

IDENTIFYING THE CANADIAN FOREST BIOREFINERY

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ABSTRACT

This paper presents an overview of certain emerging biorefinery process options, and highlights the complex and ambiguous decision-making challenges that mills will face who would like to consider implementing the biorefinery. While most biorefinery developments have focused on process technologies, it is critical a) to first define the specific products that the mill should seek to produce considering such factors as market demand, product margins, production flexibility, and the supply chain, and b) to model and examine the process and accounting models for the existing mill in order to ensure that this asset value is maintained. The set of systems analysis techniques and process integration tools for examining these questions are reviewed, and some key issues facing the Canadian industry relative to the biorefinery are presented.

INTRODUCTION

The pulp and paper industry is primarily a commodity industry, and only companies that have established niche markets are enjoying a good financial situation today [1]. With competition from low-cost countries using fast growing raw materials, staying within the commodity sector and remaining profitable has recently been and will continue to be nearly impossible. The last ten years of company mergers and cost-cutting activities may have helped in the industry's survival for the shorter term, but this strategy is not enough to guarantee success over the longer term [2].

In order to be profitable in the North American market, a new business strategy is necessary for the pulp and paper industry. Instead of focusing on being the low cost producer in a commodity sector, companies need to examine the potential for making new products. According to Thorp [1], the biggest challenge for the industry is to change the mentality within its organizations. It is critical that we move away from the commodity business mentality.

The forest biorefinery is an exciting concept for the pulp and paper industry, however in many ways, the industry has been considering its implementation for decades. There have been numerous examples where mills have produced organic chemicals in addition to pulp and paper, e.g. vanillin, bioethanol, etc. The biorefinery builds on the same principles as the petrochemical refinery. In a petrochemical refinery the

raw material is normally crude oil, whereas in the forest biorefinery the raw material is wood/biomass. The raw material stream is fractionated into several product streams. The products can be a final product or a raw material for another process. New technology is being developed that could be integrated into an existing pulp and paper mill, transforming it into a forest biorefinery. There are still significant challenges associated with these new technologies, but several of them look promising. Research is initiating focused on biorefinery technology development in North America and around the world [3, 4].

However these process technology development activities alone do not address most of the significant risks associated with implementing the forest biorefinery.

Biorefinery technology development will typically be implemented in retrofit, and must be accompanied by a careful process systems analysis in order to understand the impact on existing processes, e.g. pulp yield reductions since carbon is used to make alternative products, and the potential for changed black liquor scaling characteristics in evaporators. The objective of this process systems analysis would be to preserve the value of the existing pulp and paper producing asset.

In addition to process technology development, product development will be essential for identifying successful new markets for biorefinery products, and their supply chain management strategies. These are again systems-oriented issues whose evaluation will be critical for the success of the forest biorefinery.

OBJECTIVE

The objective of this paper is to identify critical systems analysis methodologies for evaluating different forest biorefinery options.

In this paper, a number of promising forest biorefinery technologies is surveyed, followed by an overview of process integration tools for systems analysis that should be applied for mitigating the risk associated with implementing the forest biorefinery. The goal of applying these process integration tools is to identify the most promising biorefinery approach on a mill-by-mill basis. Finally, some of the specific challenges and opportunities for the Canadian pulp and paper industry are discussed.

EMERGING BIOREFINERY TECHNOLOGIES

There is a growing number of process alternatives that should be considered for biorefinery implementation in a pulp and paper mill, such as recovering more of the biomass left in the forest, removing lignin from the black liquor in the digester, pyrolysis of bark, etc.. The technologies presented here are not intended to be an exhaustive list of possible, but rather the ones that have gained some notoriety. These are technologies that would be implemented in retrofit to existing mills, and that are closest to commercialization.

At a recent biorefinery workshop called “Capturing Canada’s Natural Advantage” [5], one important consensus reached was that before mills can implement the forest biorefinery, they need to increase its energy efficiency, eliminate fossil fuels from their operations, and maximize carbon availability for the forest biorefinery. Since many of the activities today regarding the forest biorefinery are motivated by the Kyoto Protocol, this is a valid point. Why produce green chemicals from biomass when fossil fuels are still used for the pulp and paper processes within the mill? In the shorter term, mills should and indeed are already focusing on these issues.

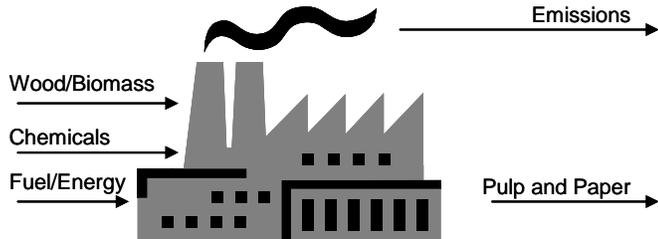


Figure 1. Today's Pulp and Paper Mill

In Figure 1, the basic material streams to and from a pulp and paper mill today are shown. Figure 2 shows the possible material streams for a future biorefinery mill where not only pulp and paper is produced. The product streams in Figure 2 are not all cumulative or necessary.

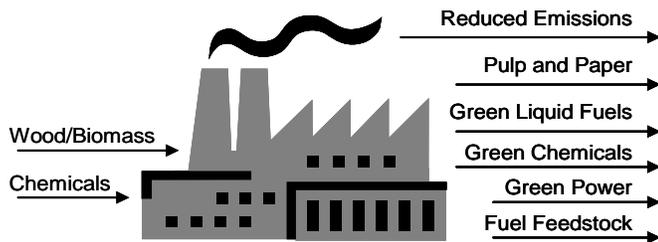


Figure 2. Biorefinery Pulp and Paper Mill

The biorefinery technologies currently under development are typically characterized as biochemical and thermochemical processes. The former based on chemical fractionation and metabolic transformation of the raw material, and the later based on gasification/pyrolysis of carbon-based feeds.

In Table 1 the different technologies discussed in this paper are summarized. The first three technologies are biochemical and the last one is thermochemical.

The choice of biorefinery technology will depend firstly on the choice of appropriate products as they relate to markets and the supply chain. Depending on the choice of technologies implemented, the yield, the impact on the pulp and paper process and the capital cost will vary. Since the processes in a pulp and paper mill are strongly linked, it is difficult to foresee the impact implementing these different technologies might have on the entire mill. Plus, adding two or more technologies to one mill bring process issues that are even complex to anticipate.

Table 1. Forest biorefinery options considered

Technology	Yield	Impact on process	Capital cost
Hemi-cellulose extraction	Low	Low	Medium
Lignin precipitation	Low/High	Low/High	Low/High
Tall oil extraction	Low	Low	Low
Black liquor gasification	High	High	High

As mentioned by Farmer [6], one of the key criteria for forest biorefinery options is that the processes are adaptable. For many of the products that could be produced in a forest biorefinery follows different value cycles. If these products could be changed the most profitable product could be produced at a time where the value of said product is the highest. By developing a concept of adaptable forest biorefinery, the mill would be less economically vulnerable, since the product produced could change over time.

Hemi-cellulose extraction before the digester

This is a process where the wood chips are leached prior to pulping, in order to extract acetic acid and hemi-cellulose. The acetic acid is separated and the hemi-cellulose is fermented to ethanol. Amongst the challenges for this process to reach commercialization are finding techniques to efficiently ferment pentose at the large-scale, which is the main sugar in hemi-cellulose, as well as to raise the concentrations of the dilute products. Removing hemi-cellulose from the chips prior to pulping might also lead to improved throughput/reduced energy consumption in the digester [7].

This process may comprise a promising way to produce ethanol. However, ethanol is a commodity chemical and the quantities produced from a biorefinery mill may not be attractive. Using ethanol to produce added-value green organic products for the regional market may be a more attractive possibility.

Black liquor gasification

Black liquor gasification would replace the Tomlinson recovery boiler for the recovery of spent chemicals and energy. Black liquor gasification has been under development for many years now, and today there is a small number of installations and some additional ones being planned. The two main technologies under development are pressurized and atmospheric gasification, being commercialized by Chemrec AB and ThermoChem Recovery International (TRI) respectively.

The advantages of the pressurized technology are the richer fuel coupled with a smaller unit. The disadvantage is mainly related to materials that can withstand the corrosiveness of the aggressive environment. The atmospheric technology also has materials challenges, and the gas produced has a lower heating

value. The main challenge for the atmospheric technology is a considerable increase of lime kiln load, up to 44% increase [8]

There are mainly two alternative pathways for integrating black liquor gasification: Black Liquor Gasification Combined Cycle (BLGCC) to produce electrical power, and Black Liquor Gasification to produce liquid fuels and other green chemicals. The revenue stream from BLGCC is expected to be lower than if liquid fuels are produced from the syngas. A recent EU study [9] shows that the economics for producing a motor fuel via black liquor gasification is competitive with fossil fuel based gasoline. At the same time, the combined cycle technology is more mature and there is less risk. A selection of possible chemicals that can be produced from the syngas is presented in Figure 3.

A report published in 2003, evaluated the opportunity for black liquor gasification in the US [8]. It showed that for the reference mill chosen an internal rate of return of 20% could be achieved for this type of investment. The two different technologies mentioned here was the focus of said report. It showed that considerable increased production of electricity could be achieved at a mill and allowing for additional gasification of biomass could lead to considerable energy savings and reduction of both pollutants and green house gases.

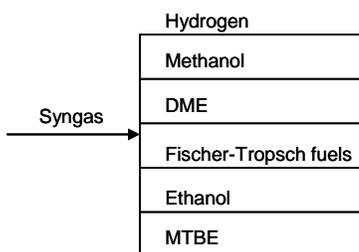


Figure 3. Possible products from syngas [10]

Lignin precipitation

This is an established technology, and has been in use to de-bottleneck recovery boilers for some time. Lignin precipitation can be implemented either at the smaller scale for de-bottlenecking the recovery boiler, or at the larger scale where a significant percentage of the lignin in the black liquor is precipitated. Depending on its size, the yield, impact on process and capital cost can vary as summarized in Table 1.

The precipitation efficiency and yield are critical parameters for the process. If the lignin is to be used as fuel, it is important that it is pure and dry. This is not just for combustion reasons, but also so that it is stable for transportation and storage. Also if the recovery boiler is a bottleneck in a mill, lignin precipitation would relieve the recovery boiler and the pulp output could be increased [11]. A selection of possible products from lignin can be seen in Figure 4.

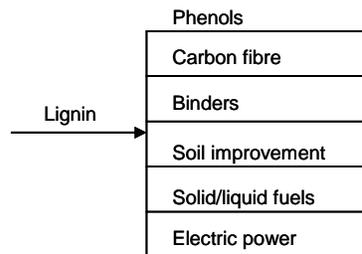


Figure 4. Possible products from lignin [12]

Tall oil extraction

Typically the tall oil produced in a pulp and paper mill is burnt in the recovery boiler. Instead it could be used to produce green fuels, for example bio-diesel. Producing bio-diesel from tall oil via hydrogenation is more economically attractive than producing bio-diesel via esterification [13]. This process could make bio-diesel from tall-oil competitive with traditionally derived diesel.

CANADIAN KRAFT PULP AND PAPER INDUSTRY

The technologies presented above are some of the technologies under development today. The aim is not to give a complete list of the technologies under development for the forest biorefinery, but rather, to show that there is a large number of process opportunities, and combinations of process opportunities. The optimum biorefinery configuration for a given mill depends upon factors such as local market supply chains, price of electricity, availability and need for cheap fuels, cost of transportation, possible energy integration, size of mill, carbon trading, etc. Production flexibility will be a critical factor for the forest biorefinery, and *ad hoc* opportunities to joint venture with other companies. These factors will be different for different mills, and therefore the forest biorefinery that will/can be implemented in this retrofit context will vary from site to site. The selection of “the best” pathway for implementing the forest biorefinery is complex and far from obvious.

There are a little less than fifty kraft pulp mills and more than ten sulfite pulp mills in Canada (Figure 5).

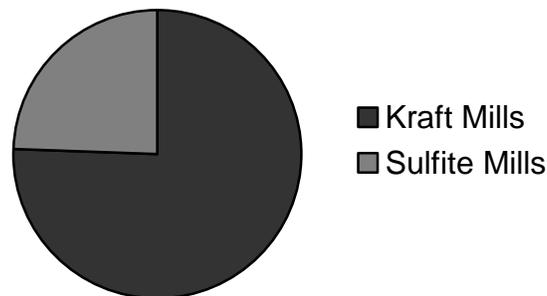


Figure 5. Kraft and sulfite mills in Canada

About half of the kraft pulp mills are non-integrated and produce market pulp, while the remaining are integrated pulp and paper mills producing mostly paper but typically also some market kraft pulp. The biorefinery opportunities

associated with integrated or non-integrated mills are significantly different. For example there is a larger steam demand associated with an integrated mill compared to a non-integrated mill, and the margins and supply chains for market pulp are different to that of specific paper grades.

The mills range in sizes between 250 and 2000 tons of kraft pulp produced per day. The majority of the kraft pulp and/or paper mills in Canada produce a little less than 1000 tons of kraft pulp per day, and approximately 20% produces less than 700 tons of kraft pulp per day. For a larger mill there might be a bigger opportunity to produce ethanol from hemi-cellulose compared to a smaller mill, for example, since the process yield is fairly low and commodity chemicals need higher production levels. As another example, lignin precipitation might be suitable for both small and large mills.

The mills are spread across Canada, with a concentration in BC and eastern Canada. With a few exceptions, the mills are located in rural areas, often being the main employer in the area. For mills located in rural areas, the transportation cost might be a crucial factor for making the forest biorefinery processes profitable. On the other hand, there may be an availability of agricultural wastes which could be considered as feedstock for biorefinery options. If transportation costs are important, producing green energy might be an attractive solution.

There are pulp and paper mills in Canada that were built early 1900 that are still in operation today. About a quarter of the kraft mills were built in the 1960's, whereas only four mills have been built in the last 25 years [14]. Due to this the many Canadian mills are old and a large part of the equipment has survived long past their lifetime. Since some of the equipment needs to be replaced, this actually represents an increased opportunity to install forest biorefinery processes in conjunction with replacement or as the replacement equipment.

There are many opportunities and alternatives for transforming pulp and paper mills into forest biorefinery mills. There are however many different alternative processes to choose from, which will be more or less suitable dependent on the current mill configuration, age, size and location. Indeed, selecting the wrong biorefinery configuration will undoubtedly lead to financial disaster. A systematic methodology is needed to examine the biorefinery options available, based on the specific and detailed process configuration in place and the opportunities for selling products at reasonable margins.

PROCESS INTEGRATION

Process Integration as the International Energy Agency (IEA) defines it is "the common term used for the application of methodologies developed for system-oriented and integrated approaches to industrial process plant design for both new and retrofit applications. Process Integration refers to Optimal Design; examples of aspects are: capital investment, energy efficiency, emissions, operability, flexibility, controllability, safety and yields. Process Integration also refers to some aspects of operation and maintenance".

In the development of the forest biorefinery, most efforts to date have been directed to the development of process technologies. Little attention has been given to the integration aspects of biorefinery technologies. In order to find economically viable solutions, the integration aspects are at least as important as the technical ones. As mentioned by Larson et al. [ref Larson] a mill could become an independent power producer if more biomass could be brought to the mill and gasified. This can only be identified if evaluating the new technology not only on a mill scale but also regional and national scale.

As with the different forest biorefinery options presented in this paper the different process integration tools that could be used when evaluating the forest biorefinery are not exclusive to the ones presented here. Also, using an approach like the one presented here requires a multi-disciplinary team. Expertise in different areas is crucial to the successful application of the combination of tools suggested here.

Overview of process integration tools

In the context of the biorefinery, process integration tools can be used to systematically evaluate new processes. The new biorefinery processes can be evaluated not only from a technical perspective, but also all the above mentioned aspects including detailed economics, the supply chain, and life cycle assessment. Some of the process integration tools that could be used to evaluate the forest biorefinery are summarized in Table 2.

Data reconciliation

Data reconciliation refers to the treatment of process signals to remove noise, detect steady state, and eliminate gross error. At a higher level, it refers to the reconciliation of process and accounting data. All of the process integration tools depend upon reliable data as their input. Typically, process and accounting data have not been reconciled, and contain gross error and noise. If using non-reconciled data as a basis for further analysis, the result will not be close to optimum. Data reconciliation is thus a crucial technique for all the other process integration tools.

Process Simulation

Process simulation is one of the basic tools necessary to apply other process integration methodologies and tools. With a process simulation, one can evaluate the impact changing a part of the process can have on the remaining process. Importantly as new biorefinery processes are explored, estimates can be made for important criteria such as yield changes, and the fate of non-process elements (NPE's). Certain other important process integration tools can be used in conjunction with process simulation, such as multivariate analysis for empirically describing important process phenomena when first-principle models are inadequate.

While steady state process simulation is adequate for many design decision-making activities, dynamic process simulation and controllability analysis are critical for understanding and optimizing process dynamics and process control issues.

Table 2. Overview of Process Integration Tools for System Analysis

Process Integration Tool	Input	Output
Data processing and reconciliation	Measured/estimated data from process and accounting data management systems	Validated process and economic data for other decision-making methods
Process Simulation	Measured/estimated/reconciled process data, process understanding and knowledge	Validated simulation model, suitable for estimating process impacts from biorefinery implementation
Energy benchmarking and analysis including thermal pinch analysis	Reconciled process and energy data, and data from validated process simulation	Optimum energy design of mill to maximize carbon availability for the biorefinery
Mill-wide process optimization	Reconciled process data, and data from validated process simulation	Best overall operation of mill to optimize specified objective function
Life Cycle Assessment (LCA)	Reconciled process data, data from validated simulation model, and various LCA databases	Environmental impact assessment for the biorefinery product chains
Supply Chain Management (SCM)	Reconciled process and accounting data, data from validated simulation model, and product logistics data	Optimal product production and management for the product chain
Multi-Criteria Decision-Making (MCDM)	Design, environmental and economic data	Optimal selection of forest biorefinery option for mill

Energy Analysis

The most common tool for mill-wide energy analysis and design is thermal pinch analysis. By applying this tool, the optimal energy integrated process configuration can be identified. Using more advanced thermal pinch analysis techniques, other design objectives can be addressed such as simultaneous water use reduction analysis, and the ease/cost of changing the process.

Since much of the development of the forest biorefinery is to a large extent motivated by finding a replacement for fossil based products, energy integration is important. A thermal pinch analysis approach is important in order to not sub-optimize the processes.

Optimization

Two different applications of optimization have been identified in this context. The first one is plant-wide process optimization. By applying plant-wide optimization techniques, the optimal operation of the designed process chosen can be identified. The success of the optimization process depends primarily on the correct and complete formulation of the problem and the input parameters. Mill-wide optimization for production decision-making and energy decision-making is becoming increasingly applied.

Secondly, optimization can also be used to optimize all the different criteria in order to choose the optimal configuration for the biorefinery. Once the results from the different tools have been obtained, the different process options can be optimized. This optimization can have different objectives. It can be focused on minimizing costs, environmental impact, energy consumption, or it can be multi-objective.

Life Cycle Assessment

Life Cycle Assessment (LCA) is a product analysis technique that can be applied to different process alternatives in order to estimate the relative potential environmental impact the different alternative might have on the environment compared to a base case. LCA translates mass and energy quantities into local, regional and global environmental impact categories, so that a quantitative but broad perspective and analysis can be obtained.

When changing from fossil-fuel based products to bio-based products, environmental implications are important. Not only the local emissions to the particular mill receiving environment, but also the emissions associated with the entire product chain over the life cycle of the product.

Supply Chain Management

Supply chain modeling and management considers at the entire supply chain of a product to optimize the flow of information and materials between internal and external suppliers, production, distributors and customers in order to increase a company's efficiency and reduce costs. This can be critical and unknown when a pulp and paper mill starts to produce new products by implementing the biorefinery.

A number of forest biorefinery processes could lead to small quantities of a range of products. With these small quantities, the supply chain might be more critical than the actual investment and operating costs for the process modification. For a specialty product, this might be less critical however most of the suggested processes close to commercialization produce bulk chemicals.

Using supply chain modeling and management techniques, the new product mix from a biorefinery can be evaluated before implementation. This is important in order to move from the research-driven process technology development to product design and engineering. Once the products that are profitable at a mill have been identified, the process needs to be designed and integrated to fit this objective.

Multi-Criteria Decision-Making

This tool that can help in the decision making process. Since making a decision often involves uncertainty, multi-criteria decision-making techniques have been developed in order to reduce and/or organize the uncertainty. In this context it can be used to weigh different alternatives in order to make an optimal decision.

Combination of process integration tools

Different products can be profitable for different mills, depending on the parameters that define the mill and the markets available to the mill. It is important to identify possible successful forest biorefinery concepts which are under development today and under which criteria they will be successful. These criteria will not only be technical and economical, but also policy will play an important role. Specifically the policies that will roll-out from Canada's commitment to the Kyoto Protocol and the associated capital investment will undoubtedly be critical to enhance investment in new forest biorefinery concepts.

A mill can start by developing process and cost accounting models using reconciled data. Once the models are validated, process integration tools can be applied and opportunities can be identified. A proposed methodology for the evaluation of different forest biorefinery options is proposed in Figure 6.

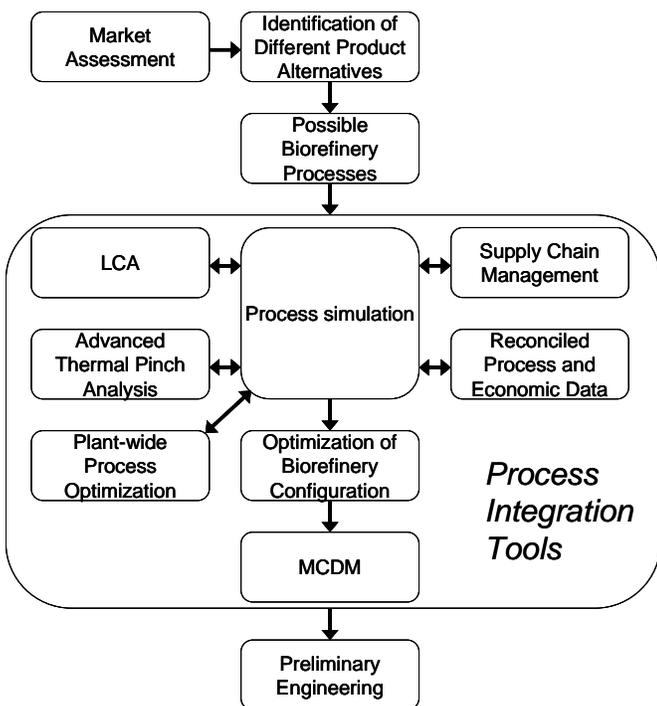


Figure 6. Proposed methodology

Once a product has been identified as having a potential to meet all the criteria discussed, the process design phase starts. This is where the actual technology is evaluated. The process needs to be designed so that its impact on the existing process can be minimized. For example, how does extracting hemicellulose before the digester affect the control of the digester?

Or, how can the process be designed so the operability of the evaporation plant is not jeopardized?

In order for the forest biorefinery to be successful, it needs to be economically attractive. Today the tools exist to evaluate these new processes before implementation. We must not focus only on solving the technical aspect of the new processes but rather use our tools and evaluate what products that can become profitable for a specific mill.

THE CANADIAN FOREST BIOREFINERY CONTEXT

The Canadian pulp and paper industry plays a vital role in Canada's economy, and supports many small rural towns across the country. Our mills are aging. Compared to recently-built mills, older mills have the opportunity to justify implementing new processes. Newer mills have invested in equipment that has up to a 40 year lifetime, whereas much of the Canadian industry infrastructure is at the end of its lifetime.

The pulp and paper industry in Canada has some key competitive advantages for the biorefinery including a well trained workforce, strong community support, and while access to fibre is limited, at the same time Canada has an abundance of wood fibre. Canada's energy supply is diverse and stable, and the Canadian government seeks to optimize this national strength. Certainly Canada has other issues that it must address such as low productivity, and a tax structure that does not encourage investment in the pulp and paper sector.

Some other key issues that would undoubtedly need to be considered in the Canadian context include the following:

- Depending on where a mill is situated it can be more or less profitable to produce and sell electricity to the grid.
- Mills are often in rural areas with access to farm crops and wastes, where a combined forest and agricultural biorefinery might be an opportunity.
- It will be important for the successful implementation of the biorefinery to identify strategic collaborators that are expert in specific technologies and markets. For example, collaborating with an energy company if venturing into gasification and combined cycle power production, or partnering with ethanol producers that are already producing ethanol from agricultural waste.
- By creating small consortia the mill may acquire access to existing supply chains that might not have been available to the mill prior.

CONCLUSIONS

Identifying possible products that can be economically produced by a pulp and paper mill is the key to the successful implementation of the forest biorefinery in Canada. Process integration tools can be used to identify these products. Once the products have been identified, a successful implementation

roadmap can be developed. The successful implementation of the forest biorefinery will likely be mill specific, and will in many cases require strategic collaborations with experts in the given technology or market.

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