bioresources.com

Bio-oil and Biochar as Additional Revenue Streams in South American Kraft Pulp Mills

Marcelo Hamaguchi,* Jussi Saari, and Esa Vakkilainen

Pulp and paper companies are seeking opportunities beyond the traditional production of market pulp. One interesting alternative is to expand their revenue streams by adding value to the wood residues that they generate. Considering that excess heat and electricity can be used for biomass pre-treatment and conversion, the aim of this work is to show how the integrated production of bio-oil or biochar would affect the operation of a 1.5M t/a kraft pulp mill in South America. Detailed balances with a focus on modern eucalyptus mills are then developed for this purpose. Since the attractiveness of increasing renewable energy is often influenced by energy policies or local market development for the new products, the target was not to determine the best investment decision. Nevertheless, an economic analysis was performed to observe the main variables affecting the viability of these technologies. The results showed that satisfactory internal rates of return can be achieved for multiple technologies depending on the price of electricity, torrefied pellets, or bio-oil.

*Contact information: Lappeenranta University of Technology, Department of Sustainable Energy Systems, P. O. Box 20, FI-53851, Lappeenranta, Finland; *Corresponding author: hamaguchi.marcelo@gmail.com*

INTRODUCTION

Brazil and Uruguay together produced approximately 13.3 million tons of bleached eucalyptus pulp in 2010 (92% in Brazil) (FAO 2010). This represents an increase of 52.6% in comparison with 2005, mostly attributed to the start-up of several large standalone mills during this period. Given the potential productivity of eucalyptus in South America, single line pulp mills designed to produce up to 1.75 million tons per year of pulp are currently under study or being implemented (Pöyry 2011; Labigalini 2011). These mills can produce a considerable amount of excess heat, enabling them to generate and export surplus electricity. This, however, might not be the most profitable option. Firstly, the price per kWh in the local electricity market may not be attractive, especially without renewable incentives. Secondly, if condensing electricity is produced, then a considerable fraction of steam enthalpy is not converted into work, but is lost in the condenser. Thirdly, many mills are being built in remote areas and would require additional investment in electricity transmission infra-structure.

In this scenario, the integrated production of alternative fuels for export might make economic sense, especially when wood residues can be used as raw materials. The attractiveness, however, will depend on critical factors such as the possibility to invest, the required internal rate of return, the maturity of the process, and, especially, the renewables market development for the new products.

Wood-based oil has been assessed as a promising biofuel alternative over the past few years. The result is a considerable growth of activities, either with innovation in the types of reactor (Bridgwater 2012) or in attempts to find optimum process conditions. For achieving high liquid yields, pyrolysis reactors require temperatures of 450 to 500 °C, residence times of 0.5 to 2 s, and high heating rates (~1000 °C/s) (Demirbas 2009). These conditions, combined with the chemical composition, moisture, and particle size of biomass, are key factors to be considered when studying the quality and potential of bio-oil production. Alternatively, fuel can be exported in the form of torrefied pellets (Pirraglia *et al.* 2012) or pyrolysis char, both classified here as biochar.

Torrefaction occurs between 220 and 300 °C, with typical reaction times ranging from 0.5 to 2 h. The optimal parameters depend on the feedstock composition, but torrefaction is characterized by low particle heating rates (<50 °C/min) (Bergman *et al*. 2005). Under these conditions, the moisture is removed and hemicellulose is decomposed, causing the release of volatile compounds (Prins *et al*. 2006). The resulting material becomes brittle and hydrophobic, with intermediate characteristics between coal and untreated biomass.

Increasing generation of electricity from kraft pulp mills has been reported (Raukola *et al*. 2002; Vakkilainen 2005; Kankkonen *et al.* 2010). Techno-economical analysis of transport biofuel production in pulp mills has been presented by Frederick (2009). Integration of processes has been analysed by *e.g*. Sadhukhan *et al.* (2009) and Ng and Sadhukhan (2011). In the present work, the fast pyrolysis and torrefaction are considered alternative pathways for kraft pulp mills to convert the wood residues into sellable products. This choice will be compared to more traditional ways of increasing electricity generation.

Availability of Wood Residues

The amount of bark entering the Brazilian pulp mills for incineration depends essentially on the electricity demand (Pöyry 2011). This includes, for example, the existence or not of a sodium chlorate unit, integrated paper machine, or supply agreement with nearby communities. For standalone pulp production, modern recovery boilers are able to generate much more steam than what is required in the process. As a result, there is no actual need for wood residues as additional fuel. However, the biomass boiler can bring some other advantages such as elimination of residues and production of steam for equipment start-up.

Maximizing the debarking efficiency can lead to a better quality of pulp, but also to higher operational costs and wood losses (Foelkel 2007). It is then usual to define an allowable content of bark that can enter the digester, typically less than 1 wt% of dry chips. The debarking process, either at the forest or mill, leaves the logs susceptible to losses of 3 to 5 wt.% (dry), depending on the debarking methods applied (*e.g.* rotary drums, harvesters, or manual). When forest-debarked, some residual bark still enters the mill, which in case of eucalyptus, may be shed in long strings and unbroken strips during the conveying of logs. Afterwards, a reasonable amount of fines are generated during the chipping and screening stages, estimated as 1 to 2% of dry incoming wood (Foelkel 2010). It is important to point out that the wood consumption per ton of pulp varies between pulp mills. This is mostly attributed to the cooking yield required for each wood species (Hamaguchi *et al*. 2012), which also results in a varying amount of wood residues generated.

Bio-oil from Forest Residues

Forest residues contain higher amounts of extractives and alkali metal salts when compared to bark-free wood (Werkelin *et al*. 2005). Since mineral salts are known to catalyze thermal decomposition reactions, their presence can result in i) accelerated conversion rates, ii) lower temperatures at which pyrolytic decomposition proceeds, iii) decreases in the bio-oil molecular weight, and iv) significant impacts on the product yields.

The organic liquid yield in fast pyrolysis can be up to 65 wt.% for sawdust, 46 to 55 wt.% for forest residues, and less than 40 wt.% for straw and hay (Oasmaa *et al*. 2010). Eucalyptus bark contains 2 to 10 wt.% (dry basis) of mineral ash (Foelkel 2010), depending on the varying composition of inner and outer parts. The crude bio-oils from the residues can also exhibit a separated top layer, originating mainly from extractive derivatives (Manuel *et al*. 2006). However, this might be reduced by adding few percentage points of alcohol (Oasmaa *et al*. 2004) such as methanol.

METHODS

In the kraft pulping process, white liquor is consumed during the cooking of wood chips. The result is the production of wood pulp containing dissolved organic and soluble inorganic materials. After a washing stage, the pulp is sent to be screened, and the separated liquid, known as black liquor, is sent to the evaporators. The concentrated black liquor is then burned in the recovery boiler for the regeneration of pulping chemicals, and in turn, for the production of steam. The high-pressure steam generated is sent to the turbo generators to produce electricity and heat.

The reference mill in study is designed to produce 1.5 M Adt/a of bleached eucalyptus pulp in Brazil, operating at 8400 h/a. The amount of residues generated is based on an average pulping yield of 52.5%, as shown in Table 1. Following the forest debarking trends in South America, one third of logs are delivered with 10 wt.% of bark, with the remaining logs (forest-debarked) carrying 2 wt.% of residual bark. The calculations were performed using the Millflow spreadsheet, which is useful for designing pulp mills by equipment vendors and for evaluating new processes alternatives (Hamaguchi *et al*. 2011). Different steam levels serve the mill: LP (160 ºC, 5.4 bar), MP (200 ºC, 12 bar), and MP2 (330 ºC, 30 bar), with pressure units indicated as absolute values. The recovery boiler produces steam at 486 ºC and 86 bar. Examples of operational data for steam and electricity generation in South American mills can be found elsewhere (Germiniani 2011; Fernandez 2011).

The total generated residues are indicated in Table 1 and represent approximately 125 MW$_{th}$ of biomass input. The target is to evaluate four integration cases, described in this section as: **BB)** Incineration of the wood residues in a biomass boiler with generation of additional steam and electricity; **T)** Torrefaction of wood residues with biochar for sale; **FP)** Fast pyrolysis of wood residues with bio-oil and biochar for sale; and **FP2)** Fast pyrolysis of bark-free biomass and incineration of wood residues with bio-oil for sale. A comparative analysis involving the three first cases can be performed for the reference mill. The FP2 scenario is specifically applicable to existing mills already operating with a biomass boiler and is, therefore, treated as an isolated case.

Table 1. Generation of Wood Residues and Energy Balance for Reference Mill

Residues, dry	Unit	Values	Observations
Bark	t/d (MW$_{th}$)	368.0 (67.2)	Debarking loss of 3wt% for 1/3 of logs. For forest-debarked logs, 0.5%wt% loss
Fines	t/d (MW$_{th}$)	120.0 (24.1)	1.5wt% of loss as fines
Other losses [a]	t/d (MW$_{th}$)	182.0 (33.3)	bark in chips: 0.6 wt%
Energy Balance			**T$_{ref}$: 25ºC**
Recovery boiler steam	t/h (MW$_{th}$)	890.0 (693.0)	Black liquor: 927MW$_{th}$ (14.1MJ/kg)
Power consumption	MWe	106.3	NaClO$_3$ unit disregarded
Power generation	MWe	150.8	Steam to TGs: 483ºC, 84 bar
Exportable power	MWe	44.5	Without biomass boiler

[a] Higher wood losses when rotary drums are used for logs debarking

Biomass Boiler: BB

The incineration of wood residues in this study is considered as an alternative. The steam flow is calculated based on a eucalyptus wood dry composition of 49% carbon, 5.3% hydrogen, 0.3% nitrogen, and 0.05% sulphur, with an ash content of 5% for bark and 1% for fines. The oxygen content is calculated by difference. The moisture content is 45%, with a lower heating value (LHV, dry) of 17.4 MJ/kg for fines and 15.8 MJ/kg for bark and other losses. The average temperature of the combustion air, with 25% excess ratio, is 150 ºC. The boiler thermal efficiency can be calculated by an indirect method (EN12952-15 2003), with boiler feed water entering at 130 ºC and flue gas exiting at 190 ºC. The steam is generated at 486 ºC and 86 bar.

Biomass Pre-treatment

Feedstock preparation is crucial to minimize feeding instabilities and to improve the efficiency of torrefaction or pyrolysis processes. Firstly, a dedicated area for cleaning is required to remove the undesirable particles such as sand, dust, or metals. Afterwards, a drying step is needed to reduce the biomass moisture content, which is not necessary in the case of direct combustion in a biomass boiler. It is assumed that low-pressure steam is utilized for drying and that the condensate is fully returned for boiler feed water treatment. Although modern dryers allow the use of hot water at 65 to 90 °C as a heat source, this option is not considered in the present work. The energy requirement of biomass dryers, H$_{DSt}$, is obtained from,

$$H_{DSt} = \frac{1}{\eta_{dryer}} \dot{m}_{ut} \left\{ \begin{array}{l} (MC_{ut} - MC_d)(h_{wL,in} - h_{wV,out}) + \\ \left[(1 - MC_{ut})c_{p,dry} + MC_d c_{p,wL} \right] (T_{out} - T_{in}) \end{array} \right\} \quad (1)$$

where h is enthalpy [kJ/kg], c_p the specific heat [kJ/kgK], and MC is the moisture content [kg$_{H2O}$/kg$_{total}$]. The subscripts *ut* and *d* refer to untreated and dried biomass and *wL* and *wV* to liquid and vapour-phase water, respectively. A $c_{p,dry}$ value of 1.6 kJ/kg is assumed for the biomass, with water enthalpies estimated according to temperature. The moisture content is reduced from 45% (MC$_{ut}$) to 10% (MC$_d$) and a dryer efficiency (η_{dryer}) of 60%

is considered. The exhaust moist air exits at 70 ºC, resulting in a dryer heat requirement of approximately 1.2 kWh/kg of evaporated water (Salo 2011).

After drying, the biomass has to be ground. This will enable the fast heat up of the particles to the optimum temperature, providing as short as possible exposure at lower temperature. For fast pyrolysis, reports show that suitable particle sizes range from 0.5 to 2 mm (Oasmaa *et al*. 2010; Manuel *et al*. 2008; Kumar *et al*. 2010). In the case of torrefaction, different sizes have been tested, ranging from less than 1 mm (Prins *et al*. 2006) to more than 50 mm (Almeida *et al*. 2010). The electricity required for biomass crushing/chipping depends on the final particle size (Wright *et al*. 2010).

Fast Pyrolysis

Several types of reactors have been developed for fast pyrolysis tests (Hulet *et al*. 2005; Brown 2005). Currently, one of the most favored options is to utilize hot sand as a heat carrier, since high heating rates can be achieved. The fluidized bed pyrolyzer types have, therefore, good technological strength and market attractiveness for large-scale units. They can be classified into bubbling fluidized bed (BFB), with the bed material remaining suspended in one reactor, or circulating fluidized bed (CFB). The latter, sometimes referred to as transport bed, often has a separate combustion reactor used to re-heat the sand, which is continuously recirculated. Gas exiting from the pyrolysis reactor contains entrained particles that are separated through cyclones. Examples of companies that commercialize fluidized bed technology are Envergent, Metso, and Dynamotive.

After the cleaned gases exit the cyclone unit, they must be cooled for the formation of bio-oil and separation of non-condensable pyrolysis gases to prevent further detrimental reactions from taking place. The non-condensable gases can be used as fluidizing agents, although other gases such as N_2 can also be applied for this purpose. In a typical continuous process, the oil can be cooled, recirculated, and sprayed to quench the gases through direct contact heat transfer.

It is important to point out that there will always be a challenge of using the sub-products in an optimum manner (Oasmaa *et al*. 2010), suggesting that modifications to the char/gas handling can be very common. Taking into account that steam is required for biomass drying, and that residues are to be pyrolyzed, the following configurations are presented, as seen in Fig. 1.
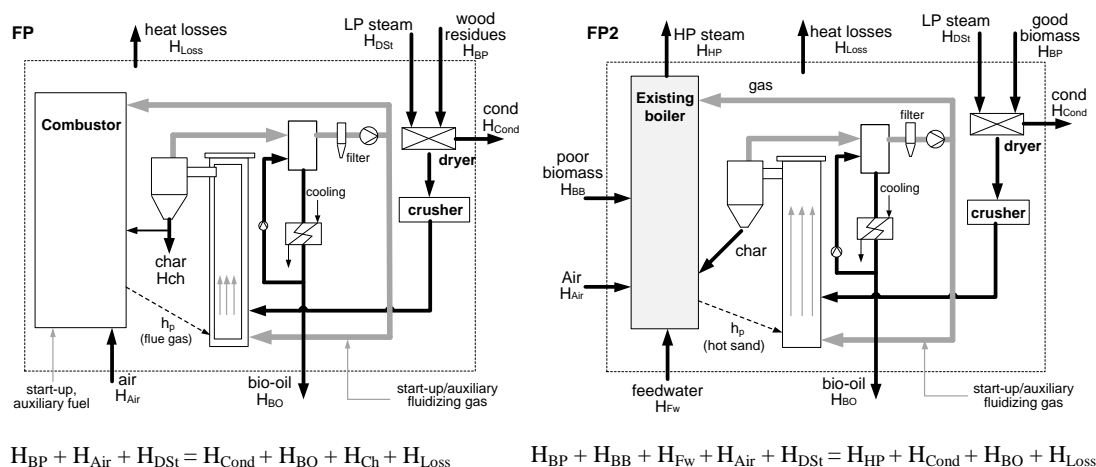

$$H_{BP} + H_{Air} + H_{DSt} = H_{Cond} + H_{BO} + H_{Ch} + H_{Loss}$$

$$H_{BP} + H_{BB} + H_{Fw} + H_{Air} + H_{DSt} = H_{HP} + H_{Cond} + H_{BO} + H_{Loss}$$

Fig. 1. Overall balances of integrated combustion and pyrolysis

FP: Co-production of biochar

Fractions of pyrolysis by-products are burned to produce hot flue gases, which are subsequently used to indirectly heat the bed material through, for example, a reactor jacket (Hulet *et al*. 2005). The hot sand acts as a heat carrier for the pyrolysis reactions. Since forest residues are used as feedstock, the quality and yield of bio-oil are expected to be lower when compared to bark-free wood. In this configuration with the BFB concept, the biochar is not fully mixed with the recirculating sand and can be alternatively recovered (Dynamotive 2013). As a result, biochar becomes a sellable high heating value by-product.

FP2: Co-production of steam

This scenario is suitable for existing mills already operating with fluidized bed boilers. Therefore, a separate combustor for the pyrolysis by-products would not be necessary. The idea is to maintain the same heat load that would be achieved with a standalone biomass boiler (BB case). With the integration of a CFB pyrolysis unit, the biochar, wood residues, and part of the pyrolysis gases are burned to generate high-pressure steam and also to provide the heat for pyrolysis through sand recirculation. This concept has been developed by VTT in Finland (Oasmaa *et al*. 2010). The bio-oil production would be limited to the boiler heat load and solids recirculation capacities.

Key assumptions

Discrepancies between yields of pyrolysis products are usually observed in the literature. This can be attributed to the differences in biomass composition, process conditions, apparatus reliability, and measurement errors. The average values however, including commercial scale units, are in the range of 60 to 70% of crude bio-oil (Badger *et al.* 2012; Envergent 2012; Dynamotive 2013; Oasmaa *et al*. 2010; Kumar *et al*. 2010), with lower yields expected for forest residues.

The heat for pyrolysis (h_p), for example, is dependent on the biomass species, reactor temperature, and consequently, on the changes in the pyrolysis reaction chemistry. Since large scale units processing eucalyptus are not presently in operation, exact h_p values are difficult to access. Therefore, the feasibility study relies on reported values for different biomass species (Daugaard and Brown 2003; Oasmaa *et al*. 2010). The assumptions for the balance are summarized in Table 2.

Table 2. Assumptions for Pyrolysis Balance

Stage	Assumptions	Ref
Pyrolysis and char removal	Yields: 70/60% bio-oil, 12/18% gas and 18/22% char; h_p for bark-free-wood/residues: 1.6/1.5MJ/kg; Efficiency of indirect heat exchange in FP1: 90%; Char removal efficiency of 95%	(Envergent 2012, Daugaart and Brown 2003, Dynamotive 2013)
Combustion	Biochar heating value: 26MJ/kg for FP and 30.6MJ/kg for FP2. These values are based on the balance between biomass input and products output; 70% of gas is burned; Flue gas to stack at 190ºC.	(Demirbas 2004, Wright *et al.* 2010)
Oil recovery	Quench, collection of aerosols (gas): 95%; Bio-oil heating value for bark-free-wood/residues: 15.6/14.9 MJ/kg;	(Oasmaa *et al.* 2010, Wright *et al.* 2010)

In the FP2 case, the pyrolyzer-to-boiler feed ratio should be balanced to avoid possible instabilities in the continuous recirculation of sand. Although different ratios can be expected for each application, experimental values between 0.55 and 0.65 (MW%) have been reported (Oasmaa *et al*. 2010). Taking this issue into account, the present work assumes that the poor biomass (bark and debris) available is incinerated and that approximately 280 t(dry)/d of bark-free biomass enter the pyrolyzer. This represents 2% of additional logs to complement the fines fraction, with a proportional increase in wood losses. On the other hand, improvement in the bio-oil quality is expected.

Torrefaction: T

The severity of the torrefaction process depends on the biomass type, residence time, and temperature. The effect of temperature is significant, with mass and energy losses increasing fast above 250 °C (Bergman *et al*. 2005). Severe torrefaction would result in higher mass losses and increased brittleness of the product, which could bring problems for integrity of the produced pellets. Hence, a relatively mild torrefaction temperature of 250 °C was assumed in this study. At this temperature, most experiments have resulted in 90 to 95% of the energy and 80 to 90% of the mass of the untreated dry biomass retained in the product (Prins *et al*. 2006; Almeida *et al*. 2010; Arias *et al*. 2008; Chew and Doshi 2011; Zanzi *et al.* 2004; Oliveira and Rousset 2009). The higher loss of mass than energy leads to slightly increased LHV.

One important issue is to determine the appropriate design for the heat integration. For this purpose, different configurations can be suggested, either by indirect or direct heating (Bergman *et al.* 2005). In this work, steam at pressure level used for boiler sootblowers (MP2) is assumed to provide indirect heat to the torrefaction reactor. The integration also allows the released non-condensable volatiles to be incinerated in the recovery boiler, as seen in Fig. 2.
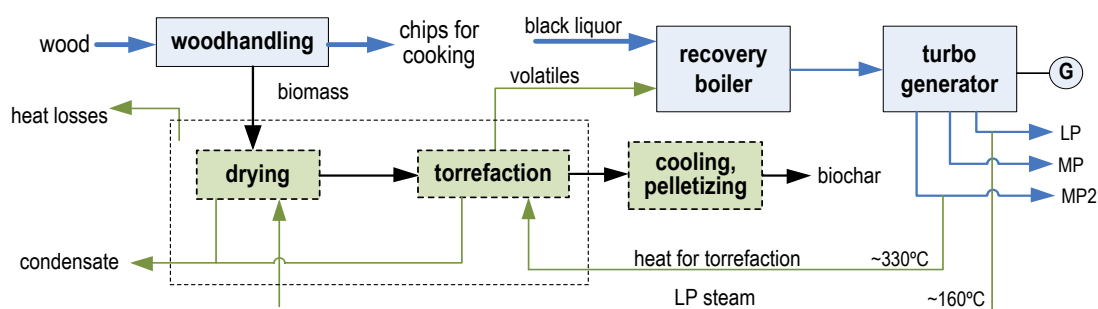

Fig. 2. Overall balance of integrated torrefaction

The torrefaction model was developed using IPSEpro, which is an equation-oriented stationary-state software developed by SimTech for power plant simulation. IPSEpro is a flexible tool for simulation, modeling, analysis, and design of components and processes in energy and process engineering (SimTech 2012). SimTech Simulation Technology is an Austrian firm providing the IPSEpro tool for a wide range of power and process industries. IPSEpro is used for this research to create the required models where needed. In addition to a library of common components used in thermal power plants, IPSEpro provides a Model Development Kit (MDK) by which the designer can build new models or modify the existing models according to the project's requirements. The steam

and power balance of the reference mill was reproduced with the objective of evaluating the possible changes after integration. The model is based on the assumptions of negligible energy needed in devolatilization reactions and negligible loss of heating value through partial combustion of the biomass. The energy requirement of torrefaction, H_{Torr}, is therefore obtained from:

$$H_{Torr} = \frac{1}{\eta_{torr}} \dot{m}_d \{ MC_d(h_{wL,in} - h_{wV,out}) + (1 - MC_d)c_{p,dry}(T_{out} - T_{in}) \} \quad (2)$$

An efficiency of $\eta_{torr} = 0.9$ was assumed, with the gas exiting at 250 °C from the reactor. The module was adjusted to produce a solid product, with mass and energy contents obtained experimentally from the torrefaction tests of *E. grandis* (Almeida *et al.* 2010*)* for both wood and bark. The solid mass flow rates and LHV values are given on a dry ash-free basis (daf). Therefore, with the net loss of heating value negligible, the LHV of gas phase becomes:

$$LHV_g = \frac{(\dot{m}_{ut}LHV_{ut} - \dot{m}_{torr}LHV_{torr})_{daf}}{\dot{m}_g} \quad (3)$$

Economic Analysis

Investment and operational costs for fast pyrolysis or torrefaction are not easy to access. One reason is attributed to the lack of references for large-scale units. Predicting future renewable energy prices is also subject to considerable uncertainty, since the market for the products is still developing and may vary between countries. The results of the economic analysis are presented in the form of series of curves at different investment costs, showing internal rate return (IRR) as a function of energy price. Fixed payback period of 10 years, NPV zero at the end of payback time and annual operating time of 8400 h/a, same as for the reference mill, are considered for all cases. When economical parameters were not treated as variables, the values presented in Table 3 were used. The analysis was based on solving for the interest rate by finding such present value factor *a* that yields a NPV (net present value) of zero with the chosen interest rate.

$$NPV = a(C_e + C_{product} - C_{O\&M} \pm C_{wood}) - C_{inv} \quad (4)$$

The variable $C_e = \Delta P_e \cdot t \cdot c_e$ represents the difference in annual value obtained from exported electricity in comparison with the reference mill. In the specific case of FP2, the C_e value is compared to the BB scenario. $C_{product}$ is the annual value of produced fuels for sale, $C_{O\&M}$ the annual operating and maintenance cost, and C_{inv} the total investment cost ($C_{O\&M} / C_{inv}$ of 5% is considered). The parameter C_{wood} refers to the cost for disposing the residues or for the additional wood brought from the forest.

In the reference mill, a minimum amount of residues is generated and have to be preferably disposed if not processed. With the integration of BB, T, or FP cases, the cost with disposal would be saved. For FP2, there is an extra expense with additional wood, as seen in Table 3. The investment cost analysis is not presented in detail, as this was done previously by Bagramov (2010) and Starck (2011). The values were derived from a confidential joint project involving the equipment vendors and one of the largest forest product companies.

bioresources.com

Table 3. Basis for the Economic Analysis

		BB	T	FP	FP2	Based on
Investment cost C_{inv}	M US$	50±15	40±15	85±20	45±15	(Bagramov 2010, Starck 2011, vendor quotes)
Construction	M US$	8.0	4.5	11.0	4.4	
Equipment	M US$	31.6	28.8	55.1	33.8	
Piping, electrification and automation	M US$	4.1	3.1	6.5	3.6	
Engineering and project management	M US$	6.3	3.6	7.4	3.2	
Residues disposal	US$/BDt	30	30	30	0	(Foelkel 2007)
Electricity price, c_e	US$/MWh	35-80	30/60	50	30/60	(FGV 2011)
Additional wood	US$/MWh	0	0	0	10	(Foelkel 2010)
Biochar price	US$/MWh	0	10-30	15/30	0	-
Bio-oil price	US$/MWh	0	0	20-60	45-85	-

The torrefaction and pyrolysis equipment prices as well as other major parts such as pyrolysis oil tanks and product silos are based on vendor quotes for piping, building, electricity, engineering, and project management costs with similar actual project data. The investment costs were compared to literature values (Felix 2005; Bergman 2005; Jones and Zhu 2009). Since actual project reference costs are still unknown, one should realize that the presented investment costs are to be considered as best estimates. The investment cost for the BB case includes the boiler facility and the increased costs with turbo generators and steam piping. However, the biomass pre-treatment can be disregarded.

For the FP2 case, the combustor is not needed, although additional wood and minor modifications in the existing boiler structure are required. A power consumption of 210 kWh per ton of dry input biomass and 300 kWh per ton of pellets were considered for pyrolysis and torrefaction, respectively. To evaluate the influence of the selling electricity prices on the PBP, two scenarios are considered for T and FP2, as indicated in Table 3. In the FP case, 50 USD/MWh is assumed for two different market prices for biochar. The revenue from pulp sales has no effects on the IRR calculation.

RESULTS AND DISCUSSION

A great advantage of processing the wood residues for additional income comes from the fact that the pulping process, sales, and pulp quality are not affected. The integrated technologies will require heat and electricity. For BB and FP2 cases, additional steam is generated. These differences result in varying amounts of exportable electricity that will affect the economic calculations.

The attractiveness of the processes in study will strongly depend on how the selling price of the new products sets itself in the market. Therefore, the purpose of the economic analysis is not to define the option with the highest revenue, but rather to show the main variables affecting the viability of each option. Table 4 summarizes the main results from the integrated mill balances.

bioresources.com

Table 4. Results of Integrated Mill Calculations

		BB	T	FP	FP2
Main inputs					
LP steam (dryer)	MW_{th}	3.7	24.1	24.1	10.1
MP2 steam (torrefaction)	MW_{th}	-	4.9	-	-
Heat load to boiler/combustor	MW_{th}	124.7	-	13.2[a]	120.3[a]
Pyrolysis/torrefaction feed	MW_{th}	-	124.7	124.7	56.4
Main outputs					
Steam generation	MW_{th}	102.4	-	-	95.9
Volatiles	MW_{th}	-	4.1[b]	-	-
Bio-oil	MW_{th}	-	-	69.3	35.4
Biochar for export	MW_{th}	-	121.1	37.7	-
Power balance					
Diff in power generation [c]	MW_e	+34.2	-4.3	-4.0	-4.1
Net power diff, ΔP_e [c]	MW_e	+32.2	-10.3	-9.0	-7.1
Sellable power	MW_e	76.7	34.2	35.5	69.6

[a] It includes the partial incineration of pyrolysis sub-products.

[b] Torrefaction gases as additional heat load to recovery boiler.

[c] In comparison with reference case for BB, T or FP, and with BB case for FP2.

The decrease in power generation is mainly attributed to the heat requirements for biomass drying, torrefaction, or pyrolysis processes. As expected, the ΔP_e values are negative for T and FP, and positive for the BB case. If incentives are offered for selling bioelectricity, the surplus amount can be increased almost 72% by installing a biomass boiler. When the residues are fully torrefied or pyrolyzed, the surplus amount of electricity is decreased by 23 or 20%, respectively. Nevertheless, approximately 35 MW_e can still be sold to the grid.

Heat is inevitably lost during several stages. In drying, steam is required to heat the ambient air and the wet biomass and also to vaporize the water. The condensate is fully returned to the boiler water treatment area, but the moist exhaust air is counted as a loss. In combustion, the losses are mostly attributed to hot flue gas, radiation/convection, and carbon in ash. In pyrolysis, heat will be lost during the bio-oil recovery (cooling) or radiation in the reactor and cyclones.

Figure 3 shows satisfactory prospects for new investments, reminding that FP2 is not comparable to any other but to the BB case. It can be observed that with a torrefied pellet price of over 17 USD/MWh, an IRR of higher than 10% can be achieved for the estimated range of investment costs. The figure also shows that torrefaction becomes more viable when electricity prices are not attractive for sale. The same concept is valid for the FP scenario, where there is also a challenge to assess the market values for two sellable products. In order to achieve an IRR of over 10% with biochar at 15 USD/MWh, the price of bio-oil would range from 20 to 26 USD/MWh. It is important to emphasize that the graphs do not indicate which technology is more economically attractive. The final decision will strongly depend on the local market requirements.
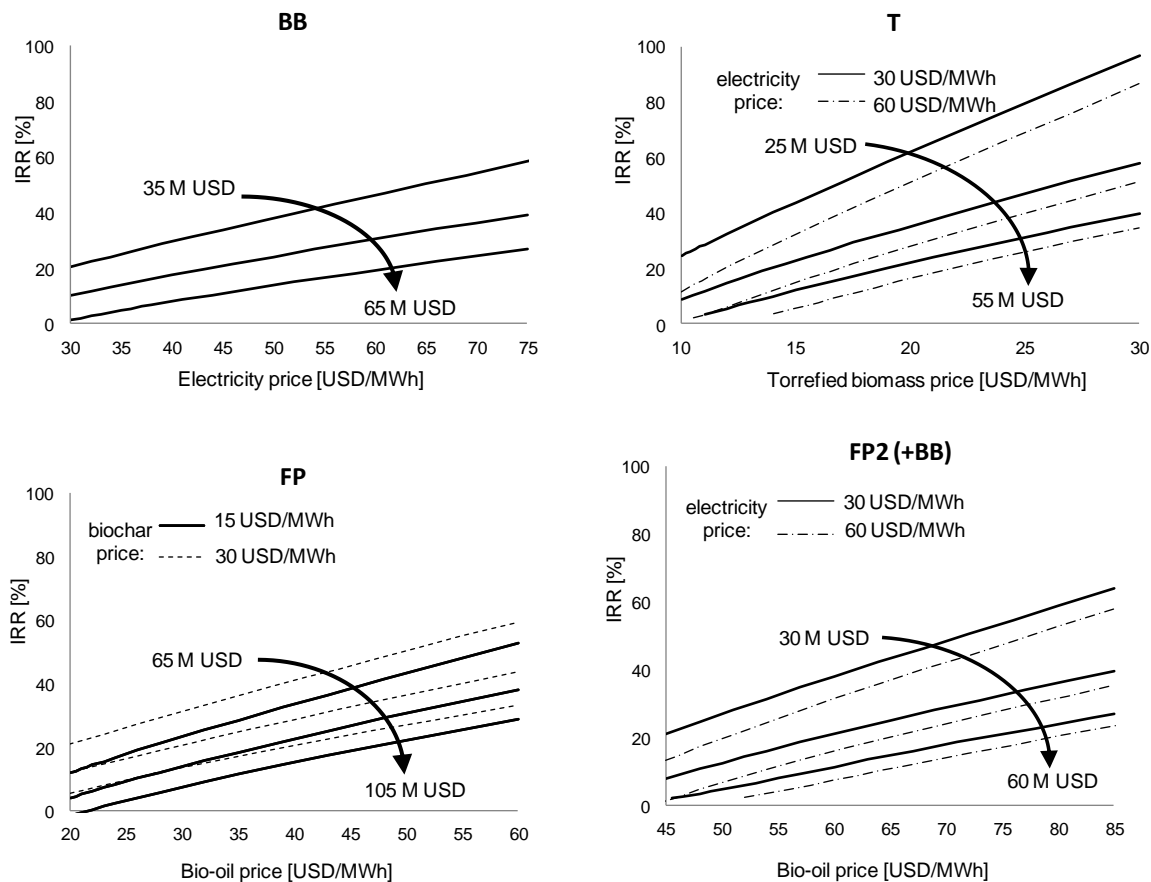
bioresources.com

Fig. 3. Internal return rate for the different cases

The steam generation in the FP2 case is 6.4% lower compared to the BB scenario. The biomass flow to pyrolysis should be approximately 50% higher to achieve the same BB steam rate, considering that only the poor biomass (fines excluded) is incinerated. This would result in a high pyrolyzer-to-boiler feed ratio, leading to probable instabilities in the recirculation of bed material. The new stream revenue has to then compensate for the decrease in exportable electricity and for the extra wood. In addition, the cost of disposal is not accounted for. When the price of FP2 bio-oil is 48 USD/MWh or higher for electricity price 30 USD/MWh, or 54 USD/MWh or higher for electricity price 60 USD/MWh, the IRR of over 10% is achieved for the estimated investment cost. For upper bound of the investment price, a bio-oil price of 58 USD/MWh to 64 USD/MWh is required to achieve an IRR of over 10 %. On the other hand, bark-free wood is used as feedstock and a better quality for the bio-oil is expected.

Regarding market development, the biochar has been already utilized for many years. Some applications for torrefied wood can include bakery ovens and replacement of coal in existing power plants. Bio-oil is still not well established as a sellable fuel. Bringing a new technology to market can be very challenging and expensive. In the same time there is a need to increase the familiarity of users, with companies eager to provide the resources or fortitude to progress beyond availability testing.

At mid-short term, bio-oil can be used as direct substitute to fossil fuels in power plants or in the industry of different segments. However, the substitution is not straight-

forward. Modifications in the feeding system are still required due to the higher density and lower heating value compared to light fuel oil. The adaptation of equipment material is also relevant, given the higher bio-oil acidity and the presence of ash. A promising option in the future is the upgrading to transport fuels such as diesel, gasoline, kerosene, methane, or jet fuels. For this purpose, full de-oxygenation followed by conventional refining would be required, since crude bio-oil contains high levels of oxygen and water.

CONCLUSIONS

1. Evaluating the future market value of the new products is challenging but indispensable to assess the feasibility of the technologies in study. The renewables incentives and selling electricity price are also important factors affecting the attractiveness.

2. Approximately 121 MW_{th} of torrefied pellets (T) or 107 MW_{th} of bio-oil and biochar (FP) can be produced in the pulp mill, but with the amount of exportable electricity reduced by 23 or 20%, respectively. As one alternative, the residues can be incinerated (BB) to generate steam and increase the surplus electricity by 72%.

3. In case a pyrolysis unit is attached to the biomass boiler (FP2), 158 t(dry)/d of additional wood is brought from the forest for pyrolysis. This results in a projected 35 MW_{th} of bio-oil but in 9.3% reduction in surplus electricity, attributed also to the limiting value assumed for the pyrolyzer-to-boiler feed ratio.

4. The results showed that investing in the production of bio-oil or torrefied pellets can bring satisfactory results regarding IRR. In order to achieve an IRR of *e.g.* over 10 % for the estimated investment cost, the price of electricity, pellets, and bio-oil should be approximately 30, 13, and 26 USD/MWh for BB, T, and FP cases, respectively. The selling price of FP2 bio-oil has to be higher to compensate for the additional wood and decrease in electricity generation.

REFERENCES CITED

Almeida, G., Brito, J. O., and Perré, P. (2010). "Alterations in energy properties of eucalyptus wood and bark subjected to torrefaction: The potential of mass loss as synthetic indicator," *Bioresource Technology* 101, 9778-9784.

Arias, B., Pevida, C., Fermoso, J., Plaza, M. G., Rubiera, F., and Pis, J. J. (2008). "Influence of torrefaction on the grindability and reactivity," *Fuel Processing Technology* 89, 169-175.

Badger, P., Badger, S., Puettmann, M., Steele, P., and Cooper, J. (2012). "Techno-economic analysis: Preliminary assessment of pyrolysis oil production costs and material energy balance associated with a transportable fast pyrolysis system," *BioResources* 6(1), 34-47.

Bagramov, G. (2010). "Economic of converting wood to biocoal," Master thesis, Lappeenranta University of Technology, 113 pp.

bioresources.com

Bergman, P. C. A., Boersma, A. R., Kiel, J. H. A., Prins, M. J., Ptasinski, K. J., and Janssen, F. J. J. G. (2005). "Torrefaction for entrained-flow gasification of biomass," Report ECN-C-05-067, Netherlands.

Bridgwater, A. V. (2012). "Review of fast pyrolysis of biomass and product upgrading," *Biomass Bioenerg* 38, 68-94.

Brown, J. N. (2005). "Development of a lab-scale auger reactor for biomass fast pyrolysis and process optimization using response surface methodology," Master thesis, ISU, US.

Chew, J. J., and Doshi, V. (2011). "Recent advances in biomass pretreatment – Torrefaction fundamentals and technology," *Renewable and Sustainable Energy Reviews* 15, 4212-4222.

Daugaard, D. E., and Brown, R. C. (2003). "Enthalpy for pyrolysis for several types of biomass," *Energy Fuels* 17, 934-939.

Demirbas, A. (2004). "Determination of calorific values of bio-chars and pyro-oils from pyrolysis of beech trunk barks," *J. Anal. Appl. Pyrolysis* 72, 215-219.

Demirbas, A. (2009). "Biorefineries: Current activities and future developments," *Energy Convers Manag* 50. 2782-2801.

Dynamotive Energy systems. Available online: http://www.dynamotive.com/news/presentations (accessed on 5 Jan2013).

EN12952-15. (2003). "European Standard: Water-tube boilers and auxiliary installations - Part 15: Acceptance tests.

Envergent Technologies, RTP yields. Available online: http://www.envergenttech.com/rtp.php. (accessed on 15 Dec 2012).

FAO yearbook of forest products. (2010). ISBN 978-92-5-007216-6.

Fernandez, V. (2011). "Air distribution influence on reduction degree target, 18th Latin America Congress on Recovery boiler," Fray Bentos – Uruguay, 15-17 Aug.

Felix, F. F. (2005). "Bioware Tecnologia" in Rocha J.D., Bioware Tecnologia and Nucleo Interdisciplinar de Planejamento Energetico (UNICAMP), Campinas-SP, Brazil.

FGV projetos. (2011). "Electricity and energy innovation," Report 1. In Portuguese. Available in http://fgvprojetos.fgv.br/

Foelkel, C. (2007). "Resíduos sólidos industriais do processo de fabricação de celulose e papel de eucalipto, parte 1 – resíduos orgânicos fibrosos," Eucalyptus online book & Newsletter. In Portuguese.

Foelkel, C. (2010). "Resíduos sólidos industriais do processo de fabricação de celulose e papel de eucalipto, parte 4 – casca suja," Eucalyptus online book & Newsletter. In Portuguese

Frederick, W. J. (2009). "Biorefineries for co-production of renewable transportation fuels," 45 Years Recovery Boiler Co-operation in Finland, Finnish Recovery Boiler Committee, Helsinki, pp. 145-156.

Germiniani, A. (2011). "Upgrade da Caldeira de Recuperação da Veracel utilizando a modelagem CFD," 18th Latin America Congress on Recovery boiler, Fray Bentos – Uruguay, 15-17 Aug.

Hamaguchi, M., Vakkilainen, E., and Ryder, P. (2011). "The impact of lignin removal on the dimensioning of eucalyptus pulp mills," *Appita J* 64, 433-438.

Hamaguchi, M., Cardoso, M., and Vakkilainen, E. (2012). "Alternative technologies for biofuels production in kraft pulp mills—Potential and prospects," *Energies* 5, 2288-2309.

Hulet, C., Briens, C., Berruti, F., and Chan, E. W. (2005). "A review of short residence time cracking processes," *IJCRE* 3, 1-72.

Jones, S. B., and Zhu, Y. (2009) "Preliminary economics for the production of pyrolysis oil from lignin in a cellulosic ethanol biorefinery," report PNNL-18401 Pacific Northwest National Laboratory for U.S. Department of Energy.

Kankkonen, S., Suutela, J., Polikarpova, M., and Vakkilainen, E. K. (2010). "Enhancing the power generation in a modern greenfield pulp mill," Proceedings of the 2010 International Chemical Recovery Conference, March 29 - April 1, 2010, Williamsburg Lodge, Williamsburg, Virginia, USA, Vol. 2, 323-335.

Kumar, G., Panda, A. K., and Singh, R. K. (2010). "Optimization of process for the production of bio-oil from eucalyptus wood," *J. Fuel Chemistry Technology* 38, 162-167.

Labigalini, A. (2011). "Eldorado and Suzano Maranhão: XL size Recovery Boilers with ash leaching duo, 18th Latin American Congress on Recovery boiler, Fray Bentos – Uruguay, 15-17 Aug 2011.

Manuel, G. P., Xiao, S. W., Jun, S., Martin, J. R., Fujun, T., Woo-Jin, L., Hongwei, W., Chun-Zhu, L. (2008). "Fast pyrolysis of oil mallee woody biomass: Effect of temperature on the yield and quality of pyrolysis products," *Ind. Eng. Chem. Res*. 47, 1846-1854.

Manuel, G. P., Chaala, A., Pakdel, H., Kretschmer, D., Rodrigues, D., and Roy, C. (2006). "Multiphase structure of bio-oils," *Energy Fuels* 20, 364-375.

Ng, K. S., and Sadhukhan, J. (2011). "Process integration and economic analysis of bio-oil platform for the production of methanol and combined heat and power," *Biomass & Bioenergy* 35, 1153-1169.

Oasmaa, A., Kuoppala, E., Selin, J. -F., Gust, S., and Solantausta, Y. (2004). "Fast pyrolysis of forestry residue and pine. 4. Improvement of the product quality by solvent addition," *Energy Fuels* 18, 1578-1583.

Oasmaa, A., Solantausta, Y., Arpiainen, V., Kuoppala, E., and Sipilä, K. (2010). "Fast pyrolysis bio-oils from wood and agricultural residues," *Energy Fuels* 24, 1380-1388.

Oliveira, R. T., and Rousset, P. L. A. (2009). "Effects of torrefaction on energy properties of *Eucalyptus grandis* wood," *CERNE* 5, 446-452.

Pirraglia, A., Gonzalez, R., Saloni, D., Wright, J., and Denig, J. (2012). "Fuel properties and suitability of *Eucalyptus benthamii* and *Eucalyptus marcarthurii* for torrefied wood and pellets," *BioResources* 7(1), 217-235.

Pöyry. EIA/RIMA da expansão da unidade industrial. (2011). Available online: www.fibria.com.br/shared/midia/publicacoes/EIA_RIMA_Tres_Lagoas.pdf

Prins, M. J., Ptasinski, K. J., and Janssen, F. J. J. G. (2006). "Torrefaction of wood. Part 2. Analysis of products," *J. Anal. Appl. Pyrolysis* 77, 35-40.

Raukola, A. T., Ruohola, T. and Hakulinen, A. (2002). "Increasing power generation with black liquor recovery boiler," Proceedings of 2002 TAPPI Fall Technical Conference, September 8 - 11, San Diego, CA, 11 pp.

Sadhukhan, J., Ng, K. S., Shah, N., and Simons, H. J. (2009). "Heat integration strategy for economic production of CHP from biomass waste," *Energy & Fuels*, 23, 5106-5120.

Salo, K. (2011). "Biomass gasification in pulp and paper industry," IEA Task 33 report Meeting, Piteå, Sweden, Oct 19.

SimTech (2012). "IPSEpro," [online] last update October 2011. Available at: <http://www.simtechnology.com/IPSEpro> [Accessed 3 June 2012]

bioresources.com

Starck, J. (2011). "The business model and commercial profitability of fast pyrolysis-based bio-oil production facility in Savonlinna region in Finland," Master thesis, Lappeenranta University of technology, 85 pp.

Vakkilainen, E. K. (2005). "Kraft recovery boilers – Principles and practice," Suomen Soodakattilayhdistys r.y., Valopaino Oy, Helsinki, Finland, 246 p. ISBN 952-91-8603-7.

Werkelin, J., Skrifvars, B. J., and Hupa, M. (2005). "Ash-forming elements in four Scandinavian wood species. Part 1: Summer harvest," *Biomass Bioenergy* 29, 451-466.

Wright, M. M., Satrio, J. A., Brown, R. C., Daugaard, D. E., and Hsu, D. D. (2010). "Techno-economic analysis of biomass fast pyrolysis to transportation fuels," Subcontractor Report NREL/SR-570-2761; NREL: Lakewood, Colorado, USA, 2010.

Zanzi, R., Ferro, T., Torres, A., Soler, P. B., and Björnbom, E. (2004). 2nd World Conf. on Biomass for Energy, Industry and Climate Protection, 10-14 May 2004, Rome, Italy, pp. 859-862.