport.

In this work, different thermo-mechanical conversion processes that influence the logistics of energy generation with biomass are compared and evaluated.

2. METHODOLOGY

The model used for the methodology involves the supplying of a train wagon full of eucalyptus to a thermoelectric plant that uses it in the combustion process that feeds its boilers. The supply to three plants in the state of Bahia, Campo Grande and Boltbah in the city of São Desidério and the one belonging to the Dow Company in the city of Aratu were considered. The climatic conditions in São Desidério are more favorable to solar drying than in Aratu, so in this study these conditions are called positive and negative respectively. The analysis for locations other than these two was made considering these two conditions.

The analysis for São Desidério (positive) was made based on the city of Barreiras that has very similar climate conditions and the analysis for Aratu (negative) was based on the climate conditions of the city of Alagoinhas. The equilibrium moisture contents of wood for the two conditions were determined according to Denig et al. (2000) and it is a function of the temperature and the relative humidity of the air. The averages of the compensated average temperatures and the relative humidities (INMET, 2017) from 01/01/2000 to 08/15/2017 were used in the determination of the equilibrium moisture contents as shown in Tab. 1.

Table 1. Climate conditions of the cities analyzed.

City	Condition	Compensated average temperature (°C)	Relative humidity (%)	Equilibrium moisture content (%)
São Desidério	Positive	25.3	65.2	12
Aratu	Negative	24.6	78.6	15.2

According to CPRM (2017), the compensated average temperature is the average of three readings in different times of the day plus the maximum and minimum temperatures and the equilibrium moisture content is the content that the wood has when it is in equilibrium with the air (Denig et al., 2000).

For the positive conditions three scenarios were considered for the eucalyptus supply:

- 1, solar dried eucalyptus with *12%* moisture content;
- 2, solar dried eucalyptus to *40%* moisture content, torrified and briquetted;
- 3, solar dried and briquetted eucalyptus with *12%* moisture content.

In scenario 2 the eucalyptus is solar dried to *40%* moisture content before torrefaction because according to the torrefaction company Agritech (James, 2016) it is not necessary to dry it any further and if the wood is too dry (*10%* or less) it can jeopardize the torrefaction system.

For the negative conditions three scenarios were considered for the eucalyptus supply:

- 2, solar dried eucalyptus to *40%* moisture content, torrified and briquetted;
- 4, solar dried eucalyptus with *15.2%* moisture content;
- 5, solar dried eucalyptus to *15.2%*, oven dried to *12%* and briquetted.

In all scenarios but the 2 the eucalyptus is solar dried to the equilibrium moisture content. Scenario 2 is compatible with both negative and positive conditions. In scenario 5 the wood is oven dried from *15.2%* to *12%* moisture content because this is the maximum humidity the briquetting machines can work with according to the briquetting company Radhe (Sorathiya, 2016).

The ultimate analyzes of biomass in the evaluated processes are detailed in Tab. 2.

Table 2. Ultimate analysis of all five scenarios.

Scenarios	C (P. %)	H (P. %)	O (P. %)	Moisture content (P. %)
1(2)	44.11	5.38	38.51	12
2(1)	69.64	4.3	25.8	
3(2)	44.11	5.38	38.51	12
4(2)	42.51	5.19	37.11	15.2
5(2)	44.11	5.38	38.51	12

(1)(Borges et al., 2015), (2)(Agrawal et al., 2014)

It is possible to notice that the percentage of carbon increases with the reduction of moisture content and with the torrefaction process, which is one of the reasons for the higher energy density.

The following equations summarize the methodology:

$$C = (FF \times D \times 2 \times ME + PE) \times 1.1 \quad (1)$$

In Eq. (1):

- C represents the summed costs of the train freight, eucalyptus and *10%* of profits;
- FF is the train freight cost (*U$/1000 t.km*);
- ME is the mass of the eucalyptus in the wagon;
- D is the distance between the source of the eucalyptus and the plant. It is multiplied by 2 because the train does round trips;
- PE is the price of the eucalyptus in the wagon;

$$TE = EF \times ME \times PC \quad (2)$$

In Eq. (2):

- TE is the amount of energy produced in the boiler of the plant;
- EF is the value of the efficiency of the combustion process. The efficiency values were all kindly provided by the thermoelectric company Caldema S.A (Vallt, 2017);
- ME is the mass of the eucalyptus in the wagon;
- PC is the lower heating value of the eucalyptus.

$$E = C/TE \quad (3)$$

In Eq. (3), E is the price of the energy produced in the boiler in *U$/GJ*.

According to (SVANBERG et al., 2013) in all scenarios but the 2 (torrified biomass) a mass loss of *15%* during storage was considered in the calculations due to the higher reactivity of non-treated biomass. Torrified biomass has properties that allow it to be stored for longer periods, so no mass loss was considered in the storage phase for scenario 2 (Silva, 2017).

3. CASE STUDIES

The case studies are about the transportation of eucalyptus by train from the places where they are cut and processed to the thermoelectric plants. Eucalyptus suppliers for the Dow plant at the city of Aratu and Boltbah and Campo Grande plants in the city of São Desidério are within a radius of *150* and *30 km* respectively (Celulose Online, 2014 and Dow, 2016). These were the distances considered in this study.

4. RESULTS AND DISCUSSION

Figure 1 shows the price of the energy in *U$/GJ* for distances from *0* to *1600 km* and all the five scenarios and the distances where the cheapest scenario changes for both negative and positive conditions.

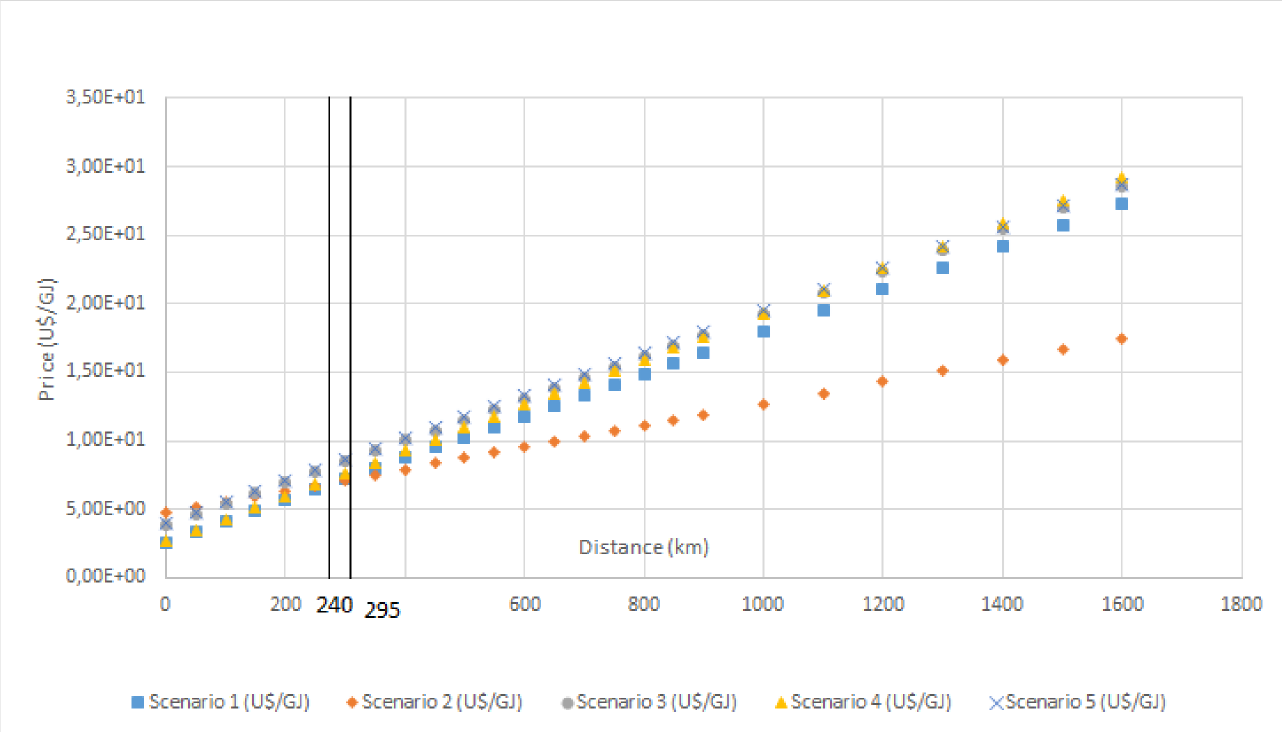

Figure 1. Price of the energy for all the scenarios

The results are summarized in Tab. 3, 4 and 5:

Table 3. Prices of the energy for the two case studies.

Price (U$/GJ)		
Distance (km)	30	150
Scenario		
1	3.00	4.86
2	4.98	5.94
3	4.29	6.15
4	3.14	5.15
5	4.44	6.29

It can be noticed that scenario 1 is the one that enables the production of the cheapest energy for the analyzed cases in positive conditions and in general. For negative conditions, scenario 4 is the cheapest. The reason for this is that each treatment applied to the eucalyptus causes an increase in costs, which may compensate only if the distance of the travels is high enough. Tab. 4 and 5 provide a summary of the results for any distance.

Table 4. Summary of the results for positive conditions for any distance.

Distance (D)	D > 295 km	D < 295 km
Scenario providing cheaper energy for positive conditions	2	1

Table 5. Summary of the results for negative conditions for any distance.

Distance (D)	D > 240 km	D < 240 km
Scenario providing cheaper energy for negative conditions	2	4

The distance for scenario 2 (torrified eucalyptus) to become the cheapest is higher in positive conditions for drying, as expected.

5. CONCLUSIONS

The scenario that provides the cheapest energy for positive conditions is the 2 for distances greater than *295 km* and scenario 4 for smaller distances. For negative conditions, scenario 2 is the cheapest for distances greater than *240 km*, for smaller distances scenario 1 is the cheapest. Scenarios 3 and 5 do not have the cheapest prices for any distance.

The calculations were made using data from the literature and from companies in the area of thermomechanical conversion of biomass, such as Radhe (Sorathiya, 2016), Lehra (Singh, 2016), RUF (Schmid, 2016), Agritech (James, 2016) and Earthcare (Bijoy, 2107) to determine the most appropriate processes to use before transporting eucalyptus.

The use of renewable energy sources must be encouraged and this is one of the goals of this work. It is important to help authorities and entrepreneurs to find the best ways to use energy from biomass to fight against the deterioration of the environment.

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