The Forest Biorefinery and its Implementation in the Pulp & Paper Industry

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Abstract

Incorporating a biorefinery unit to an operating Kraft pulping has significant technological, economic and social advantages to process forest biomass over the construction of a grassroots biorefinery. Also, the conversion of a Kraft mill from 100% pulp making to 100% biorefinery can be done in a stepwise fashion and it gives the company the opportunity to master the new technologies, evaluate options and develop an appropriate business plan. In all cases however, the road to conversion presents serious challenges. As components of the wood such as lignin or hemicelluloses are withdrawn from the Kraft pulp line, the heat production capacity from the recovery boiler where they are currently burnt in diminished. At the same time the operation of the added biorefinery unit increases the steam demand. In order to avoid fossil fuel dependency, the total site must be highly integrated and optimized. The application of a new comprehensive and innovative energy analysis methodology to actual case studies has shown that the green, low GHG emissions biorefinery is feasible. The economics can be attractive for a site combining specialty wood pulp and bio-product, biomass gasification, power cogenerations and heat upgrading by optimally positioned and designed absorption heat cycles. The methodology has been applied to the extraction of lignin and hemicelluloses, both technologies being coupled with gasification of wood residue.

Keywords

Forest biorefinery, integrated biorefinery, green biorefinery, renewable energy, progressive implementation of biorefinery, energy efficiency, bioproducts, sustainable development, pulp and paper industry

Introduction

Biorefining has been defined by the International Energy Agency (Biorefinery, task 42) as the sustainable processing of biomass into a spectrum of marketable products and energy [1]. The potential of implementing any biorefinery should be assessed in the context of available feedstock, applicable technological processes and market demand. Amongst all different sources of renewable carbon-based raw materials, lignocellulosic crops or residues of forestry sector are the most appropriate feedstocks for biorefineries specially when integrated into a pulp and paper mill. The biorefinery does not compete with agricultural crops for fertile land and relies on larger biomass yields [2]. Lignocellulosic biomass has three major components: cellulose, hemicellulose and lignin. Cellulose is a complex carbohydrate, $(C_6H_{10}O_5)_n$, that is composed of glucose units and forms the main constituent of the cell wall of vascular plants. It is the major component of many manufactured products such as paper, paperboard, packaging and building materials, and of textiles made from cotton, linen, and other plant fibers. It is more difficult to hydrolyze cellulose into glucose monomers than starch. Hemicellulose $(C_5H_8O_5)_n$

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has a random, amorphous structure with little strength to hydrolysis or heat and contains a mix of C6 and C5 sugars which can be fermented into ethanol. Lignin $(C_9H_{10}O_2(OCH_3)_n$, a phenolic polymer, is a complex chemical compound; it is an integral part of the secondary cell walls of plants which can be chemically extracted from residual pulping liquors by acid precipitation. Wood also contains a large number of other organic components in small quantities that can be transformed into high value special products (pharmaceutical or food additives). Typical compositions of wood biomass are given in Table 1.

Table 1: Typical components of wood (%) [3]

Component	Softwood	Hardwood
Cellulose	40-50	40-50
Hemicelluloses	15-20	20-35
Lignin	23-33	16-25
Other organics	1-5	1-2
Inorganics (ash)	0.2-0.5	0.2-0.5

Forest biorefineries have received much attention from the pulp and paper sector in industrially mature countries primarily in North America and Western Europe as a way to diversify its product mix and generate new revenues. The industry has been in a precarious economic situation for some time because large and modern producing facilities established in countries with abundant fast growing resources in the southern hemisphere, and low manufacturing costs have created a competitive environment. This has driven traditional manufacturing countries like Canada to take a fresh look at their renewable resources and seek alternatives to convert into sustained and profitable businesses [4].

The Integrated forest biorefinery (IFBR) consist of implementing biorefining units into existing pulp and paper mills. Maintaining the production of paper or pulp type product may be a necessity when the bioproduct is a low price commodity such as biofuel [5], when the bioproduct is a high value specialty product, couple conversion to biorefinery may be more advantageous. The integration approach provides opportunities for diversifying the industry product mix and penetrating new profitable markets which can generate substantial revenues and profits. This concept has considerable economic advantages over autonomous grassroot biorefineries due to the availability of installed infrastructures, supplier and services network, direct access to feed stocks, and skilled labor force. This possibility is particularly attractive when the forest industry goes through a period of continuing economic uncertainty as is presently the case and closures of inefficient mills have devastating social and economic consequences on small towns whose economy is dependent on this industry.

In this paper the concept of sustainable green integrated biorefinery in Kraft mills in combination with poly-generation and refocusing the product line on high value added products is presented. The advantages and challenges of such integration are discussed. A brief survey of major biorefinery technologies and product options such as ethanol, furfural, lignin, heat and power pathways is presented. A strategy for progressive implementation coupled with intensive process integration and energy optimization is also presented.

Green integrated biorefinery opportunities for Kraft process

The Kraft pulping process entails treatment of wood chips with a mixture of sodium hydroxide and sodium sulfide (the white liquor), to convert wood into marketable pulp, steam and power [6]. A simplified schematic of the Kraft process is shown in Figure 1. Wood chips are cooked in a digester where lignin and hemicelluloses are degraded into fragments and dissolve in the strongly basic delignification liquor. The discharge from the delignification stage essentially consists of cellulose fibers in suspension in residual digestion liquor. The fibers are cleaned and separated from liquor in series of vacuum drum washers and bleached to remove the residual trace of lignin and other impurities. The bleached pulp is dried with steam and hot air in dryers to a water content of 10%. To recover the active cooking agents, the residual black liquor is concentrated in evaporators and burned in a recovery boiler to generate process steam and yield an inorganic smelt. The smelt is dissolved, recaustified by live lime produced on site and returned to the digester as white liquor.

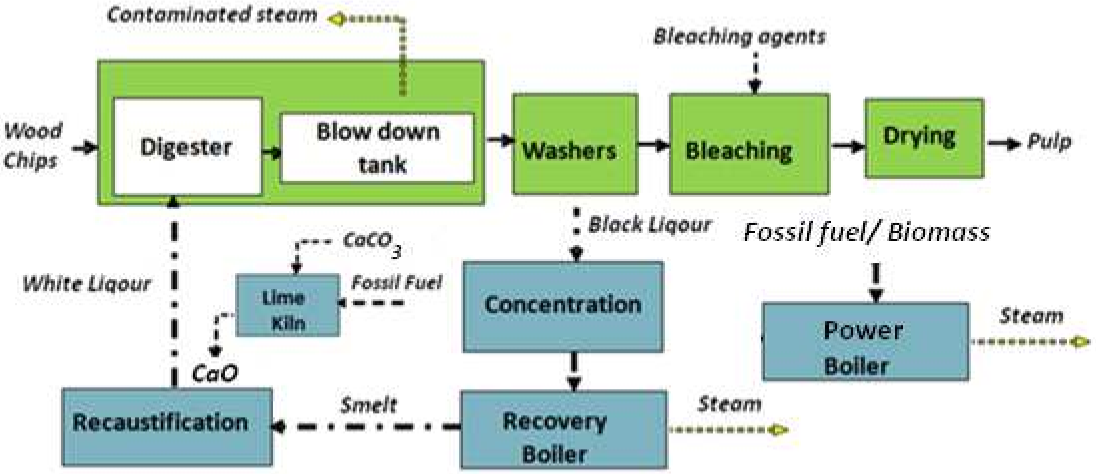

Figure 1: simplified schematic of the Kraft process

In the Kraft pulping process only 42% of woody biomass is converted to pulp and the rest (lignin and hemicelluloses) is combusted to produce energy for the process. This portion can be better utilized to increase the revenue margin of the mills, it can be converted into higher marketable products such as biofuels, syntethic gas, chemicals, heat and power through various technological paths. This possibility along with the vicinity to numerous sources of biomass and accessible existing infrastructure make Kraft mills excellent candidates as biorefinery receptors. The potential biorefinery options that have been identified for integration into Kraft process are [7]:

- Hemicellulose extraction from wood chips prior to pulping and its conversion into ethanol, furfural, polymers, and chemicals
- Precipitating lignin from the black liquor in order to transform it into valuable chemicals such as carbon fibres, phenol, road additives, and surface active dispersants or even carbon fiber
- Gasifying wood residues to produce synthetic gas as a source of heat, power, fuels or chemicals.

The technological paths for desired and selective material transformation can be thermochemical, biochemical, or chemical. In a forest-based biorefinery all different technological process paths are applied. The hydrolysis of hemicelluloses and acid precipitation of lignin fall in chemical process pathway. Fermenting sugar constituents of hemicelluloses to produce ethanol requires biochemical process at close to ambient temperature. On the other hand gasifiying biomass is a thermochemical means to produce synthetic gas, an intermediate platform for Fischer-Tropsch fuels, chemicals, heat and power.

Energy and material integration is an issue of the outmost importance, because of increase energy and water consumption and effluent production of the integrated site. The energy efficiency of the complete site should be improved by applying advanced process integration and energy optimization techniques to respond to the increase in energy and water demand and the reduction in steam production capacity due to the reduction in calorific values of black liquor. Meanwhile the integration should be performed in a manner that minimizes the environmental impact by reducing green house gases (GHG) emission of the total integrated site, to achieve sustainable development.

It is now admitted by scientific community that the concentration of CO_2 in the atmosphere will continue to rise as more countries achieve high standard of industrialisation. It is currently 390 ppm [8]. An equilibrium level of 550 ppm is considered as an achievable and acceptable target provided concerted worldwide efforts are devoted to the following strategies [9]:

- Rational use of energy (doing more with less)
- Development of alternate renewable energy sources (including biomass)
- Creation of carbon sinks (preferably on site)

Therefore the Green Integrated Forest Biorefinery (GIFBR) is a critical technical concept of sustainability. It is defined as a site with:

- Intensive advanced process integration from the stand point of thermal energy (steam & water)
- Renewable, forest-based, main feed stock & fuel
- Minimal intake of fresh water & minimum liquid effluent
- Consumption of zero fossil fuel
- Reduced CO_2 emission and on site capture of CO_2 whenever feasible

Figure 2 shows the integrated green biorefinery into a Kraft mill receptor. Bioproducts of biorefinery can be ethanol, furfural or lignin whereas extra energy demand and fuel for lime kiln can be provided by biomass gasification. The produced syngas can be utilized in combined heat and power cycle to generate green power and satisfy the steam demand of the mill. Simultaneously it can fire lime kiln to eliminate the fossil fuel consumption and reduce CO_2 emission.

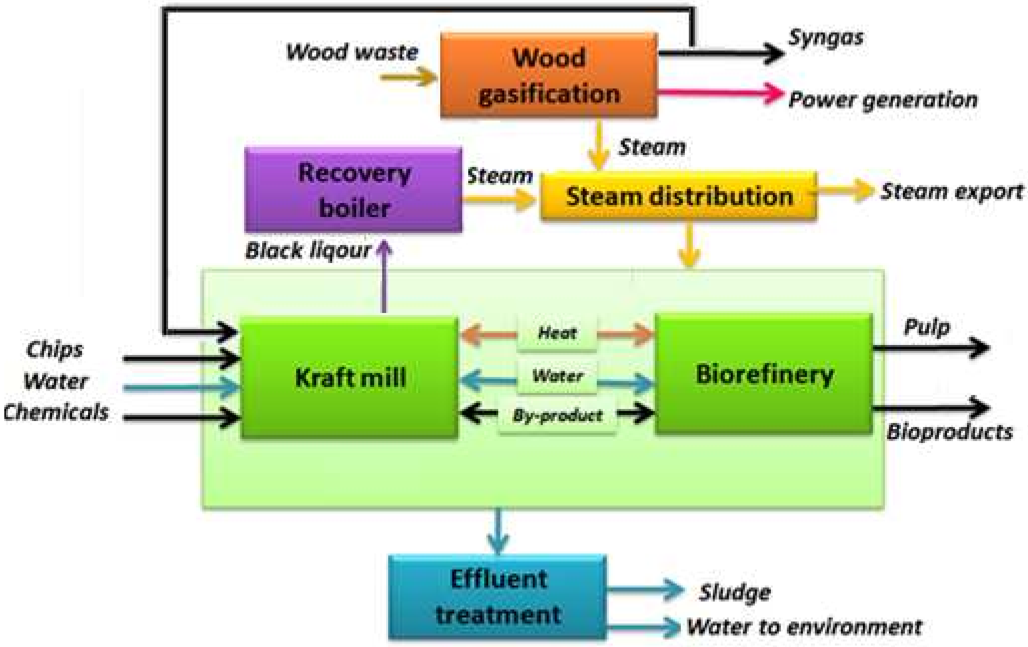

Figure 2: Green integrated forest biorefinery (GIFBR)

GIFBR advanced process integration and energy optimization

Integrating biorefinery units in to Kraft process place additional demand for utility systems, electricity and waste water treatment. Thus the challenge is to revamp the mill in such a way as to satisfy the energy and water demand of GIFBR without creating a dependency on fossil fuels. Evidently further biomass can be burnt to produce the extra energy demand of GIFBR, but gasification is a better alternative for conversion of biomass into energy due of higher heat value of its product. However the ultimate practical solution is to identify energy implications of biorefining units, take advantage of interactions within the GIFBR, and increase the overall energy efficiency of the overall site [10]. The GIFBR must be at the forefront of energy efficiency through applying advanced process integration. To achieve maximum energy efficiency the following procedure has been developed:

- Equipment performance analysis (design improvement, debottlenecking)
- System performance analysis (comparison, targeting)
- System interaction analysis

The first step is to define and characterize the base case process by means of validated process simulation model. The validated simulation supplies data for energy and water studies. Utility and effluent system should be analyzed to provide detail information on production, distribution, utilization and post-utilization treatment of steam and water [11]. Analysis of equipment and system performance and benchmarking their key performance indicators (KPIs) is the next step. System interaction analysis is the core element of the methodology that leads to energy saving projects and potential of poly-generation opportunities. Figure 3 shows the stepwise intensive energy optimization from base case definition to implementing strategy and post-benchmarking, which has been developed and put in practice in actual case study [12].

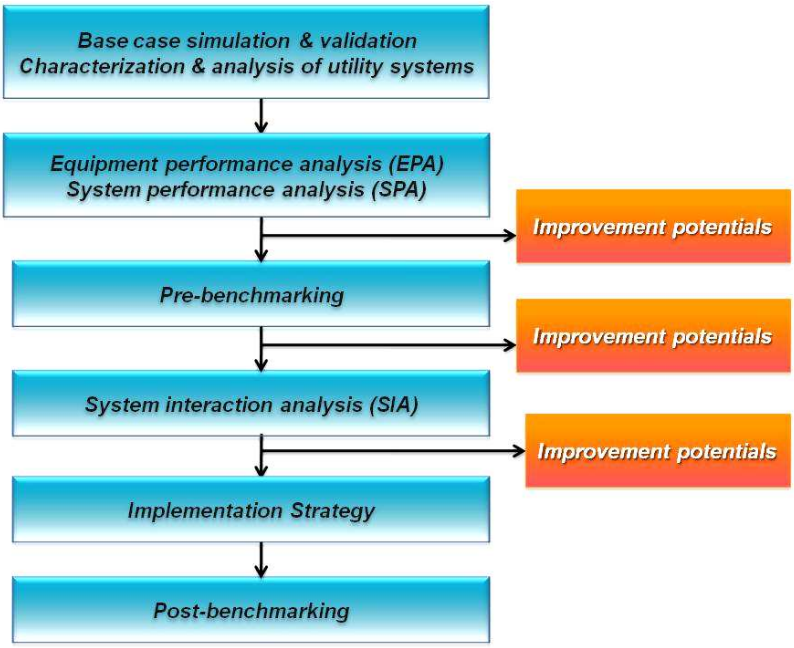

Figure 3: Stepwise intensive energy optimization approach

Equipment performance analysis (EPA)

Process integration techniques are commonly applied with the assumption that all equipments and sub-systems are working efficiently which is not always the case in an existing mill. Therefore identifying and benchmarking by means of KPIs of individual equipments from the stand point of water and energy consumption is an important first step. This leads to design improvements and debottlenecking of the process with energy savings in the range of 5-15% [13] and payback period of few weeks to several years (for projected equipment replacement) [14].

System performance analysis (SPA)

To evaluate the energy efficiency, the global KPIs of the process should be identified and calculated before developing energy enhancement measures. KPIs are benchmarked by comparison to average and best current practice of the industry to assess inefficiencies [15]. The level of process constraints depends on the goals and policies of the biorefinery receptor mill and should be taken into account to decide on the extent of energy saving potentials and investment costs. The next step is targeting based on process constraint analysis in order to determine the minimum energy and water requirements and utility levels. There are several techniques and tools to analyse non isothermal mixing points, water tank types, and energy and water-based systems to assist targeting [16].

System interaction analysis (SIA)

The energy efficiency of the Kraft process is strongly related to the proper management of water and steam which must take into account their strong interactions. Moreover several techniques should be applied to improve the energy performance of a process such as internal heat recovery, water reutilization, condensates return, energy upgrading and conversion. They are applied to specific energy systems on the utility or process side. Since those systems are interconnected, their synergetic or counter action effects should be considered [17] (figure 4). The comprehensive performing of iterative SIA maximizes the potential steam and water savings, and increase the potential of implementation of absorption heat pumps and co-, tri-generation within the mill. It is reported by Marinova et.al that implementation of a tri-generation unit consisting of a back pressure steam turbine and absorption heat pump could reduce the cooling demand of the process by 17% and increase the steam production by 30% while 2.2 MW of electrical power is produced [18].

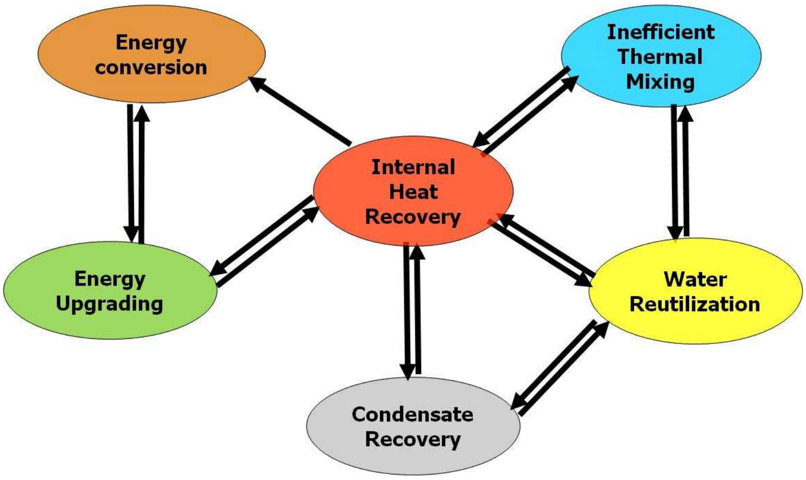

Figure 4: System interaction analysis

Kraft-based biorefinery unit integration

Hemicelluloses extraction

The recovery of hemicelluloses from wood chips is a specially interesting case of pretreatment processes for biological conversion to ethanol or other products [19]. Efficient and cost-effective hydrolysis of the carbohydrates into monosaccharides is a challenge [20]. Another technical challenge is the selective removal of hemicelluloses from wood chips without degrading the cellulose component of the papermaking fiber. Amongst proposed pretreatment methods, Mao and et.al have reported “near-neutral” extraction of hemicelluloses integrated in an existing hardwood Kraft mill [21]. Subsequent extraction of hemicelluloses will reduce the calorific value of black liquor and steam production capacity. Ethanol and furfural are two potential products of IFBR and their production paths are shown in figure 5. Hardwoods are rich in five-carbon sugars while softwoods contain mostly six-carbon sugars. Therefore it is more economical to produce ethanol from soft wood and furfural from hard wood feedstock.

The potential world market for ethanol is 65 billion L/a at the price range of 0.7-0.9 $/L. It is mostly used as biofuel with high processing and capital cost due to more complex process. On the contrary furfural has smaller global market of 250 000 t/a, but high market price of 1000 $/t. It is used mostly as extractive solvent, adhesive, bleaching agents and other aromatic derivatives. The integration of biorefinery units into the Kraft process and the concept of biorefinery cluster can contribute to reduce operating and investment costs.

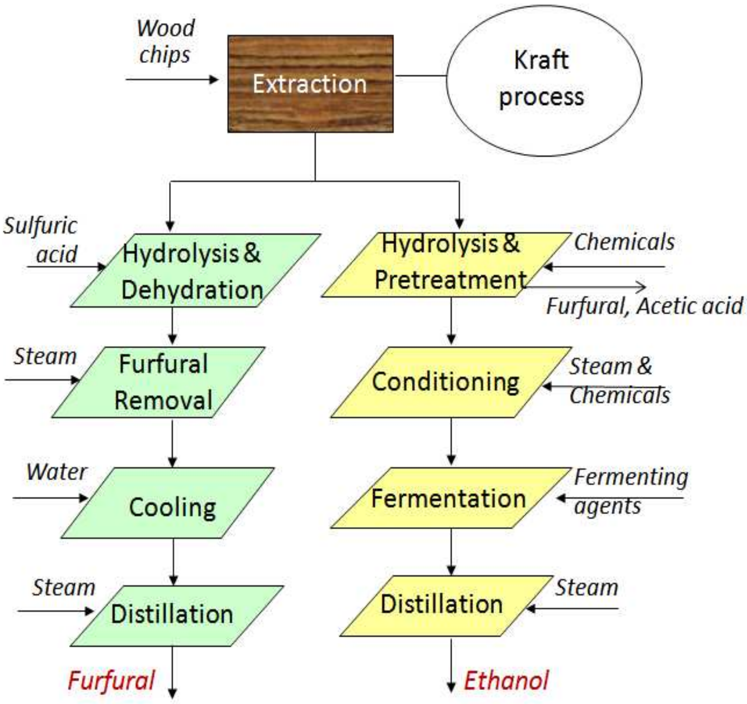

Figure 5: Ethanol and furfural production pathways

The incorporation of the hemicellulose extraction stage prior to Kraft pulping and its subsequent conversion will affect the energy balance of the mill. As the result the calorific value of black liquor and consequently steam production capacity reduces. Simultaneously additional steam is required for the extraction and conversion steps. Marinova et. al showed that for an existing Kraft mill implementing this process increases 15.5% of the base case steam demand. But by implementing the energy efficiency measures for the mill, the anticipated steam production capacity satisfies the energy demand of total integrated site [7].

Lignin extraction

The extraction of lignin from black liquor is possible through acid precipitation, electrolysis and ultrafiltration. Acid precipitation is the most developed and cost-effective method when implemented on a large scale [22]. Lignin extraction from black liquor reduces the load on the recovery boiler which is the bottleneck for mill expansion and increase profit margin by generating value-added products such as energy, carbon fibres, phenol, road additives, surface active and dispersants in secondary processes. At equal extraction rate, the impact of lignin extraction will be significantly larger than in the hemicelluloses case because it has close to double specific heat content. The lignin extraction pathway is presented in figure 6. The acidification agent for the process is CO_2 to lower the pH for lignin precipitation. After filtering, the lignin cake is washed in acidic condition (sulphuric acid) and wash filtrates are returned to evaporation section of Kraft process [23]. Integration of lignin extraction units into Kraft process increases the opportunity of energy, water and chemicals savings. Recovering CO_2 from the stack gases of mill boilers or lime kiln is a potential source of chemicals for biorefinery and creates CO_2 sinks which results in GHG emission reduction. Sulphuric acid for washing might also be available from ClO_2 making plant of the Kraft process. It is reported by

Perin-Levasseur et. al that integrating lignin extraction biorefibery into a Kraft mill with 10% increase in pulp production results in 20% increase for steam demand of the integrated site and can increase up to 23% for the highest lignin production rate [24]. It is anticipated that implementing the energy efficiency measures for integrated site can satisfies projected energy and water demand.

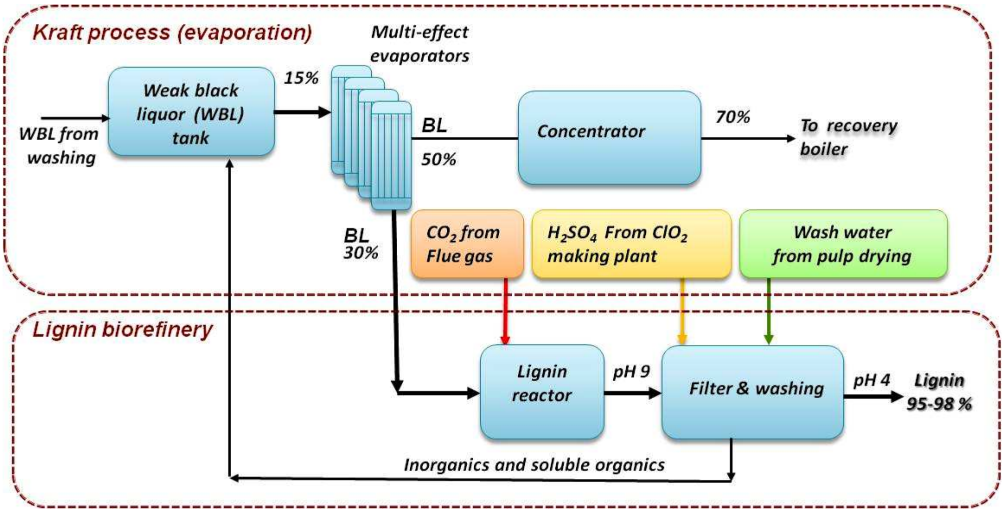

Figure 6: Lignin extraction pathway from Kraft black liquor

Biomass gasification

The Kraft process consumes large quantities of energy generated from several types of fuels (black liquor, biomass or fossil). Expensive fossil fuels are consumed in lime kiln and power boilers to satisfy the energy demand of the process with contribution to CO_2 emissions to the higher atmosphere. Biomass, which is generally combusted for steam production, can be used more economically in poly-generation pathways to generate high value products, heat and power. Furthermore energy saving projects targeting only biomass reduction are not efficiently attractive unless it is combined with poly-generation [10]. Gasification, instead of complete combustion, converts biomass into a combustible gas mixture of carbon monoxide, hydrogen and methane with high heating value. The produced syngas can be used in cogeneration to produce steam and power or it can undergo secondary processing to produce methanol, alcohols or Fischer-Tropsch liquids (figure 7).

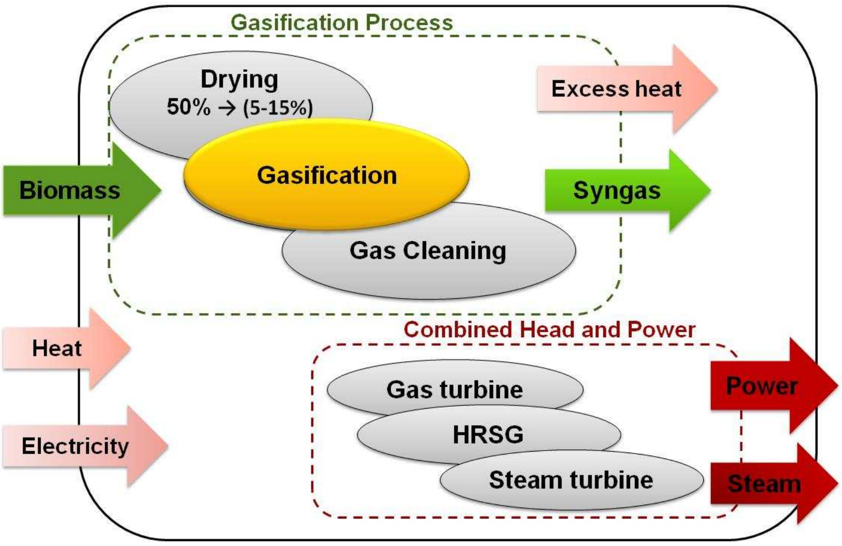

Figure 7: Integrated biomass gasification combined heat and power cycle

Implementing biomass gasification into the integrated biorefinery site can replace the fossil fuel boilers to satisfy the energy and power demand of the integrated site and replace lime kiln fossil fuel to reduce GHG emissions to realize GIFBR. Moshkelani et. al have reported that integration of biomass gasification units into an existing Kraft mill is promising as long as the mill is optimized. The steam and power demand of the optimized Kraft process are produced in cogeneration cycle despite shutting down the bark boiler. Meanwhile lime kiln is fired with syngas which results in GHG emission reduction [25].

Strategy for implementation of GIFBR

Forestry sectors in industrially mature countries must revitalize their traditional business models to develop new sources of revenues in order to regain profitability and remain competitive in global market. Any remedy and recommendations should strongly inspire the sustainable renewal strategy for a prosperous future for of the pulp and paper industry. Decision making to choose among various pathways, products and conversion policies would be selective and uniquely tailored for every individual Kraft mills considering mill constraints, available sources, and business plan. Kraft mills might partially be converted into biorefineries while keeping their Kraft product line in operation, or completely be converted into biorefineries. Moreover, the following development priorities can be established in Kraft mills as well:

- Totally new high value specialty products e.g. bio-sensitive papers, intelligent papers
- New applications e.g. composite packaging materials, construction materials
- New properties of cellulose and wood composites, e.g. nanotechnology
- Dissolving pulp for rayon production

However, the implementation strategy has a number of unusual challenges such as:

- Making appropriate choices among various production pathways and mastering new technologies
- Managing the implementation for manufacturing high value added products but limited in tonnage to avoid over-saturation of the market
- Achieving the integration of downstream processing chain with the chemical and petro-chemical industry
- Ensuring the durability of new operations within a context of sustainable development

The essential key to any successful sustainable conversion is intensive integration and energy optimization, and progressive implementation. Energy optimization provides the mill with opportunities to save steam and water. The liberated energy production capacity can be available to support other revenue generating initiatives such as: biorefinery, trigeneration, steam sales (district heating), power generation, eco-industrial clusters. The combination of process optimization and implementation of gasification of wood residue can supply a facility totally free of fossil fuel and reduce its carbon foot print. Meanwhile progressive integration of projected transformation minimizes the involved business risk, increases the chance for combining different technology pathways, and diversifies the product mix by adding bioproducts, while maintaining the production of pulp derived products but in new high value niches.

Conclusions

The pulp and paper sector of mature industrial countries have the potential to transform into more diversified and profitable businesses. Developing a single road map for the entire industry is not a desirable model since there are various possible products with different market demand and value. The transformation pathways, product mix, suitable conversion technologies, market uncertainties evaluations, and sustainable development are challenges to be tackled. Successful conversion will require progressive implementation of new business plans to give companies the opportunity to master the new technologies, minimize the risks and increase profitability.

The sustainability of the conversion will depend upon the successful implementation of intensive energy integration and optimization measures.

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