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The forest biorefinery and its implementation in the pulp and paper industry: Energy overview

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ABSTRACT

Incorporating a biorefinery unit to an operating Kraft pulping process has significant technological, economic and social advantages over the construction of a grassroot biorefinery. Also, the conversion of a Kraft mill from total pulp making to complete biorefinery can be done in a stepwise fashion and so give a company that envisages such transformation 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 As components of the wood such as lignin or hemicelluloses are withdrawn from the Kraft pulp line, the heat production capacity from the recovery boiler where they are currently burnt is diminished.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 an intensive and innovative energy optimization 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 cogeneration and heat upgrading by optimally positioned and designed absorption heat cycles. The methodology has been applied to biorefining technologies for lignin and hemicelluloses extraction and valorisation, both technologies being coupled with gasification of wood residue.

1. 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 is assessed in the context of available feedstock, applicable technological processes and market demand. Lignocellulosic crops or residues of forestry sector are attractive feedstocks for biorefineries specially when integrated into a pulp and paper mill because it does not compete with agricultural crops for fertile land and relies on larger biomass yields [2]. The forest biorefinery has received much attention from the pulp and paper sector in industrially mature countries primarily in North America and Western Europe as a potential 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, 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 [3].

The Integrated forest biorefinery (IFBR) consists of implementing biorefinery units into existing pulping mill called receptor Kraft. The Kraft process is a receptor process of choice. It entails treatment of wood chips with a mixture of sodium hydroxide and sodium sulfide (the white liquor), to convert wood into pulp and steam [4]. A simplified schematic of the Kraft process is shown in Fig. 1. Wood chips are cooked in a digester where lignin and hemicelluloses are degraded into fragments and dissolved in the strongly basic delignification liquor. The discharge from the delignification stage consists of cellulose fiber in suspension in residual digestion liquor. The fibers are cleaned and separated from liquor in a series of washers and bleached to remove the residual traces of lignin and other impurities. Bleached pulp is then dried with steam and hot air. 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.

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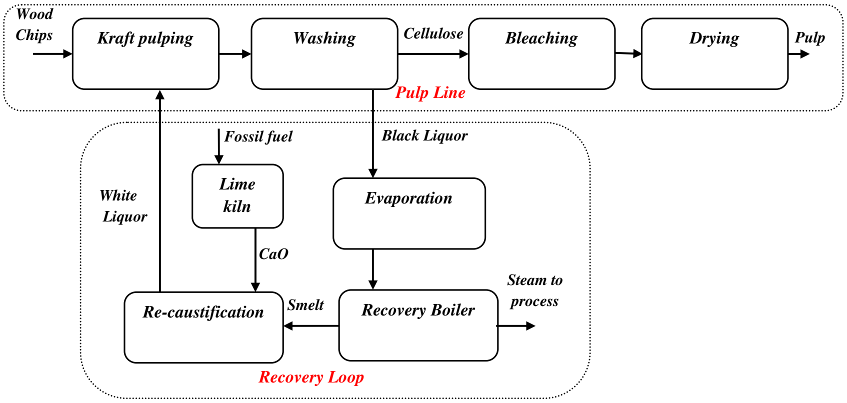


Fig. 1. Simplified schematic of the Kraft process.

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 networks, direct access to feedstocks, and skilled labor force. This opportunity 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 dependent on this industry for their livelihood.

In this paper the concept of green forest biorefinery integrated in a Kraft mill and the strategy for its progressive implementation is presented. The advantages and challenges of such integration are discussed. An innovative methodology to perform high level process integration and intensive energy efficiency is developed and a brief survey of energy implication of major biorefinery technologies and product options such as ethanol, furfural, lignin, and heat and power generation are presented.

2. Integrated forest biorefinery and energy concerns

Typically, the operations used in a biorefinery for conversion, separation and purification are energy intensive and require significant amounts of water. It is expected that the integration of biorefinery units into a Kraft process will place additional demands on existing utility systems and waste water treatment. Furthermore, in the case of lignin or hemicelluloses extraction, the steam production capacity of the receptor Kraft mill will decrease due to the reduction in calorific values of the black liquor. The challenge is to revamp the receptor mill in a way to satisfy the energy and water demand of the total integrated site without creating a dependency on fossil fuels. The procedure to supply the energy demand and compensate the steam deficit of the total integrated site is to identify energy implications of biorefinery units, take advantage of interactions within the total integrated site, and to increase the overall energy efficiency through an inclusive systematic approach [5]. The proposed approach is described in the following subsections.

2.1. *Intensive energy optimization methodology*

The proposed novel methodology encompasses six steps in which energy improvement potentials are identified. The first step of this methodology is to define and characterize the base case process by means of a validated simulation model. The base case represents a typical Canadian Kraft pulp mill from which data is extracted for energy and water studies. In this work the base case is simulated using CADSIM Plus software. Flow diagrams of steam, water and effluent networks are extracted from the simulation to provide detailed information on production, distribution, utilization and post-utilization treatment of steam and water [6]. The efficiency of individual equipment is characterized by performance indicators and benchmarked. System performance analysis is the mean to analyse the process constraints. Performing system interaction analysis leads to energy saving projects with polygeneration opportunities. Fig. 2 gives the stepwise procedure from base case definition to post-benchmarking, which has been developed and put in practice in actual case studies. This unique approach is based on the methodology developed by Mateos et al. [6,7]. However, innovative features have been developed to improve the potential of water and energy savings. The focus of this work is more on these three recent features, and they are introduced as follows:

- Equipment performance analysis (design improvement, debottlenecking)
- System performance analysis (comparison, targeting)
- System interaction analysis (combined energy and water optimization)

2.1.1. *Equipment performance analysis (EPA)*

Process integration techniques such as pinch analysis are commonly applied with the assumption that all equipments and subsystems are working efficiently which is not always the case in an existing mill. In this step of the methodology, the key performance indicators (KPIs) of individual equipment and subsystems of the process are analyzed and diagnosed. This can lead to design improvements, process debottlenecking and energy savings generally in the range of 5–15% [8] and payback period of few weeks to several years (for projected equipment replacement) [9]. The EPA is applied for an existing Kraft mill located in Eastern Canada, to evaluate the potential of energy saving for the equipments with major water and energy consumption. Hence the steam production, black liquor evaporation and brown stock washing departments have been analysed and energy and water saving projects are proposed.

2.1.1.1. Brown stock washing. Brown stock washing is a significant water consumer section in the reference mill with 35.6 m^3 per air dry tone (adt) of produced pulp. Since water and steam are highly interconnected, reducing water consumption directly affects steam

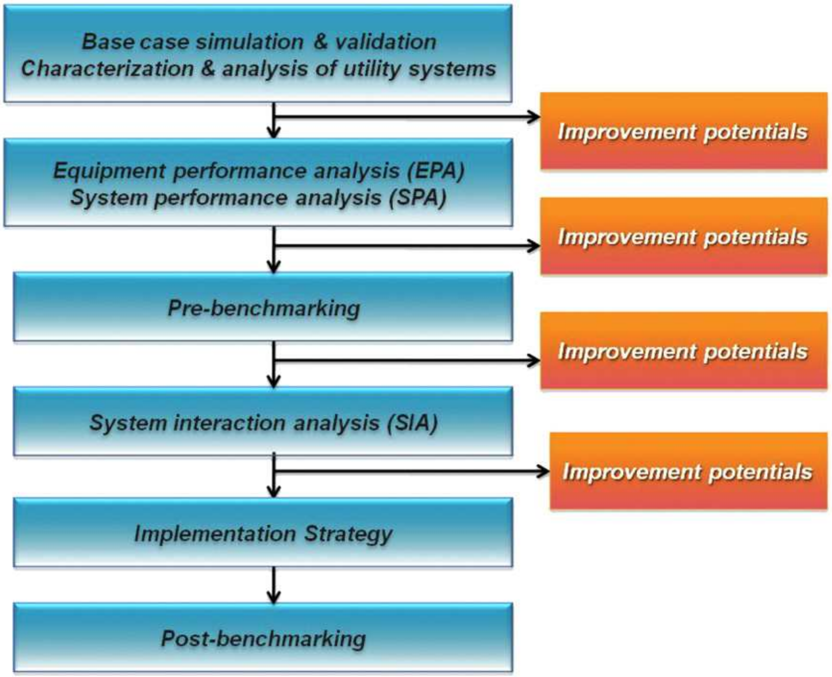


Fig. 2. Stepwise intensive energy optimization approach.

consumption. Modified Norden efficiency factor and equivalent displacement ratio have been computed and compared with typical operation values for 5 washers in the mill. It was found that replacing the three vacuum drum washers with a wash press, preheating bleaching agents and reutilizing effluents from paper machine in washers not only saves water and energy but also results in discharging a cleaner pulp for bleaching. Fig. 3 illustrates the analysis of washing section and potential of energy and water savings are presented in Table 1.

2.1.1.2. Evaporators train. Evaporators are important steam consumers in the mill, 12.5 (t/hr), and they concentrate black liquor to be burnt in the recovery boiler. Studying evaporation section showed that preheating the black liquor entering the multi effect evaporator train will be concentrated and hot black liquor exiting the train will increase the economy. Moreover recompressing the steam used for evaporation increases the potential of live steam saving. The analysis and benchmarking of evaporation train is presented in Fig. 4 and Table 2 shows the energy saving potential.

2.1.1.3. Boiler area. Steam is produced in boiler area. Boiler inefficiency lowers the potential of steam quality and production. The reference mill has one recovery boiler and four power boilers. They were analysed and potential steam savings recognized. Results show that reducing heat loss from the recovery boiler results in increasing the steam production capacity and flashing the blow down to preheat the boiler makeup water leads to steam saving. The results of analysis and energy improvement are presented in Fig. 5 and Table 3.

2.1.2. System performance analysis (SPA)

To evaluate the system energy efficiency, the global KPIs of the process such as steam production and utilization, water consumption and effluent production are identified and computed before developing energy enhancement measures. Then they are compared with a wide number of mills and best current practice of the industry to assess inefficiencies [10]. There are tools and techniques which lead to targeting the energy and water for the process and better understanding the constraints levels in the mills. Thermal pinch is the process integration technique to target minimum heating and cooling requirements of the process and extent of internal heat recovery. Water pinch targets the potential of water and effluent reutilization in the process. Combined thermal and consistency profile of pulp depicts dilution and non

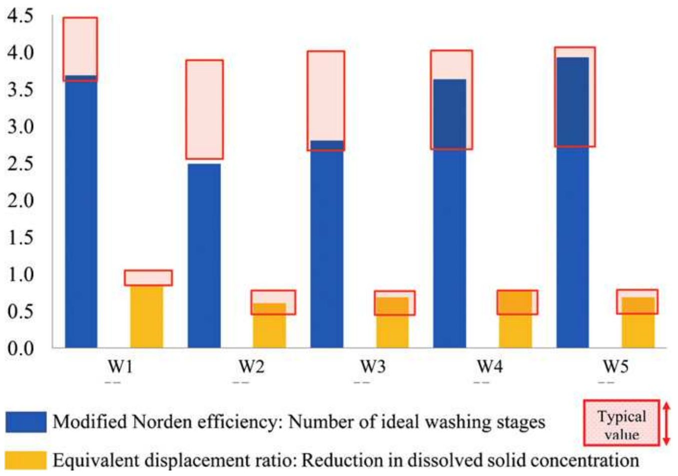


Fig. 3. Washing section analysis of the reference mill.

Table 1
Steam and water saving potential in washing section.

Water saving (m^3/adt)	3.1
Mill water reduction%	3.4
Steam saving (GJ/adt)	0.64
Mill steam saving%	1.8

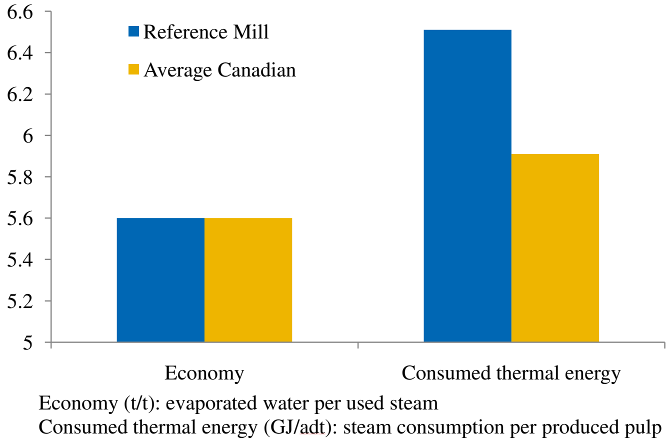


Fig. 4. Evaporation section analysis of the reference mill.

isothermal mixing points along the pulp line. There are several composite curves that represent the different aspects of the water system in the mill. The composite curves for process water, water heat exchanger network, and water tanks, analyse the energy inefficiencies in the water system [11]. Constraint analysis is the key aspect of SPA by distinguishing between the different levels of energy saving projects with their incorporated economic aspects; it gives the mill the opportunity to choose the extent of the energy saving projects (retrofit or grassroot) with respect to the investment cost. The results for applying constraint analysis to an existing Kraft mill are presented in Table 4.

2.1.3. 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. The combined water and energy optimization approach proposes the fresh water reduction path with the highest energy saving response from the point of demand back to the source. For the reference mill six water reduction projects are recognized and presented in Table 5. Effluents are mostly reutilized in these projects to reduce fresh water consumption without necessity of a heat exchanger.

Applying the intensive energy optimization approach for the reference mill saves 21–34% of total steam consumption (higher saving by means of higher investments e.g. compressor) and 27% of mill fresh water consumption. Several techniques are applied on the utility or process side to maximize the energy performance and address the synergetic or counter action effects of different projects [12]. The SIA maximizes the potential for steam and water savings, for heat upgrading by means of absorption heat pumps and, for heat and power production by co- and tri-generation within the mill (Fig. 6). Upgrading the low energy level of some hot streams in the process using a heat pump can increase the steam saving and power production. 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 [13].

Table 2
Energy saving potential in evaporators.

Potential of improvement	Economy	Steam saving %
Black liquor preheating	6.2	0.5
Steam recompression	5.9	8.2

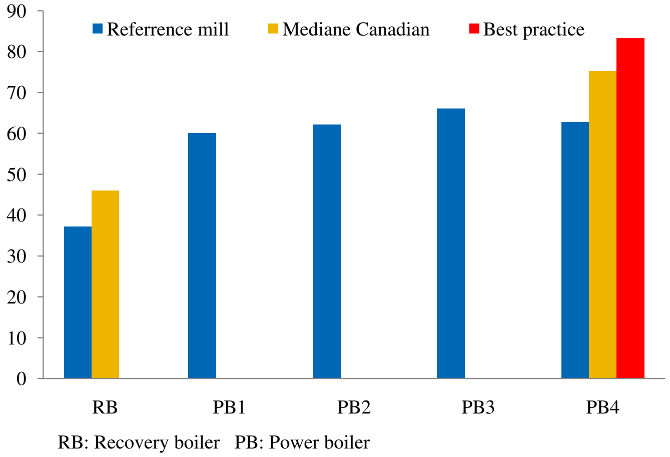


Fig. 5. Steam production analysis of the reference mill, boiler efficiency.

2.2. Selected biorefinery options for Kraft process

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, specialty products e.g. nanocrystalline cellulose, viscose and rayon as well as paperboard, packaging and building materials. Hemicellulose $(C_5H_8O_5)_n$ has a random, amorphous structure with little strength to hydrolysis or heat and contains a mix of C6 and C5 sugars which can be converted into value-added products. 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 6.

In the Kraft pulping process only 42–44% of woody biomass is converted into pulp and the rest (mainly lignin and hemicelluloses) is combusted in the recovery boiler. This portion can be better utilized to increase the revenue margin of the mills, by being 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 sources of biomass and accessible existing infrastructures make Kraft mills excellent candidates as biorefinery receptors. The biorefinery based on Kraft process is composed of two sides – upstream and downstream (Fig. 7). The upstream side, which is the Kraft process itself, is well defined in terms of technology, energy and material requirements, water utilization and products. However, the definition of the downstream side is a challenge and it is essential to appropriately assess the feedstock, product options, pathways, and energy and material requirements.

Table 3
Energy saving potential in boiler area.

Potential of improvement	Increase in steam production capacity %	Steam saving %
RB maintenance improvement	6.4	–
Blow down heat recovery	–	3.1

Table 4
Energy saving project types and constraints.

Level of modification	Steam saving %
Minor Adjustments (Retrofit-Low) • Direct and indirect steam heat exchangers	11
Major adjustments (Retrofit-High) • Direct and indirect steam heat exchangers • Pinch violations • Non isothermal mixing points	16
Restructuring existing network (Grassroot) • Direct and indirect steam heat exchangers • Pinch violations • Non isothermal mixing points • Restructuring water network	17

The biorefinery options selected for integration into Kraft process are [15]:

- Hemicelluloses extraction from wood chips prior to pulping and their conversion into polymers, fuels and chemicals. In this study particular attention is paid to two product options: ethanol as a biofuel, a high volume but a low profit product and furfural as an intermediate feedstock for further synthesis which is a small volume product but high in profit.
- Extraction of lignin from black liquor by precipitation followed by washing and drying. Lignin can be further transformed into valuable chemicals such as phenol, road additives, and surface active dispersants or even carbon fibers;
- Gasification of wood residues to produce synthetic gas as a source of heat, power, fuels or chemicals.

The technological paths for selective transformation are thermochemical, biochemical, or chemical. 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 conversion.

2.2.1. Hemicelluloses extraction

The extraction of hemicelluloses from wood chips prior to pulping and their conversion into value-added products is a key biorefining technology. The efficiency of the technology strongly depends on the pre-treatment operation, the challenge being to extract a significant amount of hemicelluloses without a negative impact on pulp quality and quantity [16,17]. Mao and et al. have proposed the near-neutral extraction process integrated within an existing hardwood Kraft mill [18]. The “near-neutral” process uses green liquor, composed primarily of Na_2CO_3 and Na_2S, in the wood extraction stage. In the study conducted by Mao and co-authors, a portion of the hemicelluloses is extracted from wood prior to pulping and converted into acetic acid and ethanol while using the extracted wood chips for pulp production. The biorefinery is treated as an adjunct to the base Kraft process, which maintains the pulp production. The implementation of the “near-neutral” process modifies the energy balance of the Kraft pulp mill. Approximately 10% of the wood, mainly hemicelluloses and lignin, are extracted during chips pre-treatment. Nevertheless, the calorific value of the hemicelluloses is low (about 13 MJ/kg) compared to that of lignin (25 MJ/kg) and the impact on the black liquor combustibility is less than in the case of lignin extraction. However, the transformation of the hemicelluloses sugars into value added products requires energy intensive operations.

Table 5
Combined water and energy saving projects.

Type of project	Water saving %	Steam saving %
Replacing grinder fresh water with paper machine effluent	16.4	0
Replacing bleaching fresh water with paper machine effluent	2.3	2.7
Reducing vacuum pump fresh water by filtering and reutilizing the effluents	0.7	0
Reutilizing vacuum pump effluent in paper machine	1.1	0
Reutilizing bleaching effluent in recaustification	1.6	3.1
Reducing washing fresh water by reutilizing washer effluent	1.5	2.9
Total	**23.6**	**8.7**

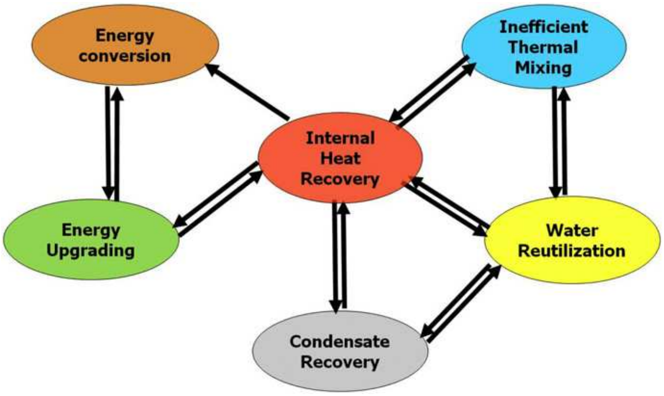


Fig. 6. System interaction analysis.

Ethanol and furfural are two attractive product options; their production paths are shown in Figs. 8 and 9. The potential world market for ethanol is 65 billion L/a with a price ranging from 0.7 to 0.9 $/L. It is mostly used as biofuel requiring high processing and capital cost due to the complexity and efficiency of the 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 agent and feedstock for other products.

The incorporation of the hemicellulose extraction stage prior to Kraft pulping and its subsequent conversion affects the energy balance of the mill. Marinova et al. have shown that the implementation of the “near-neutral” process into a typical Canadian Kraft pulp mill increases the base case steam demand by 15.5%. An approach for energy optimization is proposed to face the energy shortage of the modified process. A combination of several measures reduces the steam demand of the Kraft process and satisfies the increased energy requirement of the biorefinery. Energy optimization should be an integral part of any attempt to successfully convert a conventional Kraft pulp mill into a biorefinery [15].

The hemicelluloses biorefinery requires new operations, some of them non typical for the pulp and paper industry and implies high investment costs. The concept of the biorefinery cluster is an

Table 6
Typical components of wood (%) [14].

Component	Softwood	Hardwood
Cellulose	40–50	40–50
Hemicelluloses	15–20	20–35
Lignin	23–33	16–25
Other organics	1–5	1–2
Inorganic as ash	0.2–0.5	0.2–0.5

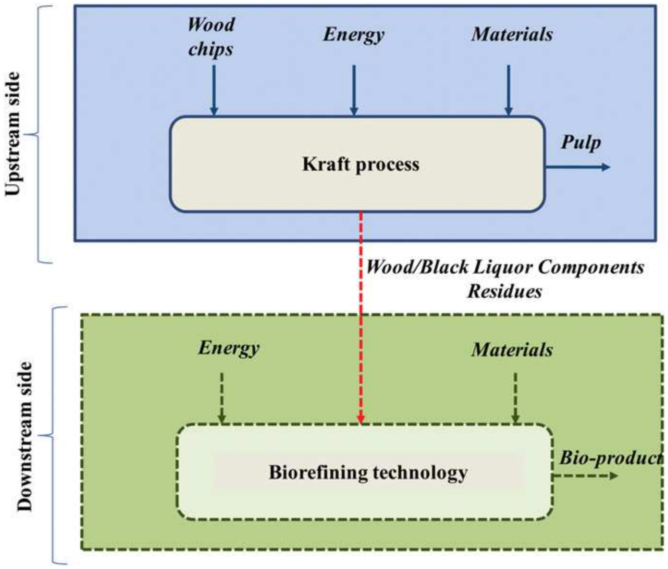


Fig. 7. Upstream and downstream sides of a biorefinery based on the Kraft process.

opportunity to address this major economic concern. Several pulp mills could be involved in the initiative, offering to the participants a mutually beneficial venture by sharing investment and operating costs. Each of the pulp mills will supply feedsock, e.g. concentrated pre-hydrolysate; and one of them serves as the centre of the cluster where the hemicelluloses transformation is carried out. A simplified representation of a biorefinery cluster is illustrated in Fig. 10.

Several parameters should be optimized in order to establish a profitable biorefinery cluster based on hemicelluloses extraction and transformation; those parameters are: concentration of the pre-hydrolysate, distance between the mills, transportation costs, energy and material use. The participants in the initiative should agree to collaborate and share the required investments costs as well as the profits. Then the cluster concept could be a profitable option for the pulp and paper industry.

2.2.2. Lignin extraction

The advantage of extracting lignin from black liquor is to reduce the load on the recovery boiler which is the bottleneck for pulp production. It also increases profit margin by generating energy or value-added products such as carbon fibers, phenol, road additives, surface active agent and dispersants in secondary processes. Lignin extraction is possible through acid precipitation, electrolysis and ultrafiltration. Acid precipitation is the technique which has reached the most advanced state of development and implementation [19] and is presented in Fig. 11. Black liquor at 30% dissolved solids concentration is withdrawn from the evaporator train and precipitated in acidic condition. The acidification agent used to lower the pH for precipitation is CO_2. After filtering, the lignin cake is washed in acidic conditions (sulfuric acid, pH = 4) and wash filtrates are returned to the evaporation section of the Kraft process [20]. Integration of lignin extraction units into Kraft process increases the opportunity of water and chemicals saving. Filtrate from pulp drying can be used for lignin washing. Recovering CO_2 from the stack gases of mill boilers or lime kiln creates CO_2 sinks which results in GHG emission reduction. Sulfuric acid for washing may be available onsite from the ClO_2 making plant (ClO_2 is produced onsite and used as a bleaching agent).

However, such integration has evident impact on energy demand of the global site (Fig. 12). Extracting lignin from black liquor decreases the steam production capacity of the reference mill recovery boiler. At equal extraction rate, the energy impact of lignin extraction on the recovery boiler will be significantly larger than in the hemicelluloses case because of its higher specific heat content. Moreover reutilizing biorefinery weak filtrate in the Kraft evaporation section increases the demand for live steam. The energy implication of biorefinery units is mostly to heat up chemicals and water and adds to the energy demand of the integrated site. The evaporation section generally accounts for almost 92% of increase in steam demand. This deficit in steam is partially compensated by increasing the feed rate of chips to Kraft process. It is reported by Perin-Levasseur et al. that a 10% increase in pulp production results in 20% increase in total steam demand [21]. Since the recovery boiler capacity is the limiting factor in increasing the production, optimizing the energy efficiency of the integrated site is the ultimate solution to address its energy requirement.

2.2.3. Biomass gasification

The Kraft process consumes large quantities of energy, 26% of the total energy used by the Canadian industry sector, which is generated from several types of fuels (black liquor, wood residues or fossil). Expensive fossil fuel is consumed in lime kiln and power boilers to satisfy the energy demand of the process while contributing to CO_2 emissions to the higher atmosphere. Biomass, which is generally combusted for steam production, can be used more efficiently in poly-generation pathways to generate high value

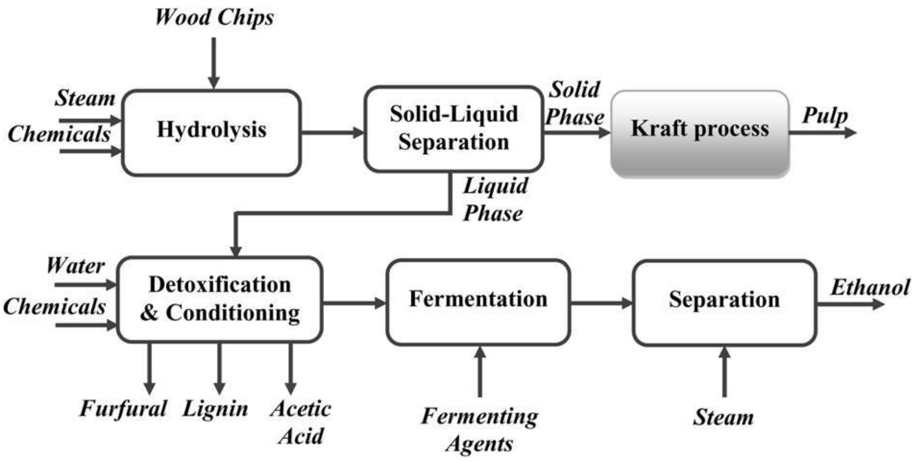


Fig. 8. Pathway for ethanol production from wood chips.

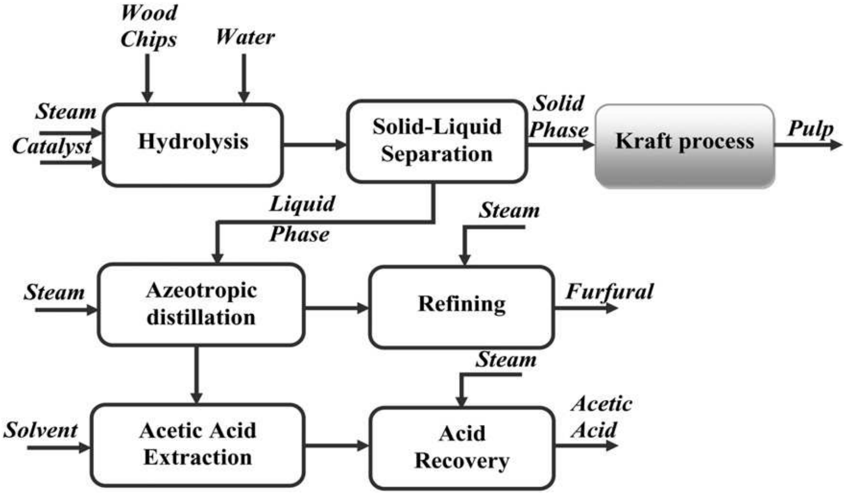


Fig. 9. Pathway for furfural production with acetic acid recovery.

products, heat and power. On the other hand, due to the low price of biomass, energy saving project targeting only reduction in biomass consumption is not very attractive unless they are combined with poly-generation [5]. Gasification, instead of complete combustion, converts biomass into a fuel 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. The gasification process essentially encompasses the following units:

- Biomass drying to reduce its moisture from 50% to 5–20%
- Gasification process to convert biomass into syngas at high temperature
- Syngas cooling and cleaning units to remove H_2S from syngas

If biomass gasification is coupled with hemicelluloses or lignin biorefinery in order to achieve the concept of green integrated biorefinery, gas turbine, heat recovery steam generator, and steam turbine are required to generate power and steam (combined heat and power cycle, CHP) (Fig. 13). A biomass gasification unit installed in an integrated biorefinery site replaces the power boilers (fossil or wood fired) to satisfy the energy and power demand of the integrated site and fire lime kiln to reduce GHG emissions. Biomass is dried by either produced steam in CHP or gas turbine hot exhaust. The gasifying agent is hot air and steam to improve the heat value of syngas. Heat is recovered from hot syngas and utilized in the process. To remove H_2S from syngas Rectisol, Selexol or Claus/SCOT technologies are applied. Moshkelani et al. have reported that integration of biomass gasification units into an existing Kraft mill is advantageous as long as the mill energy efficiency is optimized. The steam and power required by the optimized Kraft process are produced in cogeneration cycle and the lime kiln is fired with syngas which results in GHG emission reduction up to 70,282 ton/a [22].

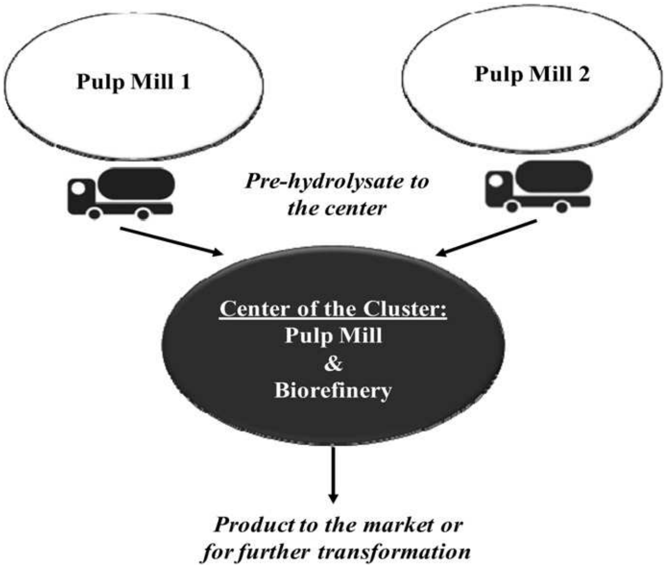


Fig. 10. Example of biorefinery cluster based on pulp mills with hemicelluloses extraction stage.

3. Kraft-based green integrated forest biorefinery

The integration of biorefinery technologies into the receptor Kraft should be performed in a sustainable manner in order to minimize the environmental impact. This is achieved by reducing greenhouse gas (GHG) emissions of the total integrated site. It is now admitted by the scientific community that the concentration of CO_2 in the atmosphere, which is currently 390 ppm [23], will continue to rise as more countries achieve a high level of industrialisation. An equilibrium level of 550 ppm is considered as a tolerable which could be maintained provided concerted worldwide efforts are devoted to the following strategies [24]:

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

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

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

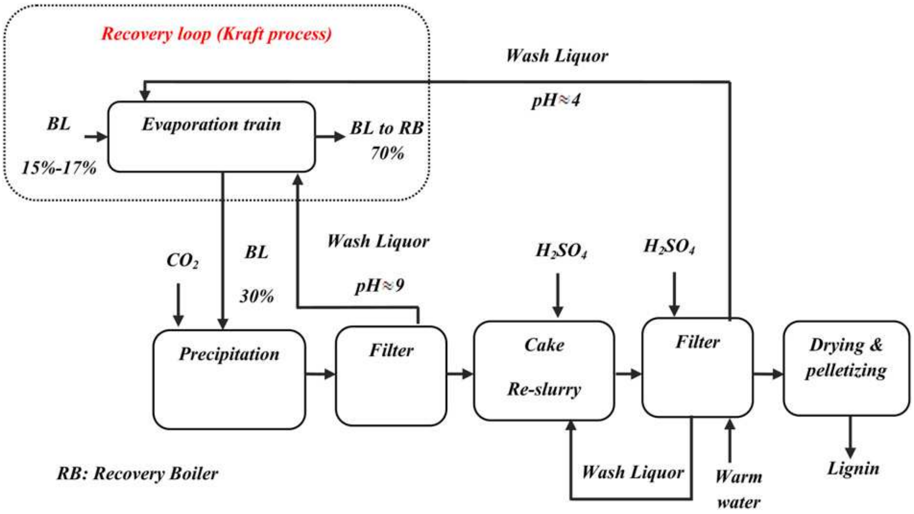


Fig. 11. Lignin extraction from Kraft black liquor.

Fig. 14 shows the integrated green biorefinery into a Kraft mill receptor. The bio-products are ethanol, furfural or lignin whereas energy demand (steam and power) is provided by biomass gasification. The produced syngas is utilized in combined heat and power cycles to generate green power and satisfy the steam demand of the mill. Simultaneously it can fire the lime kiln to eliminate the fossil fuel consumption and reduce CO_2 emission. Intensive energy optimization is applied to improve the energy efficiency of individual receptor Kraft, biorefinery units and global integrated site.

4. Strategy for progressive implementation of GIFBR

The forestry sectors in industrially mature countries must revise their traditional business models to develop new sources of revenues in order to regain profitability and remain competitive in global market. In order to manage the risk that is associated with such conversion, progressive implementation is proposed in this paper. The advantage of this approach is to permit the mill to have the pulp line in production in order to keep its revenue throughout the transformation period. It also increases the chance for combining different technology pathways, and diversifies the product mix. Decision making to choose among various pathways, products and conversion policies is selective and uniquely tailored for every individual Kraft mill considering its constraints, available sources, and business plan. For instance, as a converted mill, maintaining the Kraft production line may be a necessity when the bio-product is a low price commodity such as biofuel [25], but in high value specialty production scenarios, total conversion to biorefinery might be more advantageous. Consequently there could be Kraft mills partially be converted into biorefineries while keeping the pulp line in operation, mills completely converted into biorefineries, or others that choose to produce value added pulp and paper derivatives such as:

- Bio-sensitive papers, intelligent papers
- Composite packaging materials, construction materials
- Rayon from dissolving pulp

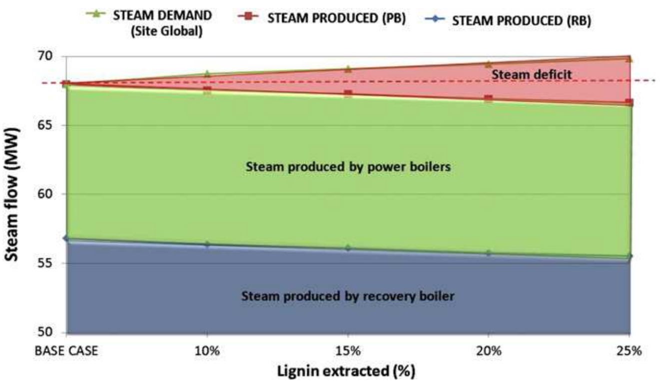


Fig. 12. Energy impact of different lignin extraction rate on total site (reference mill + biorefinery).

However, irrespective of the conversion path selected by the mill, optimizing the energy demand of the receptor Kraft mill is the first and critical step of the conversion process. An intensive energy optimization methodology, such as the one presented in this paper, provides a road map for the mill to save energy and water within different investment levels. Then the liberated energy production capacity can be made available to support the demand of the other revenue generating initiatives such as: biorefinery, tri-generation, steam sale, and power generation. The next step is to select the biorefinery technology, identify the energy implications and optimize its energy efficiency. Integrating a biorefinery unit into a receptor Kraft mill creates interactions within the overall site. Therefore intensive energy and material integration is highly recommended. Implementing gasification units completes the concept of green integrated site by eliminating fossil fuel consumption and increases the possibility to upgrade the steam production rate for cogeneration. Fig. 15 presents the strategy for progressive implementation of GIFBR.

Nevertheless, the implementation strategy raises 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 industries
- Ensuring the durability of new operations within a context of sustainable development

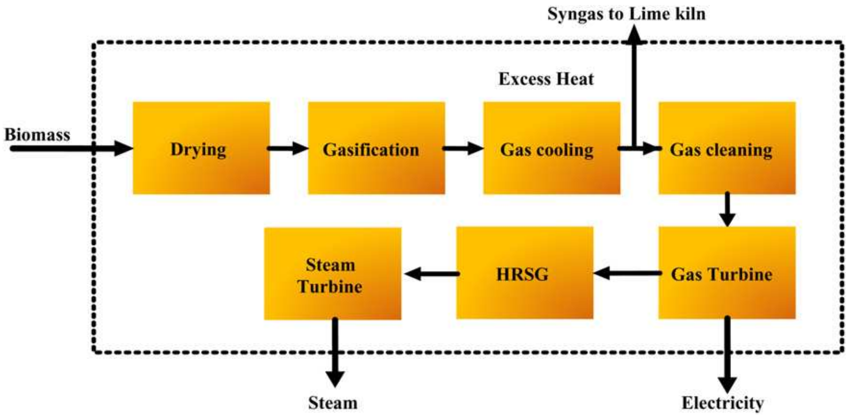


Fig. 13. Gasification biorefinery units with CHP.

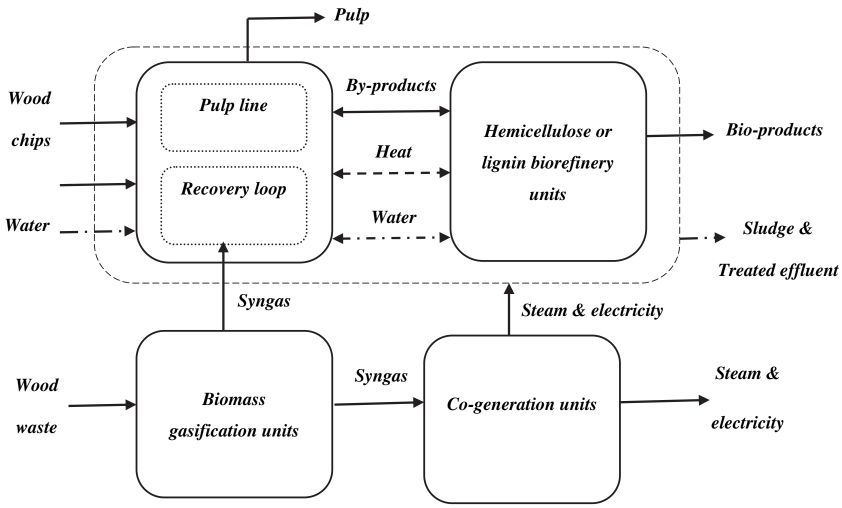
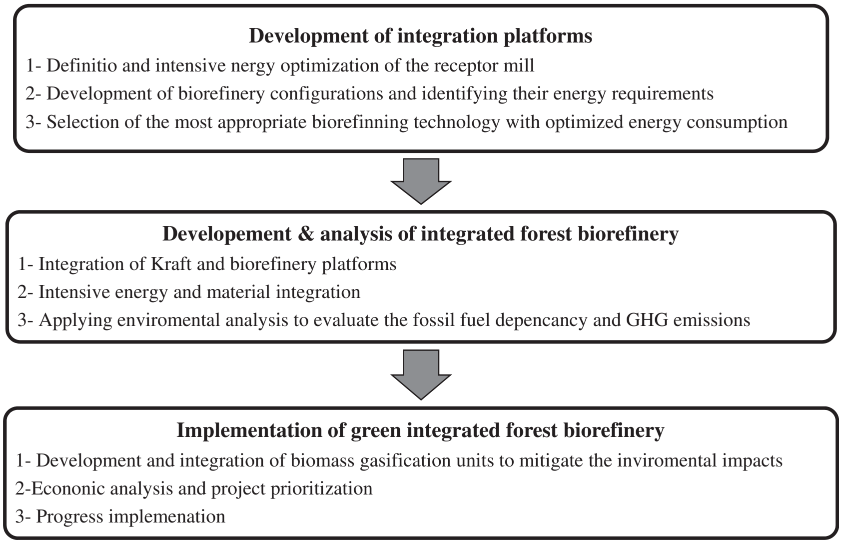


Fig. 14. Green integrated forest biorefinery concept (GIFBR).



Development of integration platforms

1- Definitio and intensive nergy optimization of the receptor mill
2- Development of biorefinery configurations and identifying their energy requirements
3- Selection of the most appropriate biorefinning technology with optimized energy consumption

Developement & analysis of integrated forest biorefinery

1- Integration of Kraft and biorefinery platforms
2- Intensive energy and material integration
3- Applying enviromental analysis to evaluate the fossil fuel depencancy and GHG emissions

Implementation of green integrated forest biorefinery

1- Development and integration of biomass gasification units to mitigate the inviromental impacts
2-Econonic analysis and project prioritization
3- Progress implemenation

Fig. 15. GIFBR progressive implementation.

5. 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 since there are various possible products with different market demand and value. The transformation pathways, product mix, suitable conversion technologies, market uncertainty 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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References

[1] IEA, in: IEA Bioenergy Task 42 on Biorefineries: Co-production of Fuels, Chemicals, Power and Materials from Biomass, Minutes of the Third Task Meeting, Copenhagen, Denmark, 2007.http://www.biorefinery.nl/ieabioenergy-task42.
[2] F. Cherubini, The biorefinery concept: using biomass instead of oil for producing energy and chemicals, Energy Conversion Manage. 51 (2010) 1412–1421.
[3] M. Towers, T. Browne, P. Stuart, J. Paris, in: Biorefining: The Pulp and Paper Industry in Transition, 6th International World Energy System Conference, Turin, Italy, July 10–12, 2006, pp. 55–62.
[4] G. Smook, Handbook for Pulp and Paper Technologists, third ed. Angus Wilde, Vancouver, 2002.
[5] E. Mateos-Espejel, M. Moshkelani, M.J. Keshtkar, J. Paris, in: Sustainability of Green Integrated Forest Biorefinery: Question of Energy, Annual Conference of the Canadian Pulp and Paper Industry, Montreal, Canada, February 1–3, 2011, pp. 139–143.
[6] E. Mateos-Espejel, L. Savulescu, J. Paris, Base case process development for energy efficiency improvement, application to a Kraft pulping mill. Part I: definition and characterization, Chem. Eng. Res. Des. 89 (6) (2011) 742–752.
[7] E. Mateos-Espejel, L. Savulescu, F. Maréchal, J. Paris, Unified methodology for thermal energy efficiency improvement: application to Kraft process, Chem. Eng. Sci. 66 (2011) 135–151.
[8] CETC, CanmetENERGY – Pinch Analysis: For Efficient Use of Energy, Water & Hydrogen, Catalogue M39–96/2003E, 2003.
[9] P. Navarri, S. Bédard, Part II: Assessing Water and Energy Consumption and Designing Strategies for Their Reduction, Handbook of Water and Energy Management in Food Processing, Woodhead Publishing Limited, Cambridge, UK, 2008.
[10] E. Mateos-Espejel, L. Savulescu, F. Maréchal, J. Paris, Base case process development for energy efficiency improvement, application to a Kraft pulping mill. Part II: benchmarking analysis, Chem. Eng. Res. Des. 89 (6) (2011) 729–741.
[11] A. Alva-Argaez, L. Savulescu, Water reuse project selection. A retrofit path to water and energy savings, Chem. Engineering Transactions 18 (2009) 403–409.
[12] E. Mateos-Espejel, L. Savulescu, F. Maréchal, J. Paris, Systems interactions analysis for the energy efficiency improvement of a Kraft Process, Energy 35 (12) (2010) 5132–5142.
[13] M. Marinova, E. Mateos-Espejel, B. Bakhtiari, J. Paris, in: A New Methodology for the Implementation of Trigeneration in Industry: Application to the Kraft Process, 1st European Conference on Polygenration, Tarragona, Spain, October 16–17, 2007, pp. 1–20.
[14] M. Towers, Y. Boluk, J. Paris, T. Browne, in: The Biorefinery: A Vision for Canadian Pulp and Paper Industry, World Congress on Industrial Biotechnology and Bioprocessing, Toronto, Canada, July 11–14, 2006.
[15] M. Marinova, E. Mateos-Espejel, N. Jemaa, J. Paris, Addressing the increased energy demand of a Kraft mill biorefinery: the hemicellulose extraction case, Chem. Eng. Res. Des 87 (2009) 1269–1275.
[16] H. Huang, S. Ramaswamy, U.W. Tschirner, B.V. Ramarao, A review of separation technologies in current and future biorefineries, Sep. Purif. Technol. 62 (1) (2008) 1–21.
[17] B. Kamm, M. Kamm, Principles of biorefineries, Appl. Microbiol. Biotechnol. 64 (2) (2004) 137–145.
[18] H. Mao, J.M. Genco, S.H. Yoon, A. Van Heiningen, H. Pendse, Technical economic evaluation of a hardwood biorefinery using the “near-neutral” hemicelluloses pre-extraction process, J. Biobased Mater. Bioenergy 2 (2) (2008) 177–185.
[19] M. Davy, V. Uloth, J. Cloutier, Econimic evaluation of black liquor treatment processes for incremental Kraft pulping production, Pulp Paper Can. 99 (2) (1998) 35–39.
[20] F. Ohman, Precipitation and separation of lignin from Kraft black liquor, PhD thesis, Department of chemical and biological engineering, Chalmers University Technology, 2006.
[21] Z. Perin-Lavasseur, L. Savulescu, M. Benali, in: Lignin Production and Processing Path Assessment: Energy, Water and Chemicals Integration Perspective, Annual Conference of the Canadian Pulp and Paper Industry, Montreal, Canada, February 1–3, 2011, pp. 87–90.
[22] M. Moshkelani, E. Mateos-Espejel, W. Kamal, J. Paris, in: Integration of a Gasification Unit Into a Kraft Process: Energy and Economic Feasibility, Annual Conference of the Canadian Pulp and Paper Industry, Montreal, Canada, February 1–3, 2011, pp. 238–241.
[23] Earth System Research Laboratory, Global Monitoring Division, http://www.esrl.noaa.gov/gmd/ccgg/trends/.
[24] F. Meunier, Domestiquer l’effect de serre énergies et changement climatique, second ed. (2008) Dunod, Paris.
[25] T. Browne, in: Economics of Commodity Chemicals and Fuel From Forest Biomass, Annual Conference of the Canadian Pulp and Paper Industry, Montreal, Canada, February 1–3, 2011, pp. 30–33.