UNIVERSIDADE ESTADUAL DE CAMPINAS
Faculdade de Engenharia Química

SANDRA PATRICIA IGLESIAS GUERRERO

ANÁLISE TÉCNICO-ECONÔMICA NA PRODUÇÃO DE BIO-ÓLEO DE RESÍDUOS DE EUCALIPTO: UNIDADES DE PRODUÇÃO CENTRALIZADA NO ESTADO DE SÃO PAULO

TECHNO-ECONOMIC ANALYSIS OF BIO-OIL PRODUCTION FROM EUCALYPTUS RESIDUES: CENTRALIZED PRODUCTION UNITS IN THE STATE OF SÃO PAULO

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Dissertação apresentada à Faculdade de Engenharia Química da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Mestra em ENGENHARIA QUÍMICA.

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DEDICATION

To my parents, my siblings, my Hannita, and my future husband. I give special thank you to Beli, Mariela, Candy, Alex, and Vicky, I will always appreciate all you have done.

Para mis padres, mis hermanos, mi Hannita, y mi futuro esposo. Doy un especial agradecimiento para Beli, Mariela, Candy, Alex, y Vicky, yo siempre voy apreciar lo que han hecho por mí.

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RESUMO

Recentemente, a pirólise rápida tem atraído o interesse da indústria como um dos processos em potencial para converter a biomassa lignocelulósica em bio-óleo. Também é notável que a análise técnico-econômica é uma das atividades mais importantes durante a fase de desenvolvimento das biorrefinarias. Sendo assim, o objetivo deste trabalho é avaliar a viabilidade técnico-econômica de unidades centralizadas para a produção de bio-óleo por meio da pirólise rápida, utilizando resíduos de eucalipto provenientes da indústria de papel e celulose do Estado de São Paulo (SP), Brasil.

Este trabalho considerou 243.000 ton/ano de resíduos de eucalipto em SP; esses resíduos foram distribuídos em 16 biorrefinarias (denotadas com as letras A, B, C, D) com 106 km de raio e uma biorrefinaria com 125 km de raio com centro em Limeira. Nestas condições, a produção simulada anual de bio-óleo foi de 60 milhões de litros (46% de rendimento de bio-óleo). De acordo com o total de bio-óleo produzido, SP poderia contribuir com o fornecimento de 3,4% de bio-óleo para o co-processamento de gasóleo (ou diesel é um óleo derivado da destilação do petróleo bruto) em uma refinaria com capacidade anual produtiva de 20 milhões de toneladas.

Conjuntamente, uma análise do fluxo de caixa descontado (FDC) foi avaliada para estimar a atratividade de cada biorrefinaria através do preço mínimo de venda (PMV). O PMV foi de 194 USD / tonelada (12 USD / GJ) para a biorrefinaria com a maior capacidade de produção. Devido às premissas empregadas no FDC, a sensibilidade e a análise de Monte Carlo foram realizadas a fim de se analisar o impacto das premissas sobre a viabilidade. Foi observado que a variável disponibilidade de resíduos tem alto impacto no PMV, podendo aumentá-lo em até 50% e diminuí-lo em até 26%.

Por fim, as biorrefinarias simuladas apresentaram bom desempenho econômico baseado no Valor Presente Líquido (VPL), a Taxa Interna de Retorno (TIR), e o payback descontado. Elas foram C4 (VPL: 15 MM USD, TIR: 33%, Payback 2,0 anos), C3 (VPL: 12 MM USD, TIR: 30%, Payback 2,3 anos), D3 (VPL: 7 MM USD, TIR: 26%, Payback 3,1 anos), B4 (VPL: 5 MM USD, TIR: 24%, Payback 3,5 anos), C5 (VPL: 4 MM USD, TIR: 22%, Payback 4,2 anos), B3 (VPL: 3 MM USD, TIR: 22%, Payback 4,4 anos, C6 (VPL: 1 MM USD, TIR: 16%, Payback 7,1 anos), D4 (VPL: 0,83 MM USD, TIR: 15%, Payback 8,1 anos), B5 (VPL: 0,67 MM USD, TIR: 14%, Payback 8,7 anos), A4 (VPL: 0,22 MM USD, TIR: 12%, Payback 12,5 anos).

Palavras-chave: resíduos de eucalipto, bio-óleo, análise de sensibilidade, avaliação de risco, viabilidade econômica, São Paulo.

ABSTRACT

Latterly, fast pyrolysis has attracted industry increasing interest as one of the potential processes to convert lignocellulosic biomass into bio-oil. Being the study of economic viability one of the most important stages during the development of biorefineries. Hence, the objective of this work is to evaluate the techno-economic feasibility of centralized unit for the production of bio-oil via fast pyrolysis using eucalyptus residues from pulp and paper industry sources in the State of the São Paulo (SP), Brazil.

This work identified 243,000 ton/year of eucalyptus residues in SP; those residues were distributed in 16 biorefineries (preceded by the letters A, B, C, D) with 106 km of radius, and one biorefinery with 125 km of radius located. The total simulated bio-oil production was 60 million L/year (46% bio-oil yield). According to the total bio-oil produced, SP could contribute 3.4% of bio-oil to co-processing with gas oil at refinery that producing 20 million ton per year.

Jointly, a discounted cash flow (DCF) analysis was evaluated to estimate the attractiveness of each biorefinery through the minimum selling price (MSP). The MSP for a simulated large-scale biorefinery was 194 USD/ton (12 USD/GJ). Due to the DCF being based on assumptions, sensitivity, and Monte Carlo analysis were done, as it allows us to look at the impact that changes to these assumptions may have on feasibility. The sensitive analysis showed the MSP was sensitive to the variation of plant capacity (available residues), it is a variable that could increase the MSP up to 50%, and decrease it up to 26%.

The biorefineries presented a good economic performance based on economic indicators Net Present Value (NPV), Internal Rate of Return (IRR) and discounted payback. They are C4 (NPV: 15 MM USD, IRR: 33%, Payback 2.0 years), C3 (NPV: 12 MM USD, IRR:

30%, Payback 2.3 years), D3 (NPV: 7 MM USD, IRR: 26%, Payback 3.13 years), B4 (NPV: 5 MM USD, IRR: 24%, Payback 3.5 years), C5 (NPV: 4 MM USD, IRR: 22%, Payback 4.2 years), B3 (NPV: 3 MM USD, IRR: 22%, Payback 4.4 years), C6 (NPV: 1 MM USD, IRR: 16%, Payback 7.1 years), D4 (NPV: 0.83 MM USD, IRR: 15%, Payback 8.1 years), B5 (NPV: 0.67 MM USD, IRR: 14%, Payback 8.7 years), A4 (NPV: 0.22 MM USD, IRR: 12%, Payback 12.5 years).

Keywords: eucalyptus residues, bio-oil, sensitivity analysis, risk assessment, economic viability, São Paulo.

RESUMEN

Recientemente, la pirólisis rápida ha atraído el interés de la industria como uno de los procesos potenciales para convertir la biomasa lignocelulósica en bio-aceite. Siendo el estudio de la viabilidad económica una de las etapas más importantes durante el desarrollo de las biorefinerías. Por lo tanto, el objetivo de este trabajo es evaluar la viabilidad técnica-económica de unidades centralizadas para la producción de bio-aceite mediante la pirólisis rápida utilizando residuos de eucalipto provenientes de la industria papalera en el Estado de São Paulo (SP), Brasil.

Este trabajo identificó 243000 ton/año de residuos de eucalipto en SP; esos residuos se distribuyeron en 16 biorrefinerías (denotadas con las letras A, B, C, D) con un radio de 106 km, y una biorrefinería con 125 km de radio con centro en Suzano de Limeira. La producción total simulada de bio-aceite fue de 60 millones de L/año (46% de rendimiento de bio-aceite). Tomando en cuenta toda la producción de bio-petróleo simulada, SP podría contribuir con el 3.4% de bio-aceite en el co-procesamiento de gas óleo (o diesel que es un óleo derivado de la destilacón de petróleo bruto) para una refinería que produce 20 millones de toneladas por año.

Conjuntamente, se hizo un análisis de flujo de caja descontado (FDC) para estimar la viabilidad de cada biorrefinería usando como indicador económico, el precio mínimo de venta (PMV). La biorrefinería con mayor capacidad de producción tuvo un PMV 194 USD / tonelada (12 USD / GJ). Debido a que el FDC se basó en suposiciones, se realizaron análisis de sensibilidad y Monte Carlo, que permiten ver el impacto de los parámetros considerados sobre el PMV. El MSP es una variable sensible a la variación de la disponibilidad de residuos, pudiendo aumentar hasta un 50% y disminuir hasta un 26%.

Las biorrefinerías simuladas presentaron un buen desempeño económico basados en los indicadores económicos Valor Actual Neto (VAN), Taxa Interna de Retorno (TIR), y payback. Ellas fueron C4 (VAN: 15 MM USD, TIR: 33%, Payback 2.0 años), C3 (VAN: 12 MM USD, TIR: 30%, Payback 2.3 años), D3 (VAN: 7 MM USD, TIR: 26%, Payback 3.13 años), B4 (VAN: 5 MM USD, TIR: 24%, Payback 3.5 años), C5 (VAN: 4 MM USD, TIR: 22%, Payback 4.2 años), B3 (VAN: 3 MM USD, TIR: 22%, Payback 4.4 años), C6 (VAN: 1 MM USD, TIR: 16%, Payback 7.1 años), D4 (VAN: 0.83 MM USD, TIR: 15%, Payback 8.1 años), B5 (VAN: 0.67 MM USD, TIR: 14%, Payback 8.7 años), A4 (VAN: 0.22 MM USD, TIR: 12%, Payback 12.5 años).

Palabras claves: residuos de eucalipto, bio-aceite, análisis de sensibilidad, análisis de riesgos, viabilidad económica, São Paulo.

CONTENT

1. INTRODUCTION

Brazil has 9.85 million hectares of planted forests, and eucalyptus plantations accounting for 75% (IBÁ, 2019). Eucalyptus is used mainly by the paper and pulp industry, and Brazilian pulp producers are seeing that demand for forest business is growing. Investors and farmers are interested in diversifying their business through a sustainable economy, and investing in bioprocesses using lignocellulosic biomasses is an opportunity for environmental engagement contributing to a green economy, also called bio-economy (MARIANO, 2015; PENÍN et al., 2020).

Eucalyptus industry gives rise to residues, those is representing around 30 – 40 % of the fraction of the whole tree (AMUTIO et al., 2015). Eucalyptus residues left in the harvest area representing 243,000 ton/year (area=874,000 ha) in the State of the São Paulo. Therefore, this is an opportunity in order to lignocellulosic biomasses receive attention as a renewable energy resource for producing bioenergy and biofuels in order to address various energy and environmental issues due to fossil fuel use (SEABRA, 2008).

Biomass can be converted into several useful forms of energy using different conversion technologies. The fast pyrolysis is one of them, this is a technology for thermal treatment based on a thermochemical conversion of biomass without oxygen into bio-oil (DHYANI; BHASKAR, 2018). Fast pyrolysis offers particular promising advantages in the conversion of biomass because pyrolysis can be used to produce bio-oil with an efficiency according to reactor (BRIDGWATER, 2012). Previous researchers have successfully conducted pyrolysis of forest residues to produce bio-oil (AMUTIO et al., 2015; JOUBERT et al., 2015; PIGHINELLI; SCHAFFER; BOATENG, 2018; PIMENTA et al., 2018). Nonetheless, despite the high yield and chemical process that requires little equipment, the industrial implementation of the biomass pyrolysis technology needs to solve several challenges, one of the most important ones being the regular supply of biomass resources (AMUTIO et al., 2015; HO; NGO; GUO, 2014).

The availability of second-generation feedstocks based on lignocellulosic is essential for the development of biorefineries from fast pyrolysis at large scale, the feedstock is one of the variables that influences the feasibility of this type of projects (CARVALHO et al., 2019; MUSSATTO; BIKAKI, 2016). During the development of biorefineries one of the important activities is the evaluation of their viability (STAFFORD et al., 2020); it is possible through a process known as techno-economic analysis (TEA) which provided to an investor a base for an investment decision (ALVES et al., 2017; BROWN, 2015; BROWN et al., 2014).

TEA of production bio-oil with eucalyptus residues as feedstock from fast pyrolysis in São Paulo has not been studied extensively in the literature. Some authors have been used TEA to calculate the minimum selling price (MSP) for bio-oil (ONARHEIM; LEHTO; SOLANTAUSTA, 2015; RINGER; PUTSCHE; SCAHILL, 2006; VAN SCHALKWYK et al., 2020). They have evaluated the MSP of pyrolysis oil and upgraded bio-oil based on different biomass capacities ranging from 10 to 2,000 metric ton per day (LI; ZHANG; HU, 2015; ROGERS; BRAMMER, 2012; WRIGHT et al., 2010).

Based on different assumptions made by these authors the MSP of bio-oil has been estimated between from 200 to 500 USD/ton. in other example, authors calculated the MSP of bio-oil, it was 133 USD/ton (7.62 USD/GJ) at a production at a 550 dry MT/day biorefinery via fast pyrolysis in USA (RINGER; PUTSCHE; SCAHILL, 2006). In Brazil, the authors Pighinelli et al. (PIGHINELLI; SCHAFFER; BOATENG, 2018) have simulated a process of a 2000 metric ton per day of eucalyptus *benthamii*, they calculated the high heating value and minimum selling price for the bio-oil generated, 30.76 MJ/kg (dry basis) and 480 USD/ton, respectively. According to (PINHEIRO et al., 2019), bio-oil production cost varies between 98 and 860 USD/ton; efforts are needed to keep bio-oil production costs below 150 USD/ton.

The MSP is a variable depending on parameters of the economic analysis. Sensitivity analysis is a tool that can be employed to determine the changes in outputs of a system to different sources of uncertainty in its inputs. Jones et al. (JONES et al., 2013), conducted a sensitivity analysis to determine the effect of different financial and operating assumptions on the MSP. They concluded that plant scale, capital investment and the internal rate of return (IRR) were the largest market and financial type effects.

Another parameter that an effect on the MSP is the location. Researchers (WRIGHT; BROWN; BOATENG, 2008), studied the logistics related to the distribution of the biomass and bio-oil processing. According to their study, the ideal distribution is to have a small bio-oil processing unit close to collect biomass. Other study identified the hotspots (in terms of bioenergy availability) in São Paulo state, they concluded that establishment of biorefinery is an attractive option due to a primary energy potential 3,932 PJ/year with biomass residues (CARVALHO et al., 2019).

The fast pyrolysis for bio-oil production has been studied as feasible processes on a large-scale as it involves low energy requirements, and the capital investment (ALI; MUSTAFA; YASSIN, 2018; PINHEIRO et al., 2019). Therefore, within the research environment, it is necessary to technically and economically evaluate the conversion of biomass into bio-oil, taking advantage of byproducts such as bio-char, non-condensable vapors, and acid extract, those can be used to generate revenues for our biorefinery.

Brazil has high competitiveness in biorefineries, such as planting in a short period of time, in addition to advanced forestry technology which allows the development of engineering aimed at bioproducts (FORSTER-CARNEIRO et al., 2013). Therefore, within the research environment, it is necessary to technically and economically evaluate projects that allows to general overview to an investor.

Brazil wants to install up to 250 plants that allow the production of 83 million liters per year from 400 dry tons of biomass per day (PAPEL, 2016). Hence, for an investor, it is interesting to know the technical and economic viability of bio-oil biorefineries. In view of the above, the objective of this present work is to assess the technical-economic feasibility of bio-oil production via fast pyrolysis using eucalyptus residues available in the state of São Paulo. This work evaluated two scenarios: the SP state and the centralized unit in Limeira (due to strategic place and near to big refinery in SP). 16 centralized biorefineries are modeled, and the capital investment, the operating expense, and the MSP of bio-oil are estimated. The effect of economic parameters on the MSP is also evaluated by sensitive and Monte Carlo risk analysis.

2. OBJECTIVES

2.1. General objective

The purpose of this dissertation was to evaluate a techno-economic feasibility of bio-oil production by fast pyrolysis using eucalyptus residues available in the state of São Paulo, Brazil. This assessment was performed through process simulation and the minimum selling price of bio-oil.

2.2. Specific objectives

1. To determine best locations to establish biorefineries in the state of São Paulo using Geographical information systems (GIS).

2. To calculate material and energy balances through Microsoft Excel with information provided by literature.

3. To estimate a capital expenditure (CAPEX) and operational expenditure (OPEX) for each plant.

4. Evaluate the projects viability using the net present value, the internal rate of return and the minimum selling price of bio-oil as economic indicator.

5. To employ sensitivity and Monte Carlo risk analysis to gauge the economic model performance and investment risk.

3. OUTLINE OF THIS DISSERTATION

Chapter 1: This chapter provides an overview of the literature review setting the context of the review by first providing: a) composition of eucalyptus. b) Brazilian eucalyptus forest. c) Eucalyptus residues. d) Fast pyrolysis. e) Process description. f) Market products and byproducts. g) companies of bio-oil. h) Mass and energy balance. i) Economic aspects.

Chapter 2 organizes the description of methodology and assumptions used for the simulated biorefineries, as also the results and discussion through the following draft article: “Techno-economic assessment of bio-oil of eucalyptus residues from São Paulo state”.

In Chapter 3, general conclusions and suggestions for future work are presented.

Chemical composition of the biomass, product and byproducts are described in detail in Appendix A. Process parameters and operations are given in Appendix B. The process flow diagram, energy and material balances is presented in Appendix C for the biorefinery Limeira.

4. CHAPTER 1: LITERATURE REVIEW AND METHODOLOGY

4.1. Composition of eucalyptus

Biomass is the generic term for the plant (*phytomass*) and animal (*zoomass*) material considered as a potential source of energy applications because of its large-scale availability, low cost (MCKENDRY, 2002; SHABANI; AKHTARI; SOWLATI, 2013).

A major source of biomass which will form the focus of energy research is the lignocellulosic biomass which is particularly well suited as an alternative for fossil fuel (VAN MEERBEEK; MUYS; HERMY, 2019). Lignocelluloses are composed of 38-50% cellulose, 23-32% hemicellulose, 15-25% lignin, extractives, and several inorganic materials (HAMEED et al., 2019; VASSILEV et al., 2010).

Understanding the structural features in biomass material is important to optimize the industrial utilization of lignocellulose. Eucalyptus represents an important biomass source for the production of bio-products. Its industrial benefit can be achieved by processes following the biorefinery concept, which is based on the selective separation of the major components (hemicelluloses, cellulose and lignin), and on the generation of added-value from the resulting fractions (PENÍN et al., 2020). The typical chemical composition of eucalyptus is 46–49 % cellulose, 18–23 % hemicelluloses, 29–33 % lignin, 0.1–0.2%, ash, and 2–5% extractives (PEREIRA et al., 2014). As seen in Table 1, several studies quantified the chemical composition of eucalyptus.

Table 1. The chemical composition of eucalyptus species.

Eucalyptus species	Location	Cellulose (%)	Xylan (%)	Lignin (%)	Extractives (%)	Ashes (%)	Reference
urophylla	João Pinheiro, Brazil	45.6	21.9	29.7	2.7	0.1	(CARVALHO et al., 2015)
camaldulensis	Curvelo, Brazil	44.6	22.1	30.3	2.8	0.2	(PEREIRA et al., 2014)
globulus	Concepción, Chile	47.2	22.1	28.0	2.7	---	(MUÑOZ et al., 2011)
Sp	Fujin, China	48.2	19.6	28.3	3.0	0.9	(WEI; WU; LIU, 2012)
globulus	Pontevedra, Spain	48.3	18.9	29.9	3.0	0.2	(ROMANÍ; GARROTE; PARAJÓ, 2012)

4.2. Brazilian eucalyptus plantation

The Brazilian forestry sector is a world leader in timber productivity, its forest plantations cover 7.84 million hectares in 2018; it represents less than 1% of the Brazilian territory, but they are responsible for more than 90% of all the wood used for industrial purposes (IBÁ, 2019).

Eucalyptus plantations occupied 5.7 million hectares of the area of trees planted in Brazil. They are mostly located in the states of Minas Gerais (24%), São Paulo (17%), and Mato Grosso do Sul (15%) (Table 2). Over the last seven years, the area planted with eucalyptus has grown 1.1% per year, representing 72% of the total area planted (IBÁ, 2019).

Table 2. Planted area with eucalyptus trees, 2010-2016.

	Eucalyptus (ha)						
State	2010	2011	2012	2013	2014	2015	2016
Minas Gerais	1,400,000	1,401,787	1,438,971	1,404,429	1,400,232	1,395,032	1,390,032
São Paulo	1,044,813	1,031,677	1,041,695	1,010,444	976,186	976,613	946,124
Mato Grosso do Sul	378,195	475,528	587,310	699,128	803,699	826,031	877,795
Bahia	631,464	607,440	605,464	623,971	630,808	614,390	612,199

Rio Grande do Sul	273,042	280,198	284,701	316,446	309,125	308,515	308,178
Espírito Santo	203,885	197,512	203,349	221,559	228,781	227,222	233,760
Paraná	161,422	188,153	197,835	200,473	224,089	285,125	294,050
Maranhão	151,403	165,717	173,324	209,249	211,334	210,496	221,859
Mato Grosso	150,646	175,592	184,628	187,090	187,090	185,219	185,219
Pará	148,656	151,378	159,657	159,657	125,110	130,431	133,996
Goiás	116,439	118,636	115,567	121,375	124,297	127,201	127,201
Tocantins	47,542	65,502	109,000	111,131	115,564	116,365	116,798
Santa Catarina	102,399	104,686	106,588	107,345	112,944	116,250	116,240
Amapá	49,369	50,099	49,506	57,169	60,025	63,026	65,026
Piauí	37,025	26,493	27,730	28,053	31,212	29,333	26,068
Others	4,650	9,314	18,838	15,657	18,157	19,358	19,239
Total	4,900,949	5,049,714	5,304,164	5,473,176	5,558,653	5,630,606	5,673,783

Source: (IBÁ, 2017).

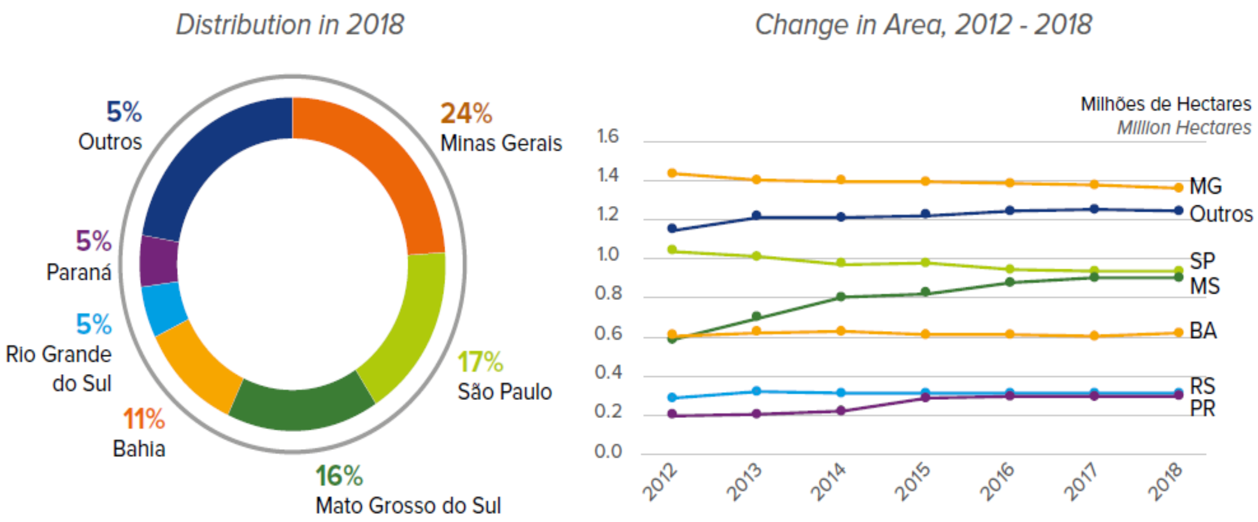

Figure 1. Eucalyptus plantations in Brazilian states, 2018.
Source:(IBÁ, 2019)

4.3. Eucalyptus residues

Forestry residues are organic material that remains in the field after the harvest. In the eucalyptus case, only trunks with 6 m and 4 cm of diameter are used for industrial processes; the other fraction, called biomass residues (branches, barks and leaves not included) corresponds to 29 wt% weight of the whole tree that is left on the harvest area (GONÇALVES, 2013).

The wood lost in the forest harvest may be in the form of: tall stumps of harvested trees, thick branches from the tops of harvested trees, shaft pointers below a predetermined diameter for unplugging; thin trees discarded by the harvesting machine operator, logs lost, forgotten or inadvertently dropped on the field, sawdust generated from tree felling and sectioning of logs (FOELKEL, 2007).

The amount of residues can be estimated by Equation 1 using the information provided by FOELKEL (FOELKEL, 2007), and considering the average density of those residues is 0.54 ton/m^3, and Volume/ha is 4.5 m^3/ha.

$$R = (A)(B)(C) = (2.43)(A) \qquad (1)$$

Where:

R = eucalyptus residues (ton).

A = area for the planting of eucalyptus (ha).

B = volume of residue / ha (m^3/ha)

C = density of eucalyptus (ton/m^3)

4.4. Fast pyrolysis

Pyrolysis is one of the thermochemical conversion methods that can be used for the conversion of biomass feedstock into bio-fuels, solid and gaseous fractions and value added chemicals by heating the biomass in the absence of air to around 500 °C (MUTSENGERERE et al., 2019). The rapid heating of biomass in such inert atmosphere results in the production of organic vapor composed of fragments of cellulose, hemicellulose, and lignin polymers found in the biomass. These vapors can be condensed to give a freely flowing organic liquid, commonly known as bio-oil (DHYANI; BHASKAR, 2018).

Table 3 relates the yield for the products and byproducts from type of pyrolysis (ASTON, 2019).

Table 3. Comparison of main parameters for slow, fast and flash pyrolysis of wood.

Pyrolysis mode	Heat rate (°C)	Temperature (°C)	Residence time	Bio-oil (%)	Bio char (%)	Gas (%)
Slow	0.1 -1	300 – 400	Hours – days (long vapour)	30	35	35
Torrefaction (slow)	0.1-1	290	10 – 60 minutes (solids)	0	80	20
Fast	10 – 200	500	1 s (short hot vapour)	75	12	13
Intermediate	10 - 200	500	10 – 30 (hot vapour)	50 in 2 phases	25	25
Flash	1,000	750 - 900	0.5 s	5	10	85

Source: (BRIDGWATER, 2012; MUTSENGERERE et al., 2019; SALEMA; ANI, 2012)

In reference to Yang et al., fast pyrolysis can be a technology able to maximize the production of pyrolytic oils from trunk wood and other lignocellulosic raw materials (YANG et al., 2007). Eucalyptus was recently used as a raw material for bio-oil production by fast pyrolysis, the yield reported by various authors are compared in Table 4.

Table 4. Comparison of the yield, temperature and scale for the fast pyrolysis using eucalyptus residues.

Raw material	Reactor	Scale (kg/h)	Temperature (°C)	Bio-oil yield (wt.%)	Reference
Eucalyptus *globulus* branches (wood, bark and leaves)	Conical spouted bed	0.12	500	75.4	(AMUTIO et al., 2015)
Eucalyptus *tereticornis* chips	Ablative	0.15	550	42.4	(GÓMEZ-MONEDERO et al., 2015)
Eucalyptus *grandis* wood	Transport bed	20	500	70.8 (dry basis)	(OASMAA et al., 2010)
Eucalyptus *grandis*	Twin screw	10	500	60.3	(JOUBERT et al., 2015)
Eucalyptus *grandis*	Fluidized bed	0.1	500	68.9	
Eucalyptus *grandis*	Fluidized bed	1	500	62.4	
Eucalyptus *grandis* woodchips	Fluidized bed	0.85	500	62.4	(CARRIER et al., 2013)
Eucalyptus (debarked)	Fluidized bed	0.15	500	59.2	(KIM et al., 2013)

Eucalyptus *loxophleba* wood	Fluidized bed	1	450	63	(GARCIA-PEREZ et al., 2008)
Eucalyptus *loxophleba* leaves	Fluidized bed	1	450	53 (dry basis)	(HE et al., 2012)
Eucalyptus wood	Fluidized bed	1	500	59	(CHANG et al., 2013)
Eucalyptus wood	Fluidized bed	0.1	450	71.1	(HEIDARI et al., 2014)
Eucalyptus wood	Fluidized bed	Batches of 10 g	450	48.2	(SULAIMAN; LEE, 2012)
Eucalyptus *grandis* (debarked)	Fixed bed	Batches of 200 g	450	45.5	(PIMENTAA et al., 1998)

Source: (AMUTIO et al., 2015)

4.5. Market fast pyrolysis product and byproducts

During the heating pyrolysis reaction, the eucalyptus residues are decomposing to form vapors condensable, non-condensable gases (CO_2, CO, CH_4, H_2) and solid byproduct called char or charcoal. The vapors can be condensed to form a liquid mixture of two phases: an aqueous (acidic extract), and an organic (bio-oil). The gases non-condensable are fuel for immediate use. While the acid extract has been used in the production of insecticides and fungicides, natural fertilizer and in the production of light fuels (SANTOS, 2011). Fig. 2 shows some application for products and byproducts from fast pyrolysis.

Bio-oil is a mixture of water (15–35% wt) that cannot readily be separated, and organic chemicals. Organic components consist of acids, alcohols, aldehydes, ketones, esters, phenols, guaiacols, syringols, sugars, furans, alkenes, aromatics, nitrogen compounds and miscellaneous oxygenates. Recovery of pure compounds from bio-oil is presently economically unattractive. Their average molecular weight varies in the range of 300–1,000 g/mol (VAMVUKA, 2012). Bio-oil has a higher heating value of about 17 MJ/kg, it is composed of a complex mixture of oxygenated compounds that provide challenge for utilization in co-processing with conventional fuels (HU; GHOLIZADEH, 2019).

Bio-oil has advantage such as storable and transportable fuel, as well as a potential source of a number of valuable chemicals, resins, binders, preservatives, etc. All products that currently result from the processing of petrochemicals can be produced from biomass feedstocks. These include lubricants, polymers, high matrix composites, textiles, biodegradable plastics, paints, adhesives, thickeners, stabilizers, etc. Advanced biomass conversion processes, which provide an opportunity to supply commodity chemicals at costs that are potentially competitive with the costs of the same chemicals from fossil feedstocks, are being developed (CZERNIK; BRIDGWATER, 2004; PINHEIRO et al., 2019; VAMVUKA, 2012).

The bio-char by-product contains virtually all the ash with effective separation from the pyrolysis vapors. About 25% of the energy in the biomass is contained in the char. In fluid bed technology, the char is separated and commercially, part would be burned externally to provide heat for the pyrolysis reactions. The surplus can be exported for other uses (ASTON, 2019).

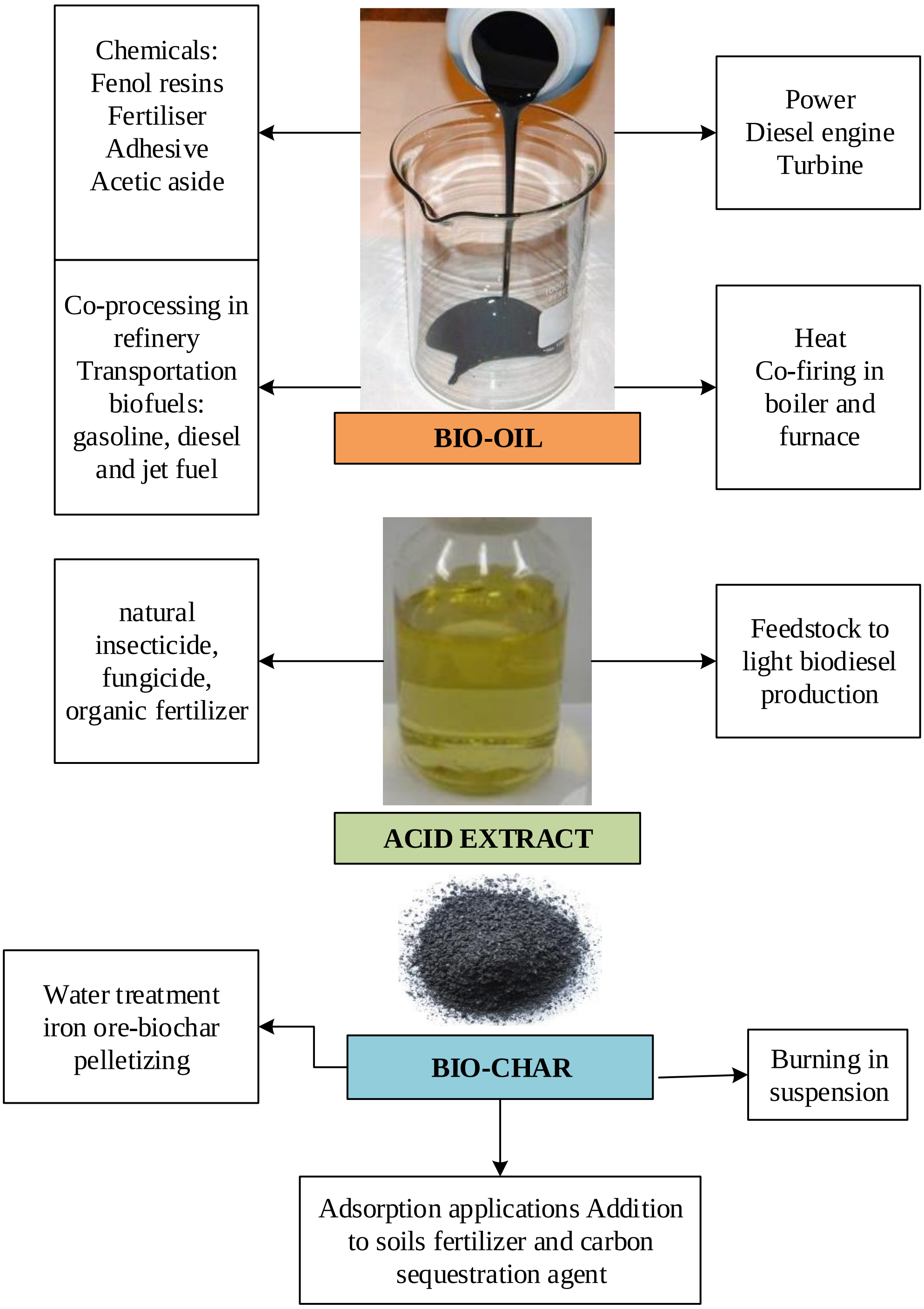

Figure 2. Applications of fast pyrolysis product and byproducts.
Source: Google images, (SANTOS, 2011).

4.6. Companies of bio-oil

There are three commercial companies producing bio-oil from biomass at the international level, Fortum, BTG-BTL, and Ensyn. Table 5 summarizes the main company data information.

Table 5. Capacity and bio-oil production of the companies Fortum, BTG-BTL and Ensyn.

Company	Location	Technology	Biomass	Feedstock (ton/year dry base)	Bio-oil (ton/year)	Investiment (USD million)
Fortum	Joensuu, Finland	Fluid Bed	Forest residues	100,000	50,000	36
BTG-BTL	Hengelo, The Netherlands	Rotating Cone Reactor	Wood pellets	43,800	28,000	19
Ensyn	Port-Cartier, Canada	Circulating Fluid Bed	Forest residues	65,000	48,000	103

Source: (BTG-BTL, 2019; ENSYN, 2019; FORTUM, 2019)

Suzano incorporated Fibria and positioned themselves in the renewable energy sector for the use of forestry waste to produce bio-oil. Suzano invested around 20 million USD in partnership with the American multinational Ensyn Corporation. Basic engineering plant was completed for implementation in Aracruz, Espírito Santo at the end of 2015. The initial capacity production will be 84 million liters per year, using 2.3 million tons / year forest residues and its investment is 96 USD million (ECONOMIA, 2020).

Bioware is a company located in Campinas with a capacity between 2,000 to 4,000 kg/h of biomass (forest residues or garbage). Theirs projects may include a fractional separation system for pyrolysis vapors in order to offer different products, such as: 20% organic acids, 35% bio-oil, 20% gases, and 15% bio-char in dry eucalyptus (BIOWARE, 2020).

5. METHODOLOGY

5.1. Mass and energy balance

A steady-state simulation model has been developed in Microsoft Excel to estimated mass and energy balances for a fast pyrolysis process using eucalyptus residues as feedstock, and supported information by literature (JONES et al., 2013; ONARHEIM; SOLANTAUSTA; LEHTO, 2015; SALMAN, 2014). We assumed that the temperature is considered uniform throughout the reactor for energy balance, and the operating pressure and pressure of vapors from the reactor is considered the same, not accumulation. Take into account the biomass moisture. Mass balance equations corresponding the law of conservation of mass. Process conditions, parameters and results for the biorefinery Limeira are detailed in Appendix B and C.

Bio-char generated during the fast pyrolysis reaction was modeled as a component consisting of carbon, hydrogen, oxygen, and nitrogen elements. The heat capacity of sand (heating medium) varies with temperature and sand type. Jones at al, (JONES et al., 2013) used SiO_2 as a model compound for sand. The temperature of the sand in the reactor is 800 °C.

Higher heating value and lower heating value:

The heating value is expressed as Higher Heating Value (HHV) and Lower Heating Value (LHV). The difference is caused by the heat of evaporation of the water formed from the hydrogen in the material and the moisture. HHV is measured using a bomb calorimeter, and defined as the amount of heat released when fuel is combusted and the products have returned to a temperature of 25°C. The heat of condensation of the water is included in the total measured heat. LHV is defined as the net heating value and is determined by subtracting the heat of vaporization of water vapor (generated during combustion of fuel) from the higher heating value (BILGEN; KELEŞ; KAYGUSUZ, 2012). The products ad byproducts pyrolysis compositions are presented in Appendix A, where C, H, etc. are the mass and the ash fractions in wt% of dry material. HHV and LHV are calculated by using the following equations:

Biomass:

HHV: (TONG et al., 2018)

$$HHV\left(\frac{MJ}{kg}\right) = \frac{(146.58C + 568.78H - 51.53(O + N) - 6.58Ash + 29.45S)}{430} \tag{2}$$

LHV: (MOKA et al., 2012)

$$LHV = HHV - 51.14(H) \tag{3}$$

Bio-char:

HHV: (GANDHI, 1940)

$$\mathrm{H}HV\left(\frac{MJ}{kg}\right) = \frac{146.58C\ +\ 568.78H\ -\ 51.53(O + N) -\ 6.58Ash\ +\ 29.45S}{430} \tag{4}$$

LHV: (TORRES-ROJAS et al., 2008)

$$LHV\ \left(\frac{MJ}{kg}\right) = HHV - 23.96(9H) \tag{5}$$

Bio-oil:

$$HHV_{Milne}\left(\frac{MJ}{kg}\right) = 0{,}341\ x\ C + 1{,}322\ x\ H - 0{,}12\ x\ O - 0{,}12\ N + 0{,}0686\ S - 0{,}0153\ Ash \tag{6}$$

$$LHVdry = HHVDry - 2.443\left(\frac{8.936H}{100}\right) \tag{7}$$

Syngas: (YAO et al., 2018)

$$LHV\ \left(\frac{MJ}{kg}\right) = \frac{10.79.H_2 + 12.63.CO + 35.8CH_4}{100} \tag{8}$$

Where: composition molar

In order to estimate energy balance, the design basis for the biomass dryer, fast pyrolysis reactor, combustor, condenser are assumed according literature (PATHWAY et al., 2013; SALMAN, 2014).

Condenser

The specific heat capacity of moisture is taken to be constant at C_{pw} = 4.19 kJ kg^{-1} K^{-1}. A constant value of specific heat capacity of vapor C_{pv} = 1.88 – 1.90 kJ kg^{-1} K^{-1} with increasing temperature from 0°C to 1000°C (SCIENCE, 2009). Bio-oil is captured in a liquid recovery system consisting of a water-cooled condenser (Tin 5 °C, Tout 60 °C). The condensed bio-oil is cooled to 60 °C or less, in order to limit polymerization and secondary reactions, especially of cellulose derivatives in the liquid phase. The equations are (GAVHANE, 2014):

Heat lost by the hot fluid:

$$Q = m_h x C_{ph}(T_{outh} - T_{inh}) \qquad (9)$$

Heat gained by the cold side:

$$Q = m_c x C_{pc}(T_{outc} - T_{inc}) \qquad (10)$$

Where:

Q: heat gained by the cold side (kW)

m_h: mass flow rate of the hot fluid (kg/h)

C_{ph}: mass heat capacity of the hot fluid (J/kg°C)

T_{outh}, T_{inh}: outlet and inlet temperarures on exchanger hot side (°C), respectively.

m_c: mass flow rate of the cold fluid (kg/h)

C_{pc}: mass heat capacity of the cold fluid (J/kg°C)

T_{outc}, T_{inc}: outlet and inlet temperarures on exchanger cold side (°C), respectively.

Grinding:

The energy required for grinding and chopping has been calculated by (SALMAN, 2014). This method required one range of size from 0.5 – 3.5 mm.

$$G_E = 5.31Z^2 - 30.86Z + 55.45 \tag{11}$$

Where:

G_E: energy required (kWh/ton)

Z: size of feedstock (mm)

Drying:

The eucalyptus residues is dried to achieve a moisture content of 10% from 45% moisture. The dryer was modeled using the energy balance on the dryer (SALMAN, 2014).

$$D_E = FCp_{wood}dT + MCp_w dT + L_{HV}M_V \tag{12}$$

Where:

D_E: heat flux required for drying (kJ/h)

dT: drying temperature less the romm temperature (75 K = 373 – 298)

M: mass rate of water in the wood (kg/h)

F: mass of feed (kg/h)

M_V: mass rate of water evaporated (kg/h)

Cp_w: heat capacity of dry wood (4.184 kJ/kgK)

Cp_o: heat capacity of dry wood (kJ/kgK)

L_{HV}: latent heat of vaporization of water (kJ/kg)

Cp_{wood}: heat capacity of wood (kJ/kgK)

Crushing: see the reference (SILVA, 2012). The methodology to calculate the energy consumption for crushing operation was based on experimental work from University Federal of Itajubá. The energy consumption for chopping the biomass was 1,000 mL of diesel oil in 5 minutes of operation with the engine at the nominal speed of 2,000 rpm, crushing 145 kg of eucalyptus (moisture: 55%). Considering the LHV diesel of 10,100 kcal/kg and the density of 0.8 kg / L, the energy consumed to chop the biomass was: 56.5 kcal / kg of eucalyptus chopped. Resulting in a relative fuel consumption of 7 mL fuel /kg biomassa.

Pyrolysis reactor

The fast pyrolysis reactor was modeled using Equation 13 according to the method described in (SALMAN, 2014).

$$Q_{py}\left(\frac{MJ}{kg}\right) = heat\ of\ pyrolysis\ x\ mass\ feed\ to\ reactor \tag{13}$$

The heat of pyrolysis by using the fluidized bed reactor at 500 °C, it is valor was considered as 1.5 MJ/kg for eucalyptus wood.

Pyrolysis Thermal efficiency:

The pyrolysis thermal efficiency of the system is defined as the following equation (SALMAN, 2014):

$$n_p = \frac{Q_L + Q_C + Q_G}{Q_F + G_E + D_E + Q_{PY}} \tag{14}$$

Where:

n_p: Thermal pyrolysis efficiency

Q_L: chemical energy of bio-oil (kJ/h)

Q_c: chemical energy of bio-char (kJ/h)

Q_G: chemical energy of syngas (kJ/h)

Q_F: chemical energy of feed (kJ/h)

Q_{PY}: energy required pyrolysis reactor (kJ/h)

G_E: energy required grinder (KJ/h)

D_E: energy required drier (KJ/h)

Combustor:

Heat generated in the combustor is used in the dryer to dry the fast pyrolysis feedstock and to reheat the sand to the fast pyrolysis reactor. Calculating for heat available assumed that combustion of syngas is combusted, with an efficiency of 90%.

Heat of combustion of syngas as: (SALMAN, 2014)

$$HC = \sum_{i}^{n} HC_i x MF_i \quad (15)$$

Where: HC_i: heat of combustion of components in syngas (kJ/kg)

MF_i: mass fraction of component (wt%)

5.2. Economic aspects

5.2.1. Capital investment

For the economic evaluation the first step is to estimate the capital cost. One of the methods to evaluate the capital cost is a feasibility study which is a way to evaluate the practicality and desirability of a project relies on cost information for a complete process taken from previously built plans. Capital investment for the entire plant based on the unit costs of equipment will scaled from base equipment cost following the 6-10th's rule, Equation 16; it will be calculated as factors of the equipment cost, and the size adjusted cost is adjusted for inflation by using published price indices (TURTON, 2009).

$$C_n = C_B \left(\frac{S_n}{S_B}\right)^n \qquad (16)$$

Where:

C_n = cost of equipment to be estimated (new cost)

C_B = cost of existing equipment (old cost)

S_n = capacity of new piece of equipment

S_B = capacity of existing piece of equipment

n= the specific scaling factor for a particular equipment (from 0.6 to 0.8).

Equation 16 is then adjusted using appropriate scaling factors, for capacity, and for inflation, to provide the estimated capital cost. It is generally used by engineers for evaluating the best option, the establishment of plant size and the economic feasibility of the project (TURTON, 2009). This estimation requires the following general and engineering information:

- Plant capacity
- General scope description
- Process block diagrams
- General geographic location
- The cost of a similar previous project

Other cost is providing of manufacturing that is include fixed capital investment, cost operating labor, cost of raw materials, cost of utilities, and cost of waste treatment. A modular method to estimate the manufacturing cost is presented in the methodology section.

5.2.2. Profitability analysis

An analysis of cost and revenue of the project which determines whether or not is profiting is known as profitability analysis. Parameters used in capital budgeting to estimate the profitability of potential investments including: NPV, the IRR, and payback period (PBP) (TURTON, 2009).

The NPV summing all inflows and outflows of cash over the project lifetime. A positive NPV indicates that the project earnings surpass the expected costs, meaning that the project is profitable, while a negative NPV will event in a net loss. In order to assess the value of the project, financed by a combination of debt and equity, the discount rate applied to the cash flows in NPV calculation correspond to an overall cost of capital from a weighted average cost of all capital sources invested in the project. The NPV considers this discount rate over the project lifetime, giving the annual cash flows in present values. The present value of money is always less than its future value as it has interest-earning potential.

IRR is the minimum discount rate that management uses to identify what capital investments or future projects will yield an acceptable return and be worth pursuing. The IRR for a specific project is the rate that equates the NPV of future cash flows from the project to zero (OZONOH et al., 2018).

The PBP is the time required to recover the initial cost of an investment. It is the number of years it would take to get back the initial investment made for a project.

Investors constantly consider investments for new products, but they need to have a measure that helps them determine if these new projects are viable.

The minimum acceptable rate of return (MARR) is the minimum profit an investor expects to make from an investment, taking into account the risks of the investment.

In summary:

- If the NPV is positive: investment is accepted.
- If the NPV is negative or NPV=0: investment is not accepted.

The IRR and MARR are related to each other by the following:

- If the IRR is greater than the MARR, the NPV is positive → investment is attractive.
- If the IRR is less than the MARR, the NPV is negative → the investment is not attractive.

5.2.3. Sensitivity and Monte Carlo analysis

Sensitivity analysis explores the relative effects on the economic viability of a project of possible changes in the forecast data which contribute to the project cash flows. It focuses on the areas which are most critical in terms of any uncertainty, and it indicates where confidence in forecast is most vital.

Sensitivity analysis also enables the economic effects of changes in a project to be reviewed; for example, changes in fixed and variable costs resulting from the use of different equipment types, different phasing of investment, delays in plant start-up, and the effect of possible different market growth patterns. It can also be used to explore the effects on the economic viability of a project with uncertainty in different areas, but does not attempt to quantify the uncertainty in an area. In general, it is worthwhile to make tables or plot curves that show the effect of variations in costs and prices on profitability. Sensitivity analysis should always be carried out to observe the effect of departures from expected values (COKER, 2007).

Monte Carlo simulation allows accounting for risk in quantitative analysis and decision making. The technique is used by professionals in such widely disparate fields as finance, project management, energy, manufacturing, engineering, research and development, insurance, oil-gas, transportation, and the environment (PALASADE, 2019).

Monte Carlo simulation furnishes the decision-maker with a range of possible outcomes and the probabilities they will occur for any choice of action. It shows the extreme possibilities—the outcomes of going for broke and for the most conservative decision—along with all possible consequences for middle-of-the-road decisions (PALASADE, 2019).

5.2.4. The minimum selling price (MSP)

Consequently, the minimum selling price (MSP) of bio-oil which is defined as the lowest market price capable of yielding; it will be determined using a discounted cash flow (DCF) analysis taking into account operating and capital costs under a 10% IRR over a 25 year plant life (RINGER; PUTSCHE; SCAHILL, 2006). The DCF requires economics assumptions that are depended on type of projects; its models are based on the assumption that the value of any firm is the present value of the expected cash flows. Table 6 shows calculated MSP of bio-oil in some countries.

Table 6. MSP of bio-oil via fast pyrolysis.

Country	Biomass	Biomass capacity (MTPD)	Bio- oil yield (10^3 L/h)	Bio-oil MSP (US$/L)*
USA	Biomass	1,650	24	0.95
Brazil	Eucalyptus	2,000	20	0.58
USA	Wood	550	13	0.30
Finland	Wood	184	6	0.24
USA	Wood	400	6	0.24
USA	Agricultural biomass	1,000	28	0.15

*Conversion based on bio-oil density of 1.20 kg/L.
MTPD: Metric ton per day
Source: (PIGHINELLI; SCHAFFER; BOATENG, 2018)

CHAPTER 2_Draft: Techno-economic assessment of bio-oil production using eucalyptus residues.

TECHNO-ECONOMIC ASSESSMENT OF BIO-OIL PRODUCED FROM EUCALYPTUS FORESTRY RESIDUES IN THE STATE OF SÃO PAULO

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ABSTRACT

Forestry residue is feedstock potentially useful to obtain bio-oil and byproducts (biochar, syngas, and acid rich aqueous extract) via fast pyrolysis. A techno-economic analysis of the production of bio-oil from eucalyptus residues (ER) and of their availability in the state of São Paulo (SP), Brazil, was performed. Discounted cash flow was used to calculate the minimum selling price (MSP) of bio-oil. Georeferencing allowed locating 20 eucalyptus plantations (106 km of radius), 10 of which were selected due to better economic performance, being potentially able to produce 59 million L/year of bio-oil. The economic analysis of the biorefineries showed that an MSP of 190 to 300 USD/ton was capable of processing 60,000 to 5,000 tons/year of ER. A simulation of a large biorefinery revealed a capital investment (CAPEX) of around 6 MM USD, reaching a peak of operating expenditure of about 3 MM USD/year. The sensitivity analysis identified that plant capacity has the most significant impact on MSP, while the byproducts (acid extract and biochar) lowered it by 22%. The large biorefinery simulated using the Monte Carlo method had 80% chance of reaching a net present value (NPV) > 0, and 80% probability of reaching an internal rate of return (IRR) > 10%. This study demonstrates that the production of bio-oils by the 10 centralized biorefineries simulated is economically viable based on the NPV and IRR indicators.

Keywords: lignocellulosic feedstock; pyrolysis; sensitivity analysis; minimum selling price, georeferencing analysis.

1. INTRODUCTION

Biofuels obtained as direct by-products of first-generation ethanol from sugarcane in Brazil, corn in the USA, and sugar beet in Europe, were the first to be produced on a large scale [1–4]. Nonetheless, more recent concerns about their competition with food and the sustainability of first-generation biofuels have increased the interest in the development of second-generation biofuels from lignocellulosic biomass. Feedstocks such as forestry residues represent an alternative for a potential future bio-based economy.

Fast pyrolysis is one of the simplest thermochemical decomposition methods used to obtained bio-oil from lignocellulosic biomass [5,6], with biochar, acid extract, and non-condensable gases (CO_2, CO, H_2, CH_4) as byproducts [7]. Biochar and acid extract are high-value byproducts which increase the simulated process' economic profitability due to the assimilation of new markets [8]. The incorporation of bio-oil into the market of chemicals, heating and fuels has been studied by researchers [9]. Co-processing is another interesting application that has been explored, with its commercial adaptation in petroleum refineries as an option to produce renewable hydrocarbon fuels and petrochemical raw materials from lignocellulosic biomass [10–14].

In this context, the availability of feedstock is an important factor to be considered in a biorefinery's design. Brazil is a country with large availability of planted forestry, 7.83 million hectares in 2018, of which eucalyptus plantations correspond to 5.7 million hectares [15].

Eucalyptus is used mainly in the paper and pulp industries [16], which own 36% of planted trees, producing residues which have been increasingly studied as feedstock to produce bio-oil and expand these companies' business towards bio-economy [17]. As biorefineries are considered the key infrastructure of bio-economy [18,19], fast pyrolysis is being developed and improved to optimize the use of forest residues and generate several value-added products.

The biorefinery´s location is the first factor to be considered to reduce the cost of feedstock and ensure its availability. To this end, geographical information systems (GIS) allow determining the best location according to the availability of feedstock [20].

São Paulo (SP) ranks second among the main eucalyptus-producing states in Brazil, with 1 million hectares of eucalyptus plantations [15]. As eucalyptus residues (ER) represent 30 – 40 % of the whole tree [21,22], their production in the state corresponds to 243,000 tons/year. Assuming a 46% yield [23] and 45% moisture [24], fast pyrolysis has the potential of producing 61 million liters of bio-oil per year. Therefore, the use of ER as feedstock is essential to the development of biorefineries using fast pyrolysis on a large scale.

Techno-economic analyses (TEA) have been performed to evaluate the minimum selling price (MSP) of bio-oil [25], which is the lowest market price covering production costs at a 10% internal rate of return (IRR). Some authors have calculated this price based on different plant capacities, ranging from 10 to 2,000 MTPD (metric tons per day), obtaining an MSP of 0.20 to 0.50 USD/kg [26–28].

In Brazil, Pighinelli et al., [29] considered a production capacity of 2,000 MTPD of eucalyptus *benthamii* to calculate the high heating value (LHV) and MSP of bio-oil, obtaining 30.76 MJ/kg (dry basis) and 480 USD/ton, respectively. In turn, Ringer et al., [30] considered a production capacity of 550 tons/day of biomass, which resulted in a MSP of 133 USD/ton , or 7.62 USD/GJ in terms of energy, and a LHV of 17 MJ/kg. According to Pinheiro Pires [31], bio oil's production costs vary between 98 and 860 USD/ton; moreover, efforts are needed to keep these costs below 150 USD/ton

The aim of this paper is to assess the techno-economic feasibility of bio-oil production in the state of SP with ER as feedstock by identifying its availability. Two questions are also addressed: what is the MSP of bio-oil? Which parameters influence the calculation of MSP? To answer them, TEA was performed while considering the discounted cash flow (DCF), economic indicators, the net present value (VPN), and IRR. Additionally, sensitivity and Monte Carlo risk analysis were also analyzed, using simulation assess economic model feasibility over a 25-year period.

2. MATERIAL AND METHODS

Fig. 1 depicts the methodology adopted for the technical and economic analyses. The former pertain to the availability of feedstock, and to the mass and energy consumed in the process (pretreatment and fast pyrolysis). The latter pertain to economic assessment, with determination of feasibility based on economic indicators, MSP, VPN, and IRR. The mass and energy balances and the economic analyses were simulated in Microsoft Excel.

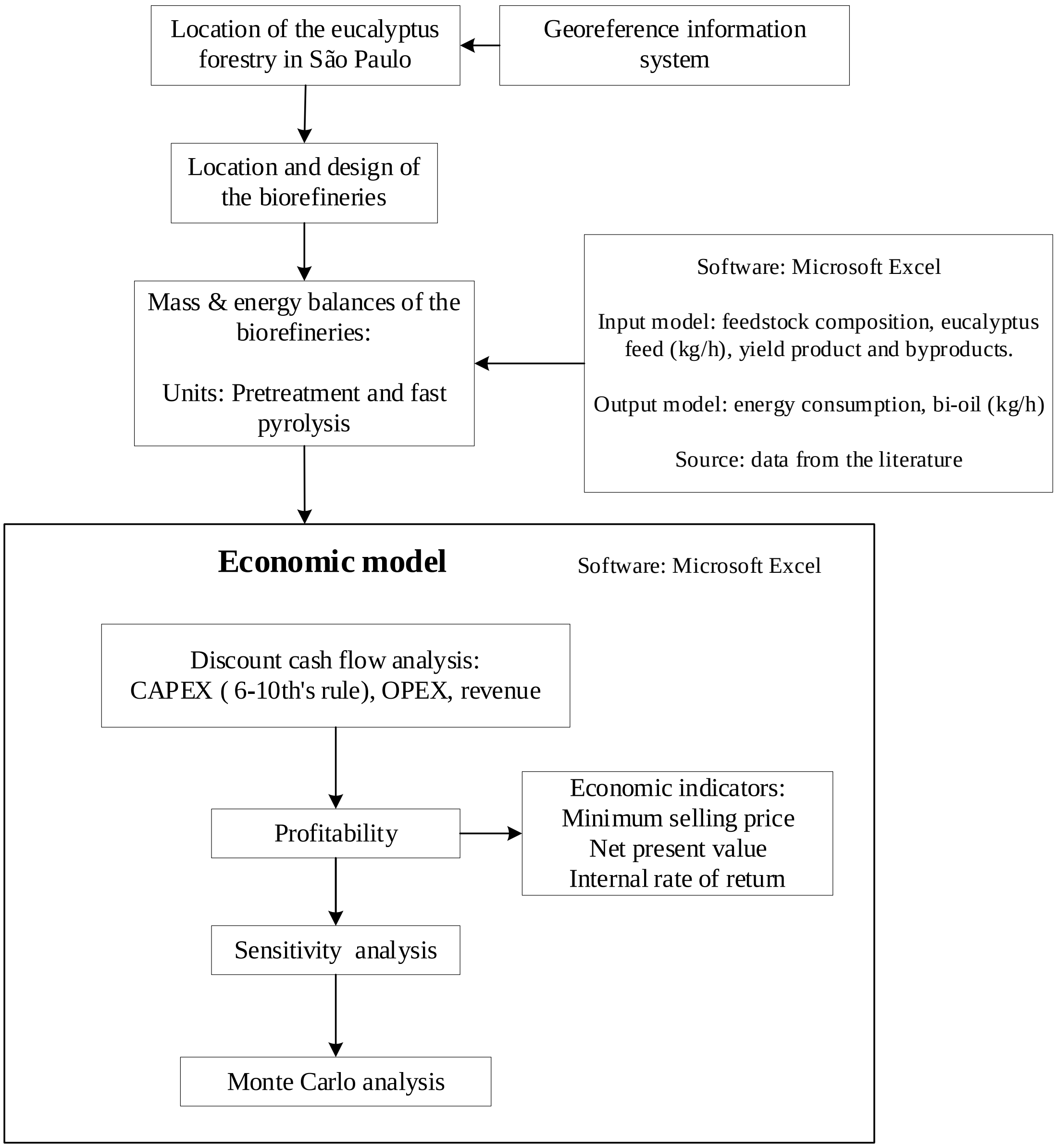


Fig. 1. Methodology developed to simulate the biorefineries and calculate the minimum selling price of bio-oil.

2.1. Feedstock availability

In order to calculate feedstock availability, two open-source databases were used; IBGE [32] to obtain data on the harvested area and production (2010/2017 harvest) of eucalyptus, and the MapBiomas collection v.4.0 to obtain land use maps. The planted area of a 7-year eucalyptus plantation was considered, according to LeMaire et al. [33].

The fast pyrolysis plant uses ER as feedstock, which is organic forestry material (branches, barks, and leaves are not included left in the forestry after harvesting). Its composition is 45% moisture and 55% wood + ash [24]. The processing capacity depends on the availability of residues in SP.

Assuming a total eucalyptus residues production of 4.5 m^3/ha and a mean residue density of 0.54 ton/m^3 [7], the plantation can produce 2.43 ton/ha of usable residues. Therefore, the available residues were calculated according to Equation 1, following the methodology described by Romero [34]

$$R = 2.43xA \tag{17}$$

Where, R = residues (ton) and A = eucalyptus plantation area (ha).

Two scenarios were considered: a centralized unit in Limeira (125 km radius), and the entire state of São Paulo, subdivided in 150 km^2 grids (106 km radius). The biorefinery in Limeira was simulated because it is a strategic point, it is located in a pulp and paper plant, and it is located near one of the largest refineries in Brazil (27 km).

2.2. Process design

Fig. 2 illustrates scenarios A and B. Scenario A depicts a biorefinery in Limeira annexed to a large pulp plant located in the region, facilitating feedstock storage and transportation. The bio-oil produced in this scenario is transported to a petrol refinery to be co-processed with gas oil via fluid catalytic cracking (FCC) [12]. Scenario B depicts centralized production units, with 20 eucalyptus plantations. The bio-oil produced in this scenario is transported to the Limeira plant, and then it transported to the Refinery.

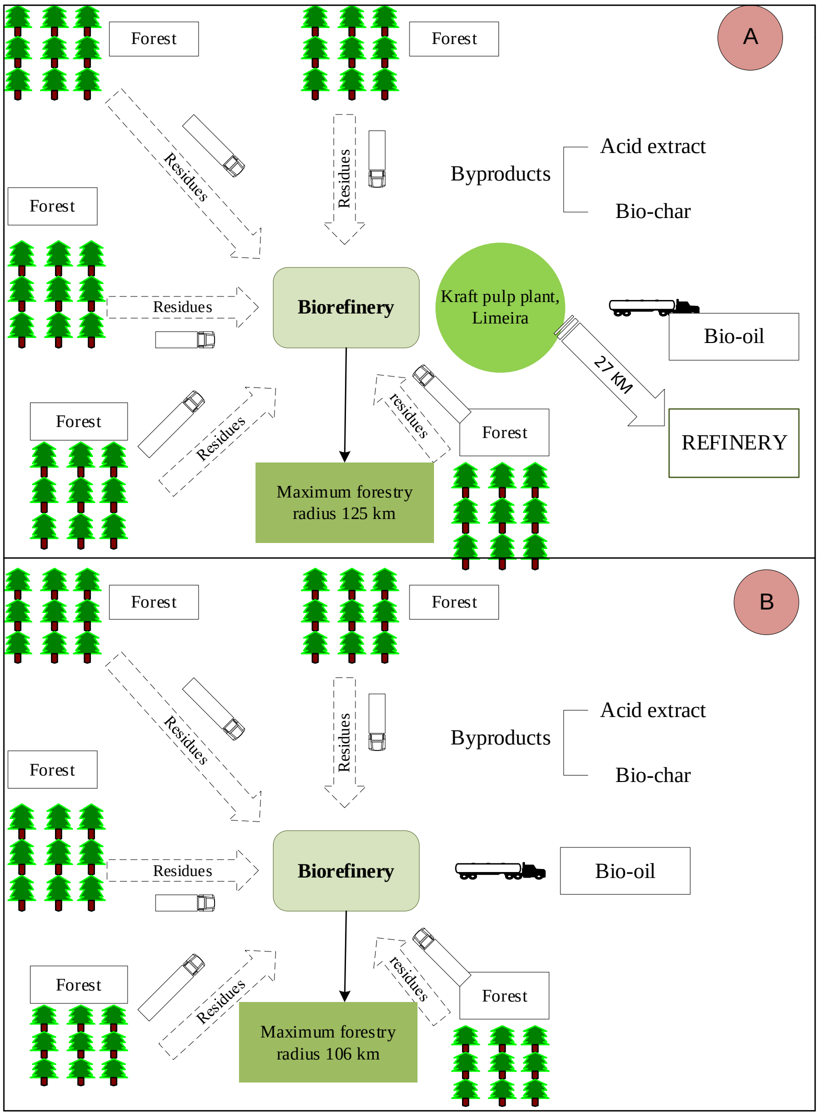


Fig. 2. Centralized bio-oil production diagram. A) Biorefinery annexed to the Kraft pulp plant with 150 km radius, Limeira; B) Biorefinery with 106 km radius.

The biorefinery has three processing units (Fig. 3), with the following purposes: transportation, pretreatment (crushing, drying, grinding), and performance of fast pyrolysis using a fluidized bed reactor (FBR).

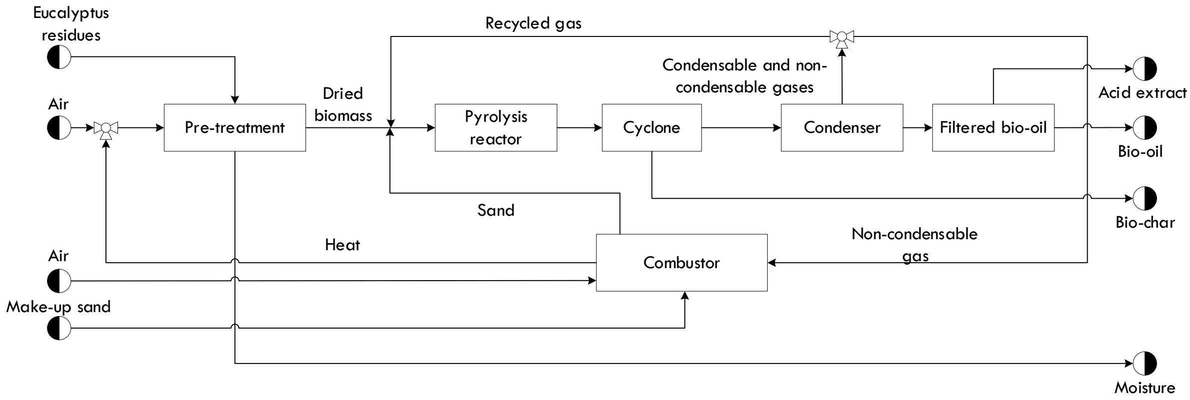


Fig. 3. Block diagram of the fast pyrolysis process using eucalyptus residues. Main product: bio-oil, byproducts: acid extract, biochar.

In the pretreatment unit, the biomass is chopped, dried to about 10% moisture, and milled to 1.5 mm diameter [35]. The dryer uses heat generated in the combustor to dry the feedstock. The dried biomass is fed continuously to an FBR, and heated to 500°C in less than two seconds at atmospheric pressure. The FBR uses recycled gases as a fluidizing agent (fluidized gas/dry biomass = 3) and sand as a heating agent (sand/dried biomass = 14.5; make-up sand/dried biomass = 0.034); the sand is extracted from the combustor at around 900°C. Heat losses of around 27% of the biomass' lower heating value (LHV) in the pyrolysis reactor are estimated.

The dried biomass is converted into condensable and non-condensable gases. The pyrolysis vapors can be condensed to form a liquid mixture with two phases, one aqueous (acid extract) and the other organic (bio-oil). The main product is bio-oil (46 wt.% yield) [23], and the byproducts are solid char (18 wt.% yield), acid extract (18 wt.% yield), and non-condensable gases (18 wt.% yield) [23,36].

Then, two cyclones separate the sand and char from the vapors; the sand is led to the combustor, where it is reheated, and the biochar is sold as a by-product. The pyrolysis vapors are condensed, and cooled bio-oil and non-condensable gases are separated from the condensed bio-oil. The condenser uses a recirculating water-cooling system (5°C in, 60°C out), with a loss of around 5%. The non-condensable gases exit the scrubber and are partly recycled as fluidizing agent (96% wt.) in the pyrolysis reactor, while the remaining gases (4% wt.) are combusted in the combustor (90% yield, 20% excess oxygen, 600°C).

Electricity is obtained from the grid. Energy efficiency is a useful measure for identifying the a fast pyrolysis' yield, which can be expressed as thermal efficiency (η), corresponding to the ratio of the pyrolytic products' total heating values and the thermal energy required to heat the biomass to the energy contained in the feedstock at higher heating values [37].

2.3. Process simulation

The fast pyrolysis process' mass and energy balances were modeled in Microsoft Excel using information (yield, combustion reactions, ER and bio-oil composition, data design, energy balance assumptions) provided by the literature, considering the lower heating value (LHV) of ER (19 MJ/kg), bio-oil (17 MJ/kg), syngas (10 MJ/kg) and biochar (24 MJ/kg).

2.4. Economic performance of a biorefinery

The economic model, DCF, sensitivity and Monte Carlo analyses developed in Microsoft Excel are connected to the mass and energy balances. After the biorefineries had been dimensioned, the total capital investment (CAPEX) was estimated for each of them.

CAPEX refers to the cost of building a new chemical plant. It is calculated by Equation 2 according to the base equipment cost (provided by a representative of Bioware), following the 6-10th's rule [38] and considering a scale factor of 6. The CAPEX is adjusting to 2018 using the Chemical Engineering Plant Cost Index (CEPCI) which is 617.6 [39].

$$C_n = C_B \left(\frac{S_n}{S_B}\right)^n \qquad (18)$$

Where, C_n = estimated cost of equipment; C_B = cost of existing equipment (USD); S_n and S_b are the estimated new pieces of equipment and the existing pieces, respectively; n = specific scaling factor for a particular piece of equipment (0.6).

The cost of a fast pyrolysis biorefinery includes the CAPEX and the operating expenses (OPEX). These costs are combined in a DCF to estimate the MSP (expressed in USD/ton) needed to meet a 10% IRR [40]. Additionally, DCF is used to calculate the NPV and IRR. The MSP does not consider the revenue of byproducts (biochar and acid extract).

The development of a DCF takes into consideration: plant design, 354 days/year of operation for a total of 25 years, a working capital of 5% of the CAPEX, an income tax of 34%, and an annual lineal depreciation of 10%. The OPEX is estimated as fixed and variable costs; the cost of transporting ER is determined by Equation 3 [41].

$$C_T = 5.62 + (0.04)d \quad (19)$$

Where, C_T = transportation cost (USD/ton); d = transportation distance (km).

The sensitivity analysis consists in finding the effects of various parameters on the MSP of bio-oil. In this study, the variation range is ± 30% of the base MSP of bio-oil for some of the parameters evaluated according to the most critical assumptions. Once the sensitivity analysis revealed the most critical variables, those were included as input variables in order to determine the most impactful uncertainties and to assess the biorefinery's financial risk by simulating it with a triangular probability distribution, according to the Monte Carlo method, and implementing 5,000 iterations as an Excel macro to measure the probability of NPV > O and IRR > 10%. The sensitivity and Monte Carlo analyses were performed for the biorefinery located in Limeira. The main assumptions to calculate the DCF and estimate the fixed and variable cost, sensitivity, and Monte Carlos inputs are presented in Table 1.

	Value	Unit
Discounted cash flow analysis		
Plant location	São Paulo, Brazil	
Cost year of analysis	2018	
Plant scale	Depends on the scenario	tons /year
Construction time	2	Years
Plant lifetime	25	Years
Operating hours	8,400	hours/year
Production ramp-up schedule	100	% of nominal capacity in the first year of production
Financing	100	% of own capital
Income tax	34	%
Depreciation period	10	years (linear model)
Discount rate	8	%
Scrap value	0	
Working capital	5	% of total capital investment
Exchange rate	4.7	R$/USD

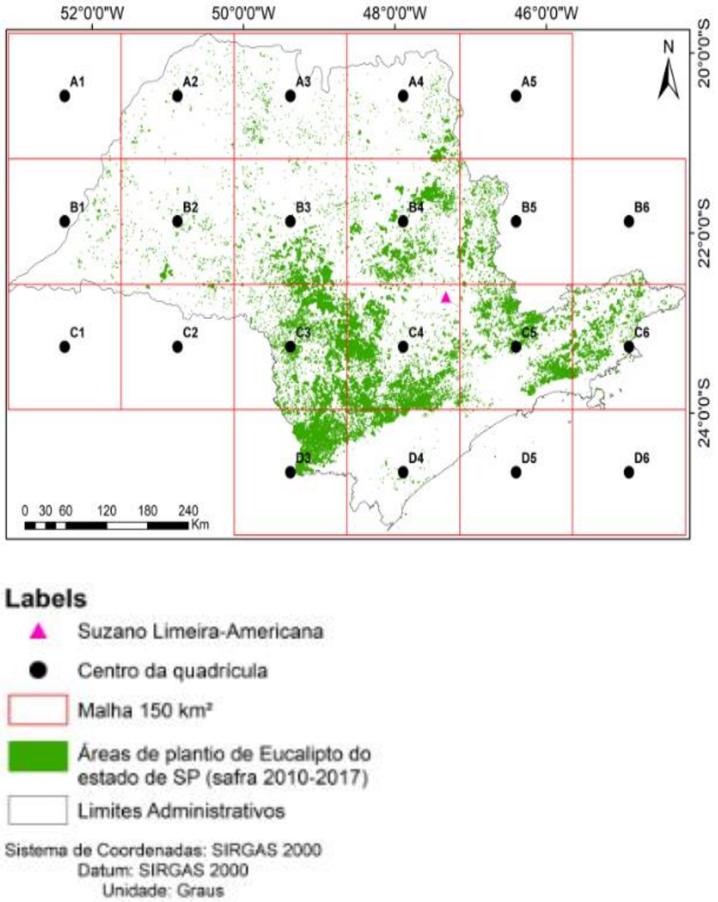
Base CAPEX (Bioware; feedstock: 50,400 tons/year; year: 2016; location: Brazil; CEPCI: 541.7)[42]		
Pretreatment [29]	1.38	MM USD
Fast pyrolysis, combustor, product recovery, storage, electromechanical assembly, civil construction, services, others	3.51	MM USD
OPEX		
Fixed operating costs		
Labor	1.0	% of total capital investment
Maintenance	2.0	% of total capital investment
Others	0.2	% of total capital investment
Contingency	1.0	% of total capital investment
Variable operating costs		
Feedstock cost [43]	15	USD/ton
Electricity [44]	74.47	USD/MWh
Residual sand [45]	97.87	USD/ton
Water [46]	11.19	USD/m^3
Biomass transportation cost	11.62	USD/ton
Monte Carlo analysis inputs (biorefinery in Limeira)		
Capacity (ton/year)	Triangular distribution (25,000; 49,200; 59,000)	
Yield	Triangular distribution (41; 46; 48)	
OPEX (MM USD/ year)	Triangular distribution (1.47; 2.01; 3.15)	
Biomass cost (MM USD/year)	Triangular distribution (0.91; 1.31; 1.58)	
CAPEX (MM USD)	Triangular distribution (4.13; 5.50; 8.25)	

Table 7. Main assumptions of the economic analysis.

3. RESULTS AND DISCUSSION

3.1 Feedstock availability

The georeferencing analysis revealed several eucalyptus plantations in SP. The total eucalyptus area was estimated as 700,000 ha, and divided in 20 grids (Fig. 4), which represent the location of the biorefineries simulated. The total availability of biomass was estimated as 1,700,000 tons over 7 years. Ten grids (C4, C3, D3, B4, C5, B3, C6, D4, B5, A4) have the most significant concentrations of eucalyptus residues.



Grid	Area (ha)	Residues (ton/year)
C4	173,361	60,181
C3	143,949	49,971
Lim	141,828	49,235
D3	89,248	30,982
B4	74,244	25,773
C5	57,533	19,972
B3	53,982	18,739
C6	26,458	9,185
D4	25,709	8,925
B5	22,757	7,900
A4	14,634	5,080
B2	8,690	3,017
B1	2,324	807
A3	2,155	748
C2	1,955	679
A2	1,385	481
B6	686	238
D5	55	19
A1	28	10
A5	17	6
C1	5	2

Fig. 4. Map of eucalyptus plantations in the state of São Paulo, divided in grids. The pink triangle indicates a biorefinery in Limeira.

However, there is no biomass in D6, while A1, A5, C1, and D5 have a few eucalyptus plantations, totaling 256 tons (0.015% of the total biomass availability in SP). Based on the area and biomass availability calculated, it is possible to estimate the concentration of ER as a linear function of area, as shown in Fig. 5.

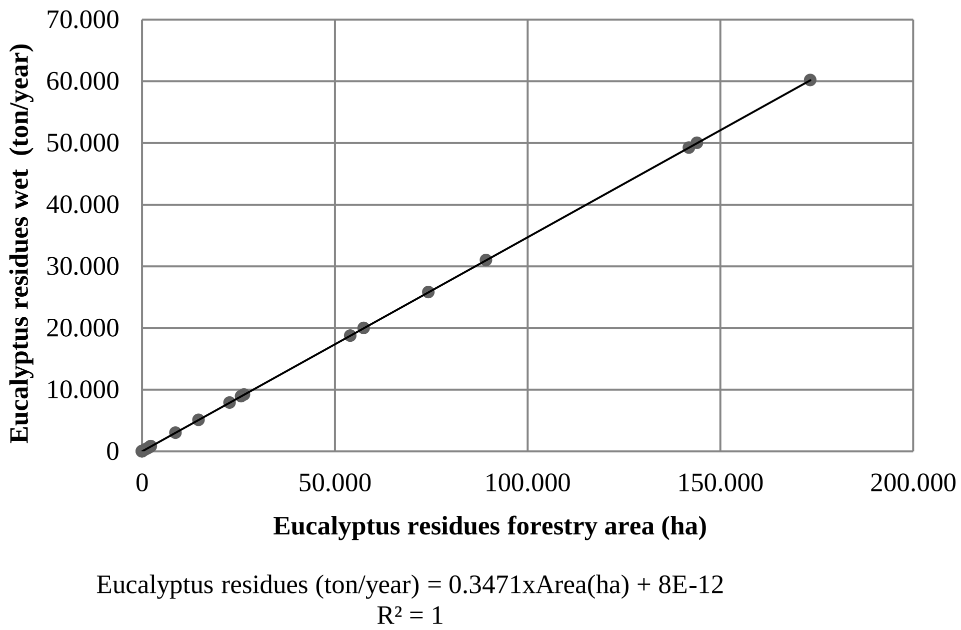


Fig. 5. ER as a linear function of area.

3.2. Technical results

The percentage of bio-oil produced depends on the drying method. The products obtained in the simulation using ER with 10% water had the following composition: 46 wt.% bio-oil, 18 wt.% biochar, 18 wt.% syngas, and 18 wt.% acid extract.

The simulation of the fast pyrolysis process for the 20 scenarios was capable of processing 39,000 to 1 ton/year of dry feedstock. The highest yields were obtained in C4, with annual production of 18,000 tons of bio-oil (15 million L of bio-oil/year), and the lowest yields were obtained in C1, with annual production of 1 ton of bio-oil. In this study, 16 yield scenarios (A2 to A4, B1 to B6, C2 to C6, D3 to D4, and Limeira) were considered for economic evaluation.

Biochar and acid extract are important byproducts of fast pyrolysis: the biorefinery in C4 produced 7,000 ton/year of biochar, and 7,000 tons/year of acid extract.

In terms of energy distribution, bio-oil corresponded to 40%, biochar to 23%, syngas to 10%, and losses to 27% of the total. The energy from bio-oil varies from 35,000 to 1 MJ/h, depending on capacity.

The thermal efficiency of pyrolysis was 65% when using the conventional method in C4. This highlights the benefits of this process, which uses residues exclusively and has a low energy demand.

The total energy demand of the large biorefinery (C4) simulated in this study was 6,000 MWh/year, which is purchased from the grid, except for the energy demand of the drying process. The thermal energy obtained from burning the syngas amounts to 1,600 kW, and that generated by the condenser amounts to 600 kW. This thermal energy is used to dry the biomass, which requires 2,000 kW. In summary, pretreatment corresponds to 80% of this process' energy demand.

3.3. Economic performance

Fig. 6 summarizes the total capital investment, operating cost and revenue estimated for the 16 biorefineries simulated. The CAPEX for the larger plants (C4, Limeira, C3, D3) totaled 6 and 4 MM USD, while the CAPEX for the smaller plants was less than 4 MM USD. Based on the assumptions established in this study, the biorefineries had reasonable techno-economic performance considering the low capital investment and operating cost.

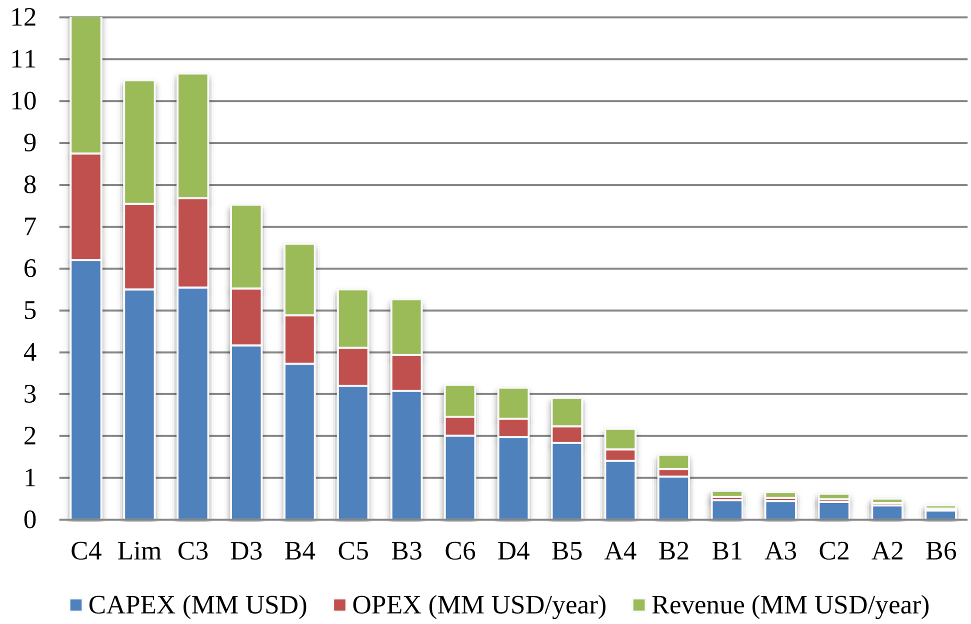


Fig. 6. CAPEX, OPEX, and revenue for the 16 biorefineries simulated and the one in Limeira (Lim).

The OPEX for A2, A3, B1, B2, B6, C2 did not significantly change. Of the operating expenses, the cost of biomass (including transportation) is the most important, amounting to almost 63% of the total for large plants and 50% for small plants (Fig. 7). The CAPEX and OPEX vary depending on the plant capacity, as well as the location of the biorefinery, which affects transportation costs.

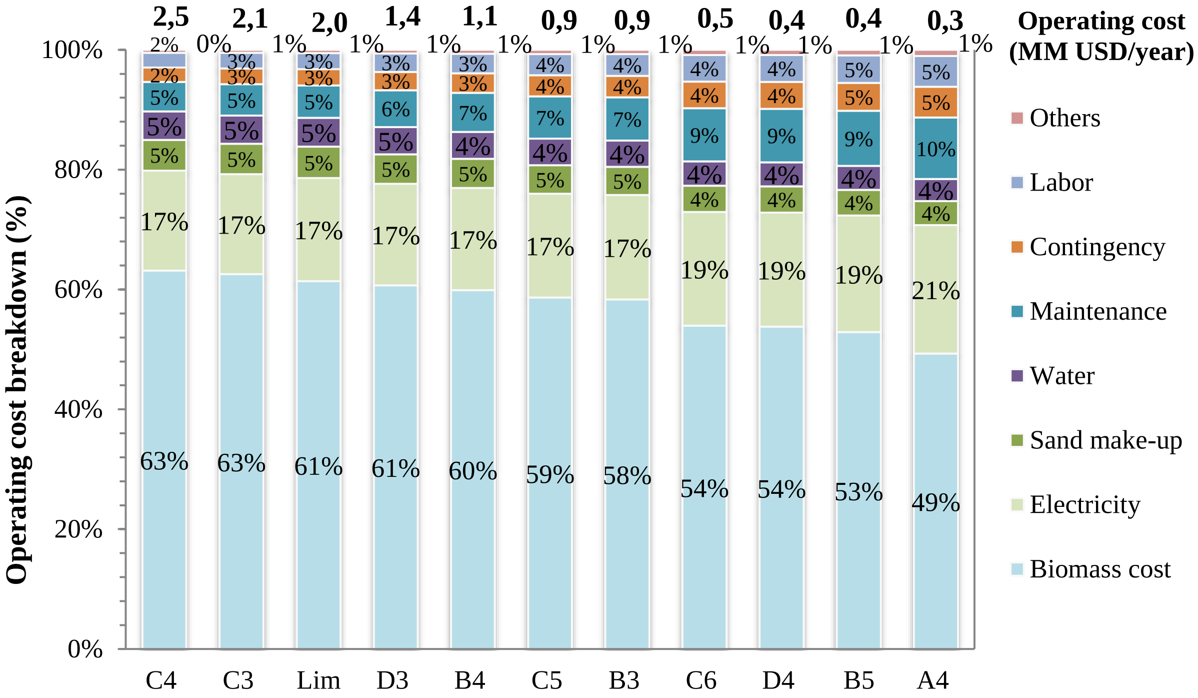


Fig. 7. Breakdown of the OPEX estimated for large and small biorefineries.

The CAPEX, OPEX and revenue estimates were used to determine the profitability of the scenarios based on DFC, given by the competitiveness of the MSP of bio-oil in the Brazilian market, with NPV and IRR as economic indicators.

The simulation pointed to the economic feasibility of 10 scenarios (corresponding to large biorefineries) and the Limeira biorefinery. The NPV was positive, with values of around 15 MM USD, whereas the IRR was 33% in C4 (Fig. 8) and 12% in A4.

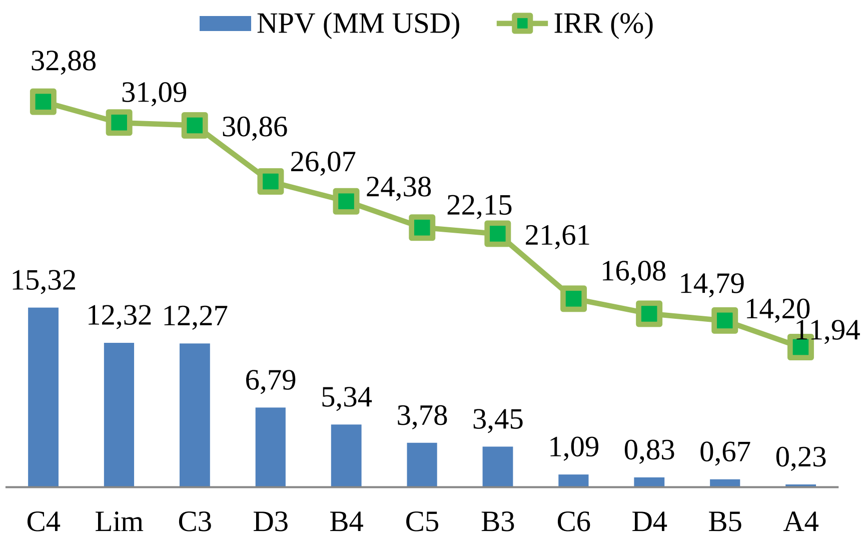


Fig. 8. Economic indicators (NPV and IRR) for the biorefineries simulated.

Another economic indicator used to evaluate the feasibility of this project was the MSP of bio-oil, which was shown to be economically competitive. Fig. 9 compares the MSP of bio-oil between the biorefineries simulated. The lowest MSP of 195 USD/ton was obtained in C4 (42,000 L/day of bio-oil from 7,000 kg/h of ER), and the most expensive MSP of 320 USD/ton was obtained in A4 (3,600 L/day of bio-oil from 600 kg/h of ER). It is important to note that many factors impact the MSP of bio-oil, such as plant size, economic parameters and location, which may be evaluated based on a sensitivity analysis.

The bio-oil MSP C4, C3 and Limeira presenting an energetic cost of 12 USD/GJ, which is more than three the gasoline (31 USD/GJ), and ethanol (33 USD/GJ) price, twice the diesel (22 USD/GJ) price, and competitive with petroleum (13 USD/GJ) and natural gas (9 USD/GJ) according to sources studied in this work [47,48]. The calculated MSP on this work is competitive depend on the market, and the market price represents the value consumers is willing to pay for.

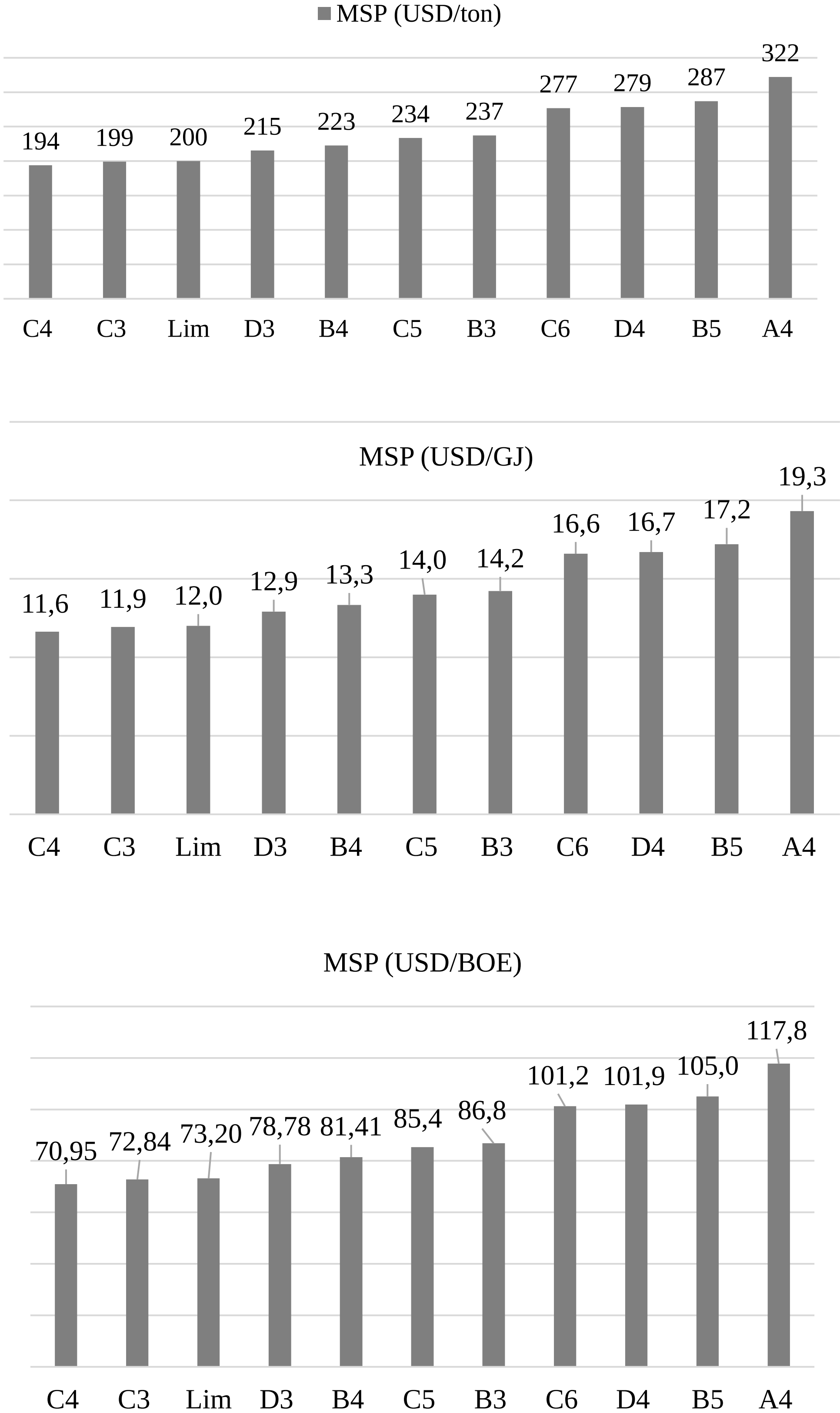
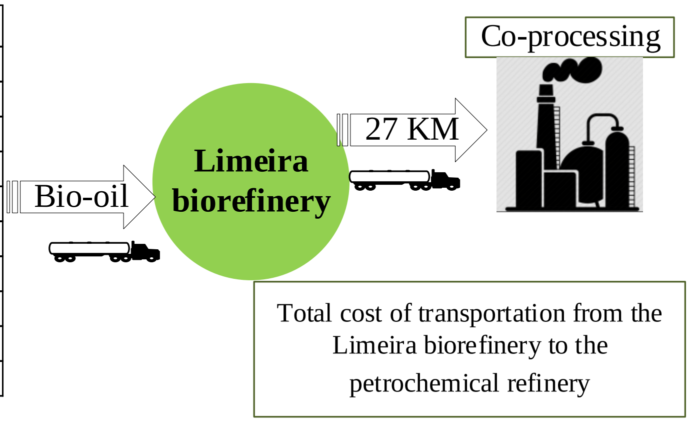


Fig. 9. Minimum selling price (MSP) in USD/ton, USD/GJ and USD/BOE of bio-oil obtained in the biorefineries simulated. *BOE=barrel of equivalent.

One of the applications of bio-oil could be co-processing with gasoil. Pinho et al. [12], when performing FCC with 10 wt.% bio-oil and vacuum gas oil, observed that direct co-processing in a regular petroleum refining method, which allows increasing biofuel production without losing quality standards. The area of the eucalyptus plantations in SP is able to provide enough ER to supply the 10 largest biorefineries, producing 71,000 ton/year of bio-oil, making it economically feasible.

A petrochemical refinery located 27 km from the Limeira biorefinery processes 20 million tons of petrol per year [49]. The sum of the production of the 10 most profitable biorefineries simulated amounts to 71,000 tons bio-oil/year, which would contribute with 3.4% of "green co-processed fuel" (containing 10% of co-processed bio-oil) [12]. This fuel could be co-processed with the gasoil from the Paulinia refinery. In this case, the total cost of transportation from the biorefineries to the petrochemical refinery would be 990,000 USD/year (freight cost: 0.07 USD/km ton [50]). Fig. 10 shows the distance of each biorefinery from the one in Limeira, and the total transportation cost.

Biorefinery	Distance from Limeira (km)
C4	85
C3	210
D3	302
B4	112
C5	111
B3	224
C6	244
D4	234
B5	133
A4	266



Total cost of transportation from 10 profitable biorefinery to the one in Limeira = 859,000 USD/year
10 simulated biorefineries produced 71,000 ton/year of bio-oil.

Fig. 10. Total cost of transportation of bio-oil from each biorefinery to the one in Limeira and then to the petrochemical refinery (application: co-processing).

The challenges associated with the co-processing of bio-oil should be further studied to reduce the dependence on fossil fuels by replacing them with renewable bio-oil, used as feedstock in the refinery [51]. The state of SP is a promising place to establish biorefineries due to the availability of feedstock, the possibility of co-processing with conventional feed in one of its petroleum refineries, and for having the largest population of any Brazilian state, with 44 million inhabitants, allowing the use of ER as feedstock to produce bio-oil.

3.4. Sensitivity and risk assessment

The MSP of bio-oil is most sensitive to plant capacity and yield, and to a lesser extent, to OPEX, cost of biomass, CAPEX and IRR. Income tax does not significantly affect it. According to Fig. 11, variations (+ and -) of 30% of the biorefinery's capacity would reduce the MSP to 148 USD/ton or increase it to 300 USD/ton; the same percentage (± 30%) of yield variation would reduce the MSP to 151 USD/ton or increase it to 280 USD/ton. The authors [7] conclude that the fast pyrolysis of ER as feedstock is influenced by the biomass' composition and on processing conditions [52].

Reducing the price of acid extract (from 200 to 157 USD/ton) and biochar (from 200 to 183 USD/ton), by 30% would positively affect the MSP of bio-oil seeing as byproducts increase the biorefineries' revenue. Plant capacity is a variable that depends on the location of the eucalyptus plantation, which influences a wide variety of factors. Hence, it is necessary to find the optimal location in order to minimize the total transportation distance [20,53].

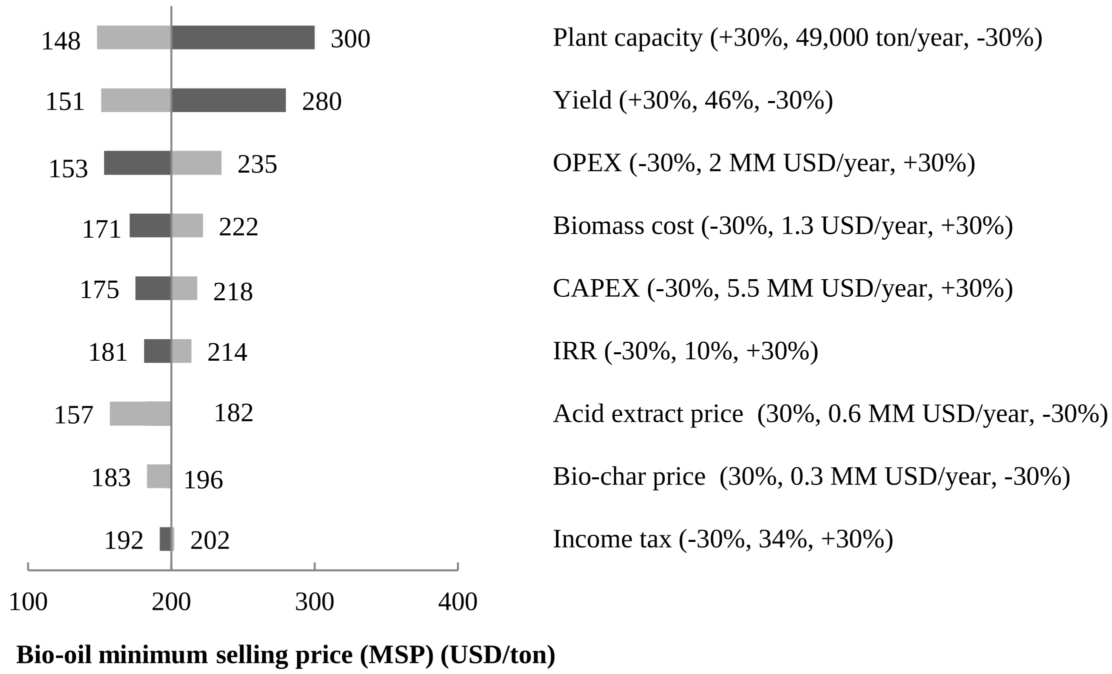


Fig. 11. Impact on the MSP of bio-oil considering a base value of 200 USD/ton (Limeira Biorefinery).

The most sensible variables found were plant capacity, yield, OPEX, cost of biomass, and CAPEX which are input variables in the Monte Carlo analysis. The risk analysis showed that project A is the best scenario to establish a biorefinery for production of bio-oil using ER as feedstock, with 84% chance of resulting in an NPV > 0 and an IRR > 10%, according to the assumptions of economic performance considered in this study, while for the other biorefineries, this chance was 80%.

4. CONCLUSIONS

We conclude that ER is a promising second-generation feedstock for use in the production of bio-oil via fast pyrolysis in the state of SP, with a financial risk of 20%. The state offers 10 potential scenarios (with 106 km of radius) for the establishment of centralized biorefineries. The large biorefineries (C4, C3 and Limeira) had an MSP of 194 USD/ton, and 200 USD/tonover the 25-year period considered in the simulations. The sensitivity analysis showed that plant capacity is the variable that most affects the MSP of bio-oil. Additionally, the production of biochar and acid extract decrease the MSP by up to 9 and 22%, respectively. This study provided information to potential investors in Brazilian industries, supporting the establishment of biorefineries for production of bio-oil from ER to increase the supply of renewable energy.

Acknowledgments

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References

[1] C.L. Crago, M. Khanna, J. Barton, E. Giuliani, W. Amaral, Competitiveness of Brazilian sugarcane ethanol compared to US corn ethanol, Energy Policy. 38 (2010) 7404–7415. doi:10.1016/j.enpol.2010.08.016.

[2] C. Manochio, B.R. Andrade, R.P. Rodriguez, B.S. Moraes, Ethanol from biomass: A comparative overview, Renew. Sustain. Energy Rev. 80 (2017) 743–755. doi:10.1016/j.rser.2017.05.063.

[3] J.R. Kwiatkowski, A.J. McAloon, F. Taylor, D.B. Johnston, Modeling the process and costs of fuel ethanol production by the corn dry-grind process, Ind. Crops Prod. 23 (2006) 288–296. doi:10.1016/j.indcrop.2005.08.004.

[4] M.O. de Souza Dias, R. Maciel Filho, P.E. Mantelatto, O. Cavalett, C.E.V. Rossell, A.

Bonomi, M.R.L.V. Leal, Sugarcane processing for ethanol and sugar in Brazil, Environ. Dev. 15 (2015) 35–51. doi:10.1016/j.envdev.2015.03.004.

[5] X. Hu, M. Gholizadeh, Biomass pyrolysis: A review of the process development and challenges from initial researches up to the commercialisation stage, J. Energy Chem. 39 (2019) 109–143. doi:10.1016/j.jechem.2019.01.024.

[6] R.E. Guedes, A.S. Luna, A.R. Torres, Operating parameters for bio-oil production in biomass pyrolysis: A review, J. Anal. Appl. Pyrolysis. 129 (2018) 134–149. doi:10.1016/j.jaap.2017.11.019.

[7] A.S. Pimenta, T.V. da C. Monteiro, M. Fasciotti, R.M. Braga, E.C. de Souza, K.M.G. de Lima, Fast pyrolysis of trunk wood and stump wood from a Brazilian eucalyptus clone, Ind. Crops Prod. 125 (2018) 630–638. doi:10.1016/j.indcrop.2018.08.083.

[8] T. Kuppens, M. Van Dael, K. Vanreppelen, T. Thewys, J. Yperman, R. Carleer, S. Schreurs, S. Van Passel, Techno-economic assessment of fast pyrolysis for the valorization of short rotation coppice cultivated for phytoextraction, J. Clean. Prod. 88 (2015) 336–344. doi:10.1016/j.jclepro.2014.07.023.

[9] S. Arnold, K. Moss, M. Henkel, R. Hausmann, Biotechnological Perspectives of Pyrolysis Oil for a Bio-Based Economy, Trends Biotechnol. 35 (2017) 925–936. doi:10.1016/j.tibtech.2017.06.003.

[10] K. Lisa, D.J. Robichaud, M.J. Watson, J. Ten Dam, A. Dutta, C. Mukarakate, S. Kim, M.R. Nimlos, R.M. Baldwin, Improving biomass pyrolysis economics by integrating vapor and liquid phase upgrading, Green Chem. 20 (2018) 567–582. doi:10.1039/c7gc02947k.

[11] S. Bezergianni, A. Dimitriadis, O. Kikhtyanin, D. Kubička, Refinery co-processing of renewable feeds, Prog. Energy Combust. Sci. 68 (2018) 29–64. doi:10.1016/j.pecs.2018.04.002.

[12] A. de R. Pinho, M.B.B. de Almeida, F.L. Mendes, L.C. Casavechia, M.S. Talmadge, C.M. Kinchin, H.L. Chum, Fast pyrolysis oil from pinewood chips co-processing with vacuum gas oil in an FCC unit for second generation fuel production, Fuel. 188 (2017) 462–473. doi:10.1016/j.fuel.2016.10.032.

[13] R.F. Beims, S.L. Bertoli, V. Botton, L. Ender, E.L. Simionatto, H.F. Meier, V.R. Wiggers, Co-Processing of Thermal Cracking Bio-Oil At Petroleum Refineries, Brazilian J. Pet. Gas. 11 (2017) 99–113. doi:10.5419/bjpg2017-0009.

[14] A.A.M. Ali, M.A. Mustafa, K.E. Yassin, A techno-economic evaluation of bio-oil co-processing within a petroleum refinery, Biofuels. 0 (2018) 1–9.

doi:10.1080/17597269.2018.1519758.

[15] IBÁ, Relatório 2019 indústria brasileira de árvores, Brasil, 2019. https://iba.org/datafiles/publicacoes/relatorios/iba-relatorioanual2019.pdf.

[16] R.G. HANCOCK TIMBER, Brazil Market Overview: Timber and Forest Products, (2014). http://htrg.com/wp-content/uploads/sites/2/2014-Brazil-Market-Overview-Timber-and-Forest-Products.pdf.

[17] A.P. Mariano, How Brazilian pulp mills will look like in the future?, Int. Bioenergy Bioprod. Conf. 2015, IBBC 2015 Leveraging For. Biomass Next Gener. Fuels Chem. (2015) 365–372.

[18] W. Stafford, W. De Lange, A. Nahman, V. Chunilall, P. Lekha, J. Andrew, J. Johakimu, B. Sithole, D. Trotter, Forestry biorefineries, Renew. Energy. 154 (2020) 461–475. doi:10.1016/j.renene.2020.02.002.

[19] A.T. Ubando, C.B. Felix, W.H. Chen, Biorefineries in circular bioeconomy: A comprehensive review, Bioresour. Technol. 299 (2020). doi:10.1016/j.biortech.2019.122585.

[20] C.W. da S. Romero, M.D. Berni, G.K.D.A. Figueiredo, T.T. Franco, R.A.C. Lamparelli, Assessment of agricultural biomass residues to replace fossil fuel and hydroelectric power energy: A spatial approach, Energy Sci. Eng. 7 (2019) 2287–2305. doi:10.1002/ese3.462.

[21] C. FOELKEL, Gestão ecoeficiente dos resíduos florestais lenhosos da eucalipto cultura, Eucalyptus Online B. Newsl. (2007) 1–78. doi:10.1139/e92-186.

[22] C. Foelkel, O problema dos tocos residuais das florestas plantadas de eucaliptos, Eucalyptus Online B. Newsl. (2014) 1–17. https://goo.gl/dgT166%0Ahttp://www.eucalyptus.com.br/artigos/news45_Cepas_Tocos.pdf.

[23] L.A.B. Ribeiro, R.C. Martins, J.M. Mesa-Pérez, W.A. Bizzo, Study of bio-oil properties and ageing through fractionation and ternary mixtures with the heavy fraction as the main component, Energy. 169 (2019) 344–355. doi:10.1016/j.energy.2018.12.042.

[24] J.A. et al Tamayo-Pena, Hydrothermal pretreatment of eucalyptus forestry residues previously to obtaining xylooligosaccharide, in: Pretreat. Eucalyptus Residues, Brazilian bioenergy science and tecnhology conference, São paulo, 2020.

[25] D.L. van Schalkwyk, M. Mandegari, S. Farzad, J.F. Görgens, Techno-economic and environmental analysis of bio-oil production from forest residues via non-catalytic and catalytic pyrolysis processes, Energy Convers. Manag. 213 (2020) 112815.

doi:10.1016/j.enconman.2020.112815.

[26] Q. Li, Y. Zhang, G. Hu, Techno-economic analysis of advanced biofuel production based on bio-oil gasification, Bioresour. Technol. 191 (2015) 88–96. doi:10.1016/j.biortech.2015.05.002.

[27] J.G. Rogers, J.G. Brammer, Estimation of the production cost of fast pyrolysis bio-oil, Biomass and Bioenergy. 36 (2012) 208–217. doi:10.1016/j.biombioe.2011.10.028.

[28] M.M. Wright, D.E. Daugaard, J.A. Satrio, R.C. Brown, Techno-economic analysis of biomass fast pyrolysis to transportation fuels, Fuel. 89 (2010) S2–S10. doi:10.1016/j.fuel.2010.07.029.

[29] A.L.M.T. Pighinelli, M.A. Schaffer, A.A. Boateng, Utilization of eucalyptus for electricity production in Brazil via fast pyrolysis: A techno-economic analysis, Renew. Energy. 119 (2018) 590–597. doi:10.1016/j.renene.2017.12.036.

[30] M. Ringer, V. Putsche, J. Scahill, Large-scale pyrolysis oil production: a technology assessment and economic analysis, (2006) 93. doi:10.2172/894989.

[31] A.P. Pinheiro, J. Arauzo, I. Fonts, M.E. Domine, A. Fernández Arroyo, M.E. Garcia-Perez, J. Montoya, F. Chejne, P. Pfromm, M. Garcia-Perez, Challenges and opportunities for bio-oil refining: A review, Energy and Fuels. 33 (2019) 4683–4720. doi:10.1021/acs.energyfuels.9b00039.

[32] IBGE, IBGE-Informações sobre silvicultura, (2019). https://sidra.ibge.gov.br/pesquisa/pevs/tabelas (accessed June 8, 2020).

[33] G. le Maire, S. Dupuy, Y. Nouvellon, R.A. Loos, R. Hakamada, Mapping short-rotation plantations at regional scale using MODIS time series: Case of eucalypt plantations in Brazil, Remote Sens. Environ. 152 (2014) 136–149. doi:10.1016/j.rse.2014.05.015.

[34] C.W. da S. Romero, M.D. Berni, G.K.D.A. Figueiredo, T.T. Franco, R.A.C. Lamparelli, Assessment of agricultural biomass residues to replace fossil fuel and hydroelectric power energy: A spatial approach, Energy Sci. Eng. 7 (2019) 2287–2305. doi:10.1002/ese3.462.

[35] R. Kumar, V. Strezov, H. Weldekidan, J. He, S. Singh, T. Kan, B. Dastjerdi, Lignocellulose biomass pyrolysis for bio-oil production: A review of biomass pre-treatment methods for production of drop-in fuels, Renew. Sustain. Energy Rev. 123 (2020). doi:10.1016/j.rser.2020.109763.

[36] E. Geraque, Conversão de biomassa substitui combustíveis fósseis por renováveis, (2020). http://pesquisaparainovacao.fapesp.br/conversao_de_biomassa_substitui_combustiveis

_fosseis_por_renovaveis/1267 (accessed April 4, 2020).

[37] H. Weldekidan, V. Strezov, J. He, R. Kumar, S. Asumadu-Sarkodie, I.N.Y. Doyi, S. Jahan, T. Kan, G. Town, Energy Conversion Efficiency of Pyrolysis of Chicken Litter and Rice Husk Biomass, Energy and Fuels. 33 (2019) 6509–6514. doi:10.1021/acs.energyfuels.9b01264.

[38] R. TURTON, Analysis, Synthesis, and Design of Chemical Processes, 3rd ed., Prentice Hall, New Jersey, 2009.

[39] ChemEngOnline, ChemEngOnline, Economic indicators CE Plant Cost Index, (2015). https://www.chemengonline.com (accessed March 5, 2020).

[40] B. Pathway, S. Jones, P. Meyer, L. Snowden-swan, E. Tan, A. Dutta, J. Jacobson, K. Cafferty, Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels Fast Pyrolysis and Hydrotreating, (2013).

[41] F. Carvalho, F.T.F. da Silva, A. Szklo, J. Portugal-Pereira, Potential for biojet production from different biomass feedstocks and consolidated technological routes: a georeferencing and spatial analysis in Brazil, Biofuels, Bioprod. Biorefining. 13 (2019) 1454–1475. doi:10.1002/bbb.2041.

[42] Bioware, Bioware, (2020). https://www.bioware.com.br/ (accessed March 10, 2020).

[43] MFRURAL, Eucalyptu residue cost, (2020). https://www.mfrural.com.br/busca/residuos-eucalipto (accessed April 5, 2020).

[44] ANEEL, Electricity cust industrial tariff, (2020). https://ma.equatorialenergia.com.br/informacoes-gerais/valor-de-tarifas-e-servicos/#demais-classes (accessed January 3, 2020).

[45] JS Texeira & CIA, Comércio de pedra e areia, (2018). http://jsteixeira.com.br/ (accessed April 5, 2020).

[46] S. Sao Paulo water supplier agency, Water industrial tariff, 2018. (n.d.). http://site.sabesp.com.br/site/interna/Default.aspx?secaoId=183 (accessed April 5, 2020).

[47] ANAP, Boletim Trimestral de Preços e Volumes de Combustíveis, (2019). http://www.anp.gov.br/arquivos/publicacoes/boletins-anp/btpvc/boletim-trimestral-2.pdf (accessed December 5, 2020).

[48] A. Lima, GERAÇÃO TÉRMICA, (2020). http://www.antoniolima.web.br.com/arquivos/podercalorifico.htm (accessed May 4, 2020).

[49] Petrobras, Refinaria de Paulínia, (2020). https://petrobras.com.br/pt/nossas-

atividades/principais-operacoes/refinarias/refinaria-de-paulinia-replan.htm (accessed July 31, 2020).

[50] Cargas líquidas, Tabelas de frete Brasil, 2016. (2016) 1. https://www.tabelasdefrete.com.br/planilha/cargas-liquidas/13 (accessed July 19, 2020).

[51] Marlon Brando Bezerra de Almeida, Bio-óleo a partir da pirólise rápida, térmica ou catalítica, da palha da cana-de-açúcar e seu co-processamento com gasóleo em craqueamento catalítico, Universidade Federal do Rio de Janeiro, 2008. http://186.202.79.107/download/bio-oleo-a-partir-da-pirolise-rapida.pdf.

[52] J.E. Joubert, M. Carrier, N. Dahmen, R. Stahl, J.H. Knoetze, Inherent process variations between fast pyrolysis technologies: A case study on Eucalyptus grandis, Fuel Process. Technol. 131 (2015) 389–395. doi:10.1016/j.fuproc.2014.12.012.

[53] M.K. Delivand, A.R.B. Cammerino, P. Garofalo, M. Monteleone, Optimal locations of bioenergy facilities, biomass spatial availability, logistics costs and GHG (greenhouse gas) emissions: A case study on electricity productions in South Italy, J. Clean. Prod. 99 (2015) 129–139. doi:10.1016/j.jclepro.2015.03.018.

CONCLUSIONS AND RECOMMENDATIONS DISSERTATION

Brazil is a rich country with a variety of natural resources, giving it the potential to explore renewable energy sources that can further develop its environmental bioeconomy. The most important contribution of our manuscript is that, to the best of our knowledge, shows a techno-economic analysis of the production of bio-oil from eucalyptus residues, and of their availability in the whole State of São Paulo. The size of Sao Paulo State approximately corresponds, to the size of the whole France. Our manuscript demonstrates that the production of bio-oil by the 10 simulated centralized biorefineries is economically viable based on the NPV and IRR indicators. We show the possibility of transporting the bio-oil to the largest petrochemical refinery in the State to be co-processed with gasoil. Renewable energy from eucalyptus residues produced by fat pyrolysis is evaluated.

Eucalyptus is the most common tree used for establishing industrial forest plantations in Brazil (average productivity 36 m^3/ha year) generating a significant amount of biomass residues leading São Paulo to rank second among the main eucalyptus-producing states with 17% of planted in Brazil.

Few studies have explored the availability and feasibility economic biorefineries of forest residues as feedstock for exploitation as biofuels and bioproducts in Brazil. For this reason, this study focused on estimating the generation of eucalyptus residues in São Paulo and establishing biorefineries.

Economic viability is the key factor in the development of commercial biorefineries. This begins with the encouragement of an economic process that can handle the combination of capital and operating costs.

The cost of a fast pyrolysis biorefinery could be classified into two main categories: CAPEX and OPEX. CAPEX includes the pretreatment module, pyrolysis module, and facility development. OPEX depend on the technology used, plant size, and the feedstock biomass. These costs are combined in a discounted cash flow analysis to estimate the minimum selling price needed to meet a 10% internal rate of return when the net present value is equal to zero.

The technology of fast pyrolysis delivers bio-oil (46% wt. yield) as the main product and byproducts such as coal (18% wt. yield) used in the steel industry, and organic acid (18% wt. yield) as an option for industries that produce insecticides, repellents, and herbicides to replace glyphosate.

The availability of eucalyptus residues in São Paulo can be simulated in 16 potential scenarios, of the total them; the simulated large-scale biorefinery used 60000 tons/year of eucalyptus residues in order to produce 42000 L/day of bio-oil, and the total capital investment was estimated to be 6 million USD with an annual operational cost of 3 million USD. With an assumed 25-year project life, a minimum selling price was determined to be 194 USD per ton. The plant capacity correlated with feedstock and location showed significant impact on the bio-oil minimum selling price, as well as the yield and OPEX associated with the biomass cost.

This study demonstrated that establishing centralized biorefineries to bio-oil production using residues eucalyptus in the state of São Paulo is technically and economically feasible.

The first author recommends collaboration between academics, pulp companies to establish pilot plants in order to take advantage of the fact that region contains a global leader in eucalyptus production, Suzano, that already has a total capacity of 11 million tons of pulp per year.

In spite of the large number of separation schemes that have been evaluated by chemical engineers, very few of them have been tested as part of fully integrated bio-oil refinery concepts. It is important to take the opportunity to do so by working the existing refineries in the region.

REFERENCES

ALI, A. A. M.; MUSTAFA, M. A.; YASSIN, K. E. A techno-economic evaluation of bio-oil co-processing within a petroleum refinery. **Biofuels**, v. 0, n. 0, p. 1–9, 2018.

ALVES, C. M. et al. Techno-economic assessment of biorefinery technologies for aviation biofuels supply chains in Brazil. **Biofuels, Bioproducts and Biorefining**, v. 11, p. 67–91, 2017.

AMUTIO, M. et al. Fast pyrolysis of eucalyptus waste in a conical spouted bed reactor. **Bioresource Technology**, v. 194, p. 225–232, 2015.

ASTON. **ASTON UNIVERSITY**. Disponível em: <https://www2.aston.ac.uk/eas/research/groups/ebri/research/pyrolysis/fast-pyrolysis/index>. Acesso em: 2 maio. 2019.

BILGEN, S.; KELEŞ, S.; KAYGUSUZ, K. Calculation of higher and lower heating values and chemical exergy values of liquid products obtained from pyrolysis of hazelnut cupulae. **Energy**, v. 41, n. 1, p. 380–385, 2012.

BIOWARE. **Bioware**. Disponível em: <https://www.bioware.com.br/>. Acesso em: 10 mar. 2020.

BRIDGWATER, A. V. Review of fast pyrolysis of biomass and product upgrading. **Biomass and Bioenergy**, v. 38, p. 68–94, 2012.

BROWN, T. R. et al. 2 - Techno-economic assessment (TEA) of advanced biochemical and thermochemical biorefineries. In: WALDRON, K. B. T.-A. IN B. (Ed.). . [s.l.] Woodhead Publishing, 2014. p. 34–66.

BROWN, T. R. A techno-economic review of thermochemical cellulosic biofuel pathways. **Bioresource Technology**, v. 178, p. 166–176, 2015.

BTG-BTL. **BTG-BTL COMPANY**. Disponível em: <https://www.btg-btl.com/en>. Acesso em: 2 maio. 2019.

CARRIER, M. et al. Impact of the lignocellulosic material on fast pyrolysis yields and product quality. **Bioresource Technology**, v. 150, p. 129–138, 2013.

CARVALHO, D. M. DE et al. Assessment of chemical transformations in eucalyptus, sugarcane bagasse and straw during hydrothermal, dilute acid, and alkaline pretreatments. **Industrial Crops and**

Products, v. 73, p. 118–126, 2015.

CARVALHO, F. et al. Potential for biojet production from different biomass feedstocks and consolidated technological routes: a georeferencing and spatial analysis in Brazil. **Biofuels, Bioproducts and Biorefining**, v. 13, n. 6, p. 1454–1475, 2019.

CHANG, S. et al. Effect of hydrothermal pretreatment on properties of bio-oil produced from fast pyrolysis of eucalyptus wood in a fluidized bed reactor. **Bioresource Technology**, v. 138, p. 321–328, 2013.

COKER, A. K. COST ESTIMATION AND ECONOMIC EVALUATION. In: COKER, A. K. (Ed.). . **Ludwig's Applied Process Design for Chemical and Petrochemical Plants**. 4. ed. Burlington: Gulf Professional Publishing, 2007. p. 69–102.

CZERNIK, S.; BRIDGWATER, A. V. Overview of applications of biomass fast pyrolysis oil. **Energy and Fuels**, v. 18, n. 2, p. 590–598, 2004.

DHYANI, V.; BHASKAR, T. A comprehensive review on the pyrolysis of lignocellulosic biomass. **Renewable Energy**, v. 129, p. 695–716, 2018.

ECONOMIA, T. **Dinheiro rural**. Disponível em: <https://www.dinheirorural.com.br/secao/agrotecnologia/nova-energia-do-eucalipto>. Acesso em: 15 jan. 2020.

ENSYN. **ENSYN COMPANY**. Disponível em: <http://www.ensyn.com>. Acesso em: 2 maio. 2019.

FOELKEL, C. Gestão ecoeficiente dos resíduos florestais lenhosos da eucalipto cultura. **Eucalyptus online book and newsletter**, p. 1–78, 2007.

FORSTER-CARNEIRO, T. et al. Biorefinery study of availability of agriculture residues and wastes for integrated biorefineries in Brazil. **Resources, Conservation and Recycling**, v. 77, p. 78–88, 2013.

FORTUM. **FORTUM COMPANY**. Disponível em: <https://www.fortum.com/>. Acesso em: 2 maio. 2019.

GANDHI, D. M. M. K. **FORMULAS FOR CALCULATING THE HEATING VALUE OF COAL AND COAL CHAR: DEVELOPMENT, TESTS AND USES**. Conference: 180. American Chemical Society meeting/2. **Anais**...Chicago: 1940Disponível em: <https://www.osti.gov/biblio/5037243-formulas-calculating-heating-value-coal-coal-char-development-tests-uses>

GARCIA-PEREZ, M. et al. Fast pyrolysis of oil mallee woody biomass: Effect of temperature on the yield and quality of pyrolysis products. **Industrial and Engineering Chemistry Research**, v. 47, n. 6, p. 1846–1854, 2008.

GAVHANE, K. A. **Unit Operations - II (Heat And Mass Transfer)**. 24 th ed. [s.l.] Nirali Prakashan, 2014.

GERAQUE, E. **Conversão de biomassa substitui combustíveis fósseis por renováveis**. Disponível em: <http://pesquisaparainovacao.fapesp.br/conversao_de_biomassa_substitui_combustiveis_fosseis_por_renovaveis/1267>. Acesso em: 4 abr. 2020.

GÓMEZ-MONEDERO, B. et al. Pyrolysis of red eucalyptus, camelina straw, and wheat straw in an ablative reactor. **Energy and Fuels**, v. 29, n. 3, p. 1766–1775, 2015.

GONÇALVES, A. **Condicionamento de resíduo de Eucalyptus grandis para produção de biocombustível sólido Condicionamento de resíduo de Eucalyptus grandis para produção de biocombustível sólido**. [s.l.] UNIVERSIDADE FEDERAL DA BAHIA, 2013.

HAMEED, S. et al. A review on biomass pyrolysis models: Kinetic, network and mechanistic models. **Biomass and Bioenergy**, v. 123, n. March, p. 104–122, 2019.

HE, M. et al. Yield and properties of bio-oil from the pyrolysis of mallee leaves in a fluidised-bed reactor. **Fuel**, v. 102, p. 506–513, 2012.

HEIDARI, A. et al. Effect of process conditions on product yield and composition of fast pyrolysis of Eucalyptus grandis in fluidized bed reactor. **Journal of Industrial and Engineering Chemistry**, v. 20, n. 4, p. 2594–2602, 2014.

HO, D. P.; NGO, H. H.; GUO, W. A mini review on renewable sources for biofuel. **Bioresource Technology**, v. 169, p. 742–749, 2014.

HU, X.; GHOLIZADEH, M. Biomass pyrolysis: A review of the process development and challenges from initial researches up to the commercialisation stage. **Journal of Energy Chemistry**, v. 39, n. x, p. 109–143, 2019.

IBÁ. **Relatório 2017 indústria brasileira de árvores**. Brasil: [s.n.]. Disponível em: <http://iba.org/images/shared/Biblioteca/IBA_RelatorioAnual2017.pdf>.

IBÁ. **Relatório 2019 indústria brasileira de árvores**. Brasil: [s.n.]. Disponível em: <https://iba.org/datafiles/publicacoes/relatorios/iba-relatorioanual2019.pdf>.

JONES, S. et al. **Process design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels**. Disponível em: <https://www.nrel.gov/docs/fy14osti/61178.pdf>. Acesso em: 8 mar. 2020.

JOUBERT, J. E. et al. Inherent process variations between fast pyrolysis technologies: A case study on Eucalyptus grandis. **Fuel Processing Technology**, v. 131, p. 389–395, 2015.

KIM, K. H. et al. Comparison of physicochemical features of biooils and biochars produced from various woody biomasses by fast pyrolysis. **Renewable Energy**, v. 50, p. 188–195, 2013.

LI, Q.; ZHANG, Y.; HU, G. Techno-economic analysis of advanced biofuel production based on bio-oil gasification. **Bioresource Technology**, v. 191, p. 88–96, 2015.

MARIANO, A. P. How Brazilian pulp mills will look like in the future? **International Bioenergy and Bioproducts Conference 2015, IBBC 2015: Leveraging Forest Biomass for Next Generation Fuels and Chemicals**, n. June, p. 365–372, 2015.

MCKENDRY, P. Energy production from biomass (part 1): overview of biomass. **Bioresource Technology**, v. 83, n. 1, p. 37–46, 2002.

MOKA, V. K. et al. **ESTIMATION OF HEATING VALUE OF BIOMASS FROM ITS ELEMENTARY COMPONENTS BY REGRESSION**. [s.l.] NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA, 2012.

MUÑOZ, C. et al. Bioethanol production from tension and opposite wood of Eucalyptus globulus using organosolv pretreatment and simultaneous saccharification and fermentation. **Journal of Industrial Microbiology and Biotechnology**, v. 38, n. 11, p. 1861–1866, 2011.

MUSSATTO, S. I.; BIKAKI, N. Chapter 25 - Technoeconomic Considerations for Biomass Fractionation in a Biorefinery Context. In: MUSSATTO, S. I. B. T.-B. F. T. FOR A L. F. B. B. (Ed.). . Amsterdam: Elsevier, 2016. p. 587–610.

MUTSENGERERE, S. et al. A review of operating parameters affecting bio-oil yield in microwave pyrolysis of lignocellulosic biomass. **Renewable and Sustainable Energy Reviews**, v. 104, n. January, p. 328–336, 2019.

OASMAA, A. et al. Fast pyrolysis bio-oils from wood and agricultural residues. **Energy and Fuels**, v. 24, n. 2, p. 1380–1388, 2010.

ONARHEIM, K.; LEHTO, J.; SOLANTAUSTA, Y. Technoeconomic Assessment of a Fast Pyrolysis Bio-oil Production Process Integrated to a Fluidized Bed Boiler. **Energy and Fuels**, v. 29, n. 9, p. 5885–5893, 2015.

ONARHEIM, K.; SOLANTAUSTA, Y.; LEHTO, J. Process simulation development of fast pyrolysis of wood using aspen plus. **Energy and Fuels**, v. 29, n. 1, p. 205–217, 2015.

OZONOH, M. et al. Techno-economic analysis of electricity and heat production by co-gasification of coal, biomass and waste tyre in South Africa. **Journal of Cleaner Production**, v. 201, p. 192–206, 2018.

PALASADE. **Monte Carlo method**. Disponível em: <https://www.palisade.com/risk/monte_carlo_simulation.asp>. Acesso em: 4 jul. 2019.

PAPEL, R. O. **Portal eletrónico meio filtrante**. Disponível em: <http://www.meiofiltrante.com.br/internas.asp?id=20129&link=noticias>. Acesso em: 19 jan. 2020.

PATHWAY, B. et al. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels Fast Pyrolysis and Hydrotreating. 2013.

PENÍN, L. et al. Technologies for Eucalyptus wood processing in the scope of biorefineries: A comprehensive review. **Bioresource Technology**, p. 123528, 2020.

PEREIRA, B. L. C. et al. Influence of Chemical Composition of Eucalyptus Wood on Gravimetric Yield and Charcoal Properties. **BioResources**, v. 8, n. 3, 2014.

PIGHINELLI, A. L. M. T.; SCHAFFER, M. A.; BOATENG, A. A. Utilization of eucalyptus for electricity production in Brazil via fast pyrolysis: A techno-economic analysis. **Renewable Energy**, v. 119, p. 590–597, 2018.

PIMENTA, A. S. et al. Fast pyrolysis of trunk wood and stump wood from a Brazilian eucalyptus clone. **Industrial Crops and Products**, v. 125, n. October, p. 630–638, 2018.

PIMENTAA, A. S. et al. Pimenta_1998_Fuel.pdf. v. 77, n. 11, p. 1133–1139, 1998.

PINHEIRO, A. P. et al. Challenges and opportunities for bio-oil refining: A review. **Energy and Fuels**, v. 33, n. 6, p. 4683–4720, 2019.

RINGER, M.; PUTSCHE, V.; SCAHILL, J. **Large-scale pyrolysis oil production: a technology assessment and economic analysis**. Disponível em: <http://www.osti.gov/servlets/purl/894989-fksp4M/>. Acesso em: 10 nov. 2019.

ROGERS, J. G.; BRAMMER, J. G. Estimation of the production cost of fast pyrolysis bio-oil. **Biomass and Bioenergy**, v. 36, n. 0, p. 208–217, 2012.

ROMANÍ, A.; GARROTE, G.; PARAJÓ, J. C. Bioethanol production from autohydrolyzed Eucalyptus globulus by Simultaneous Saccharification and Fermentation operating at high solids loading. **Fuel**, v. 94, p. 305–312, 2012.

SALEMA, A. A.; ANI, F. N. Pyrolysis of oil palm empty fruit bunch biomass pellets using multimode microwave irradiation. **Bioresource Technology**, v. 125, p. 102–107, 2012.

SALMAN, C. A. **TECHNO ECONOMIC ANALYSIS OF WOOD PYROLYSIS IN SWEDEN**. [s.l.] Royal Institute of Technology, 2014.

SANTOS, K. G. DOS. **ASPECTOS FUNDAMENTAIS DA PIRÓLISE DE BIOMASSA EM LEITO DE JORRO : FLUIDODINÂMICA E CINÉTICA DO PROCESSO**. [s.l.] UNIVERSIDADE FEDERAL DE UBERLÂNDIA, 2011.

SCIENCE, D. **Specific Heat Capacity of Water and Vapor**. Disponível em: <https://www.sciencedirect.com/topics/engineering/wood-pyrolysis>. Acesso em: 16 mar. 2020.

SEABRA, J. E. A. Avaliação técnico-econômica de opcões para o aproveitamento integral da biomassa de cana no Brasil. 2008. 298f. Tese (Doutorado). p. 298, 2008.

SHABANI, N.; AKHTARI, S.; SOWLATI, T. Value chain optimization of forest biomass for bioenergy production: A review. **Renewable and Sustainable Energy Reviews**, v. 23, p. 299–311, 2013.

SILVA, E. DA. **Estudo Comparativo entre Capim Elefante e Eucalipto com a incorporação da Energia Solar na Secagem**. [s.l.] UNIVERSIDADE FEDERAL DE ITAJUBÁ, 2012.

STAFFORD, W. et al. Forestry biorefineries. **Renewable Energy**, v. 154, p. 461–475, 2020.

SULAIMAN, W. R. W.; LEE, E. S. Pyrolysis of Eucalyptus wood in a fluidized-bed reactor. **Research on Chemical Intermediates**, v. 38, n. 8, p. 2025–2039, 2012.

TONG, S. et al. A gas-pressurized torrefaction method for biomass wastes. **Energy Conversion and Management**, v. 173, n. July, p. 29–36, 2018.

TORRES-ROJAS, D. et al. **Biomass availability , energy consumption and biochar production in rural households of Western Kenya**. [s.l: s.n.].

TURTON, R. **Analysis, Synthesis, and Design of Chemical Processes**. 3. ed. New Jersey: Prentice Hall, 2009.

VAMVUKA, D. Bio-oil, solid and gaseous biofuels from biomass pyrolysis processes—An overview D. **Archives of Thermodynamics**, v. 33, n. 4, p. 23–40, 2012.

VAN MEERBEEK, K.; MUYS, B.; HERMY, M. Lignocellulosic biomass for bioenergy beyond intensive cropland and forests. **Renewable and Sustainable Energy Reviews**, v. 102, n. May 2018, p. 139–149, 2019.

VAN SCHALKWYK, D. L. et al. Techno-economic and environmental analysis of bio-oil production from forest residues via non-catalytic and catalytic pyrolysis processes. **Energy Conversion and Management**, v. 213, n. April, p. 112815, 2020.

VASSILEV, S. V. et al. An overview of the chemical composition of biomass. **Fuel**, v. 89, n. 5, p. 913–933, 2010.

WEI, W.; WU, S.; LIU, L. Enzymatic saccharification of dilute acid pretreated eucalyptus chips for fermentable sugar production. **Bioresource Technology**, v. 110, p. 302–307, 2012.

WRIGHT, M. M. et al. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. **Fuel**, v. 89, n. SUPPL. 1, p. S2–S10, 2010.

WRIGHT, M. M.; BROWN, R. C.; BOATENG, A. A. Distributed processing of biomass to bio-oil for subsequent production of Fischer-Tropsch liquids. **Biofuels, Bioproducts and Biorefining**, v. 2, p. 229e238., 2008.

YANG, H. et al. Characteristics of hemicellulose, cellulose and lignin pyrolysis. **Fuel**, v. 86, n. 12–13, p. 1781–1788, 2007.

YAO, X. et al. ScienceDirect Kinetic and experimental characterizations of biomass pyrolysis in granulated blast furnace slag. **International Journal of Hydrogen Energy**, v. 43, n. 19, p. 9246–9253, 2018.

APPENDIX

APPENDIX A: CHEMICAL COMPOSITION BIOMASS, BIO-OIL, BIO-CHAR AND SYNGAS

Proximate analysis of pyrolysis bio oil gives the estimation of a chemical formula of bio oil $CH_{1.9}O_{0.7}$, which accounts for 46% oxygen. Oxygen is present in more than 300 compounds found in the pyrolysis bio oil. The main compounds found in the bio oil are classified into five main categories: (1) hydroxyl aldehydes, (2) hydroxyl ketones (3) sugar and dehydro-sugars, (4) carboxylic acids and (5) phenolic compounds. The more detailed categorization of bio oil compounds are: acids, alcohols, aldehydes, esters, ketones, phenols, furans, sugars, aromatics, alkenes, nitrogen compounds and miscellaneous oxygenates. The chemical nature of bio oils can be altered or manipulated by modifying the pyrolysis process (SALMAN, 2014).

Table A. Chemical composition for eucalyptus biomass, product and byproducts fast pyrolysis.

	Composition (wt%)					
	Compound	Syngas	Bio-char	Bio-oil		Biomass
				Dry	wet	
	Hydrogen	0.72				
	Carbon monoxide	39.28				
	Carbon dioxide	50.21				
	Methane	4.60				
Elementary composition	Ethane	1.02				
	Propane	0.15				
	Ethene	2.25				
	Propene	1.77				
	Hydrogen		1.30	7.50		5.10
	Oxygen		13.70	50.10		46.60
Elementary composition	Nitrogen		1.30	0.10		0.60
	Ash		6.50	0.03		1.20
	Carbon		76.30	42.30		46.50
	Acids			7.59	5.40	
	Aldehydes			3.51	2.50	
	Ketones			13.00	9.24	

	Alcohols			1.57	1.11	
	Furans			9.26	6.59	
Composition	Ethers			2.12	1.51	
	Ketones			16.71	11.89	
	Phenols			41.15	29.27	
	Saccharides			5.09	3.62	
	water				28.87	
	LHV_dry (MJ/kg)	10.00	24.12	16.68		18.95
	Bio-oil charactertistc					
	Density at 25 °C (kg/L)	1.2				
	pH	2-3				
	Viscosity (cSt) at 40 °C	15-35				
	Moisture contente (% wt.)	15-30				

Source: (PATHWAY et al., 2013; PIMENTA et al., 2018)

APPENDIX B: PROCESS PARAMETERS FOR FAST PYROLYSIS PROCESS

This section presents process parameters for the simulated fast pyrolysis process; it divided for each simulated equipment. Synthesis of pyrolysis oil depends on various process parameters such as carrier gas, heating rate, particle size, pressure, flow rate, residence time, temperature, composition of feedstocks, and types of pyrolysis reactors.

Table B-1. Parameters dryer.

Dryer	
Inlet biomass	
Temperature (°C)	25
Moisture content (% wt)	45.00
Inlet flue gas	
Temperature (°C)	306
Outlet biomass	
Temperature (°C)	71
Moisture content (% wt)	10.00
Outlet flue gas	
Temperature (°C)	72

Table B-2. Pyrolizer reactor parameters.

Pyrolizer	
Biomass moisture conten (%wt)	10
Biomass particle size (mm)	1.5
Fluidized gas (wt/wt dry biomass)	3
Sand make up (wt/wt dry biomass)	14.5
Inlet temperature (°C)	500
Pressure (psi)	21
Heat losses (% of biomass LHV)	27.12
Bio-oil yield (% dry biomass)	46.00
Bio-char yield (% dry biomass)	0.18
Syngas yield (% dry biomass)	0.18
Acid extract yield (%dry biomass)	0.18

Table B-3. Fast pyrolysis oil cold filter parameters.

Fast pyrolysis oil cold filter	
Solid removel (%)	100
Fast pyrolysis yield loss	
% of fast pyrolysis oil to the filter	3.15
Fraction weight of dry biomass	0.02

Table B-4. Combustor parameters.

Combustor	
Temperature (°C)	609
Pressure (psia)	21
Air (actual/minimum for combustor)	1.2
O_2 excess	0.2
Air composition	
Water	2%
Oxygen	23%
Nitrogen	74%
Argon	1%
Component	Molecular mass (lb/mol)
O_2	32
CO_2	44
H_2O	18

Combustions reactions:

A combustion reaction is a reaction in which a syngas reacts with oxygen gas, releasing energy in the form of heat. Combustion reactions must involve O_2 as one reactant.

$$C + O_2 \rightarrow CO_2$$

$$C + \frac{1}{2}O_2 \rightarrow CO \ (everything\ is\ consumed)$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

Table B-5. Condenser parameters.

Condenser				
Fluid	Hot		Cold	
T (°C)	in	out	in	out
	500	40	5	60
% Loss	0.05			
Specific heat capacity of vapor				
Cp, vapor=	1.88	kJ/kgK		
Cp, water=	4.19	kJ/kgK		

APPENDIX C: LIMEIRA BIOREFINERY CASE: MASS AND ENERGY BALANCES

A. Block flow diagram process.

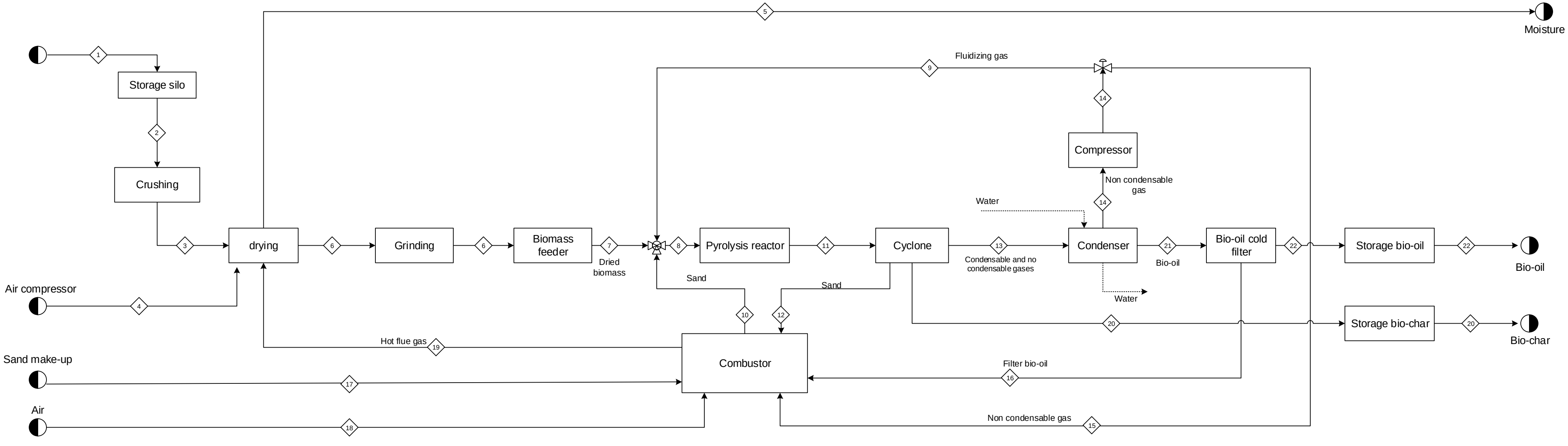

Figura C. Block flow diagram for simulated fast pyrolysis process.

A. MASS BALANCE

Mass balance biorefinery Limeira.

Table C. Mass balance for biorefinery Limeira.

Stream No.	1=2=3	4	5	6=7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Temp (°C)	25	48	72	71	500	73	609	434	99	433	72	72	54	16	48	306	433	54	54
Pres (atm)	1.00	1.14	1.07	1.41	1.41	1.57	1.41	1.20	1.22	1.21	1.57	1.57	1.22	1.20	1.14	1.41	1.21	1.22	1.22
Vapor mole fraction	0.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00
Total (kg/h)	7164.40	5338.91	12544.03	4656.86	74883.06	13970.59	56097.27	74947.16	56097.27	17806.37	14814.84	844.25	94.53	158.33	3753.80	4697.58	885.18	2997.55	2903.02
Wood	3868.78	0.00	0.00	3868.78	3868.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	3223.98	106.78	2614.32	716.44	716.44	0.00	0.00	838.24	0.00	838.24	0.00	0.00	0.00	0.00	75.08	0.00	0.00	838.24	838.24
Hydrogen	0.00	0.00	0.00	0.00	100.30	100.30	0.00	117.22	0.00	106.32	112.34	12.04	0.00	0.00	0.00	0.00	10.90	0.00	0.00
Oxygen	0.00	1211.93	1353.95	0.00	0.00	0.00	0.00	114.84	0.00	0.00	0.00	0.00	0.00	0.00	852.11	142.02	114.84	0.00	0.00
Nitrogen	0.00	3950.80	6728.61	0.00	0.00	0.00	0.00	10.90	0.00	0.00	0.00	0.00	0.00	0.00	2777.81	2777.81	10.90	0.00	0.00
Argon	0.00	69.41	118.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	48.80	48.80	0.00	0.00	0.00
Carbon monoxide	0.00	0.00	0.00	0.00	5487.59	5487.59	0.00	5816.84	0.00	5816.84	5816.84	329.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carbon dioxide	0.00	0.00	1711.78	0.00	7014.10	7014.10	0.00	7434.94	0.00	7434.94	7434.94	420.85	0.00	0.00	0.00	1711.78	0.00	0.00	0.00
Methane	0.00	0.00	0.00	0.00	643.26	643.26	0.00	681.85	0.00	681.85	681.85	38.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethane	0.00	0.00	0.00	0.00	142.78	142.78	0.00	151.34	0.00	151.34	151.34	8.57	0.00	0.00	0.00	0.00	0.00		0.00
Propane	0.00	0.00	0.00	0.00	20.74	20.74	0.00	21.98	0.00	21.98	21.98	1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N-butane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Ethene	0.00	0.00	0.00	0.00	314.11	314.11	0.00	332.96	0.00	332.96	332.96	18.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Propene	0.00	0.00	0.00	0.00	247.72	247.72	0.00	262.58	0.00	262.58	262.58	14.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1-Butene	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfur dioxide	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrogen dioxide	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Acids	0.00	0.00	0.00	0.00	0.00	0.00	0.00	162.53	0.00	162.53	0.00	0.00	5.87	0.00	0.00	0.00	0.00	162.53	156.66
Aldehydes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	75.22	0.00	75.22	0.00	0.00	2.72	0.00	0.00	0.00	0.00	75.22	72.51
Ketones	0.00	0.00	0.00	0.00	0.00	0.00	0.00	278.39	0.00	278.39	0.00	0.00	10.06	0.00	0.00	0.00	0.00	278.39	268.33
Alcohols	0.00	0.00	0.00	0.00	0.00	0.00	0.00	33.58	0.00	33.58	0.00	0.00	1.21	0.00	0.00	0.00	0.00	33.58	32.37
Furans	0.00	0.00	0.00	0.00	0.00	0.00	0.00	198.47	0.00	198.47	0.00	0.00	7.17	0.00	0.00	0.00	0.00	198.47	191.30
Ethers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45.33	0.00	45.33	0.00	0.00	1.64	0.00	0.00	0.00	0.00	45.33	43.70
Ketones	0.00	0.00	0.00	0.00	0.00	0.00	0.00	357.98	0.00	357.98	0.00	0.00	12.93	0.00	0.00	0.00	0.00	357.98	345.05
Phenols	0.00	0.00	0.00	0.00	0.00	0.00	0.00	881.51	0.00	881.51	0.00	0.00	31.84	0.00	0.00	0.00	0.00	881.51	849.67
saccharides	0.00	0.00	0.00	0.00	0.00	0.00	0.00	109.14	0.00	109.14	0.00	0.00	3.94	0.00	0.00	0.00	0.00	109.14	105.20
Sulfur (ash bio-char)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	54.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	54.49	0.00	0.00
Carbon	0.00	0.00	0.00	0.00	0.00	0.00	0.00	639.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	639.57	0.00	0.00
Ash	71.64	0.00	17.16	71.64	71.64	0.00	0.00	71.64	0.00	17.16	0.00	0.00	17.16	0.00	0.00	17.16	54.49	17.16	0.00
Sand	0.00	0.00	0.00	0.00	56255.61	0.00	56255.61	56255.61	56255.61	0.00	0.00	0.00	0.00	158.33	0.00	0.00	0.00	0.00	0.00

B. ENERGY BALANCE

Energy balance biorefinery Limeira.

Table C-1. Power process fast pyrolysis using eucalyptus residues.

Power		MWh/yr
Grinder		0.18
Motor do recuperador		0.19
Reactor		3.17
Condenser		1.33
Crushing		3.859.63
Combustor		2.28
Feeding silo		0.1514
Feeding engine (reator) 2 unidades		0.1856
Blower engine (ciclone) 2 unidades		298.89000
Total		4.166
Loss (13%)		541.58
	Total	4.708

Table C-2. Summary energy process and thermal pyrolysis efficiency.

Energy of process	Energy (MJ/h)
Biomass	72207
Bio-oil	29230
Bio-char	16541
Syngas	6855
Losses	19580
Thermal pyrolysis efficiency	63.89%

Table C-3. Energy balance pyrolysis reactor.

Heat for pyrolysis	
Specific heat of pyrolysis (MJ/kg)	1.5
mass feed to reactor (kg/h)	3810
Heat for pyrolysis (MJ/h)	5714.7
Thermal pyrolysis efficiency	63.89%
kWh	3.175

COMBUSTOR

Table C-4. Heat availability of syngas.

syngas	wt.	Heat of combustion (MJ/kg)	Average heat of combustion (MJ/Kg)
CO_2	0.5021	0	0
CO	0.3928	10.1	4.0
CH_4	0.0460	55.5	2.6
H_2	0.0072	141.8	1.0
		Average heat of combustion (MJ/kg)	7.5
		Heat of combustion in syngas produced (MJ/h)	5208.3
		Combustor efficiency (%)	90%
		Heat obtained of syngas combustor (MJ/h)	4687.5
		Syngas (kg/h)	690.7
		Heat obtained (kW)	1302.1

Table C-5. Energy balance condenser

Specific heat capacity of vapor		
Cp, vapor=	1.88	kJ/kgK
Cp, water=	4.19	kJ/kgK
m_{vapor}=	3124	kg/h
m_{vapor}=	0.867792	kg/s
1 kJ/s=	1 kW	
Density water=	997	kg/m^3
Results		
Q (kW)=	1334.872	
m_{water} (kg/s)=	5.792457	
m_{water} (kg/h)=	20852.85	
m_{water} (m^3/ano)=	175691	
Losses (%)=	5	
m_{water} (m^3/ano)=	8784.549	