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Elephant grass biorefineries: towards a cleaner Brazilian energy matrix?

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ABSTRACT

As of 2012, the share of the Brazilian domestic energy supplied by renewable energy was 42.4%, the highest among all major economies in the world. Nonetheless, there are opportunities to increase this share even further. One such opportunity is the adoption of biorefineries that could represent a viable and sustainable alternative to replace the need for oil, coal, natural gas and other non-renewable energy sources with biomass. The fact that biomass has the flexibility to be converted into distinct outputs such as electricity, biofuels, charcoal and chemicals, along with the uncertainty regarding market prices, may allow the firm to create value from the optimal exercise of these embedded options. Thus, the objective of this study is to analyze if converting a biomass power plant based on Elephant grass into a biorefinery adds value to the project and if the proposed biorefinery is economically feasible. The analysis was conducted by adopting a hybrid commercialization model where part of the plant's power generation installed capacity was sold through a 20 year long-term fixed supply contract and the remainder was optimally negotiated in the short-term market in the form electricity, charcoal or ethanol. The results show that all option values are positive ranging from approximately 90–101 million dollars, which indicates that they add value to the project. In addition, the resulting NPVs of all biorefinery strategies were positive, which indicates that biorefineries using the commercialization scheme proposed in this study represent a feasible and interesting opportunity for a sustainable energy matrix diversification.

1. Introduction

Energy generation projects can have significant environmental impacts. The growing demand for energy in recent decades has been met mainly by the increase in the use of fossil fuels, with large negative effects such as the increase in pollution and in carbon emissions. Greenhouse gases emissions from the use of fossil fuels, such as carbon dioxide, contribute to global environmental changes, while other pollutants contaminate the environment with negative effects on the quality of life (Bilgen et al., 2008; Omer, 2008). On the other hand, more efficient use of energy, changes in the world energy generation matrix, the provision for energy services such as storage, transmission and distribution and new regulatory policies can contribute to the reduction of these environmental issues. Some governments have already adopted policies to encourage the introduction of energy efficiency measures, technological changes and initiatives towards the expansion of renewable and sustainable energy sources (Andreoli, 2008).

In this context, biorefineries may represent a viable and sustainable alternative to replace the need for oil, coal, natural gas and other non-renewable energy sources, as they are able to convert biomass into chemicals, energy and other essential materials. According to Liu et al. (2012), biorefineries are renewable due to the fact that the biomass sources (i.e. energy crops, algae, etc.) synthesize chemicals by drawing energy from the sun and carbon dioxide and water from the environment, while the combustion of this biomass releases energy, carbon dioxide and water back to the environment, creating a closed cycle of carbon dioxide sequestration and emission. Thus, developing capabilities to convert a variety of plant-based biomass to chemicals, energy and materials can be instrumental in moving the world economy towards sustainable renewable energy.

Also, the fact that biomass has the flexibility to be converted into distinct outputs such as biofuels, charcoal and chemicals, associated with the uncertainty regarding market prices may allow the

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firm to create value from the optimal exercise of these embedded options. If so, the value of a biorefinery could be maximized, for example, by switching production to the most profitable output at the time.

This study analyzes the feasibility of converting a biomass power plant project based on Elephant grass into a biorefinery by investing in a charcoal production unit and/or a second generation ethanol plant. Through this analysis, it aims to answer two main research questions: Does converting a biomass power plant based into a biorefinery add value to the project? Is the proposed biorefinery an economically feasible alternative towards an increasingly environmentally sustainable energy matrix in Brazil?

2. Conceptual framework

A vast array of modern day products is derived from the refining and processing of fossil fuels. Due to uncertainty over future prices and availability and concern over the environmental impacts of this source of energy, governments actively seek alternative solutions that mitigate these negative aspects and reduce dependence on fossil fuels. One such alternative is the use of biorefineries, which use biomass as input for fuel and chemicals production, instead of fossil fuels (Liu et al., 2012).

In a biorefinery, most biomass sources can be converted into different types of biofuels and biochemicals by means of jointly applied conversion technologies. By integrating the green chemistry of biorefineries with environmentally friendly technologies, it is possible to design sustainable biofuels and high-value chemicals production chains that use biomass as input. This results in a more competitive bioindustry and approaches its ultimate goal of gradual replacement of products from petroleum refining (Cherubini, 2010; Liu et al., 2012; O'Keeffe et al., 2011; Pacca and Moreira, 2011; Takara and Khanal, 2011). Fig. 1 shows the schematics of the biomass conversion processes.

At the national, regional and global level, there are three main drivers for the adoption of biorefineries: climate change, energy security and rural development. With regard to energy security, electricity and heating can be provided by a variety of alternative sources (wind, solar, waves, biomass, etc.). However, biomass is very likely the only viable alternative to fossil fuels for the production of fuels and chemicals, since it is the only available alternative source rich in carbon. Thus, the sustainable production of biomass is a crucial issue, especially due to the competition with human and animal food production for agricultural land (Cherubini, 2010; Schaffel and La Rovere, 2010).

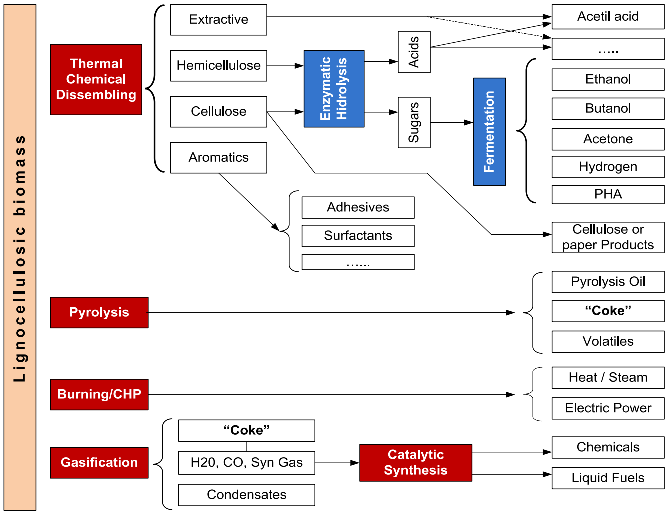

Fig. 1. Biomass conversion processes.
Source: Adapted from The Biorefinery Research Institute (2013).

Table 1
Renewables-based electricity generation in TWh.

Country	1990	2010	2015	2020	2025	2030	2035
Europe	472	887	1138	1351	1545	1734	1937
China	127	779	1223	1789	2112	2400	2689
United States	379	454	600	750	909	1074	1238
Brazil	211	437	514	585	646	701	754
Russia	166	170	176	195	224	260	305
India	72	136	213	318	466	644	826
Japan	102	116	161	199	247	292	325
World	2316	4206	5531	6999	8348	9786	11342

Source: (IEA, 2012b).

In 2011 the global demand for oil was approximately 89.0 million barrels per day (bpd) with a projected increase to about 95.7 million bpd by 2017 and of this total, the transportation sector responds for approximately two-thirds of absolute global demand (IEA, 2012a). This represents a significant opportunity for biofuels and biochemical if they are adopted as substitutes.

2.1. *The case of Brazil*

Brazil has led the world in the use of renewable sources of energy. In 2012, the share of renewable energy in the country's domestic energy supply was approximately 42.4%, while globally it accounts for only 13% of global primary energy demand (EPE, 2013; IEA, 2012b). However, regarding the specific markets object to this study one can observe very different strategies. Of the total electricity produced, 84.6% came from renewable resources, with 76.9% from hydropower. A diametrically different situation can be observed in the transportation sector that represents 57.4% of the country's total oil consumption (EPE, 2013).

In the electricity sector, the high reliance on hydroelectric power contributed to the energy crisis that led to a countrywide rationing between June 2001 and February 2002 as reservoirs became depleted due to unusually low rainfall in previous years. This led to the creation of the Thermoelectricity Priority Program (PPT) by the Brazilian government in 2002 with the objective of building 43 gas-fired power plants with a total installed capacity of 15,000 megawatts (MW) (de Oliveira and Marreco, 2006).

However, this aggressive effort to diversify the electricity generation matrix by investing in gas, coal and oil-fired power plants also contributed to make the electricity generation matrix less environmentally sustainable by increasing the consumption of nonrenewable energy resources. As a result, in 2004 the Brazilian government created the PROINFA (Incentive Program for Alternative Sources of Electrical Energy), a feed in program to foster investment in renewable energy sources such as solar, wind, biomass and small hydropower plants up to 30 MW of capacity. PROINFA's objective was to build 144 power plants totaling 3299 MW of installed capacity, with 685 MW coming from 27 biomass based plants. The contracts were guaranteed for 20 years by the Brazilian Electric Power Company (Eletrobrás) and the projects could be financed at subsidized interest rates by the Brazilian Economic and Social Development Bank (BNDES). The Brazilian government also created a commercialization rule where power generation projects using fostered energy sources with installed capacity up to 30MW were eligible for a discount of 50% in the transmission system usage fee (MME, 2010).

Both these initiatives contributed strongly towards the investment in these alternative energy sources, which have significant growth potential in Brazil. Due to these efforts towards sustainability, electricity generation from renewable sources grew from 217 Terawatt-hour (TWh) in 1990 to 437 TWh in 2010 with an expectation of reaching 754 TWh by 2035 (IEA, 2012b). Table 1 shows a comparison between renewable generation actual and expected growth in Brazil, other countries and the world.

As for biomass, Brazil has several comparative advantages relative to agricultural, agro-industrial and forestry products. Some of the most significant advantages are the vast expanse of agricultural areas available, intense solar radiation, availability of water, climatic diversity and interaction between the centers of agricultural research such as the Brazilian Agricultural Research Corporation (EMBRAPA) and agribusiness (EPE, 2007).

Brazil also has approximately 30 million hectares of degraded pastures with very low productivity for animal feeding which could be used for Elephant grass crops (MAPA, 2013). By using a head of cattle per hectare map shown by Tollefson (2010) as a proxy, one can infer that these areas are widely spread out over the Southeast, East and Northeastern regions of the country. The energy crops could partially replace natural gas and other hydrocarbons in electric power generation, gasoline in road transportation and the illegal use of native forests for charcoal production. The use of these deforested grazing lands which are not suited for food production without significant investment in soil preparation would also have a low environmental impact.

The growth of biomass' share in the Brazilian energy matrix has been steadily increasing in recent years, from 5.4% in 2009 to 6.8% in 2012 (EPE, 2010, 2013). It has mainly occurred in the form of co-generation systems where it is possible to obtain both thermal and electrical energy. Such power generation systems are usually installed on plants that weren't initially intended for the generation of electricity. This fact can be inferred by observing the distribution of biomass power plants by type of input shown in Table 2. The number of power generating units that have sugarcane bagasse as input is far superior to the others, as these units use the waste of sugar and ethanol plants to generate thermal energy and electricity for the productive process of the mill, with the surplus being exported to the Brazilian Electric System (SEB) grid.

Regarding the transport sector, the 2008 financial crisis, drought, and lack of investment in new and improved cane varieties led to the first decline in Brazilian sugarcane output in a decade in 2011. The output is expected to increase and reach 532 million tons for the 2012/2013 harvest; however, despite the increased cane output, ethanol production is declining due to the decline in the quality of the cane. The national ethanol production is expected to fall by 5.2% to 23.6 billion liters for the 2012/2013 harvest, from 24.9 billion liters. Anhydrous ethanol production is expected to decline by 0.9% to 9.7 billion liters, while hydrous ethanol production is forecast to fall by 8% to 14 billion liters. In contrast, sugar production is forecast to rise by 4.7% to 37.7 billion tons (Jagger, 2013).

While investments in first-generation ethanol production have slowed in Brazil, there has been continued interest in second-generation technologies. Brazil has lagged behind other countries, particularly the United States, in the development of commercial-scale second-generation ethanol production, but it has successfully developed technologies in laboratories and small-scale production facilities. It is estimated that, with the development of cellulosic ethanol technologies, Brazil could expand its ethanol production by up to 40% (Jagger, 2013).

Table 2
Installed capacity of biomass power plants in Brazil.

Input	Quantity	Total installed capacity (Kw)	%
Sugarcane Bagasse	378	9,338,666	81.83
Black Liquor	16	1,530,182	13.41
Wood	45	365,937	3.21
Biogas	22	79,594	0.70
Rice Husk	9	36,433	0.32
Elephant Grass	2	31,700	0.28
Charcoal	3	25,200	0.22
Palm Oil	2	4,350	0.04
Total	477	11,412,062	100.00

Source: (ANEEL, 2013).

Another important aspect of biorefinery sustainability is the possibility of producing charcoal in a sustainable way. According to de Muniz et al. (2013), Brazil has an annual production of approximately 10 million metric tons used mainly in the production of pig iron for steel and exportation. Other existing markets are food stores, pizza restaurants, bakeries, and red brick factories (Felfli et al., 2005). Although some of the charcoal comes from planted forests, there is still substantial use of wood from native forests. The State of Minas Gerais, which responds for 60% of Brazil's annual production of charcoal, plans to pass legislation that virtually bans the use of charcoal from deforestation by 2018. Thus, charcoal from an Elephant grass crops could address the deforestation problem and ensure the availability of this energy source.

3. Application

The objective of this study is to verify if converting a biomass power plant based on Elephant grass into a biorefinery adds value to the project and if the proposed biorefinery is an economically feasible alternative towards an increasingly environmentally sustainable energy matrix in Brazil. The first step is to calculate the value, as measured by the Net Present Value (NPV) of the power plant. The second is to calculate the NPVs of the different biorefinery setups proposed.

We assume the plant has four possible operating and commercialization strategies. In the base case, the plant produces only electricity and sells its entire capacity through a 20 year long-term supply contract at a fixed price. In this scenario, there are no market uncertainties and the plant's future cash flows are known. The three remaining strategies require that the plant adopt a hybrid commercialization model where part of the installed capacity is sold through a 20 year long-term fixed supply contract and the remainder can be negotiated in the short-term market. By making additional investments in a charcoaling and/or a cellulosic ethanol unit, the plant can optimally choose between selling electricity, charcoal or ethanol in the short-term market.

This study considers a power plant with an installed capacity of 30 MW in order to be eligible for the PROINFA incentives and obtain a discount of 50% in the transmission system usage fee. It also considers that the hybrid commercialization models sell 20MW through 20 year long-term fixed supply contracts and the remainder 10 MW or charcoal or ethanol equivalent on the short term market. The 20 MW/10 MW split was chosen so that the plant would have a steady fixed income, thus reducing the risk of the project.

The three hybrid commercialization strategies are as follows:

1. Invest in a charcoal briquetting plant (E&C case)

The firm optimally chooses on a weekly basis whether to use the biomass to generate and sell 10 MW of electricity in the short-term market or to produce charcoal briquettes. The remaining 20 MW is sold through a 20 year long-term supply contract.

2. Invest in a cellulosic ethanol plant (E&T case)

In this case the choice of outputs now is between electricity and ethanol. The remaining 20 MW is sold through a 20 year long-term supply contract.

3. Invest in both the briquetting and a cellulosic ethanol plants (E&C&T case)

The firm can now optimally choose between selling electricity, charcoal briquettes or ethanol. The remaining 20 MW is sold through a 20 year long-term supply contract.

These strategies involve four distinct sources of revenue for the firm, as shown in Fig. 2. The first is the net revenue of selling electricity in the long-term market, which is present in all strategies. The others result from the selling of electricity, ethanol or charcoal briquettes in the short-term market, when applicable. The value of each strategy will depend on the level of expected free cash flows that will be generated and the option value of the flexibility to switch outputs.

In the base case strategy, this study assumes that the free cash flows earned from selling electricity in the long-term market are risk free since the electricity price is known and constant during the life of the project. The net revenues of this strategy in each period are given by $R(t) = V \times P \times (1-S) - V(F+C)$, and are a function of the amount of electricity sold V (assumed a constant 30 MW), the long term fixed price P of electricity, the sales tax S, the transmission fee F and the variable cost of generating electricity C, all of which are assumed constant for the base case.

The cash flow accrued to the firm in the other strategies will depend on the net revenues generated from each output and the particular choice of output in each case. In the case of short term sales of electricity, in addition to the short-term price (spot price) P_E the firm also earns a price premium γ on the amount of electricity sold V_E. Thus, the net revenues earned from the sale of electricity in the short term market in each period are given by $R_E(t) = V_E(t)(P_E(t)+\gamma) \times (1-S_E) - V_E(t)(F+C)$, where S_E is the sales tax. The sale of charcoal briquettes provide the firm with a net revenue stream of $R_C(t) = V_C(t)P_C(t) \times (1-S_C) - V_C(t)C_C$, where V_C is the volume of briquettes produced and sold in any particular period, P_C is the uncertain price of the charcoal briquettes, S_C is the sales tax and C_C are the variable costs. Similarly, for the ethanol case the net revenues are given by $R_T(t) = V_T(t)P_T(t) \times (1-S_T) - V_T(t)C_T$. The variable costs will be determined by the period's production of each output, thus are a function of $V_E(t)$, $V_C(t)$ and $V_T(t)$.

The project cash flows for each strategy can be determined as shown by Eq. (1):

$$F(t) = E(t) \times (1-T) + D(t) - \Omega - \Delta\omega \tag{1}$$

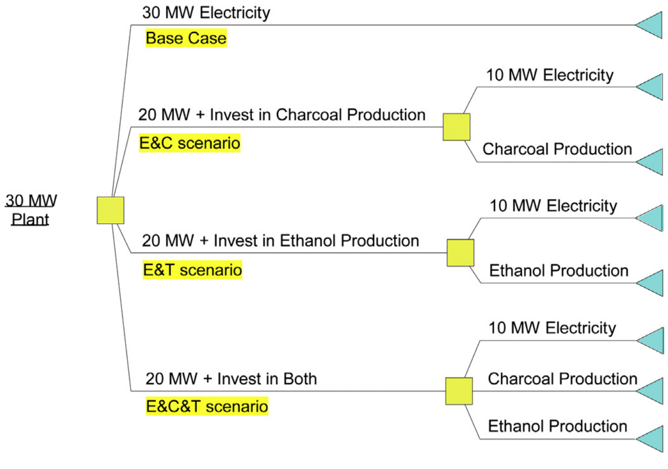

Fig. 2. Project scenarios.

where $F(t)$ are the free cash flows of each strategy in each period, $E(t)$ are the earnings before interest and tax, T is the tax rate, $D(t)$ is the total depreciation expense, Ω is the capital expenditure and $\Delta\omega$ is the change in working capital. While the tax rate (T) is the same for all cases, all other parameters will be specific to the chosen strategy. All capital investments are assumed to be linearly depreciated over a period of ten years.

In the base case, earnings before interest and tax (E) is a function of net revenues from electricity sales in the long term market, the unit fixed costs of plant operation K, the plant's power generation capacity Π, the total fixed costs of the Elephant grass crop K_G and the aggregate depreciation of the capital investment D, as show in Eq. (2),

$$E(t) = R(t) - K \times \Pi - K_G - D \tag{2}$$

For the E&C case, where the firm invests in a charcoal briquetting plant, the firm can optimally choose the most valuable output during any particular week of the year. Thus, the yearly earnings before interest and tax for this case are given by Eq. (3), where D_C is the sum of the depreciation of the capital investment in the 30 MW plant and in the briquetting unit.

$$E(t) = R(t) + \sum_{i=1}^{52} \max[R_{ES}(i), R_C(i)] - K \times \Pi - K_G - D_C - K_C \Pi_C \tag{3}$$

For the E&T case, where the firm invests in a cellulosic ethanol plant, the firm can optimally choose the most valuable output during any particular week of the year. Thus, the yearly earnings before interest and tax for this case are given by Eq. (4), where D_T is the sum of the depreciation of the capital investment in the 30 MW plant and in the cellulosic ethanol unit.

$$E(t) = R(t) + \sum_{i=1}^{52} \max[R_{ES}(i), R_T(i)] - K \times \Pi - K_T - D_T - K_T \Pi_T \tag{4}$$

Finally, for the E&C&T case, where the firm invests in both the charcoal briquetting and the cellulosic ethanol plants, the yearly earnings before interest and tax for this case are given by Eq. (5), where D_C is the sum of the depreciation of the capital investment in the 30 MW plant, the cellulosic ethanol unit and in the briquetting unit.

$$\begin{aligned} E(t) = {} & R(t) + \sum_{i=1}^{52} \max[R_{ES}(i), R_C(i), R_T(i)] - K \times \Pi - K_G - D_C \\ & - K_C \Pi_C - K_T \Pi_T \end{aligned} \tag{5}$$

This study assumes that the free cash flows to the firm in all strategies except the base case are uncertain due to the stochastic nature of future spot prices of electricity, charcoal and ethanol.

4. Price models and parameter estimation

4.1. Biomass

Among the variables associated with biomass, productivity is probably the most important since it influences the costs associated with acquisition or upgrade of physical assets such as equipment, property, or industrial buildings (CAPEX) and the expenses incurred in the course of the business, such as sales, general and administrative expenses (OPEX) of the project. Since the plant needs a predetermined amount of biomass, the size of the plantation area depends primarily on the amount of dry matter per hectare obtained per year.

Table 3
Elephant grass characteristics.

Characteristic	Limits
Altitude	Sea level to 2,200 m (best to limit to 1,500 m)
Temperature	From 18° to 30 °C, with 24 °C being an ideal temperature. Some specific type of Elephant grass can support lower temperatures and even frost.
Precipitation	From 800 to 4,000 mm annually. Sensitive to precipitation distribution and has low tolerance to drought.
Solar radiation	High photosynthetic efficiency.
Soil	Adaptable to different types of soil not subject to flooding.
Topography	Cultivation limited to lands with slopes up to 25% due to its low control of soil erosion and the need for farming mechanization.
Productivity	20 to 40 tons of dry matter per hectare. Higher yields can be obtained with increased fertilization.

Source: (Lopes, 2004).

The most common biomass energy sources in Brazil are sugarcane bagasse and reforested eucalyptus, with the former being the sole source of sugar and ethanol and the last currently being the main source of cellulose and charcoal. Another alternative is the use of Elephant grass (*Pennisetum purpureum*), a forage grass with high photosynthetic efficiency discovered in 1905 by Colonel Napier in tropical Africa which was introduced in Brazil in 1920 and is now widespread throughout the country. Being a perennial grass, it does not need replanting after each harvest and reaches 9–16 feet tall with 2 cm in diameter within 180 days. Its use is closely associated with grazing, especially as dairy cattle feed, which is object of extensive research by Embrapa.

Two key characteristics for the success of Elephant grass cultivation are temperature and precipitation. The required temperature range is 18 °C to 30 °C, with 24 °C being the ideal temperature, while annual precipitation range is 800 to 4,000 mm. Most of the Brazilian territory has temperatures above 18 °C throughout the year (IBGE, 2002), and pluviometric maps of the country show that most of the land area falls within the required rainfall range (CPRM, 2011), which indicates it to be ideally suited for Elephant grass cultivation. The full characteristics are listed in Table 3.

Table 4 shows the calorific power of selected biomass alternatives, as well as their density and humidity. Initially, Elephant grass seems to rank as a poorer choice when compared with other popular biomass choices. It is second to Eucalyptus in terms of calorific power, ahead of sugarcane bagasse. Its density is significantly lower than the other crops, which represents higher transportation costs. However, when one analyzes the productivity, Elephant grass can be far more productive than other common biomass sources. An Elephant grass crop can produce up to 29.05 tons of dry matter per hectare per year with 15% of moisture content and the first harvest can take place after only one hundred and eighty days (Morais, 2008; Vilela and Cerize, 2010). Eucalyptus can produce an average of 20 tons (approximately 31% less) of dry matter per hectare per year with 30.78% of moisture content and a forest of eucalyptus trees takes up to seven years to grow to a level where it can be used as a source of biomass (Monteiro et al., 2012; Quéno et al., 2011). Finally, sugarcane crops yield approximately 74.3 tons per hectare per year with 208 kg of bagasse per ton of sugarcane, resulting in a productivity of 20.8 tons of bagasse per hectare per year with 50% moisture content (Braga et al., 2013; Cardona et al., 2010). Since there are concerns that biofuels development may displace food crops, the smaller land area required by Elephant grass crops due to higher productivity can help minimize these concerns and possible impact on Brazilian food security (Agostinho and Ortega, 2013; Kopetz, 2013).

Considering that Elephant grass temperature and precipitation range are within most of Brazil's land area, the fact that it is adaptable to different types of soil and its higher productivity, this study opted to use Elephant grass as the source of biomass.

Having decided on the biomass source, the next step is to define its productivity. According to Vitor et al. (2009), the yield varies as shown on Eq. (6).

$$Y = 19,767.30 + 8.1478*N + 29.5690*L \tag{6}$$

where Y is the Elephant grass productivity in kg of dry matter per hectare per year, N is the quantity of fertilizer in kg per hectare and L is the irrigation level. For simplicity and lower plant deployment costs, this study conservatively assumes that no fertilization or irrigation will be used. Thus, the productivity of the Elephant grass used in this study is 19.767 tons of dry matter per hectare per year. Considering that the plant's annual need of biomass is 495,849 tons of dry matter per hectare per year, the required crop area is 25,085 ha. At an exchange rate of 2.3811 Brazilian reais per dollar (BRL/USD) and a bare land price in 2012 of 5329.24 BRL/ha, the total acquisition cost of land is approximately 56 million dollars (Instituto de Economia Agrícola, 2012).

Once the crop area size has been determined, it is possible to estimate the cost of biomass production. According to Vilela (2013), the production costs are segregated in formation and maintenance costs. Formation costs, which occur every five years, relate to preparation of the crop area and amount to 905.15 BRL/ha. Maintenance costs are annual and amount to 1485.76 BRL/ha including fertilization and irrigation costs. Since this study assumes that no fertilization or irrigation will be used, the actual maintenance cost is reduced to 685.87 BRL/ha. Using the exchange rate stated previously, the formation and maintenance costs are 380.14 USD/ha and 288.05 USD/ha respectively. Since the lower density of Elephant grass represents higher transportation costs, the

Table 4
Calorific power comparison.

Energy sources	Calorific power (kcal/Kg)	Average density (Kg/m^3)	Moisture content (%)	Productivity (tons of dry matter per hectare per year)
Elephant Grass Carajás (i.e. Paraíso)	4200[a]	50–60[a]	15[a]	19.76–29.05[b]
Eucalyptus grandis	4735[c]	499.3[c]	30.78[c]	20.73[d]
Sugarcane bagasse	2275[e]	120[e]	50[e]	20.80[f]

[a] (Vilela and Cerize, 2010).
[b] (Vitor et al., 2009).
[c] (Monteiro et al., 2012).
[d] (Quéno et al., 2011).
[e] (da Silva and dos Santos Morais, 2008).
[f] (Braga et al., 2013; Cardona et al., 2010).
Source: elaborated by the author from multiple sources.

Table 5
Technological routes.

Cycle	Cogeneration characteristic	Performance	Costs
Steam cycle with back pressure turbine	Only cogeneration	215 kWh/ton of biomass (cogeneration)	CAPEX – 830 USD/kW Fixed costs – 20 USD/kW per year Variable costs – 0.0015 USD/kWh
Steam cycle with extraction condensing turbines	Cogeneration or exclusive generation	340 kWh/ton of biomass (cogeneration) 530 kWh/ton of biomass (exclusive generation)	CAPEX – 1100 USD/kW Fixed costs – 20 USD/kW per year Variable costs – 0.002 USD/kWh
Integrated gasification combined cycle	Cogeneration or exclusive generation	1050 kWh/ton of biomass (cogeneration) 1150 kWh/ton of biomass (exclusive generation)	CAPEX – 1500 USD/kW Fixed costs – 55 USD/kW per year Variable costs – 0.006 USD/kWh

Source: adapted from MME (2007).

maintenance costs already include a baling press that compacts the biomass on the harvest site on bales to a density of 159 kg/m^3.

4.2. Electricity price model

The CAPEX and OPEX associated with the power generation plant depend mainly on the chosen technological route. In general, routes that are more complex tend to be more expensive but provide higher performance, and vice-versa. The Brazilian National Energy Plan 2030 (MME, 2007) specifies two possible routes that should be considered when projecting a biomass-fired power plant. One uses direct combustion of biomass in two possible scenarios and the other initially transform the biomass into a combustible gas before it is ignited by means of a gasification process. The first is a low cost route that uses mature technology with equipment and materials supplied by various local producers, but also provides low performance. The second alternative is a new technology still in its early stages of adoption which has high fixed and variable costs, but also has a very high performance. Table 5 summarizes these two routes and scenarios.

This study assumes the power plant will operate using a steam cycle with extraction condensing turbines with exclusive generation.

The long-term fixed price will be based on the average electricity price for biomass projects of the 18th new energy auction (A-5) held December 13th, 2013. The average price was 133.99 BRL/MWh or 56.27 USD/MWh. As the proposed project generates fostered energy, a premium equal to 50% of the distribution fee must be added. Since the value of the distribution fee is calculated individually for each distributor and the project is located in the State of São Paulo, this study will use the base fee of the local distributor Eletropaulo S.A. for June 29, 2010 of 12.99 USD/MWh. Therefore, the long-term fixed price will be 62.77 USD/MWh (ANEEL, 2010; CCEE, 2013).

The electricity spot price in Brazil varies weekly as defined by the Electric Energy Trading Chamber (CCEE). In order to simulate it for the lifecycle of the project, this study will adopt the risk neutral model proposed by Fontoura et al. (2012) shown in Eq. (7).

$$P_t = \left[\exp\left(\ln(P_{t-1})e^{-\eta_P \Delta t}\right) + \left(\ln\left(\overline{P}\right) - \sigma_P^2/2\eta_P - \pi/\eta_P\right)\left(1 - e^{-\eta_P \Delta t}\right) + \sigma_P\sqrt{\left(1 - e^{-2\eta_P \Delta t}\right)/2\eta_P}N(0,1)\right] + \left[\log N\left(\overline{k}, \gamma\right) \therefore (u_i < \phi \Delta t)\right] \tag{7}$$

where P is the simulated electricity spot price, $\overline{P}$ is the long-run equilibrium level of the electricity spot price, η_P is the speed of reversion; σ_P is the volatility; π is the risk premium, $\overline{k}$ is the average proportional size of the jump, γ is the standard deviation of the proportional size of the jump, φ is the jump frequency, u_i is a random number between 0 and 1 with uniform distribution and $N(0,1)$ is a standard normal distribution. We refer the reader to Fontoura et al. (2012) for a detailed discussion of this model.

The historical series used to calculate the parameters of the model was obtained from CCEE and comprises the period from March 2002 to November 2013 on weekly basis. Furthermore, it was inflated to November 2013 by the IGP-M index. Model parameters are shown in Table 6. The initial spot price value is 168.45 USD/MWh, which corresponds to the spot price of the last week of November 2013. Once the electricity spot prices are obtained, the net revenues can be calculated using the respective equation mentioned before. It is important to note that electricity direct taxes amount to 9.75% (EPE, 2007).

4.3. Ethanol price model

This study assumes the biorefinery will adopt a thermochemical conversion process that uses gasification or pyrolysis and relies on heat and/or physical catalysts to convert biomass to an intermediate gas or liquid, followed by a conversion step to convert that intermediate to a biofuel.

The OPEX and CAPEX of the ethanol production unit in this study are based on the results obtained by Gonzalez et al. (2012). However, as stated earlier, the cost of biomass treatment units such as the biomass receiving, handling and drying structures have been included in the costs of implementing the power plant and must be excluded. The CAPEX value must be adjusted to the size of this study's unit using the scale factor stated in Gonzalez et al. (2012).

Regarding the revenues, the risk neutral mean reversion model proposed by Bastian-Pinto et al. (2010) shown in Eq. (8) was adopted.

$$S_t = \left[\exp\left(\ln(S_{t-1})e^{-\eta_S \Delta t}\right) + \left(\ln\left(\overline{S}\right) - \sigma_S^2/2\eta_S\right)\left(1 - e^{-\eta_S \Delta t}\right) + \sigma_S\sqrt{\left(1 - e^{-2\eta_S \Delta t}\right)/2\eta_S}N(0,1)\right] \tag{8}$$

where S is the simulated ethanol spot price, $\overline{S}$ is the long-run equilibrium level of the ethanol spot price, η_S is the speed of

Table 6
Parameters for electricity spot price.

Parameter	Value	Parameter	Value
P_{t-1}	168.45	π	0.0023
η_P	0.0452	$\overline{k}$	59.52
Δt	1	γ	59.67
$\overline{P}$	70.5362	φ	0.1229
σ_P	0.2828		

Table 7
Parameters for Ethanol spot price.

Parameter	Value	Parameter	Value
S_{t-1}	0.5522	$\bar{S}$	0.5938
η_S	0.0124	σ_S	0.0476
Δt	1	π	0.0023

reversion; σ_S is the volatility; π is the risk premium and $N(0,1)$ is a standard normal distribution. We refer the reader to Bastian-Pinto et al. (2010) for a detailed discussion of this model.

The historical weekly series used to calculate the parameters of the model was obtained from the Center for Advanced Studies in Applied Economics of the University of São Paulo and comprises the period from November 2002 to May 2013. The series was also inflated with IGP-M index. The values for the parameters in Eq. (8) are shown in Table 7. Besides the parameters, an initial value for the spot price must be set in order to calculate the following values. This study will adopt the value of 0.5522 USD/l which corresponds to the ethanol spot price of the last week of May 2013. Once the ethanol spot prices are obtained, the net revenues can be calculated using the respective equation mentioned before. It is important to note that ethanol direct taxes in São Paulo amount to 21.6% (Rezende et al., 2011).

4.4. *Charcoal briquettes price model*

There are two technological routes for obtaining charcoal briquettes: the briquetting-carbonization option and the carbonization-briquetting option. In the first option, biomass is compacted to obtain a briquette. Then the briquette is carbonized in order to produce a charcoal briquette. In the second option, the biomass is first carbonize and crushed to obtain powered charcoal, which is then briquetted (Bhattacharya et al., 1990).

The briquetting-carbonization process results in higher yields, density and calorific value of charcoal, but is less environmentally friendly, requires nearly twice as much electrical energy per kilogram of charcoal briquette and is ill-suited for large scale production. Thus, this study will adopt the carbonization-briquetting process. The OPEX and CAPEX of the charcoal production unit in this study are based on Felfli et al. (2005). Regarding the revenues, the SARIMA (2,0,2)(0,1,1) model proposed by Coelho et al. (2006) will be adopted.

The historical series used to calculate the parameters of the model was obtained from the Forestry Association of Minas Gerais and comprises the period from January 1999 to May 2012 on monthly basis. The series was also inflated using the same assumptions stated before. Once the charcoal briquettes spot prices are determined, the net revenues can be calculated using the respective equation mentioned before. We assume that charcoal briquette prices are uncorrelated with the market and thus adopt a risk neutral model of the net revenues. It is important to note that charcoal direct taxes amount to 9.76% (Imana, 2011). The CAPEX, OPEX and variable costs for each route are shown on Table 8.

5. Results

The results are obtained by running a simulation model in order to determine the expected value of the project in each case, or the NPV. Since the base case is risk free and the modeling of all net revenues is risk neutral, the risk free rate was used as the discount rate of the strategies assuming a well diversified investor. The Brazilian long term interest rate, which was 5.12% a.a. as of May 2013, was considered for the value of the risk free rate. The summary results are shown in Table 9.

By analyzing the results the research questions proposed in this study can be addressed. The first one was if converting a biomass power plant based into a biorefinery adds value to the project. The base case scenario shows that there is no value in investing in this simple Elephant grass power plant, as it has a negative NPV. On the other hand, the option values are all positive, which indicates that the switch output options add value to the project. In this case, the value is sufficient to make the project economically feasible. Also, Fig. 3 show that all outputs are commercialized during the lifetime of the project which indicates that the manager is maximizing the NPV of the project by switching the output to the most profitable one at the time. For instance, ethanol is the chosen output in 62% and 32% of the weeks during the lifetime of the project in the E&T and E&T&C cases respectively while charcoal briquettes is the chosen output in 74% and 46% of the weeks in the E&C and E&T&C cases. These results reinforce the potential of the flexibilities embedded in biomass projects.

The second research question was if the proposed biorefinery was an economically feasible alternative towards an increasingly environmentally sustainable energy matrix in Brazil. The resulting NPVs of all biorefinery strategies are positive which indicates that biorefineries using the commercialization scheme proposed in this study represent a feasible and interesting opportunity for sustainable energy matrix diversification. Even taking into consideration the possibility of negative NPVs, the results are robust, since Table 9 shows that negative NPVs only occurs in the E&T case, with a probability of 7.9%. The optimal decision is to invest in the E&C&T plant, as this alternative provides the highest NPV of all at the lowest risk.

6. Conclusion and limitations

This research analyzed the feasibility of converting a biomass power plant project based on Elephant grass into a biorefinery by investing in a charcoal production unit and/or a second-generation ethanol plant. This analysis was conducted in order to verify if such conversion added value to the project and if the proposed biorefinery represented an economically feasible alternative towards an increasingly environmentally sustainable energy matrix in Brazil.

The results show that all option values are positive ranging from 90 to 101 million dollars approximately, which indicates that they add value to the project. The number of times the switch output option was exercised also presents a large opportunity for maximizing the return of the plant. In addition, the resulting NPVs of all biorefinery strategies were positive, ranging from 21 to 31 million dollars approximately, which indicates that biorefineries using the commercialization scheme proposed in this study may represent a feasible and interesting opportunity for sustainable energy matrix diversification.

Table 8
Project costs per route.

Parameter	Energy	Ethanol	Charcoal briquette
CAPEX	1100 USD/KWmed	1.6 USD/l	92,673 USD/Th
OPEX	520 USD/KWmed	3% of CAPEX	1.43 USD/T
Variable costs	2 USD/MWh	3% of revenue	4.31 USD/T
Transmission fee	1.17 USD/MWh	–	+

Table 9
Summary of the results.

Case	NPV	Option value (U$)	Probability of negative NPV
Base	−69,297,414	NA	100%
E&C	30,988,283	100,285,698	0%
E&T	21,584,451	90,881,866	7.9%
E&C&T	31,767,589	101,065,004	0%

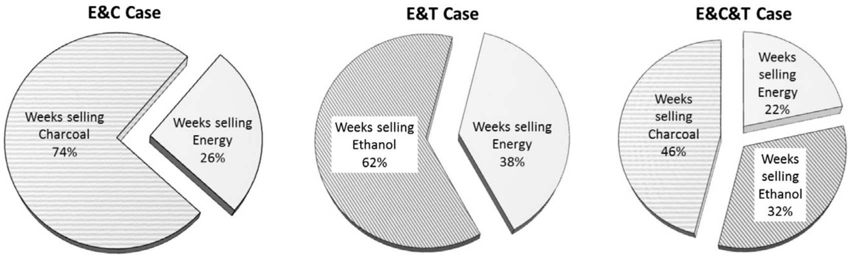

Fig. 3. Output selection.

The adoption of such biorefineries could have significant impact on the Brazilian energy matrix. As stated before, Brazil has approximately 30 million hectares of pastures in some stage of degradation. If 10% of this area was diverted to Elephant grass crops using the proposed biorefinery setup for electricity, ethanol and charcoal briquette production it would permit the substitution of 95% of the demand for electricity met today by non-renewable resources, 88% of the demand for gasoline or 343% of the demand for charcoal.

Limitations of this study include the fact that the proposed biorefinery represents only a small portion of the possible outputs of a more complete plant. The production of chemicals, for instance, which was not analyzed, could generate positive results since it is the output with the greatest potential to add value to the project due to its strategic involvement with industries such as petrochemical, pharmaceutical, automotive, construction, agribusiness, cosmetics, etc. Another limitation refers to the biomass productivity of Elephant grass in Brazilian soil. While this study opted conservatively to assume a productivity of 19.967 tons of dry matter per hectare per year, there are studies which indicate that this value could be as high as fifty tons of dry matter per hectare per year, which would result in a potentially higher impact of Elephant grass on the Brazilian energy matrix.

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