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HOW BRAZILIAN PULP MILLS WILL LOOK LIKE IN THE FUTURE?

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ABSTRACT

Based on the personal experience of the author in being part of the biorefinery team of a major Brazilian pulp company, this forward-looking paper provides a high-level discussion on major guidelines pulp companies are advised to be currently analyzing in order to support informed and systematic decisions about the design of their future mills, and possible retrofit of existing ones. The guidelines were conceived based on open-ended considerations involving major trends in the Brazilian pulp industry, as well as pertinent aspects related to product diversification, and the dispute power generation versus new products. The main line of reasoning of the guidelines is the assumption that a sequence of strategic decisions will lead to different types of mills in the future, in contrast to the current standard kraft plant model with market pulp and power production. Furthermore, with a multidisciplinary (business/technological) approach, major trade-offs are mainly discussed taking into account energy-related aspects and the valorization of by-products and residues.

Keywords: biorefinery; Brazilian; design; future; kraft pulp mill.

INTRODUCTION

Although today biorefinery is an additional opportunity for a growing eucalyptus market pulp industry, being part of the biorefinery team of a major Brazilian pulp producer was an exciting experience in which, in a daily basis, I was involved in an array of techno-economic and strategic design activities that, ultimately, would support the decision-making of the company regarding critical questions. Some of them fundamental as "should we transform our company in a biorefinery?" and others more advanced in the decision-making process, such as "should we be an equity investor in this technology or license it?" Furthermore, since pulp companies are now constantly approached by biorefinery technology developer companies offering an array of solutions for the production of cost-competitive lignocellulosic sugars, as well as for the production of chemicals, materials, and fuels, the biorefinery team was permanently interacting with these companies and critically analyzing their techno-economic reports.

After two months in the job I was given a project that was quite intriguing and, at the same time, a good opportunity to present to the team my views on biorefinery, which were supported by a background in biorefinery design and technology development. General in scope, the project consisted in defining a guideline for future investments that was supposed to be delivered to C-level managers and should give a response to the following challenging question: "how our pulp mills will look like in the future?" A starting point to address this question certainly is to recognize that modern eucalyptus kraft pulp mills in Brazil, with fiber lines that surpass the production capacity of 1.5 million adt of bleached pulp a year, are already running with state-of-the-art technologies that, in combination with operational excellence in forest, manufacturing, and logistics activities, have been continuously improving the energy and environmental efficiency of these mills, and keeping the cash cost at very competitive levels (Martin, 2013a and b; Figueiredo, 2014).

Nevertheless, although there are still plenty of room for technological improvement in the kraft process in the coming years (mostly incremental, given the capital-intensive nature of this industry and its advanced maturity), the author of this paper decided to give this project a strategic-level approach looking at potential disruptive transformations (including biorefinery products) and, most notably, the effects energy-related aspects are expected to have on the decision-making regarding these transformations.

In the next sections are presented four strategic guidelines intended to give a reasonable, although not exhaustive, answer to how pulp mills will look like in the future in Brazil. With a multidisciplinary (business / technological) approach, major trade-offs are mainly discussed taking into account energy-related aspects and the valorization of by-products and residues.

METHODOLOGY

Four strategic guidelines for future investments concerning kraft pulp mills (either greenfield or retrofit projects) were conceived based on open-ended considerations involving: (i) major trends in the pulp industry, (ii) pertinent aspects related to product diversification, and (iii) the dispute power generation vs. new products. The main line

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of reasoning of the guidelines is the assumption that a sequence of strategic decisions will lead to different types of mills in the future, in contrast to the current standard kraft plant model with market pulp and power production. Special attention was given to place energy-related aspects in the decision context.

It should be noted that the methodological approach and the answer to the title question of this paper have a generic character and solely express the views and opinions of the author.

RESULTS AND DISCUSSION

Identification of major trends in the Brazilian pulp industry

In order to foster sustainable corporation growth and business expansion, it was identified four major trends pursued by Brazilian pulp mills, namely: (a) permanent increase of eucalyptus forest productivity and sustainability, (b) continuous enhanced energy efficiency, (c) expansion of the product portfolio relying on emerging technologies, and (d) value creation from by-products and residues. In the case of major players, these trends are generally supported by in-company R&D and innovation activities in classical breeding, genetic engineering, advanced silviculture practices, and product and process development (Figueiredo, 2014). It bears noting that mergers and acquisitions (M&A) are also a strong trend in the industry, and that the four identified trends are still valid upon M&A activities.

Brazilian pulp companies have a long and steady track record in the development of increasingly more productive eucalyptus forests and improvement of wood quality for pulp production. In addition to reduced production cost, continuous productivity gains are expected to attenuate the pressure on wood prices resulting from competing uses as the sector expands its product portfolio to emerging markets including new fiber materials, lignin, lignocellulosic sugars, chemicals, and advanced biofuels. On the other hand, new plants and forests have been lately more and more advancing to central and northern regions of Brazil (e.g., Mato Grosso do Sul and Maranhão states) attracted by very competitive land prices and regional government incentives. For instance, in Mato Grosso do Sul, eucalyptus forest area soared by 475% (from 120,000 to 690,000 ha) between 2006 and 2013 as a result of the installation of two kraft pulp mills (Celulose Online, 2014). Although the transportation cost of market pulp from these new and distant investment frontiers to sea ports are offset by low land prices, should this tendency of movement persist, companies will have to include new and particular logistics constraints during the design of new product portfolios. As such, it is necessary to take into account that different bioproduct categories (energy, fuels, commodity chemicals, fine chemicals, and materials) are subject to different supply-chain competitive strategies involving procurement, production, distribution, and sales (Dansereau *et al.*, 2014).

Energy efficiency has been the main driver for technology innovation in the last decade (Martin, 2013a and b) and the decision on how to use surplus energy and biomass will greatly impact the design of future pulp mills. For the moment, prompted by steady growing power prices in the last years, investment in power cogeneration has been the preferred (or exclusive) choice, and the sale of power to the grid has become an important revenue stream for non-integrated kraft pulp mills. Indeed, this subject has attracted the attention of the eucalyptus pulp community so that the advances on integrated pulp and energy production were the main topic of the 7th International Colloquium on Eucalyptus Pulp held in Vitória (Brazil) in May 2015. Furthermore, in the midst of severe droughts (impacting hydropower generation) and shortage of natural gas, power spot price has experienced a significant run-up, giving additional strength to the attractiveness of biomass power generation (Carrança, 2014). Under this present attractive situation of the Brazilian power market, it is an educated guess to assume that a major portion of the current projects for valorization of by-products and residues are targeting their use in cogeneration.

The different aspects related to the four major trends presented in this section support the development and discussion of the strategic guidelines presented next. As noted above, instead of presenting a closed-ended response to the title question of this paper, the guidelines are built upon strategic decisions that are now on the plate of decision-makers and will ultimately lead to different types of mills in the future.

Strategic guidelines

(1) Product portfolio

Brazilian eucalyptus market pulp companies are seeking to evolve to forest companies (or even biomass companies in reference to other feedstocks) as a clear sign of their plans to expand their business to new and diversified markets. As such, the design of the product portfolio of a future installation (also referring to the retrofit of an existing mill) should be considered as the prime strategic decision, which eventually will dictate the design of the plant. As a result, different mill models are expected. Given the increasing market share of hardwood (short) fibers in tissue paper and packaging products, an important fraction of future installations are very likely to stick to the consolidated low-technology-risk design, i.e., the non-integrated kraft pulp mill aiming at U.S, European and Chinese markets. On the other hand, following a global trend, Brazilian companies are also tracking the growing demand of dissolving pulp by the Chinese textile industry. In fact, the Jari group has announced the conversion of a pulp mill from paper pulp to dissolving pulp production with an annual capacity of 250,000 metric ton (Risi, 2014). An integrated design that allows for a flexible production of both paper and dissolving pulp at the same mill will certainly mitigate market risks of both products. Particularly the dissolving pulp, anti-dumping tariffs applied by China, evolution of the cotton industry, and lack of vertical integration with textile producers are major risks for future Brazilian producers (Vidal, 2014).

The design of future plants will also consider new feedstocks and

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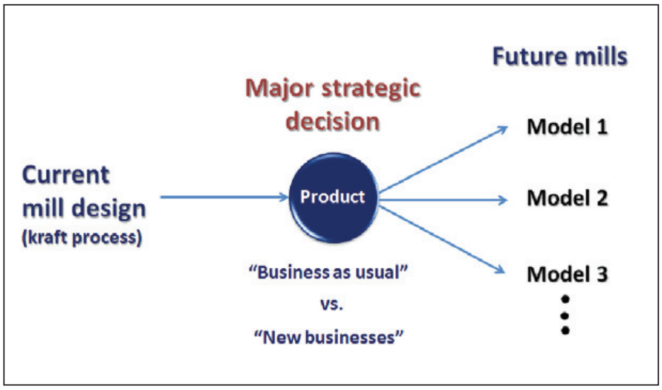

Figure 1. Product portfolio: the major strategic guideline for the definition of future investments

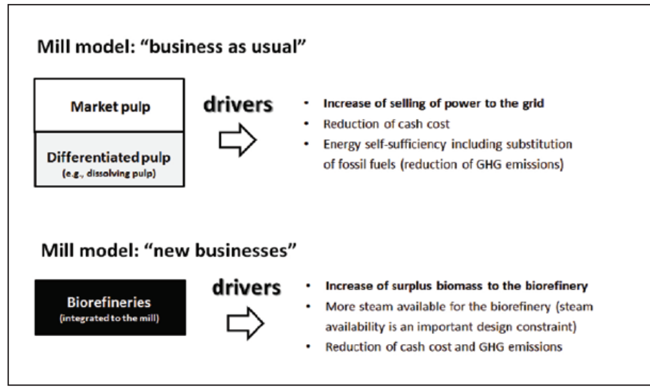

Figure 2. Drivers for energy efficiency according to mill model and associated product portfolio

emerging biorefinery product (lignin, chemicals, advanced biofuels, and new fiber materials such as nanocellulose). These plants will be either greenfield independent biorefinery units (close to feedstock sources that may be other than eucalyptus forests, e.g., energy cane), or mostly likely "bolt-on" facilities annexed to kraft mills. Whereas the former expands the business of the company also on the feedstock end, the latter design can benefit from site-specific integration opportunities in different levels (energy, mass, feedstock supply, and equipment), which are competitive advantages to be explored.

As illustrated in **Figure 1**, the decision on keeping with "business as usual" versus "new businesses" will be affected by several aspects, including how companies will evolve from both the traditional commodity thinking (competition by volume and not differentiation) and their characteristic strong aversion to risk. Furthermore, revenues diversification beyond cogeneration implicates corporate transformation and adaptation to new business models. Not less importantly, external factors will also play a significant role in the decision-making. These include the progress ratio of technological learning curves and associated cost reductions (including cost of capital), evolution of emerging markets, and government incentives.

(2) Cogeneration versus biorefinery

Whereas superior energy efficiency is a target pursued by the potential different mill models of the future, the drivers to generate energy surplus are different. Companies that eventually decide to invest in "business as usual" will mainly seek to increase penetration in the electricity market in order to reduce the cash cost of pulp, and possibly eliminate the use of fossil fuels (with attenuation of GHG emissions) (**Figure 2**). Indeed, as the majority of the pulp mills in Brazil are not integrated (without paper production, and strategically not locked to the declining printing and writing paper market), great part of these mills already have energy surplus. Notably, recent investments in new pulp mills, featuring energy-efficient equipment and more efficiently integrated units, have generated significant revenues from energy surplus. For instance, in 2013 Fibria's Três Lagoas mill (started up in 2009) reached a power surplus of 35%. In combination with another mill (older and with a balance of 9%), the revenues from selling power to the grid (30 MW) was R$ 67.3 million (USD 25 million) in that year, corresponding to a credit of approximately 6 USD/adt (Fibria, 2013).

Whereas the installation of low-pressure condensing turbines makes possible the use of excess biomass (forest and woodyard residues) and lignin to produce a positive balance of electricity through the expansion and condensation of surplus steam, the surplus material and energy streams can, otherwise, feed a biorefinery process either integrated or in parallel to the kraft process. In the biorefinery case, enhanced energy efficiency is driven by the need to minimize the investment in supplementary power boilers, as well as to avoid the purchase of relatively expensive fossil fuels (in Brazil, current natural gas price is about 10 USD/MMBTU). For instance, studies demonstrated that the production of ethylene-propylene rubber (27 kton/yr) from the gasification of excess black liquor of a standard northern bleached kraft pulp facility would demand the power boilers to run at full capacity (with additional purchase of hog fuel and natural gas) and importation of 4.3 MWe from the grid (in contrast to the original 6.8 MWe sold to the grid). Nevertheless, this project presented promising economics with reasonable capital investment (USD 237 million) and attractive IRR (26%) and payback time (3.3 years) (Mariano *et al.*, 2013).

The competition "cogeneration versus biorefinery" is not exclusive to the forest industry. Indeed, it is a trade-off frequently found in biorefinery design and permeates other industries, including sugarcane and corn (Dias *et al.*, 2011; Davis *et al.*, 2013). For illustration, in a corn stover-to-hydrocarbons biorefinery, process design studies recommended the conversion of the lignin fraction to value-added commodity chemicals such as adipic acid. In despite of the resulting importation of electricity, the credits from the lignin-derived product can potentially bring the selling price of bio-based hydrocarbons from $5.10/GGE to a 2022 target of $3/GGE (Davis *et al.*, 2013). Interestingly, and equally valid for the forest industry, this same study demonstrated that depending on the amount of lignin diverted and on the chemical produced thereof, the conversion of lignin can offer GHG emissions benefits over lignin combustion. As far as sustainability metrics concerns, it bears noting that the average

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U.S. electricity grid mixture is carbon-intensive and, thus, electricity coproduct is responsible for an expressive offset of GHG emissions of 0.78 $kgCO_2$-eq/kWh (Davis *et al.*, 2013). On the other hand, the Brazilian electricity grid is mainly based on renewable hydropower generation (~70%) and the emission factor is as low as 0.096 $kgCO_2$-eq/kWh (MCT, 2011). Consequently, in Brazil, lower emissions reductions (and potential carbon credits) can be achieved with cogeneration in comparison to the U.S., increasing the environmental performance of the biorefinery option (over cogeneration) in the Brazilian context.

Evidently, the competition "cogeneration versus biorefinery" must be carefully evaluated beyond strictly an environmental and economic context. It is advised that companies employ systematic design methodologies to support their decision-making, taking into consideration uncertainties in energy market conditions, the cost development of emerging biorefinery technologies, and market risks related to biorefinery products (Svensson & Berntsson, 2011; Cohen *et al.*, 2010; Mohammadi, 2014). Furthermore, given the economic stalemate situation faced by European and North-American pulp companies, the odds are these companies will be the first movers to biorefinery transformation. If the Brazilian pulp industry decides to keep with its usual fast follower strategy and only invest in biorefinery in a later stage at the time the penetration of short fibers into the long fiber pulp market stagnates, companies are expected to face significant barriers to access secured low-volume high-margins markets (generally, others than biofuels). The bottom line, the timing and ability of a company to evolve from the cost-competitiveness strategy of the commodity pulp market will certainly be a critical success factor should biorefinery be the choice.

(3) Biorefinery strategy and energy

From a very pragmatic point of view, for a pulp company, biorefinery is an investment option to which surplus energy (steam, power, and energy in biomass form) is deposited and superior economic return (relatively to the core business) is desired. Obviously, companies are seeking the maximization of the economic value of their eucalyptus forests, however, they will have to tackle a less tractable definition of biorefinery, which involves the creation of new business models, revenues/products diversification and penetration to new markets, and mostly important, transformation of the company (Janssen & Stuart, 2010). Furthermore, the long-term sustainability of the new business heavily depends on the solution of an intricate puzzle with pieces scattered over different domains: product portfolio, technology, and feedstock (**Figure 3**). In this task, identification and mitigation of business, financial, and technology risks are crucial. Additionally, the strong technology trend of the core business related to the development of forests with genetically modified eucalyptus trees may be conflicting with some biorefinery markets. For example, Corbion Purac states that the company "exclusively uses GMO-free feedstocks to produce its PLA monomers".

Focusing on the technology "piece", biorefinery technologies have

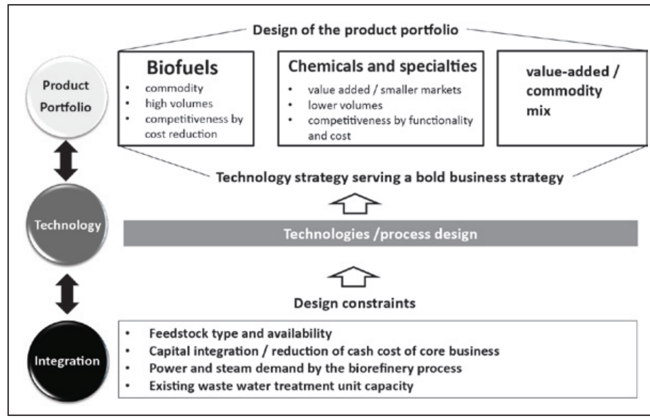

Figure 3. Pieces of the biorefinery design puzzle. Inspired by concepts presented in Batsy *et al.* (2013)

different energy efficiencies (GJ/ton product) and for this reason, an important design constraint (assuming the integrated model) is the compatibility of the amount and type of energy (steam/power) demanded by the technology with that available in the host pulp mill, whose energy profile generally is site-specific. Nevertheless, heat integration between the biorefinery process and the mill can potentially improve the overall economics and energy efficiency of the site (Svensson & Berntsson, 2011; Rohani, 2014). Generally, there is a trade-off between enhanced energy efficiency (a proxy for reduced OPEX) and CAPEX. Moreover, many times energy efficiency and improved environmental performance are offered by emerging advanced technologies, thus increasing the technology risk. For illustration, the production of bio-based n-butanol via the commercially-proven batch fermentation and product recovery by distillation implies a steam consumption of approximately 30 GJ/ton butanol and a wastewater footprint of 80 liters/liter butanol. On the other hand, advanced technologies (still under development) with bioreactors integrated to alternative product recovery systems (e.g., membranes) may bring significant energy and environmental advantages (10 GJ/ton butanol; 20 liters/liter butanol) (Mariano & Maciel Filho, 2012). The latter class of technology puts the butanol biorefinery at a similar energy efficiency level as compared to an ethanol biorefinery, and may allow for a more competitive production scale. Certainly, this is important information for a company targeting the biofuels market and deciding between a traditional biofuel (with increasingly saturated markets) against advanced biofuels (more compatible with existing infrastructure and with growing markets).

Associating technology with business robustness, it is important to recall that downstream separation processes are often the bottleneck in industrial bio-based processes and offer a large potential for energy savings (Rohani, 2014; Kraemer *et al.*, 2011). In their report to the U.S. Department of Energy, Eldridge *et al.* (2005) describe hybrid/intensified separation processes as a key technology in the effort to reduce the energy demand in manufacturing. However, from a systems perspective, the choice for advanced intensified separation/purification technologies should not (or at least to a lesser extent)

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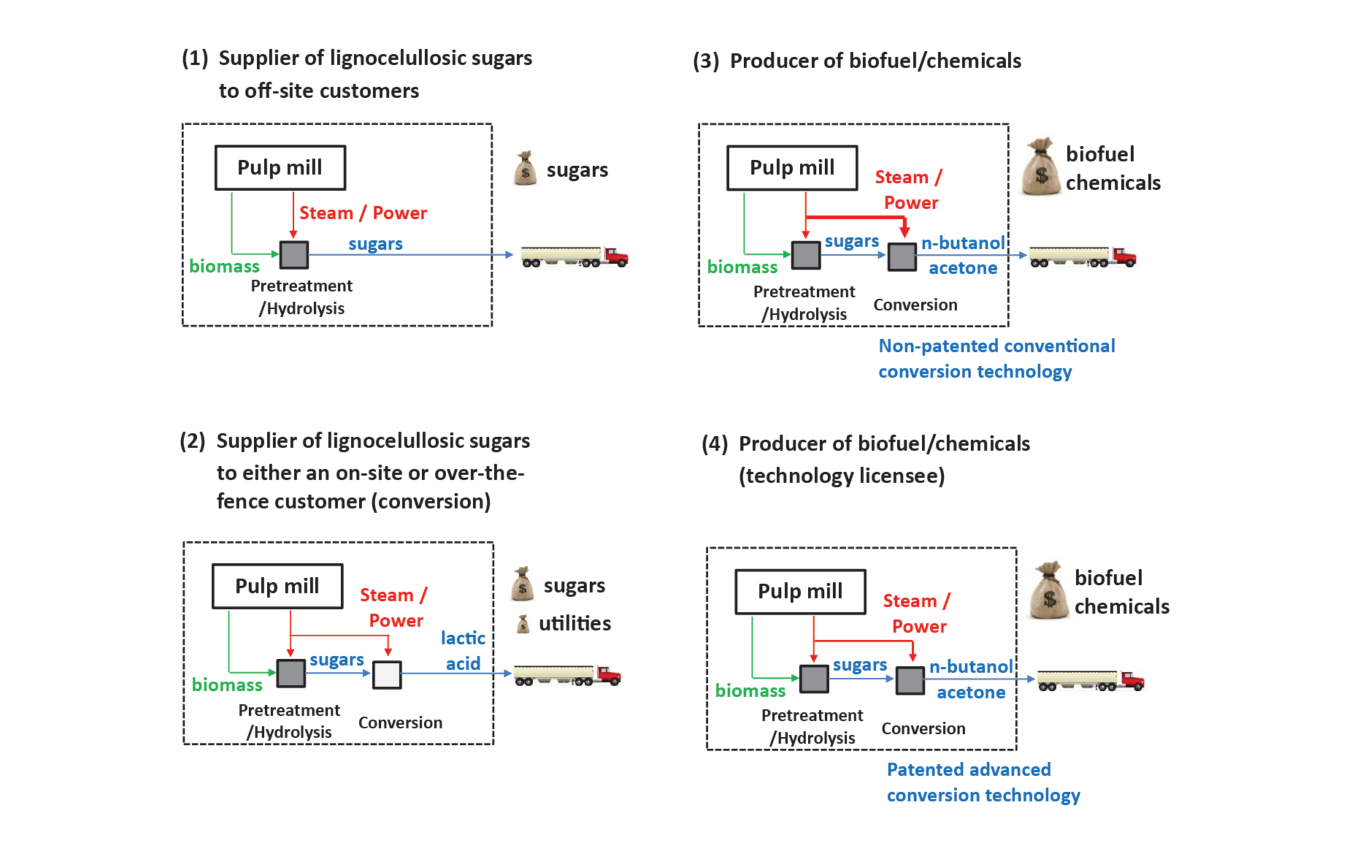

Figure 4. Business models associated with technologies of the sugar platform biorefinery and respective energy demand from host pulp mill. Products derived from lignocellulosic sugars were chosen for illustrative purposes

compromise process flexibility, which is critical for a successful biorefinery implementation in face of market volatilities, and at the same time important to meet market demands (Mansoornejad *et al.*, 2010). Thus, for different biorefinery strategies, it is important to explore the trade-offs between process flexibility and separation process intensification, considering overall energy efficiency, and the effects on costs.

On the business side, and taking as example the sugar platform biorefinery, pulp mills can build different business models and these certainly are linked to different energy demands. In the sugar platform, biomass generally goes through physicochemical and enzymatic treatment in order to break down the lignocellulosic structure and produce monomeric sugars. These are biologically converted into chemicals and fuels in fermentation vessels, followed by product separation and purification. In this value chain, a pulp company may decide to be a producer of lignocellulosic sugars and supply off-site customers, which may convert the sugars into chemicals (e.g., lactic acid) and fuels. In this business model, revenues are generated from the selling of sugars and the new process is supplied with steam and power from the mill (**Figure 4**). In the case of on-site and over-the-fence customers, the mill can also generate additional revenues from the selling of steam and power. On the other hand, in case a pulp mill decides to advance in the value chain investing in an on-site fuels/chemicals plant, the company may decide for non-patented technologies such as off-the-shelf batch fermentors for the production of solvents (n-butanol and acetone) using conventional microbes. Rather, the company may decide to license the use of advanced bioreactors with integrated product recovery and engineered microbes, seeking improved process performance (productivity, yields, and energy efficiency). In summary, whereas the business models and technology options are associated with different economic returns and risks, a critical question to be addressed already in the early stage of design is whether the energy demands of the preferred (or most promising) biorefinery strategies can be met by the energy generation capacity of the host mill. If not, the respective capital expenditure has to be added to the cash flow of the project, usually presented by the technology provider in a first moment, and an "adjusted" IRR should be considered during early stages of decision-making, as corroborated by Cohen *et al.* (2010).

(4) Valorization of by-products and residues: energy vs. new products

Residues and by-products are generated in both forest and industrial operations. In the former, eucalyptus bark deserves special attention not only because of its present use for power generation (only in mills that have log debarking as the first process step at the mill; otherwise, bark is left in the field as a soil amendment agent), but also as a source of sugars to be converted into

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chemicals and fuels. In Brazil, residues production corresponds to approximately 30% of the total eucalyptus forest production, and bark accounts for 10%-12% of the residues, or 3 to 6 million ton a year in total (Bragatto, 2010; Lima *et al.*, 2013). Interestingly, 20% w/w of bark is readily available soluble hexose sugars (glucose, fructose, and sucrose) and can be recovered in a one-step hot water extraction at 80ºC, yielding, for example, approximately 100 liters of ethanol per dry ton of bark (or 26 gallon/dry ton) (Bragatto, 2010). The leftover lignocellulosic matrix of bark can either be treated to produce lignocellulosic sugars, or fed to a power boiler. Even assuming that at least 50% of bark should be left in the field due to agronomic constraints, eucalyptus bark certainly is a promising supplementary source of sugars for a biorefinery.

In industrial operations, the pulp industry already masters the use of black liquor for energy generation purposes. In the (near) future, gasification technologies will give pulp producers the option of conversion of the black liquor stream into synthesis gas and the conversion thereof into chemicals, fuels, and energy. Moreover, the separation of a portion of the lignin from black liquor is already conducted in pioneer commercial scale plants targeting markets beyond cogeneration (for instance, Domtar's Plymouth mill in North Carolina, and Stora Enso's Sunila mill in Finland). Another important source of by-product carbons is the liquid effluents from both kraft process and some biorefineries technologies, specially the sugar platform. The anaerobic digestion of effluents with high organic load generates significant amounts of biogas, which can be burned in cogeneration systems. For example, the anaerobic reactor of the Alberta Pulp mill has been producing approximately 30,000 cubic meters per day of methane for the generation of up to 6 MW of green electricity (REW, 2013). On the other hand, other uses of biogas include its purification into pipeline quality natural gas, or the catalytically conversion of biogas to methanol. A still untapped source of carbon is the CO_2 in the flue gas of existing kraft mills and future biorefinery processes, including biogenic CO_2 such as that produced in fermentation processes. As the process design presented in Kouhia (2013), microalgae-based technologies will certainly play an important role in order to monetize CO_2 at future pulp mills.

The types and possible uses of residues and by-products presented above are not exhaustive and are intended to illustrate the decision-making "energy versus new products" associated with the monetization of side streams. In general, the cogeneration option is the one that presents lower market risk for different reasons, including: (i) pulp companies know how to play in the electricity market; (ii) long-term offtake agreements with government (at state and federal level) mitigate the volatility of prices; and (iii) legislation and government incentives are supporting the growth of cogeneration in the electricity market. Indeed, recurring droughts have been reducing the Brazilian hydropower capacity in face of an increasing demand. Furthermore, along with the reduced technology risk associated with most of the cogeneration projects, power credits can reduce the cash cost of the core business in the short term.

On the other hand, the "new products" option is a new business for the company and, in order to generate significant revenues, should not target low-volume side streams (e.g., pulping screening rejects, and wastewater-treatment residuals) that would also limit the economies of scale of the project. Whereas new products are generally associated with better returns on investment, this option incurs in increased technology and market risk, and usually the effects on the cash cost of the core busines are expetected to take place in the mid term. In this context, kraft lignin is a very promissing candidate for the near future and Stora Enso certainly offers a good example of how to strategically develop a new business with lignin. While they are advancing on the learning curve of the technology (lowering the production cost) and also developing new applications and markets for lignin, both technology and market risks are mitigated by consuming the lignin production internally as a replacement for natural gas in the lime kiln.

Undoubtedly, the decision on how to valorize side streams is site-specific and poses as a multi-variable and multi-dimensional problem, and particularly the case of eucalyptus bark, the decision involves conflicting interests between forest management and industrial operation. In order to facilitate the decision-making (also valid for the other three strategic guidelines), a systematic approach should include: (a) the proposition of technology-product alternatives and assessment of their expected development (technical/market) through the years (similar to a roadmap format), as well as (b) the definition of a set of multi-dimensional screening criteria in order to evaluate the alternatives from a business and environnemental sustainability perspective, such as those presented in Senaei (2014).

CONCLUSIONS

The four strategic guidelines presented in this forward-looking paper provides a high-level discussion on major trade-offs pulp companies are advised to be currently analyzing in order to support informed and systematic decisions about the design of their future mills and possible retrofit of existing ones. The rupture from a design with exclusive focus on market pulp and cogeneration may bring additional value for eucalyptus forests and support sustainable business expansions (in both feedstock and product ends). For that matter, success rate is expected to increase if in the synthesis phase of the design process, priority is given to the definition of candidate product portfolios and implicated business model options. Technological solutions available for a given product portfolio should be assessed according to their risks and potential integration issues with the host pulp mill, especially the availability and demand of energy. In the pathway to biorefinery transformation, until the moment the prospects of the short-fiber pulp market are still attractive, it is very likely that Brazilian pulp companies will give preference to feed the biorefinery with forest and industrial side streams (mainly lignin and forest residues). During this period, the capacity of a company to evolve from the traditional commodity thinking will be a key business success factor. ■

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REFERENCES

1. Batsy, D. R., Solvason, C. C., Sammons, N. E., Chambost, V., Bilhartz, D. L., Eden, M. R., El-Halwagi, M. M., Stuart, P. R. *In Integrated biorefineries: Design, Analysis and Optimization*; Stuart, P. R., El-Halwagi, M. M., eds; CRC Press: New York, 2013; ch 1.

2. Bragatto, J. (2010): *Avaliação do potencial da casca de Eucalyptus spp para a produção de bioetanol*. PhD dissertation. University of São Paulo, Campus Piracicaba.

3. Carrança, T. (2014): *Cogeração avança na indústria em meio à falta de gás e crise hidrológica*. DCI. Available [Online] www.dci.com.br/negocios/cogeracao-avanca-na-industria-em-meio-a-falta-de-gas-e-crise-hidrologica-id416110.html [16September2014].

4. Celulose Online (blog) (2014): *Em seis anos area plantada com eucalipto cresce 475% no MS*. Available [Online] http://celuloseonline.com.br/em-seis-anos-area-plantada-com-eucalipto-cresce-475-no-ms/ [11July2014].

5. Cohen, J., Janssen, M., Chambost, V., Stuart, P. (2010): *Critical analysis of emerging forest biorefinery (FBR) technologies for ethanol production*. Pulp & Paper Canada. May/June 24-30.

6. Dansereau, L. P., El-Halwagi, M., Chambost,V., Stuart, P. (2014): *Methodology for biorefi nery portfolio assessment using supply-chain fundamentals of bioproducts*. Biofuels, Bioproducts and Biorefining. 8 716-727.

7. Davis, R., Tao, L., Tan, E. C. D., Biddy, M. J., Jacobson, J., Cafferty, K., Ross, J., Lukas, J., Knorr, D., Schoen, P. (2013): *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons*. Technical Report, NREL/TP-5100-60223.

8. Dias, M. O. S., Cunha, M. P., Jesus, C. D. F., Rocha, G. J. M., Pradella, J. G. C., Rossell, C. E. V., Maciel Filho, R., Bonomi, A. (2011): *Second generation ethanol in Brazil: can it compete with electricity production?* Bioresourse Technology. 102 8964-8997.

9. Eldridge, R. B., Seibert, A. F., Robinson, S. (2015): *Hybrid separations/distillation technology. Research opportunities for energy and emissions reduction*. Industrial Technologies Program, U.S. Department of Energy.

10. Fibria (2013): *Firmes no Rumo*. Report. Available [Online] www.fibria.com.br/relatorio2013/shared/relatorio-de-2013-firmes-no-rumo-7abr2014.pdf [7April2014].

11. Figueiredo, P. N. (2014): *Beyond technological catch-up: An empirical investigation of further innovative capability accumulation outcomes in latecomer firms with evidence from Brazil*. Journal of Engineering and Technology Management. 31(1) 73-102.

12. Janssen, M., Stuart, P. (2010): *Drivers and barriers for implementation of the biorefinery.* Pulp & Paper Canada. 111(3) 13-17.

13. Kouhia, M. (2013): *Integration of a microalgae-utilizing biorefinery into a pulp and paper mill*", PhD dissertation, Aalto University, Espoo.

14. Kraemer, K., Harwardt, A., Bronneberg, R., Marquardt, W. (2011): *Separation of butanol from acetone–butanol–ethanol fermentation by a hybrid extraction–distillation process*. Computers & Chemical Engineering. 35 949-963.

15. Lima, M. A., Lavorente, G. B., Silva, H. K. P., Bragatto, J., Rezende, C. A., Bernardinelli, O. D., Azevedo, E. R., Gomez, L. D., McQueen-Mason, S. J., Labate, C. A., Polikarpov, I. (2013): *Effects of pretreatment on morphology, chemical composition and enzymatic digestibility of eucalyptus bark: a potentially valuable source of fermentable sugars for biofuel production – part 1*. Biotechnology for Biofuels. 6 75.

16. Mansoornejad, B., Chambost, V., Stuart, P. (2010): *Integrating product portfolio design and supply chain design for the forest biorefinery. Computers & Chemical Engineering*. 34(9) 1497-1506.

17. Mariano, A. P., Harlin, A.; Manninen, J.; Chambost, V.; Stuart, P. (2013): *Techno-economic analysis of process alternatives for the production of ethylene-propylene rubber from forest-based feedstocks*. Tappi Journal. 12 19-32.

18. Mariano, A. P., Maciel Filho, R. (2012): *Improvements in biobutanol fermentation and their impacts on distillation energy consumption and wastewater generation*. BioEnergy Research. 5(2) 504-514.

18. Martin, C. (2013a): *Eficiencia energetica*. O Papel. September 32-38.

19. Martin, C. (2013b): *Industria Ecoeficiente*. O Papel. October 32-40.

20. MCT - Ministry of Science and Technology (Brazil) (2011). Available [Online] http://www.mct.gov.br/index.php/content/view/74694.html [retrieved 21January2015].

21. Mohammadi, S. (2014): *Adapting the experience curve for estimating biorefinery costs*. MSc thesis. École Polytechnique de Montreal, Montreal.

22. REW - Renewable Energy from Waste (2013): *Alberta Pulp Mill to Upgrade Wastewater Treatment System*. Available [Online] http://www.rewmag.com/slave-lake-pulp-adi-systems-install-ad.aspx [2July2013].

23. Risi (2014): *Brazilian Jari expects to produce DP by July; negotiates antidumping duties with China*. April.

24. Rohani, N. M. (2014): *Design methodology for integrated downstream separation systems in an ethanol biorefinery*. MSc thesis. École Polytechnique de Montreal, Montreal.

25. Senaei, S. (2014): *Sustainability assessment of biorefinery strategies under uncertainty and risk using multi-criteria decision-making (MCDM) approach*. PhD dissertation. École Polytechnique de Montreal, Montreal.

26. Svensson, E., Berntsson, T. (2011): *Planning future investments in emerging energy technologies for pulp mills considering different scenarios for their investment cost development*. Energy. 36 6508-6519.

27. Vidal, A. C. F. (2014): *O renascimento de um mercado: o setor de celulose solúvel*. BNDES Setorial. 38 79.