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INTEGRATED FURFURAL AND FIRST GENERATION BIOETHANOL PRODUCTION: PROCESS SIMULATION AND TECHNO-ECONOMIC ANALYSIS

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Abstract - Furfural is a base chemical with a wide range of applications and with a great opportunity for market growth in the near term. Derived from biomass, its production may be incorporated to the Brazilian chemical industry using sugarcane bagasse as feedstock. In this context, the integration of a furfural plant to a first generation bioethanol facility, within the biorefinery concept, was simulated considering different scenarios compared to an autonomous bioethanol distillery. The economic analysis of the different scenarios showed that the revenues from furfural commercialization increase the internal rate of return of the project for maximum furfural production (22.0%) in comparison to a conventional ethanol distillery (13.5%), despite the decrease in electricity output. Moreover, the economic analysis of the results pointed out the possibility of lowering furfural prices to levels that could lead to its use as a precursor for biofuels.

Keywords: Biorefinery, Furfural, Bioethanol, Sugarcane, Bagasse.

INTRODUCTION

Nowadays, green chemistry is a widely discussed subject in academia and industry. Chemical compounds of renewable origin are gaining market share in order to reduce pressure on oil reserves and due to lower environmental impacts compared to their fossil counterparts (Moulijn *et al.*, 2012).This trend comes as a result of several factors influencing human life and economy worldwide: climate change, instability of oil prices, the search for alternative chemical sources and the vision of ensuring energy supply security for the ever-growing world demand, for instance. However, stand-alone bioprocesses may present high operational costs, which can be reduced through process integration with a consolidated facility (Raskovic *et al.*, 2009; Dias *et al.*, 2012). In order to meet these supply

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needs and at the same time offer an economically feasible option, the concept of production in biorefineries was created (De Jong and Marcotullio, 2010; Moulijn *et al*., 2012). In biorefineries, a series of different processes is used to fractionate biomass into several products, like in oil refineries, yet working with a different, renewable feedstock. The purpose is also very similar to that of an oil refinery: produce compounds for both the chemical industry and the fuel market (Kouhia *et al*., 2015). Bioethanol, the most widespread chemical and fuel product derived from renewable sources, has a consolidated market in the world and a great participation in the Brazilian fuel market. Brazilian bioethanol is produced in large scale from sugarcane, which is one of the cheapest feedstocks for biofuels production (when compared to bioethanol from corn in the United States and bioethanol from sugar beet in France – Tao and Aden, 2009; Hira, 2011). Moreover, ongoing projects on the use of bioethanol as a base chemical for other products, such as polymers, show that the possibilities for growth of this green market depend mostly on the development of economically feasible solutions (Bos *et al*., 2012).

Today, new laws in Brazil are forcing sugarcane farmers to phase out the practice of burning crops on the field during the harvesting season, increasing the demand for mechanical harvesting. This process brings from the field to the biorefinery another possibility of feedstock:sugarcane straw (Oliveira *et al*., 2013). Together with the bagasse obtained from juice extraction, it can be used as boiler fuel to produce utilities in biorefineries, which usually operate at poor efficiencies and produce process steam and electricity through cogeneration of heat and power (CHP) units. These CHP units cover the on-site demand of steam and electricity and, potentially, generate surplus electricity to be sold to the grid (Ensinas *et al*., 2007). Surplus steam could also be sold directly to other industries, thus meaning less exergy destruction (Pellegrini *et al*., 2010). However, this sort of network is not widely available for Brazilian biorefineries today, since steam grids are limited in Brazil and biorefineries are not usually located close to centers of great steam demand. Besides, the process of burning sugarcane biomass to generate electricity is associated with a high capital expenditure, but since the feedstock is cheap and readily available, the economics of the overall process are attractive (Scaramucci *et al*., 2006). However, sugarcane biorefineries can go further in profits by giving different destinations to biomass, which include second generation fuels such as cellulosic ethanol or other derivative chemicals (Dias *et al*., 2011).

In the same way that the petrochemical industry is based on about 20 base chemicals derived from oil, a series of chemical compounds can be derived from biomass that together match the same needs of base chemicals of today's industry. These chemicals are the so-called building blocks (Moulijn *et al*., 2012). One prominent, biomass-derived building block candidate is furfural, recognized as a chemical platform for furanic compounds with a wide spectrum of application (Wong and Marcotullio, 2010). Crude furfural is used as a solvent in the refining of oil lubricants and is also the precursor of furan (used in resins and further derivatives), furoic acid (bactericide and fungicide), furfuryl alcohol (production of resins), tetrahydrofurfuryl alcohol (herbicide formulation), 2-methyltetrahydrofuran (biofuel) and other specialty chemicals. Furfural is produced worldwide through hydrolysis of xylan-rich biomass, followed by dehydration of the produced pentoses. Biomass pre-treatment is generally carried out under acid conditions at high temperatures. Several processes are known worldwide, and they differ mostly due to type and xylan content of the biomass used as feedstock. The three main processes available on the market are known as Quaker Batch, Chinese Batch and Rosenlew. Both Quaker Batch and Rosenlew use sugarcane bagasse as feedstock, and they are used in the first and second largest plants in the world, respectively: Central Romana, in the Dominican Republic, and Illovo Sugar, in South Africa (Zeitsch, 2000). Together, these plants covered about 20% of the 2013 market. On the other hand, the Chinese Batch process, working with corncobs, operates in several small-scale plants across China and accounts for up to two thirds of the total market. In 2013, worldwide furfural demand was 300 kt, mostly supplied by Chinese producers. Grand Value Research (2015) forecasts the furfural demand will reach the level of 600 kt/y by 2020 due to new applications of this base chemical.

For the 2015/2016 South Central harvest season, the Brazilian Sugarcane Industry Association announced a projection of 590 million metric tons (UNICA, 2015), which amounts to about 75 million metric tons of bagasse (dry basis). This value is expected to grow substantially in the next years after introduction of energy cane, a high fiber variety of sugarcane with a higher yield of biomass production per area (Carvalho-Netto *et al*., 2014). Therefore, due to the high amount of sugarcane bagasse produced, Brazil could become one of the big players in the furfural market.

This work assesses the economic impact of the integration of furfural to a modern biorefinery in Brazil. The proposed furfural plant adopts the Rosenlew process, with data based on the furfural plant of Illovo Sugar located at Sezela, South Africa. The analysis includes one scenario with the same production of furfural as Illovo, and a second scenario with maximum capacity of furfural production in a single integrated facility. The novelty consists of incorporating an existing technology for furfural production into a modern Brazilian biorefinery in order to use bagasse for a higher potential product value destination and also to improve overall process efficiency through plant integration.

METHODS

Sugarcane biorefinery description

The first generation ethanol distillery considered in this study processes 4 million metric tons of sugarcane per year, considering an annual operational period of 200 days. Crushing one metric ton of sugarcane yields 265 kg of bagasse (50 wt% moisture) and the recovery of 50% of straw from the field produces 82 kg of straw (15 wt% moisture) per metric ton of sugarcane. The rest of the straw is left on the field for nutrient recycling and soil conditioning. The juice extraction is performed through crushing and the juice is sent to treatment and fermentation. The fermentation product (wine) is then purified and the ethanol is distilled producing hydrated ethanol. The remaining water is removed using molecular sieves, which demands a lower steam consumption when compared to conventional dehydration systems (e.g., azeotropic distillation). The conventional ethanol production process (autonomous distillery) also includes the cogeneration of heat and power (CHP) unit using bagasse and straw as fuel. The details about this process can be obtained in other already published papers (Dias *et al*., 2011; CTBE, 2012; Mariano *et al*., 2013).

Furfural production description

Furfural production was based on a typical Rosenlew reactor (continuous process), followed by a series of distillation columns for purification. Integration of this process into an ethanol distillery is depicted in Figure 1. Each block in the diagram consists on the simulation of several unit operations.

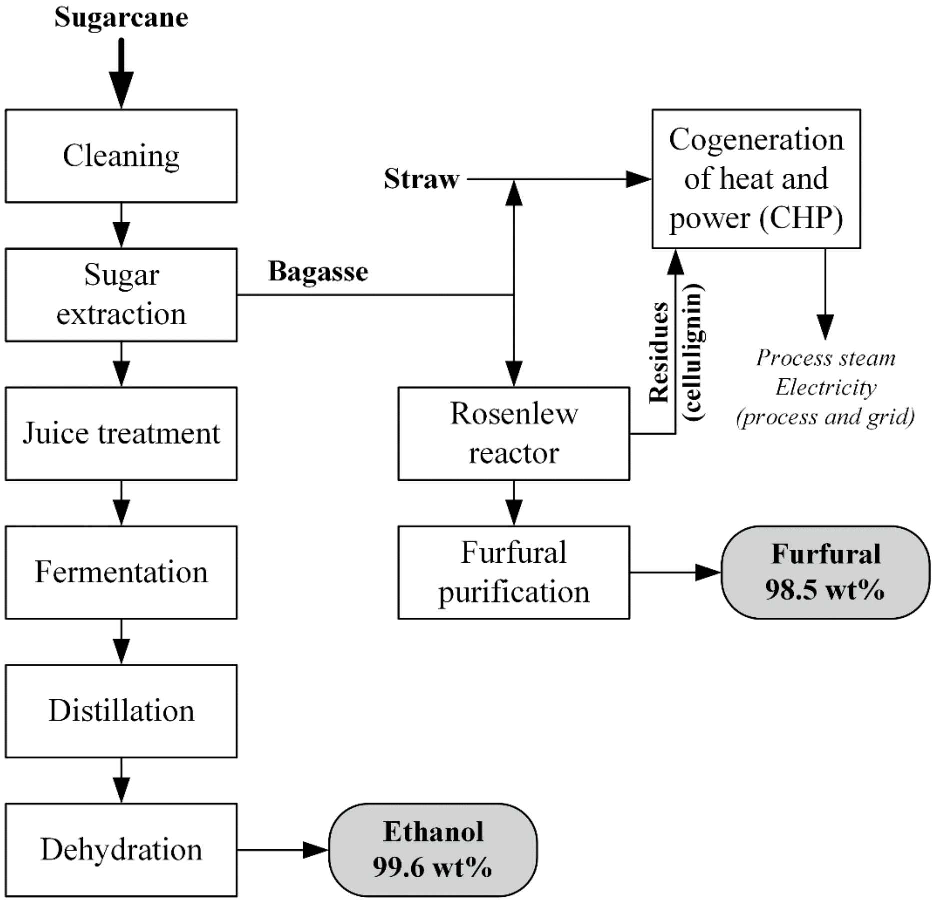

Figure 1. Block flow diagram of the biorefinery producing ethanol, furfural and electricity.

In a typical Rosenlew reactor, bagasse is injected at the top of a vertical reactor, 12 m high with a diameter of 2.5 m, and the residue (processed lignocellulosic material) is removed at the bottom intermittently, thus creating a slow displacement of the solid phase inside the reactor, with a residence time of about 120 minutes. Steam at 10 bar and

265 °C is injected in countercurrent flow at the bottom of the reactor, providing heat to the reactions and stripping the formed products (Zeitsch, 2000). The reactor operates at 10 bar, a more severe condition than other furfural processes because there is no addition of acid. The catalysis is promoted by the carboxylic acids produced during biomass decomposition, mainly acetic and formic acid. The acids formed mainly in the middle portion of the reactor are stripped by the steam. However, as colder bagasse enters the reactor, part of this acid vapor condenses on its surface and promotes hydrolysis to produce furfural and more carboxylic acids. As the solid phase flows downward, the steam promotes the stripping of the thin liquid layer above the solid particles, thus promoting the removal of furfural. The film resistance is surpassed by large steam feed rates, yet operating conditions should be carefully defined: the larger the steam feed rate, the lesser the holdup of carboxylic acids will be. With a smaller residence time for carboxylic acid inside the reactor, the total amount of catalyst inside the bed decreases and the production rate of furfural drops sharply (Zeitsch, 2000). Note that only bagasse is used as feedstock for furfural production, while the recovered straw is burned in the CHP unit along with solid residues produced in the Rosenlew reactor.

Furfural purification is not straightforward because furfural and water form an azeotrope (35 wt% furfural), and thus a series of columns must be employed, as shown in Figure 2. The Rosenlew process produces a dilute stream of furfural and other organic compounds in water, which, after condensation, follows to the first distillation column, represented as C-101 in Figure 2. This column strips furfural out of the solution, as the mixture entering this column contains less than 5 wt% furfural. To bring more furfural to the top, steam is fed at the bottom of the column, which includes a reboiler as additional heat source. Furfural is withdrawn from the column as a vapor side stream close to the azeotropic concentration (30.8 wt% of furfural). The top of the column is a stream containing the most volatile side products (low boilers), which is then fed to a second distillation column (C-102) that eliminates these side products at the top and recovers the furfural in the bottom together with water at azeotropic proportion. The bottom of column C-102 and the side stream of column C-101 are cooled down to 61 °C and fed to a decanter, where the aqueous phase returns to the first column and the organic phase is fed to a third one (C-103). The last column produces furfural at 98.5wt% purity at the bottom and has a two-phase condenser which refluxes the organic phase back to the column while the aqueous phase is sent to the decanter.

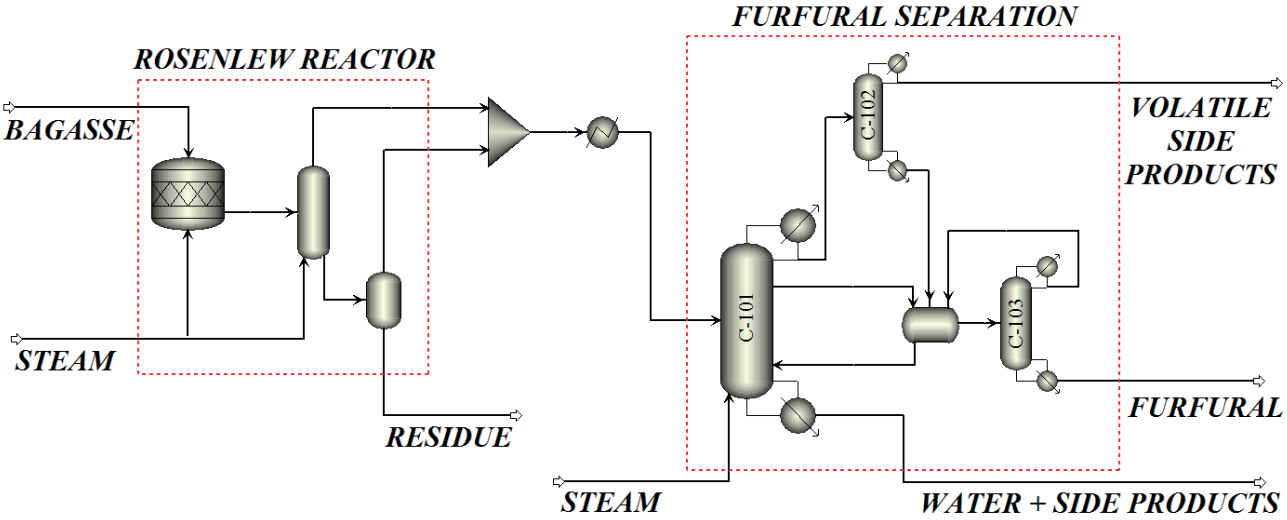

Figure 2. Process flowsheet for furfural production.

Process Simulation

The simulation and evaluation of first generation ethanol production is carried out using the Virtual Sugarcane Biorefinery (VSB), an innovative framework for assessment of biorefinery alternatives in the sugarcane production chain developed by CTBE (Brazilian Bioethanol Science and Technology Laboratory) of CNPEM (National Center for Research in Energy and Materials). Previous literature is available explaining the process in terms of simulation (Dias *et al.*, 2011; Dias *et al.*, 2012; CTBE, 2012; Mariano *et al.*, 2013). In this work, an optimized ethanol distillery with a high-efficiency CHP unit was considered, based on boilers producing steam at 65 bar. The simulation software used was Aspen Plus® 7.3.2. Due to the presence of carboxylic acids in the vapor phase, the authors used the NRTL-HOC thermodynamic model to simulate the Rosenlew process.

The furfural plant was inserted in the biorefinery simulation based on the data for the Rosenlew process available in the literature (Zeitsch, 2000). Table 1 summarizes the main process conditions of the furfural production. As previously shown in Figure 2, the Rosenlew reactor, due to its complexity, is simulated as three Aspen calculation blocks: a stoichiometric reactor (RStoic model), a rigorous three-phase fractionation column (RadFrac model) and a two-outlet flash drum (Flash2 model).Basic unit operations present in the simulation, such as heat exchangers and pressure changers, were omitted in order to simplify the drawing. The stoichiometric reactor performs the conversion based on the reaction yields for furfural and known side products in the process. The effluent is fed to a rigorous fractionation column in order to simulate the steam stripping effect occurring inside the Rosenlew reactor. At the bottom of the fractionation column, the residue is removed and then fed to a flash drum, which works at 1.4 bar to release volatile components trapped in the lignocellulosic residue before sending it to the boiler to use as fuel together with straw and the remaining bagasse. The condensed vapor thus obtained from the reactor section is fed to a series of distillation columns, operating at atmospheric pressure, with the specifications presented in Table 2. Operational parameters of column C-101 are available in Zeitsch (2000), while the other two columns were designed using Aspen Plus.

Table 1. Main process conditions of the Rosenlew process based on data available in Zeitsch (2000).

Steam injected in the Rosenlew reactor	
Steam to solids ratio (kg/kg)	30.0
Steam conditions	10 bar, 265 °C
Reactor Yields	
Furfural (kg furfural/kg xylan)	0.595
Acetic acid (kg acetic acid/kg of furfural)	0.489
Formic acid (kg formic acid/kg of furfural)	0.050
Low boilers (kg low boilers1/kg of furfural)	0.043
Steam injected at the bottom of column C-101	
Steam to furfural (dry basis) feed (kg/kg)	4.54
Steam conditions	2.5 bar, 128 °C

[1] Low boilers include methanol, ethanol and diacetyl.

Table 2. Parameters used at the simulation of distillation columns of the Rosenlew Process.

Parameter of the column	C-101	C-102	C-103
Number of stages	27	10	5
Feed stage	8[1], 11 and 26[2]	6	2
Side stream	5[3]	n.a.	n.a.
Distillate to feed ratio	0.0049	0.15	0.09
Side stream to feed ratio (kg/kg)	0.18	n.a.	n.a.
Reflux ratio	18	5	1

[1] Aqueous phase returning from the decanter.

[2] Steam injected at the bottom of the column.

[3] Side stream is withdrawn as vapor phase of that stage.

Some of the operational conditions of the columns were achieved through the use of Design Specs or Calculators of Aspen Plus in order to build a process model faithful to the process data presented by Zeitsch (2000). All distillation columns are rigorous fractionation columns (RadFrac model), and the associated decanter is a two-phase liquid-liquid decanter model.

In order to supply the utility demands of the furfural process, the CHP unit was designed to supply not only 2.5 and 6 bar steam, conventionally employed in ethanol production, but also 10 bar steam during the operation period of the furfural plant (330 d/y).

Economic analysis

In order to evaluate the outcomes of process integration, three scenarios were created as shown in Table 3. 1GBASE represents a modern ethanol distillery using all lignocellulosic material for electricity generation, and scenarios 1G+FF/S and 1G+FF/M represents two options of furfural plant size: while the former has the same capacity as the original furfural plant located at Sezela, South Africa, the latter is planned to produce as much furfural as possible from the bagasse produced on-site, minimizing electricity production to its lowest and removing the need of condensing turbines at the CHP unit. Moreover, the CHP unit operational period differs between scenarios: its operation is extended to 330 d/y when there is furfural production. The capital and operational expenditures (CAPEX and OPEX, respectively) for each scenario were estimated based on the database available at CTBE. The equipment for the furfural plant has different installation factors ranging from 2.5 to 4.0 depending on the unit operation. All the values were indexed to December 2014, and the internal rate of return (IRR) and net present value (NPV) were calculated from the discounted cash flow, considering a minimum acceptable rate of return of 12% per year. All production costs are allocated between the biorefinery products according to their participation in the revenues (economic allocation). Other data related to the economic analysis are shown in Table 4.

Table 3. Scenarios considered in the economic analysis.

Parameter	Scenario		
	1GBASE	**1G+FF/S**	**1G+FF/M**
Mill processing capacity (Mt/y)	4.00	4.00	4.00
Sugarcane straw consumed (kt/y)	278	278	278
Furfural plant capacity (kt/y)	n.a.	21.0	45.5
Operational period			
1G ethanol	200	200	200
CHP	200	330	330
Furfural plant	n.a.	330	330

Table 4. Parameters used in the economic analysis of the three scenarios.

Parameter	Value
Project lifetime (y)	25
Salvage value (R$)	0
Construction and commissioning (y)	2
Linear depreciation (y)	10
Tax rate (%)	34.0
Working Capital (based on CAPEX, %)	10

In order to evaluate the impact of uncertainties in the investment and the market on the economic performance of the assessed scenarios, risk analysis was carried out using the software @RISK 6.0. Monte Carlo simulation analysis with 5000 iterations was executed to estimate the density of probabilities associated with the economic impacts of each biorefinery. Variables considered in the simulation are listed in Table 4. Note that the capital expenditure for the furfural plant is an input apart from that of the rest of the plant, since investment for the ethanol distillery has been validated with engineering companies and sugarcane mills and consequently it is estimated with much higher precision by using the VSB database than it could be for the furfural plant.

Table 5. Parameters of Monte Carlo Simulations

Normal distribution	**Average**	**Standard Deviation**
Anhydrous ethanol price (R$/L) [1]	1.37	0.04
Furfural price (R$/kg)[2]	4.06	0.23
Triangular distribution	**Most likely value**	**Variation**
Electricity price (R$/MWh) [3]	144.42	-20%, +20%
Sugarcane price (R$/t)4	66.66	-10%, +10%
Sugarcane straw price (R$/t)4	85.81	linked to sugarcane price
CAPEX 1G+CHP, R$	estimated[5]	-15%, +25%
CAPEX FF,R$	estimated[5]	-20%, +40%

[1] CEPEA, Center for Advanced Studies on Applied Economics, moving average, 2004 to 2014.

[2] Alice Web, Brazilian Ministry of Development, Industry and Foreign Trade, moving average, 2003 to 2014.

[3] Brazilian Ministry of Mines and Energy, average of auctions, 2005 to 2014.

[4] Calculated by the agricultural module of the Virtual Sugarcane Biorefinery.

[5] CAPEX based on the results for each scenario – see Table 6.

RESULTS AND DISCUSSION

Techno-economic analysis

Results of the simulation for each of the three scenarios are shown in Table 6, along with the main results of the cash flow analysis. It can be noted that the production of furfural increased at the expense of decreasing electricity production, which is expected since bagasse is diverted from the CHP unit to be converted into furfural. In the first scenario, 1GBASE, all biomass is consumed to produce steam and electricity, the surplus of the latter being sold, thus generating a revenue of R$ 111.61 million. On the other hand, scenarios 1G+FF/S and 1G+FF/M (with production of furfural added to the portfolio) have revenues from biomass products of R$ 165.44 million and R$ 227.08 million, respectively, an increase of 48% and 103%. In spite of this substantial increase in revenues, OPEX remains almost unchanged since the amount of crushed sugarcane is the same for all scenarios. Sugarcane, straw and other inputs that belong to the core of the three scenarios, sum up to 90% of the costs. Furfural production does not require additional inputs (e.g., catalysts and chemicals), the other 10% of the costs being related to small variations in labor and maintenance costs between scenarios.

Another outcome of this reallocation of bagasse use is the decrease in capital cost of about16.6% when comparing 1G+FF/M with 1GBASE because the investment of bagasse processing to furfural is significantly lower than that associated with the CHP unit. Furthermore, in scenarios 1GBASE and 1G+FF/S, the CHP unit is equipped with extraction-condensing turbines to produce electricity from surplus steam, and such type of turbine has a higher cost than that of back-pressure turbines used in scenario 1G+FF/M. Another factor with a positive impact is that the CHP unit works 330 d/y when there is furfural production, against 200 d/y when there is only ethanol and electricity production. Since there are more revenues coming from bagasse use, the overall economics of the plant is improved, which is reflected in the IRR and NPV, as shown in Table 6. Comparing the base scenario (1GBASE) to that of maximum furfural capacity (1G+FF/M), the IRR increases 8.58 p.p. and the NPV is 6.5 times larger. The allocated costs of each product in all scenarios are also presented in Table 6, showing that there is a decrease due to better destination of bagasse.

Table 6. Results of the economic analysis of each simulated scenario.

Parameter	Value per scenario		
	1GBASE	1G+FF/S	1G+FF/M
Ethanol production (ML/y)	337	337	337
Electricity surplus sold to grid (GWh/y)	773	555	294
Furfural production (kt/y)	-	21.0	45.5
CAPEX, 1G+CHP (R$, millions)	1028.60	867.60	811.43
CAPEX, furfural plant (R$, millions)	-	29.04	46.16
OPEX (R$, millions)	339.36	336.41	336.25
Revenue (R$, millions)	573.18	627.01	688.66
Net present value, NPV (R$, millions)	113.77	457.27	744.65
Internal rate of return, IRR (%)	13.5	18.2	22.0
Allocated cost of production			
Ethanol (R$/L)	1.15	1.01	0.91
Electricity (R$/MWh)	121.85	106.45	95.74
Furfural (R$/kg)	-	2.99	2.79

The estimated production cost of furfural was between R$ 2.79/kg and R$ 2.99/kg, which is within the range determined by Lange *et al*. (2012). In their study, the authors conducted a study assessing the possibility of using furfural as a feedstock for biofuels, and in this context, estimated an overall production cost for furfural in the range of US$ 28-56/MJ (2012), which is equivalent to R$ 1.72-3.44/kg (exchange rate of December 2014, US$ 1.00 = R$ 2.64).

Risk analysis

Although the three presented scenarios have shown good results, the complete analysis demands the inclusion of the impact of investment and market uncertainties on the economic parameters. Monte Carlo simulation results for the parameters exposed in Table 5 have shown that the base scenario has a probability of 75.7% to have a NPV greater than zero. However, when there is furfural production, this probability rises to 100% for both scenarios 1G+FF/S and 1G+FF/M, i.e., typical market conditions guarantee that the investment in these scenarios is a safe choice since the event is almost sure. Regarding the project's lifetime of 25 years, it can be said that the projects comprising furfural production have more robustness in the long run compared to the base scenario. Figure 3 shows the probability density distribution of the NPV for the three scenarios. Note that all curves have similar behavior because, although there are differences between scenarios, the common part of the biorefinery (the ethanol production and the sugarcane mill) is still the flagship of the project. It can be seen from the graph that the only scenario where there is a possibility of having a net loss is 1GBASE, whereas the scenarios with furfural production are almost sure of being profitable options.

Concerning the uncertainties in estimating the capital expenditure of the furfural plant, the graph in Figure 4 shows that it has little impact on the NPV of the investment in scenario 1G+FF/M. The three major factors impacting the output are those involving the largest volumes of capital, namely: investment in 1G ethanol distillery with CHP unit, revenues from ethanol and sugarcane cost. Furfural revenues mount up to a considerable value of the total revenues, especially in the scenario with maximum production (1G+FF/M, 26.8% on revenue breakdown) and, therefore, have a considerable impact on the NPV as well.

Creating new opportunities for furfural

Results have shown that the integration of the processes is beneficial mostly because of the selling price of furfural. Therefore, it can be questioned whether the commissioning of a plant of this capacity, which could supply alone about 7.5% of the world market in 2020 in the case of scenario 1G+FF/M, could be responsible for a price decrease. One of the decisive factors on creating novel biobased processes and products is the cost of feedstock. If sold at a competitive price, the use of furfural as solvent could be extended to other processes beyond refining of lubricants. Moreover, furfural can be the precursor to a gasoline additive, 2-methyltetrahydrofuran (MTHF). As an example, the price of ethanol on an energy basis, R$ 64.20/GJ (considering the lower heating value of 27 MJ/kg), can be adopted as the selling price of MTHF since both can be blended to gasoline. MTHF has a LHV of 32 MJ/kg (Malinowski and Wardzinska, 2012) and can be blended to gasoline up to 30% with no adverse effects on engine performance as well as improving the performance of gasoline and ethanol blends (Yanowitz *et al*., 2011). In order to be competitive with ethanol, MTHF needs to be sold at a price as low as R$ 2.06/kg. Feedstock is reported to represent typically 60% to 70% of bioethanol final cost (BNDES, 2008).Considering the same baseline for the contribution of furfural on MTHF cost with a yield of 97.1% on a molar basis (Dong *et al*., 2015), the final price of furfural would need to be as low as R$ 1.16 /kg to open this new market option. Although this selling price is lower than the estimated production costs (R$ 2.79/kg and R$ 2.99/kg), the difference between revenues and expenses still remunerates the investment in furfural production and hence the scenarios with furfural production would still have an IRR greater than that of the base scenario, as can be seen on Figure 5. As a matter of fact, the last scenario with maximum production of furfural would have the same IRR

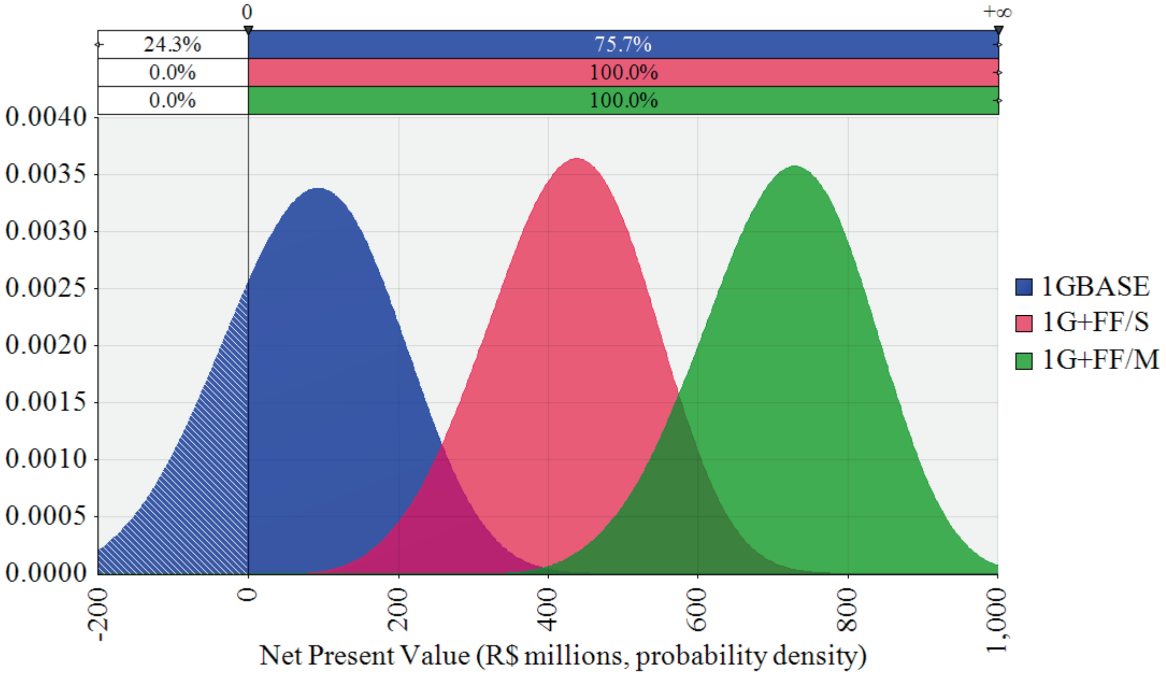

Figure 3. Probability density distribution of the NPV for the three scenarios of this study.

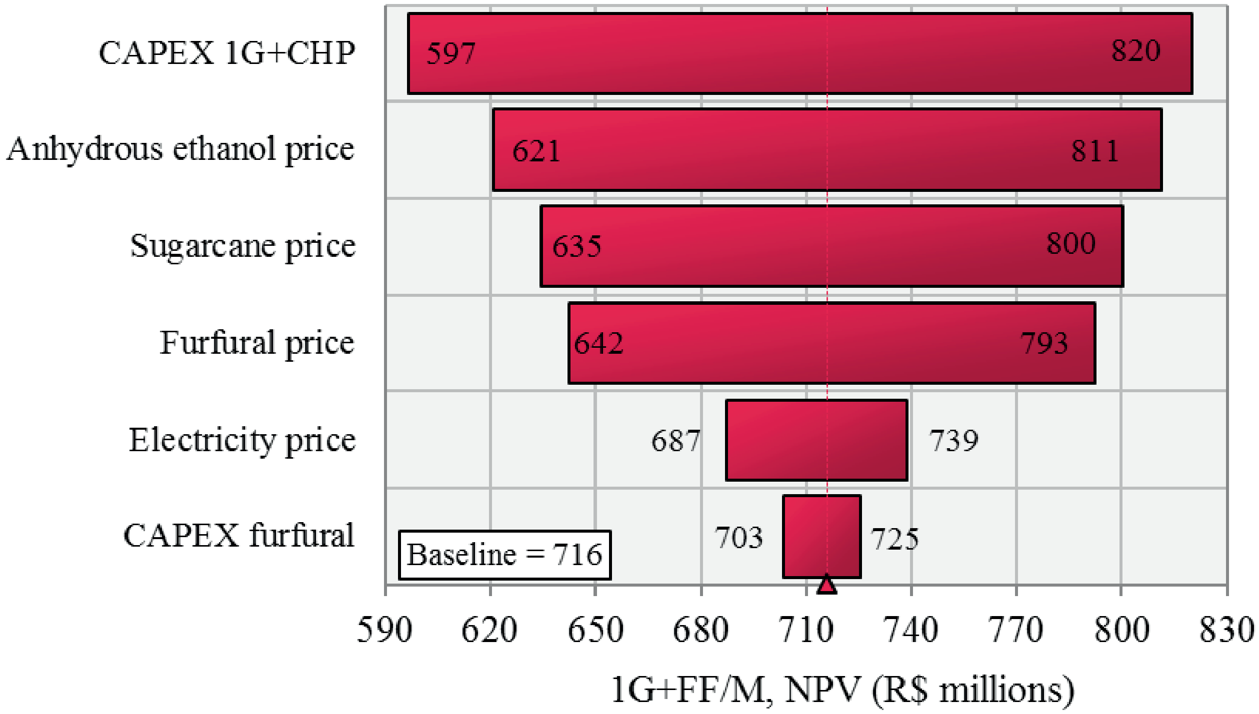

Figure 4. Impact of each input of Monte Carlo simulation in the NPV for scenario 1G+FF/M.

as the base scenario only if furfural price drops to as low as R$ 0.60/kg. In this latter option, the scenario 1G+FF/S would perform better economically than 1G+FF/M because electricity could add more value to bagasse than the conversion to furfural would do. Therefore, besides offering a better economics to the biorefinery, the furfural market could grow at the expense of the use of Brazilian sugarcane bagasse and Brazil could potentially compete with the Chinese market and become one of the biggest players.

Influence of the electricity market on biorefinery economic performance

Economic performance of furfural production is very dependent on the practiced electricity price in Brazil since both compete for the same feedstock in the three assessed scenarios. Nowadays furfural has a high price on the market and nearly always its production economically outperforms electricity generation, even for low furfural prices. Nevertheless, in the recent auctions for electricity contracts of the Brazilian Ministry of Mines and Energy, there was an increase in the electricity price, mainly due to a drought's impact on the generation of hydropower, the main source of electricity in Brazil. Therefore, if this trend of rising electricity price holds in the coming years, the 1GBASE scenario could be more competitive with the furfural-producing ones.

Figures 6 and 7 show what should be the price of electricity in order to even up the IRR of 1GBASE with the other two biorefineries, 1G+FF/S and 1G+FF/M. Figure 6 addresses the case where furfural is sold at the current price, and Figure 7 illustrates the case where furfural is directed to the biofuels market as feedstock for MTHF production. It is observed in Figure 6 that the price of electricity should rise 4.1 and 6.1 times so that 1GBASE's IRR matches those of 1G+FF/M and 1G+FF/S, respectively. However, this scenario is very unlikely, since the auctions account for factors like uncertainties in generation conditions, such as droughts for hydropower, but they do not penalize the price for electricity derived from biomass (Signorini *et al.*, 2015). When the furfural price is lower (R$ 1.16/kg), the demanded rise in electricity price to reach such level of competitiveness would be between 1.5 and 2.5 times. The increase in electricity price benefits the three projects, thus explaining the rise of the IRR in any case. Nonetheless, the historic series of electricity prices does not point to a sustained trend of high prices in Brazil. Therefore,

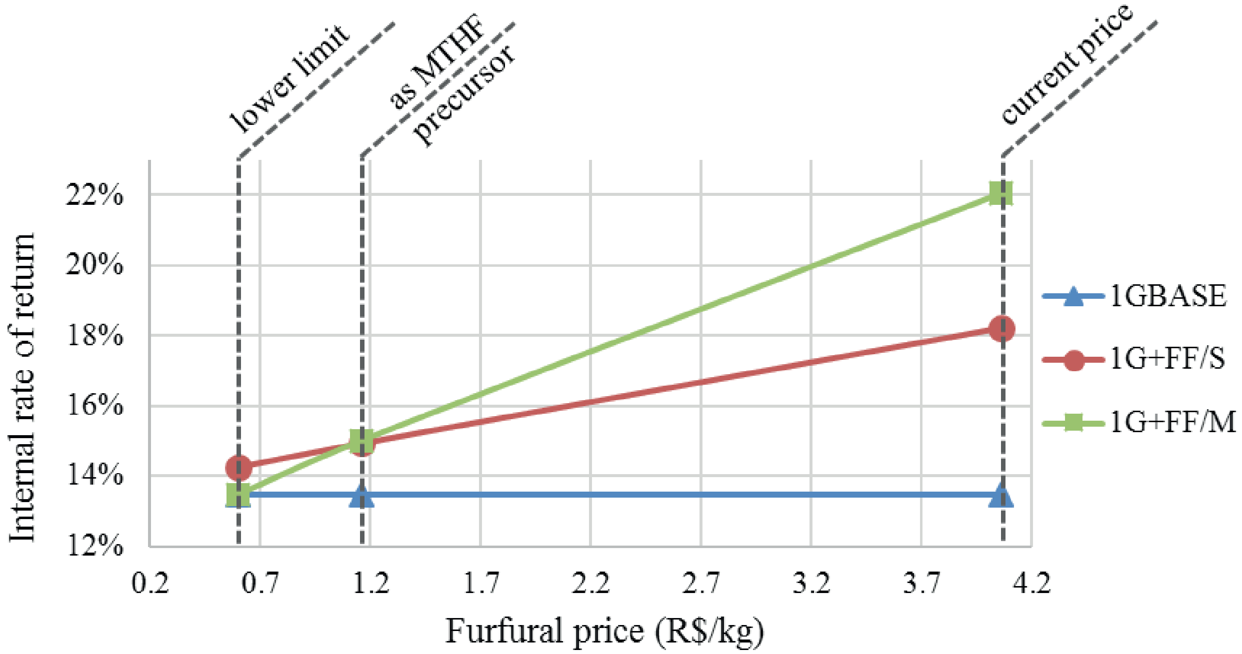

Figure 5. Internal rate of return (IRR) for different furfural prices.

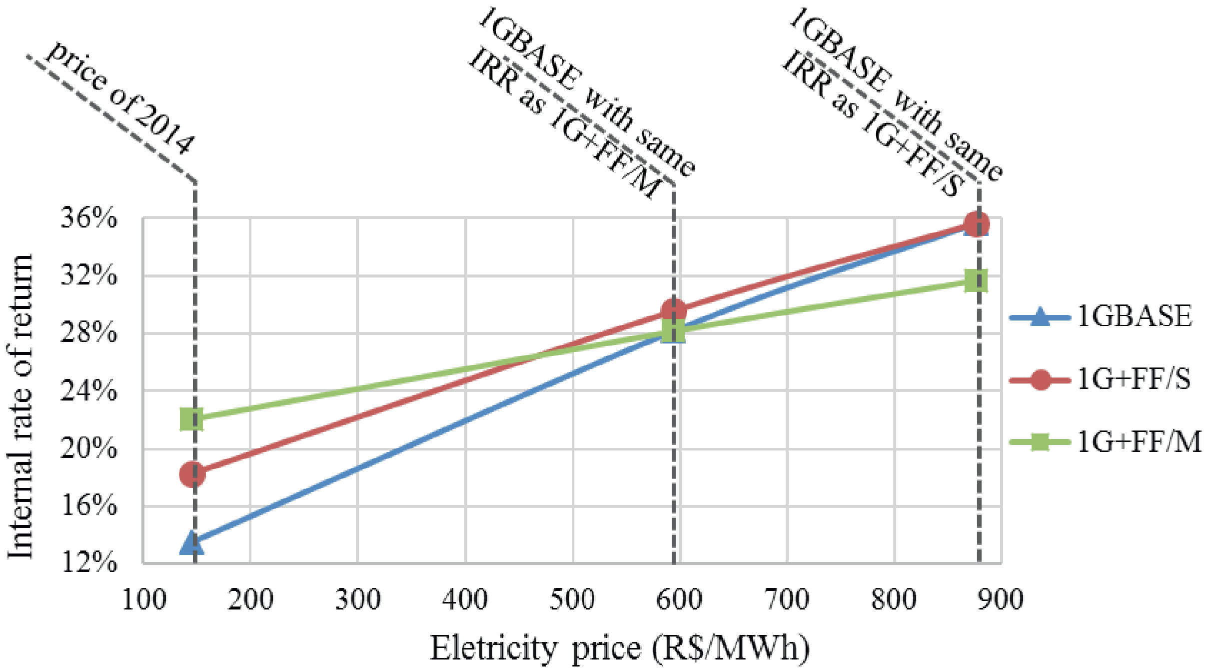

Figure 6. Internal rate of return (IRR) for different electricity prices with furfural at the current price of R$ 4.06/kg.

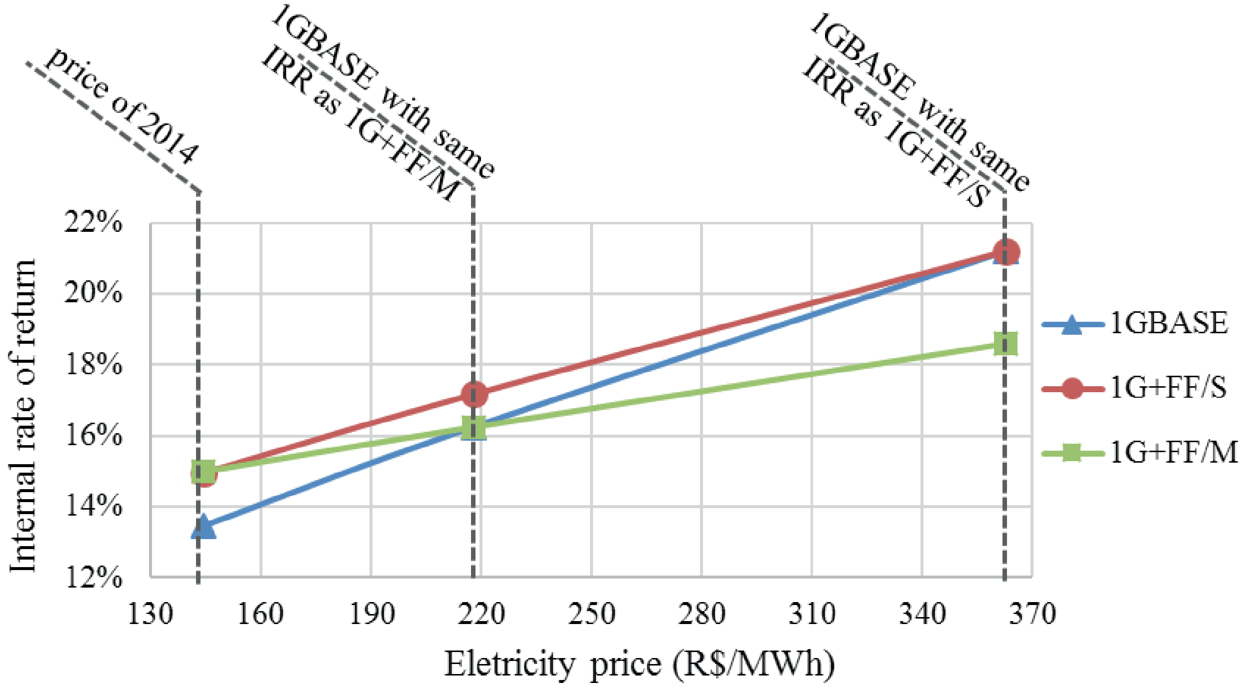

Figure 7. Internal rate of return (IRR) for different electricity prices when furfural is used as MTHF precursor, at a price of R$ 1.16/kg.

investing in furfural production appears to be an attractive integration alternative in sugarcane biorefineries.

CONCLUSIONS

This study assessed the integration of the Rosenlew process for production of furfural to a Brazilian ethanol distillery, based on operational conditions of existing processes. The option of integrating furfural production in the Brazilian context using sugarcane bagasse seems to be a viable option since this biorefinery performed better economically than the autonomous ethanol distillery, as indicated by the NPV and IRR results for each scenario. Moreover, furfural production can benefit from such integration, since its high economic performance can result in lower and more competitive prices, thus creating opportunities for furfural introduction in other markets, for instance, as a precursor of biofuels.

NOMENCLATURE

1G	First generation ethanol
CAPEX	Capital expenditure
CHP	Cogeneration of heat and power
FF	Furfural
IRR	Internal Rate of Return
MTHF	2-methyltetrahydrofuran
NPV	Net Present Value
OPEX	Operational expenditure
VSB	Virtual Sugarcane Biorefinery

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