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QUANTIFYING THE ENVIRONMENTAL RELEASES ASSOCIATED WITH THE INTEGRATION OF BIOENERGY AND WOOD PRODUCTS MANUFACTURING OPERATIONS - A CASE STUDY APPROACH

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White Paper

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1.0 INTRODUCTION

In the last decade, forest products manufacturing facilities have become increasingly interested in investing in bioenergy technologies that can take full advantage of the chemical composition of wood residues. While a number of these technologies have already been applied to woody biomass, little is known about the type and rate of the associated environmental releases.

Several years ago, NCASI published Special Report No. 07-05, *The Forest Biorefinery Environmental Footprint* (NCASI 2007). This report provided a qualitative overview of the potential environmental releases from various technologies within generic forest biorefinery configurations. While the report explored the production of bioethanol, syngas, and bio-oil from wood and highlighted potential emissions, it did not provide a quantitative assessment of the environmental releases associated with the manufacturing of these products due to the limited commercial applications operating at the time.

Although several operational biofuel plants have been reported in the literature since the publication of Special Report No. 07-05, only a few of these plants are known to be integrated into existing manufacturing operations. The extent to which the energy and environmental profiles of an existing forest products facility are affected by the on-site production of biofuels depends on the level of process integration attained.

Recognizing that process integration is a site-specific attribute, this report presents a case study to quantify the fuel energy consumption and environmental releases associated with the production and on-site use of wood-derived syngas at a plywood facility. The analysis primarily consists of a comparison between the energy and environmental profiles prior to, and after, the implementation of the bioenergy project. The information used to undertake this quantification includes mill-specific data as well as available literature on wood gasification.

2.0 WOOD GASIFICATION

The thermochemical conversion of wood residue into biofuels relies on the process of *pyrolysis*, which is the decomposition of biomass at elevated temperatures and in the presence of a limited amount of oxygen (White and Dietenberger 2001; Khan 2006). *Gasification* is a form of pyrolysis that maximizes fuel gas production. The gas produced is known as *syngas* and is primarily composed of carbon monoxide (CO) and hydrogen (H_2), with traces of other gaseous products such as methane (CH_4), lighter hydrocarbons, water vapour, ammonia (NH_3), carbon dioxide (CO_2), and nitrogen (N_2). Oxygen may be supplied directly or by means of a gasification agent like air, steam, carbon dioxide, or some combination of them (Schubert 2009; Jackson et al. 2010).

The gasification process starts by heating and drying the wood residue at temperatures below 200°C. This is followed by pyrolytic decomposition of the biomass (200–500°C) which primarily produces hydrogen, gaseous hydrocarbons, pyrolysis oils, and charcoal (Schubert 2009). The heat required by this decomposition is typically produced via (a) controlled combustion of carbonaceous material (volatile hydrocarbons and a portion of charcoal) which forms CO_2, H_2O, CO, N_2, and H_2 (Khan 2006); and (b) oxidation of H_2 to water (Dutta 2007). This heat causes the increase of temperatures to the 1200–1300°C range and also fuels the subsequent stage of reduction (Rudakova 2009). Reduction reactions primarily involve the gasification of charcoal, i.e., the reaction of charcoal (carbon), CO_2 and steam to generate CO and H_2. Hydrogen can also react with some of the charcoal to produce

methane (Higman and van der Burgt 2011; Dutta 2007). Given that reduction reactions are endothermic, the gas temperature progressively decreases during this stage (Rudakova 2009). The initial energy needed by the endothermic reactions can be supplied either by the partial combustion of biomass (direct gasification) or from an external source through a heat exchanger surface (indirect gasification) (Knoef and Ahrenfeldt 2005; Kehbila 2010).

The type of gasification agent used has an impact on the composition of the resulting syngas, and thus on its heating value (Jackson et al. 2010). For example, use of air results in low-energy content syngas due to the significant presence of nitrogen, whereas use of steam results in syngas with significantly higher heating value due primarily to the increase of CH_4 in the gas mix (Kehbila 2010; Tampier et al. 2006). Brown (2005) and Goble and Jarvis (2007) have compiled typical syngas HHV ranges for different gasification agents: 2–9 MJ/Nm^3 (air), 10–15 MJ/Nm^3 (oxygen), and 15–20 MJ/Nm^3 (steam).

3.0 CASE STUDY

3.1 Process Description

The case study mill manufactures approximately 200,000 MSF3/8" of plywood annually. The mill's feedstock consists of softwood, primarily Douglas fir, with smaller proportions of White spruce, Balsam fir, Lodgepole pine, and Western hemlock.

The mill operates a wood gasification system that transforms bark generated on site into renewable syngas. The system was developed and installed by Nexterra, and consists of two atmospheric fixed-bed updraft gasifiers. Wet bark (6–60% moisture, wet basis) is size-reduced to three inches or less in a hogger and is bottom-fed into the centre of the gasifier. Combustion air is introduced into the base of the fuel pile. Bark runs concurrently with the syngas generated. As fuel enters the gasifier, it moves through progressive stages of drying, pyrolysis, gasification, and reduction to ash. The ash migrates to the base of the gasifier and is removed intermittently through an automated in-floor ash grate. Syngas leaves at the top of the gasifier at a temperature between 260 and 370°C.

Figure 1 shows a schematic of the gasification system used on site. The syngas does not need to be cleaned and moves directly into an oxidizer where it is combusted. Flue gases leave the oxidizer at a temperature between 900 and 1050°C. A portion of the flue gases passes through a glycol heating loop for log conditioning while the other is directed to an air-to-air heat exchanger to supply the necessary heat required by one of the veneer dryers and the panel press operated by the mill. Under this configuration, gasifiers may enter periods of some instability as a result of downstream fluctuations such cycles in energy demands, dryer downtime, etc.

Figure 1. Gasification System. Description: (1) Fuel In-Feed System; (2) Gasifier; (3) Ash Removal; (4) Syngas [Source: Nexterra.]

3.2   Syngas Characteristics

The analysis presented in this report relies in large part on the accuracy of the calorific content and yield of the syngas produced on site. These parameters were estimated based on information provided in the literature for gasification units of the type operated at the plywood facility. Nexterra claims their gasification technology is capable of delivering syngas with a higher heating value (HHV) of 300 Btu/ft^3 or 11.2 MJ/Nm^3, while operating on wet bark fuel with a moisture content of 45%[1]. This value is, however, significantly higher than the 4–7 MJ/Nm^3 range expected from fixed-bed gasifiers fed with much drier wood and using air as gasification medium (Rao et al. 2004; Li et al. 2004; Jungbluth et al. 2007; Chen et al. 2012; Kwiatkowski, Dudyński, and Bajer 2013; Sethuraman, Huynh, and Kong 2011). The HHV of syngas is ultimately a function of its chemical composition. In turn, syngas composition primarily depends on the nature and moisture of the fuel, gasification temperature and technology, and oxygen supply. The available literature pertaining to fixed-bed gasifiers using air as a gasification agent (Jungbluth et al. 2007; Rao et al. 2004; Zainal et al. 2001) suggests a composition primarily dominated by nitrogen, followed by carbon monoxide, hydrogen and carbon monoxide, smaller proportions of methane, and trace amounts of other hydrocarbons and nitrogen species.

Zainal et al. (2001) provides a thermodynamic equilibrium model to predict the composition of syngas based on the moisture of wood fed into an air-blown downdraft fixed-bed gasifier. The data generated by this model were used in this report to estimate the dry composition of syngas produced from wet wood with 50% moisture (wet basis) (see **Table 1**).

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[1] http://www.nexterra.ca/files/pdf/20050715.pdf

Table 1. Approximate Dry Composition of Syngas Produced from a Fixed-Bed Gasifier*

Compounds	Composition (% vol.)
Nitrogen (N_2)	42.4
Carbon monoxide (CO)	10.3
Hydrogen (H_2)	26.8
Carbon dioxide (CO_2)	18.8
Methane (CH_4)	1.7

*Source: Based on data reported by Zainal et al. (2001). Fuel: Wood fuel @ 50% moisture (wet basis). Temperature of gasifier bed: 800°C.

The HHV of syngas can be approximated from the heats of combustion of the main individual compounds, expressed in MJ/Nm^3, and the respective dry gas contents, expressed as molar or volumetric fractions (Li et al. 2004):

$$HHV = 12.75 \times [H_2] + 12.63 \times [CO] + 39.82 \times [CH_4]$$

Solving the above equation using the information provided in **Table 1** results in an **HHV of 5.39 MJ/Nm^3**, which is very close to the value reported by Rao et al. (2004) for the gasification of wood in an updraft fixed-bed unit blowing air at an equivalent ratio[2] of 0.35-0.36. Rao et al. (2004) also estimated a **syngas yield of 2,662 Nm^3 per dry metric ton of wood**, which is the value assumed in the calculations undertaken in this report.

3.3   Wood Balance

The wood feedstock to the mill consists of logs and dry veneers. **Table 2** lists the operating parameters used to undertake a wood balance around the plywood plant. The process generates multiple wood residue streams including bark, peeler cores and clippings, trims, sanderdust, and sawdust. Results are depicted in **Figure 2** and show that approximately 13,000 dry metric tons of bark and over 53,000 dry metric tons of other wood residues are annually generated by the manufacturing process.

Table 2. Operating Parameters for the Production of 200,000 MSF3/8" of Plywood

Parameter	Value	Unit*
Conversion factor from MSF3/8" to m^3	0.8849	
Log requirement	1.67	m^3/MSF3/8"
Dry veneer requirement	0.025	odmt/MSF3/8"
Basic density of wood	0.419	odmt/m^3
Density of plywood	0.50	mt/m^3
Moisture of plywood	0.10	fraction, dry
Generation bark ratio	0.165	odt bark/odt wood in plywood

* MSF3/8": thousand square feet 3/8 in.; od: oven-dry; mt: metric ton.

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[2] The equivalent ratio represents the mass of air consumed to gasify 1 kg of wood to the mass of air required for the complete combustion of the same amount of wood.
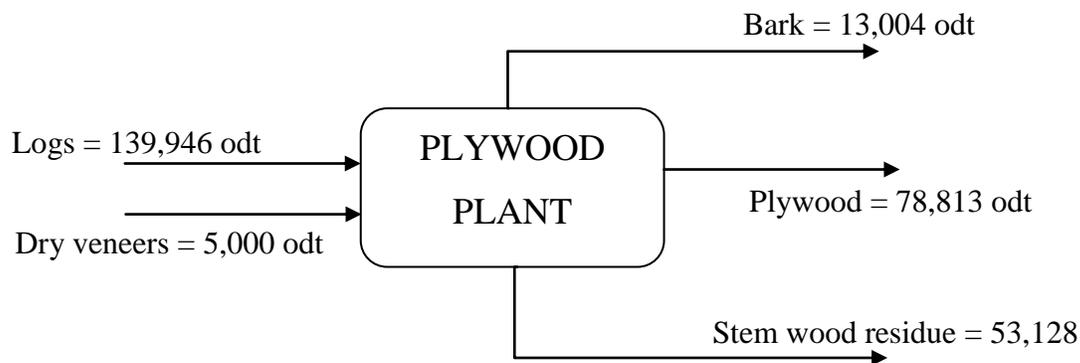
Bark = 13,004 odt

Logs = 139,946 odt

PLYWOOD
PLANT

Plywood = 78,813 odt

Dry veneers = 5,000 odt

Stem wood residue = 53,128

Figure 2. Wood Mass Balance around the Plywood Plant (Annual Amounts)

3.4 Fuel Energy Requirement

A portion of the mill's fuel energy needs is currently supplied by the oxidation of syngas. The assumption is that all 13,004 dry metric tons of bark generated every year from the manufacturing operations (see Section 0) are used as fuel to the gasification system. The net energy produced from the combustion of syngas is calculated as follows:

$$E_{Syn}=13{,}004 \text{ dry metric ton wood/yr} \times HHV_{Syn} \times Yield_{Syn} \times f_g$$

where HHV_{Syn} is the higher heating value of syngas (5.39 MJ/Nm^3), $Yield_{Syn}$ is the syngas yield (2,662 Nm^3/dry metric ton wood) and f_g (0.9) is the factor used to deduct the amount of energy necessary to vaporize the water present in the gas as well as the water formed from the hydrogen present in the gas.

Using the above equation, the **net energy generated from the combustion of syngas is 168,079 GJ per year**. According to recent mill data, the annual volume of natural gas currently burned is approximately 8.3 million Nm^3. Assuming natural gas has an HHV of 38.09 MJ/Nm^3, the **total energy supplied by both sources amounts to 452,611 GJ per year.** This amount is assumed to also be the mill's full fuel energy requirement prior to the installation of the gasification system.

Figure 3 and Figure 4 show the most relevant mass and energy flows affecting the operation of the plywood plant before and after the integration of the gasification system. The operation of the gasification system allows the mill to displace about 37% (=168,079 GJ/452,611 GJ) of the overall consumption of natural gas. This bioenergy is used to condition the logs and dry 40% of the green veneers.
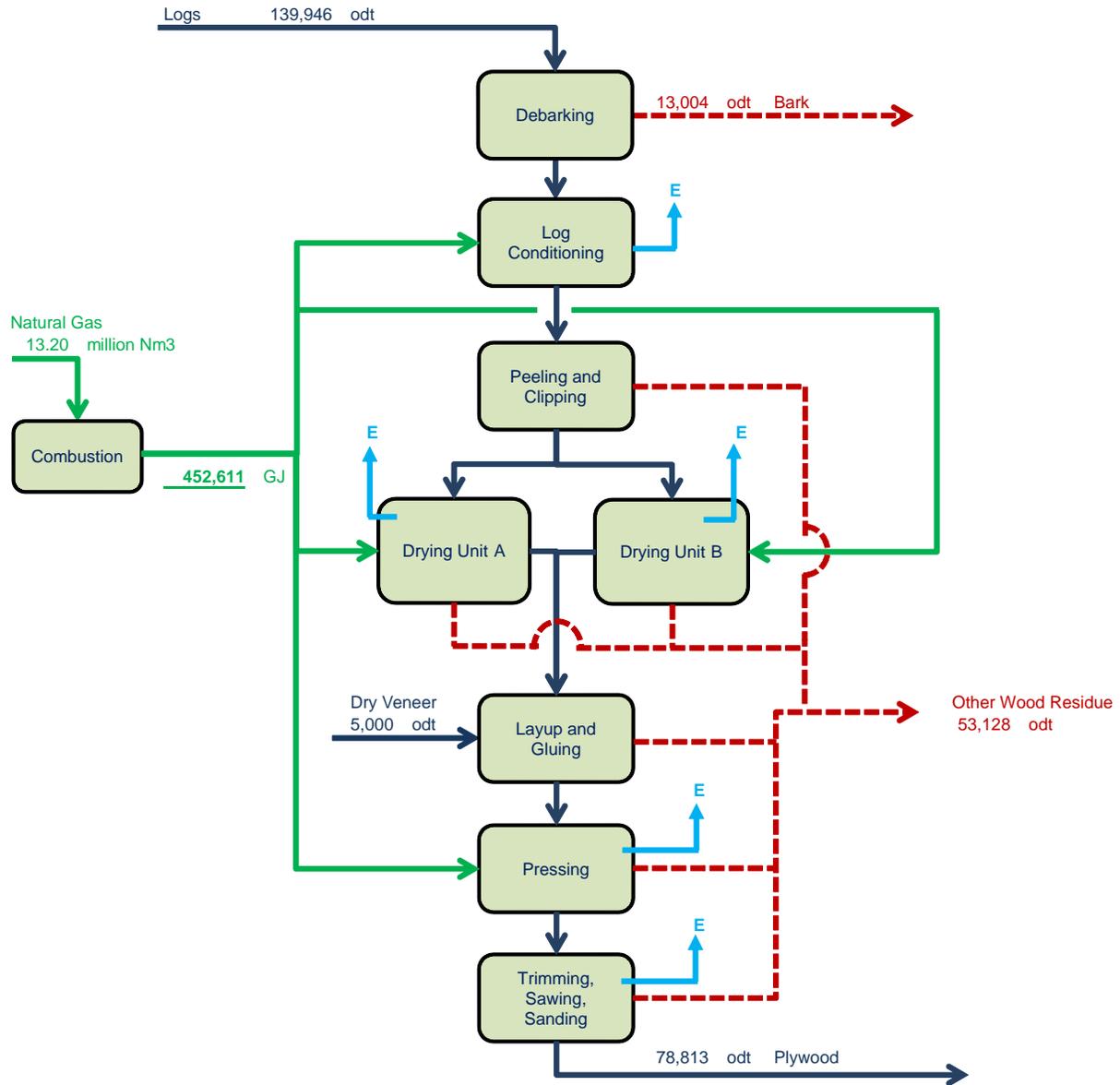
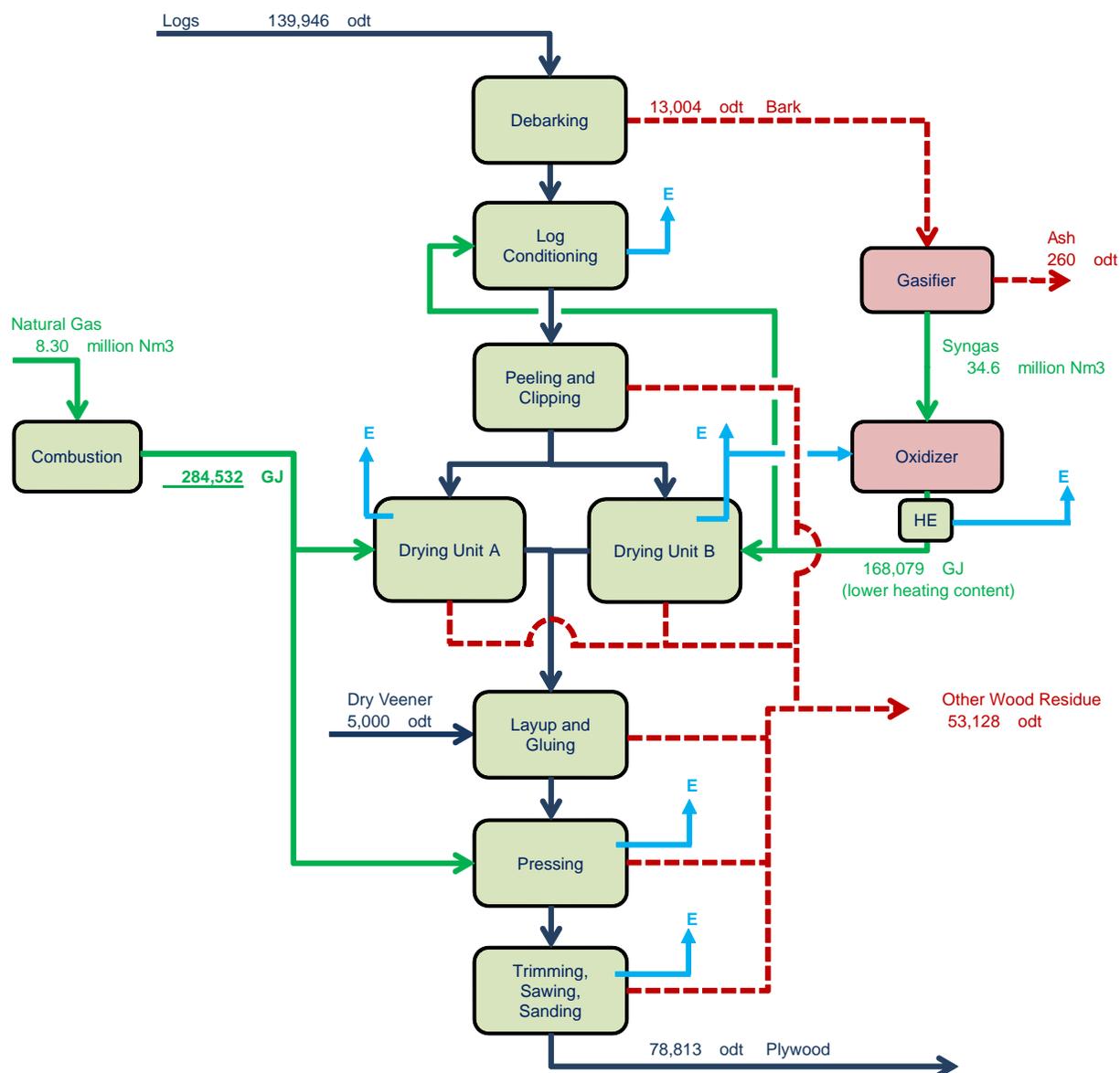**Figure 3.** Operation Fueled by Natural Gas Only [The letter "E" represents emissions.]

Figure 4. Operation Fueled Partly by Bark (Syngas) [The letter "E" represents emissions.]

Table 3 summarizes fuel energy information associated with the operation of the plant before and after the installation of the gasification system. It is worthwhile to note that the accuracy of the estimated fuel energy requirement is affected by the uncertainty associated with natural gas and bark flow accounting, and the calorific content and yield of syngas.

Table 3. Fuel Energy Parameters for the Production of 200,000 MSF3/8" of Plywood

Parameter	Value	Unit*
Fuel energy requirement	452,611	GJ
Before Operation of the Gasification System		
Natural gas consumption	13.2	million Nm^3
After Operation of the Gasification System		
Natural gas consumption	8.30	million Nm^3
Syngas yield, $Yield_{Syn}$	2,662	Nm^3/odt bark
Syngas higher heating value, HHV_{Syn}	5.39	MJ/Nm^3
Syngas production & consumption	34.6	million Nm^3
Lower heating content of syngas	168,079	GJ
Lower heating content of natural gas	284,532	GJ
Cold gas efficiency**	64.5	%

* Nm^3: cubic metres at normal conditions; GJ: gigajoules; odt: oven-dry metric ton.

** Cold gas efficiency $= \dfrac{Yield_{Syn} \times HHV_{Syn} \times f_g}{HHV_{bark} \times f_{bark}}$, where HHV_{bark} is the higher heating value for softwood bark [21,100 MJ/odt, ref. (NCASI 2011)] and f_{bark} (0.95) is the factor used to deduct the amount of energy necessary to vaporize the water present in the wood fuel as well as the water formed from the hydrogen present in the fuel.

3.5   Environmental Releases

NCASI has estimated potential emissions for a number of substances of relevance to plywood manufacturing operations. Filterable and total particulate matter (PM) estimates for the veneer dryer/cooler units are based on mill-specific stack test results. Carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOC) estimates for the gasification system are based on emission factors published by Nexterra[3]. Greenhouse gas (GHG) emissions were estimated using available emission factors for the combustion of natural gas and biogas (IPCC 2006; NCASI 1981). All other emission estimates are based on the latest NCASI wood products emission factors for log vats, direct-fired veneer dryers burning natural gas, veneer coolers, hot presses, sanders, and saws[4]. Table 4 shows estimated annual emissions before and after the installation of the gasification system.

It should be noted that at this facility, none of the veneer dryers are equipped with emission control devices. However, the operation of the bioenergy system permits the recycling of a portion of the dryer exhaust gases back to the syngas oxidizer, thus allowing for the thermal destruction of significant amounts of organic emissions generated during wood drying (see Figure 4). This reduction in emissions is reflected in Table 4 not only for VOCs, but for all organic contaminants and carbon monoxide. Significant reductions are also observed in total PM, primarily condensable PM, presumably due to the indirect drying of a portion of wood veneers (air-to-air heat exchange) as well as the destruction of some condensable organics in the oxidizer.

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[3] http://www.bcsea.org/sites/default/files/Nexterra_BCSEA0210-BW.pdf
[4] NCASI Wood Products Air Emissions Database: http://www.ncasi.org/Programs/Air-Quality/Resources/Air-Emissions-Database---Wood-Products/Index.aspx

Table 4. Estimated Annual Emissions from the Plywood Plant
with and *without* a Gasification Operation

| Emissions | Operation | | Units | Change | Process Sources for Which Emission Factors are Available* |
	Without Gasification System	With Gasification System			
CO_2eq†	25,538	16,066	tonnes	-37%	C
Organic Contaminants					
Acetaldehyde	6,923	4,539	kg	-34%	LV, VD, VC, HP, SN, SW
Acetone	7,158	4,836	kg	-32%	LV, VD, VC, HP, SN, SW
Acrolein	812	487	kg	-40%	VD
Alpha-pinene	18,040	12,856	kg	-29%	LV, VD
Benzene	516	310	kg	-40%	LV, VD
Beta-pinene	4,258	2,882	kg	-32%	VD
Formaldehyde	6,394	3,975	kg	38%	VD, VC, HP, SN, SW
Methanol	11,722	10,020	kg	-15%	LV, VD, VC, HP, SN, SW
Methyl ethyl ketone	271	192	kg	-29%	VD, VC, HP
Methyl isobutyl ketone	716	459	kg	-36%	VD, VC, HP
Phenol	310	186	kg	-40%	VD
Propionaldehyde	162	97	kg	-40%	VD
Styrene	139	83	kg	-40%	VD
Toluene	676	406	kg	-40%	VD
Criteria Air Contaminants					
Carbon monoxide (CO)	45,120	29,325	kg	-35%	VD, VC, G
Filterable PM	23,796	23,336	kg	-2%	VD, VC, G, HP
Total PM (filt.+cond.)	70,562	60,259	kg	-15%	VD, VC, G, HP
NOx	2,240	21,158‡	kg	845%	VD, G
VOC as carbon	58,494	40,009	kg	-32%	VD, VC, G, HP, SN, SW

* C: Combustion; G: Gasifier/Oxidizer System; HP: Hot press; LV: Log vat; SN: Sander; SW: saw; VC: Cooling section of dryers; VD: Veneer dryers.

† CO_2eq emissions are based on the latest emission factors for natural gas combustion and biogas combustion (IPCC 2006; NCASI 1981). These factors are incorporated in NCASI's pulp and paper GHG calculation tools.

‡ NOx emissions from the gasifier/oxidizer system are based on an emission factor published by Nexterra.

Interestingly, NOx emissions increase in spite of the lower amounts of natural gas consumed after the gasification system was put in service. NOx emissions from the combustion of natural gas are the result of the "thermal NOx" pathway, i.e., the thermal fixation of atmospheric nitrogen, which starts occurring at temperatures above 1,500-1700°K (1,227-1427°C) (Huynh and Kong 2013; Kwiatkowski, Dudyński, and Bajer 2013) and becomes predominant above 2200°K (1927°C) (Sethuraman, Huynh, and Kong 2011). Data suggest that the reduction in NOx emissions expected from the displacement of natural gas is in fact counterbalanced by the higher emissions associated with the combustion of syngas. Indeed, the available literature reports significant NOx formation in biomass-derived syngas combustion (Sethuraman, Huynh, and Kong 2011; Kwiatkowski, Dudyński, and Bajer 2013; Huynh and Kong 2013). In particular, Huynh and Kong (2013) found that NOx emissions from the combustion of wood-derived syngas are higher than those resulting from the combustion of natural gas. However, unlike natural gas, syngas is oxidized at temperatures below

those triggering the "thermal NOx" mechanism. A plausible cause of the NOx increase is, therefore, the relatively high content of nitrogen species in syngas, mainly ammonia (NH_3) with lesser quantities of hydrogen cyanide (HCN) and nitric oxide (NO), which would form NOx primarily via the "fuel NOx" mechanism (Sethuraman, Huynh, and Kong 2011).

The ash generated from gasification (around 260 metric tons per year) is given away as a soil conditioner and applied to farmland. Ash has met the provincial criteria for land application purposes. The facility is also contemplating the possibility of using the ash as an aggregate material.

There are no significant wastewater issues associated with the gasification system operated at the plywood facility.

4.0   CONCLUSIONS

The case study described in Section 3.0 suggests that integrating a wood gasification system into an existing wood products facility can result in significant reductions in fossil fuel consumption and atmospheric emissions. For a 200,000 MSF3/8" plywood plant, the **fossil fuel-derived energy displaced by combusting the syngas produced from 13,000 dry metric tons of bark is equivalent to 0.95 GJ per m^3 of wood product**. This can translate into significant energy savings considering that fuel consumption intensity is below 4 GJ/m^3 for 85% of softwood plywood/veneer facilities in Canada (see percentile distribution in **Figure 5**).

The integration of the gasification system has also resulted in reduced GHG emissions, namely about 9,500 metric tons less CO_2eq emitted to the atmosphere relative to the previous operation fueled only by natural gas. Expressed as emissions intensity, this reduction is equivalent to nearly 54 kg of CO_2eq per m^3 of wood product. Again, this is not a trivial drop given the GHG emission intensity reported by the Canadian softwood plywood sector (see percentile distribution in **Figure 6**).

As shown in **Table 4**, except for NOx emissions, the integration of the bioenergy system into the plywood facility resulted in an average 32% reduction for all emissions.

Finally, handling of the ash generated from gasification requires implementation of a special storage area on site. Equally important is the identification of an outlet for this ash, thus minimizing the need for landfilling. In this regard, the use of ash as a liming agent is a possibility, provided provincial requirements are met and nearby farmers are willing to apply it on their agricultural lands.
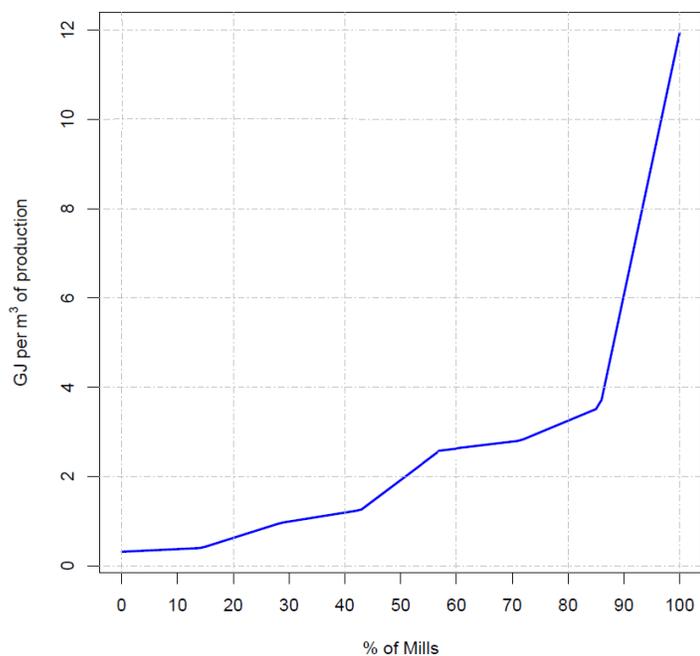
Figure 5. Fuel Energy Intensity – Canadian Softwood Plywood and Veneer Mills [Source: 2012 Canadian Wood Products Environmental and Energy Performance Benchmarking Data]

Figure 6. GHG Emission Intensity – Canadian Softwood Plywood and Veneer Mills [Source: 2012 Canadian Wood Products Environmental and Energy Performance Benchmarking Data]

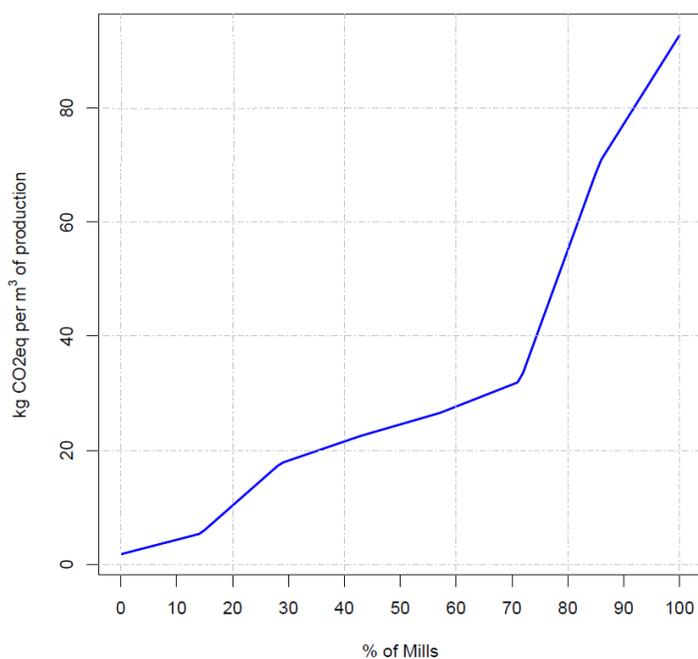# REFERENCES

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