Sustainability Assessment of OSB and Softwood Plywood Manufacturing in North America

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Abstract

The Canadian wood products industry, including structural panels, is very dependent on the US housing market. Since the US housing crisis in 2006, exports of Canadian wood products to the US significantly dropped annually at a devastating rate. With the growing trend for sustainable construction, the widespread influence of promotions from campaigns such as Wood First and Wood Works and as well as the building standards of the LEED rating system, the demand for wood products is steadily being restored. Amongst the primary construction materials, the manufacturing of structural products of OSB and softwood plywood has slightly higher environmental impact than the manufacturing of lumber due to the drying and pressing processes and the resins used as well. As the demand for structural panels is being slowly created, manufacturers in this industry need to lower the emissions generated from manufacturing to lower environmental impacts. This thesis contrasts and analyzes the emissions and emission control data from the Life Cycle Assessment and Life Cycle Inventory reports for OSB and softwood plywood. In general, between both structural panel products, plywood is the more sustainable product of the two with lower energy utilized and fewer emissions of CO_2, SOx, NOx, VOC and particulate matter generated in the manufacturing process. To further reduce emissions associated with manufacturing of both panel products, the theoretically plausible solution is to combine the use of regenerative thermal oxidizer, which can remove 99% more VOC emissions than that of the wet electrostatic precipitator (NCASI, 1999), with an emissions trading legislature.

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1 Introduction

Demand for oriented strand board and softwood plywood products were once steadily increasing in the Canadian wood exports industry before 2000 (Poon, 2010). Low strength variation and narrow allowable design stress are both engineered into these products (Ellis, 2010), which led them to become preferable single family housing construction sheathing materials. However, since the US housing crisis in 2006, demand for Canadian OSB and softwood plywood significantly fell. Exports of Canadian OSB to the US dropped at record high levels in the years of 2007 and 2008 at an average of 39.47% (Poon, 2010), while plywood exports dropped at a record high average of 30.12% from 2008 to 2009 (Poon, 2010). In the structural panel industry, plywood struggles to gain structural panel market share from OSB (Poon, 2010); nonetheless at the current decreasing rate of demand for plywood panels, plywood is not likely to be completely replaced by OSB. However, with the current growing trend in sustainable construction, wood products are promoted and demanded as construction material in North America. Noticeable campaigns include Wood First and Wood Works promote the use of wood products through public education and training. In Oregon, negotiation to pass a Wood First bill "to direct the state of Oregon to use wood as a preferred building material" (Holt, 2011) in 2011; although the negotiation was unsuccessful, Wood First will continue to involve the state of Oregon with their campaign (Andre, 2011). Other means of promotion takes place through financial incentives. LEED rates and scores buildings according to their potential impact in both the environment and human health. Grants are awarded to homeowners depending on the levels of certification their homes are qualified in. Aside from promotions, there exists pre-fab housing in the US that involves constructing the entire home within a plant and assembling the house on-site to primarily reduce cost and environmental impact. Demand for pre-fab housing was on a decline since 2006, but due to the events of hurricane Katrina, the demand was boosted as manufacturers were called upon to rebuild the many destroyed homes in New Orleans (Moldvay, 2011). Mainly because of lower cost and environmental impact, pre-fab housing is currently well recognized and the demand is forecasted to grow annually by 6.5% until 2016 (Moldvay, 2011). In general, sustainable construction is an influential growing trend that will revive the wood industry through creating demand in North America. Amongst the primary construction materials of lumber, OSB and softwood plywood, the manufacturing of structural panel products has slightly greater environmental impact than the manufacturing of lumber, because of emissions generated from the drying and pressing processes and the resins used as well (Athena Sustainable Materials Institute, 2009). Yet, these products will be greatly demanded as sheathing materials with the increasing sustainability campaigns and pre-fab housing demands. OSB and softwood plywood utilize more available timber material in a tree than lumber, thus achieving higher wood fibre utilization within a tree. The more efficient, sustainable use of wood fibre in OSB and softwood plywood when compared to lumber offsets the slightly higher emissions. In addition, OSB and softwood plywood also serve as components in engineered products such as the web of I-joist. As a result, manufacturers in the structural panel industry need to lower the emissions generated from manufacturing to lower the associated environmental impacts. In this thesis, the environmental impact and emission control systems reported in Canadian life cycle assessment reports of OSB and softwood plywood are contrasted with the data provided in the US life cycle inventory reports to search for potential improvements in the manufacturing process. The OSB manufacturing process is first described along with the subsequent emissions from each procedure. After process description, environmental impact data from Canadian life cycle assessment and US life cycle inventory reports are presented in the format of LCA impact categories. Following environmental impact from both reports, analysis and recommendations are discussed. Furthermore, the manufacturing process of softwood plywood is also described with the subsequent emissions. Environmental impacts from LCA and LCI reports on plywood manufacturing are then provided. Lastly, an analysis and recommendations are discussed regarding the sustainability of the structural panel products, emission control systems and environmental impacts.

2 Canadian and US OSB Study

2.1 OSB Manufacturing Process

The following section provides a brief description of the manufacturing processes and the subsequent emissions involved in the production of OSB.

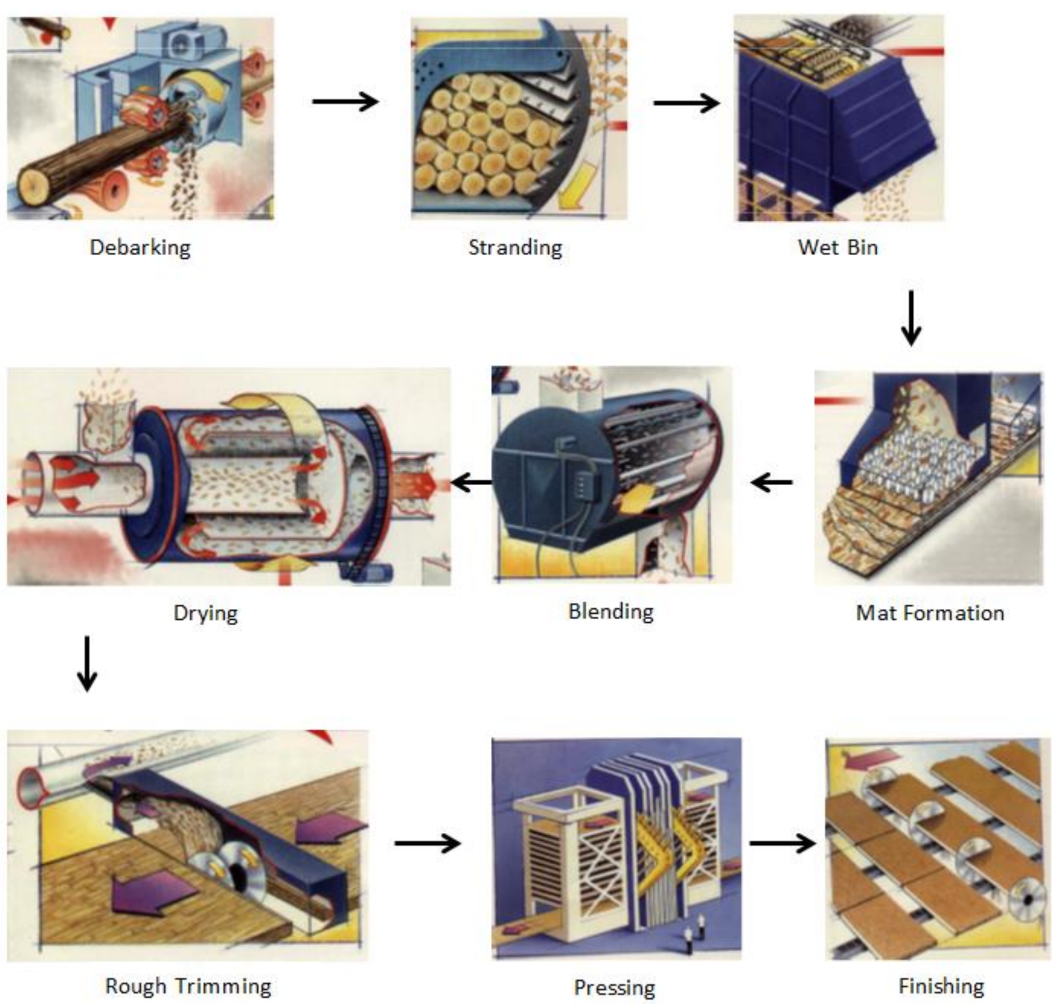


Figure 1: OSB manufacturing process

Source: Smith, G. (2012). WOOD 487. Vancouver, British Columbia, Canada. Retrieved April 10, 2012

2.1.1 Log Preparation

Log debarking and stranding are the first processes in OSB manufacturing. Within the stranding process, knives of a strander cut the logs into strands.

Wood particles and sawdust are the forms of particulates emitted from these processes. There are generally two particulate sizes produced, particulates with diameter of 10 microns or less, known as PM_{10}, and particulates with a diameter of 2.5 microns or less, referred to as $PM_{2.5}$ (Smith K. T., 2009). Additional particulates are also released from vehicle activities on the job site and wind dispersion of "uncovered bark or wood fines storage piles" (Smith M. , 2009)

2.1.2 Drying

Drying is the most energy demanding and polluting procedure in the entire manufacture process. Through a dryer, the moisture of strands are reduced from an initial moisture content of roughly 50-60% to its final moisture content of 3-4% (Ellis, 2011). Three types of dryers used in the industry are the commonly used triple-pass rotary drum (Smith M. , 2009), single pass rotary drum, and conveyor dryers. Currently, direct-fired rotary drum dryers typically use wood residue as fuel, while "natural gas or oil fired rotary drum dryers" (Smith M. , 2009) are rarely used. Conveyor dryers differ from rotary drum dryers in that the former utilizes indirect fire to dry strands entering a conveyor. The result is reduced inlet temperatures of approximately 160^{o}C, whereas rotary dryers have higher inlet temperatures of up to 870^{o}C.

During drying, the combustion of fuel and drying of strands generate harmful emissions. Depending on the fuel source, combustion typically generates "particulate matter, nitrogen oxide, carbon dioxide and carbon monoxide" (Smith M. , 2009). In addition, wood naturally contains volatile compounds that are released during the drying process as volatile organic compound (VOC) and hazardous air pollutants (HAPs). An emission known as blue haze is also generated from the dryer. This is the result of certain VOCs and condensable PM being released in the form of vapor that is later condensed in ambient air temperature (Smith M. , 2009).

2.1.3 Blending

During blending, a blender mixes surface strands with liquid or powder phenol-formaldehyde (PF) and another blender mixes strands to be used for the core of the OSB panel with PF or diphenol methane diisocyanate (MDI) resin (Smith M. , 2009).

Emissions of VOC and HAPs within this process are released by the resins, although emissions from blending are much lower compared to drying and pressing processes (Smith M. , 2009).

2.1.4 Pressing

The strands are then laid and oriented perpendicular to the previous layer of strands being laid. After mat formation, the mat is trimmed and pressing follows. Heat and pressure are applied to the mat in order to "activate the resin and bond the strands" (Smith M. , 2009). To attain this heat at the press, heat generated by a boiler is transferred to the press via steam, hot water or oil (Smith M. , 2009). The fuel sources for the boiler vary from wood residue to natural gas or oil.

Similar to drying, pressing is also primarily responsible for emitting air pollutants due to the particulates generated from fuel combustion and the volatile compounds released from the pressing process. The latter occurs through the release of vapor, consisting of formaldehyde and phenol, upon opening of the press (Smith M. , 2009).

2.1.5 Finishing

Finally, the panels are trimmed to their final dimensions and finished to customer preference. Particulate emissions are produced from the trimming procedure, and additional emissions are produced when sawdust piles are dispersed by wind (Smith M. , 2009).

2.2 Life Cycle Assessment of OSB

The following is a summary of energy utilization and air emissions released from the manufacturing process of OSB production in Canada.

2.2.1 System Boundaries

Four Canadian OSB manufacturing mills participated in this study. Their geographical locations are rather diversely distributed across the provinces of BC, Alberta, Ontario and Quebec (Athena Sustainable Materials Institute, 2008). These mills "represent slightly more than 10% of all [OSB] plants in Canada" (Athena Sustainable Materials Institute, 2008), and their annual production of 3/8-inch basis ranged approximately between 167 to 625 MMSF.

2.2.2 LCA Results

The following paragraphs and tables display the results of environmental impacts generated from the manufacturing of OSB.

Energy Source	Resource Harvesting (MJ)	Resource & Material Transportation (MJ)	Manufacturing (MJ)	Total (MJ)
Non-renewable, fossil	308	184	2,112	2,604
Non-renewable, nuclear	1	1	126	128
Renewable (SWHG)	1	0	331	332
Renewable (biomass)	0.05	0	2,399	2,399
Feedstock, fossil	0	0	899	899
Feedstock, biomass	0	0	10,612	10,612
Total Primary Energy	310	185	16,479	16,974

Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.

Table 1: Energy utilization in production of 1 MSF 3/8 inch basis OSB in absolute value

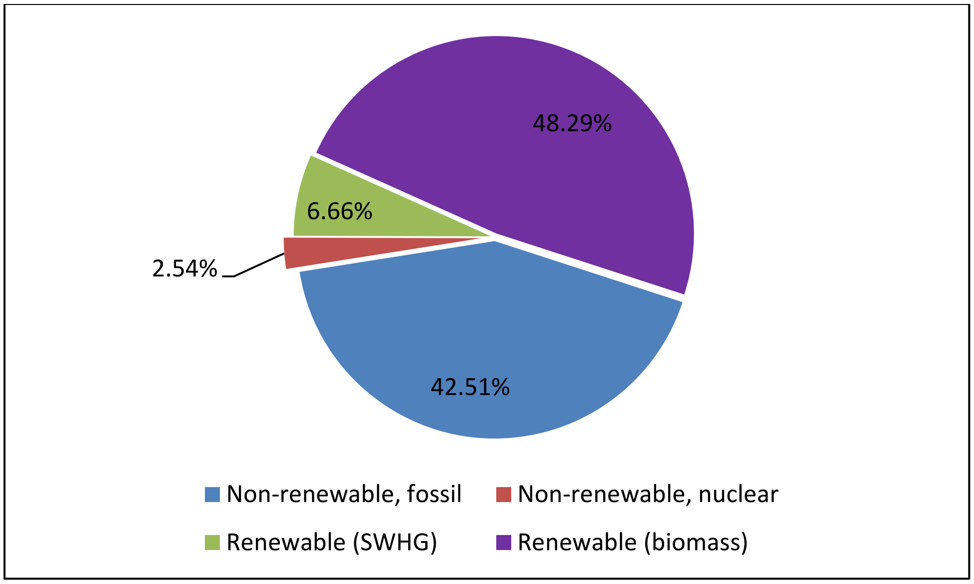
Energy Source	Resource Harvesting	Resource & Material Transportation	OSB Manufacturing	Total
Non-renewable, fossil	11.8%	7.1%	81.1%	100.0%
Non-renewable, nuclear	0.9%	0.5%	98.6%	100.0%
Renewable (SWHG)	0.4%	0.0%	99.6%	100.0%
Renewable (biomass)	0.0%	0.0%	100.0%	100.0%
Feedstock, fossil	0.0%	0.0%	100.0%	100.0%
Feedstock, biomass	0.0%	0.0%	100.0%	100.0%
Total Primary Energy	1.8%	1.1%	97.1%	100.0%

Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.

Table 2: Energy utilization in production of 1 MSF 3/8 inch basis OSB in percentage

Total Primary Energy

In this cradle-to-gate life-cycle assessment (LCA), the production of OSB is divided into three production processes of resource harvesting, resource and material transportation, and OSB manufacturing (Athena Sustainable Materials Institute, 2008). Combining the primary energy requirements of these three production processes, the total is calculated to 17 GJ of energy, and the manufacturing process accounts to 97.1% of this total primary energy. As displayed in Table 1, OSB embodies biomass and feedstock energy as well, and with this energy of 11.5 GJ removed from the energy demand, only 5.46 GJ is required for OSB production. This input energy is evenly derived at 50/50 from two types of sources, renewable and non-renewable, because of the abundant use of biomass as a thermal fuel to dry raw wood furnish and hydro power as energy in resource harvesting and manufacturing. Consumption of this cumulative energy input is, however, unequal across the unit processes. As displayed in Table 2, the manufacturing process consumes the majority of primary energy, mainly due to the high energy consumption procedures such as drying and pressing. Even with the huge demand for energy from the manufacturing unit process, the entire manufacture of OSB is almost half self-efficient (Athena Sustainable Materials Institute, 2008).

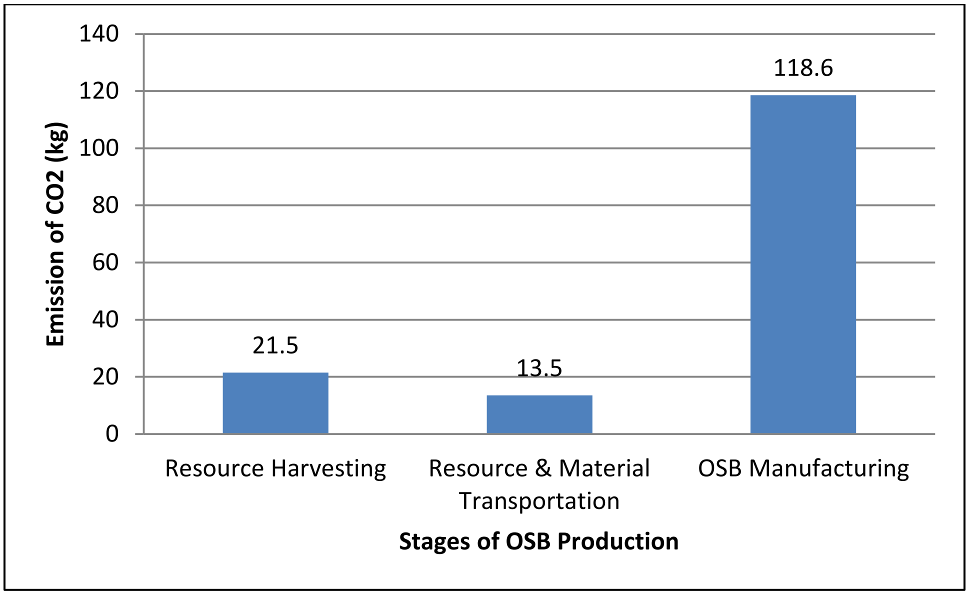


Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.

Figure 2: Energy Utilization within the Manufacturing Process (Percentage)

Shown in Figure 2, up to 48.3% of the energy consume on-site is derived from renewable biomass sources. While the other 42.5% is from the consumption of non-renewable fossil energy, which is mainly the result of converting fossil fuel into heat required for drying and pressing of the OSB mats. Thus, biomass is the dominant source of renewable energy, while fossil fuel is major source of non-renewable energy utilized in the manufacturing process.

Global Warming Potential



Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.

Figure 3: Emission of CO_2 in the production of OSB per MSF 3/8-inch basis

As for global warming potential, a total of 154 kg of CO_2 is produced per MSF of OSB (Athena Sustainable Materials Institute, 2008). Figure 2 displays the mass of CO_2 produced across the three production processes. OSB manufacturing is the greatest impacting processes for producing over 100 kg of CO_2, a mass that takes up 77.2% of the total CO_2 produced, while resource harvesting amounts to 20% and transportation accumulates the least at 8.8%.

Carbon Balance

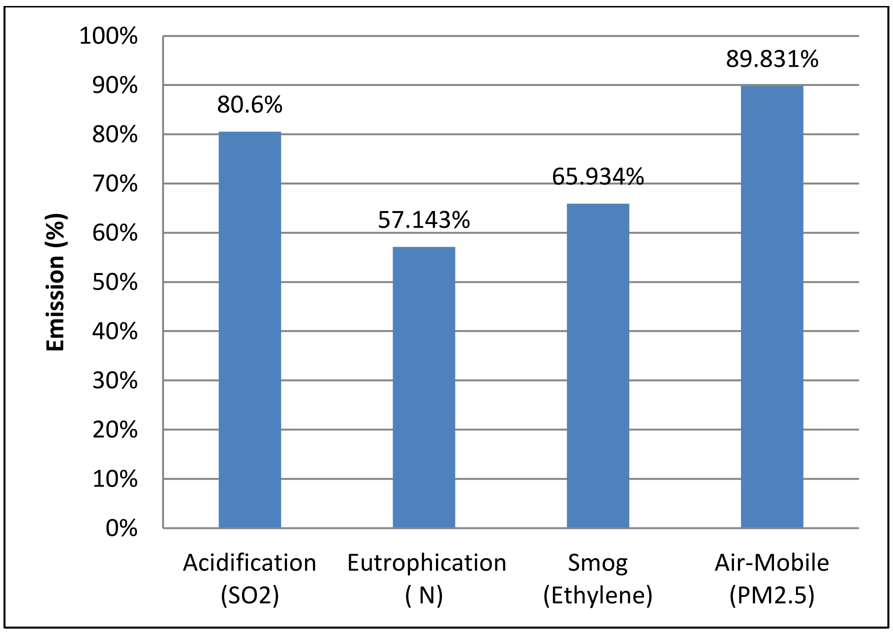
In each MSF of OSB, there is a net carbon balance of 912 kg of CO_2 sequestered within the product. Subtracting 154 kg of emissions from fossil derived sources, the carbon balance equates to a net positive carbon balance of 758 kg of CO_2 (Athena Sustainable Materials Institute, 2008).

Other Air Emissions

	Resource Harvesting	Resource & Material Transportation	OSB Manufacturing	Total
Acidification (Kg of SO_2)	0.31	0.11	1.74	2.16
Eutrophication (Kg of N)	0.002	0.001	0.004	0.007
Smog (Kg of Ethylene)	0.23	0.08	0.6	0.91
Air-Mobile (Kg of $PM_{2.5}$)	0.04	0.02	0.53	0.59

Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.

Table 3: Air Emissions generated in the production of OSB per MSF 3/8-inch basis



Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.

Figure 4: Air Emissions generated within the manufacturing process for 1 MSF 3/8-inch basis of OSB

Acidification potential is measured on the basis of SO_2 emissions. Sulfur dioxide is the product of fossil fuel combustion in the manufacturing unit process, where the drying and pressing processes consume the majority of fuel (Athena Sustainable Materials Institute, 2008). The manufacturing process accounts for 80% of SO_2 emissions.

The combined nitrogen emissions from manufacturing and resource harvesting processes accumulate to 90% of the overall water eutrophication impact. Nitrogen is released from "both fossil fuel emissions and fertilizer use in the forest" (Athena Sustainable Materials Institute, 2008).

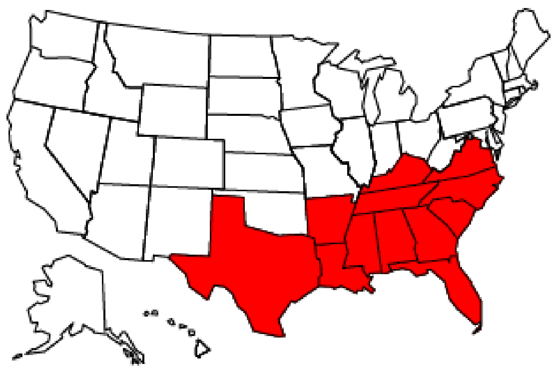
The overall smog impact is mainly contributed by the manufacturing process at 65.9% of the total ethylene emission of 0.91 kg (Athena Sustainable Materials Institute, 2008).

Production of 1 MSF of OSB releases a combined mass of 5.9 kg of particulates at 2.5 micron in diameter from all three unit processes. Up to 89.8% of these particulates are emitted from the manufacturing process (Athena Sustainable Materials Institute, 2008).

2.3 Life Cycle Inventory of OSB

The following is a summary of energy utilization and air emissions released from the manufacturing process of OSB production in the Southeast region of US.

2.3.1 System Boundaries



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.
Figure 5: Survey Region for Participating OSB Mills

An LCI survey on OSB production was conducted by 22 OSB manufacturing plants across the Southeast region of the United States (Kline, 2004). Figure 4 displays the states in which the participating mills are located. The annual production size of these mills ranged approximately between "340,000 to 380,000 MSF of 3/8 inch basis" (Kline, 2004). When surveyed, these plants produced 1.4 million MSF 3/8" OSB, which generally represented "18% of the total production in the South and 11.8% of the total US production" (Kline, 2004).

2.3.2 Life Cycle Inventory Results

The following paragraphs display results of environmental impacts generated from the manufacturing of OSB.

Total Primary Energy

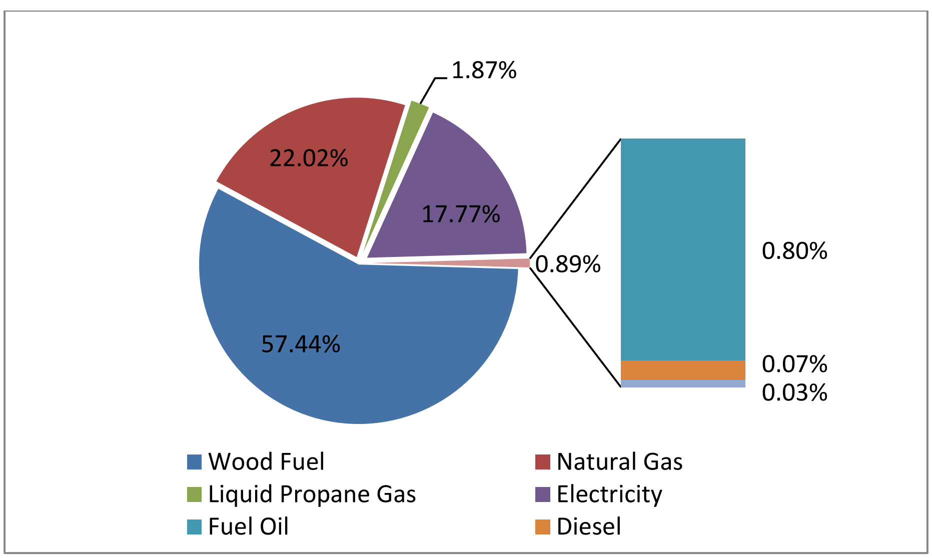
Energy Utilization per MSF 3/8" basis OSB within Manufacturing

Energy Source	Manufacturing (MJ)	Percentage
Wood Fuel	2113.03	57.44%
Natural Gas	810.19	22.02%
Liquid Propane Gas	68.95	1.87%
Diesel	2.59	0.07%
Fuel Oil	29.38	0.80%
Gasoline	0.95	0.03%
Electricity	653.76	17.77%
Total Primay Energy	3678.85	100.00%

Source: CORRIM, Southeastern OSB production, 2004

Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Table 4: Energy utilization within manufacturing for 1 MSF 3/8-inch basis of OSB



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Figure 6: Energy utilization per MSF 3/8-inch basis of OSB within manufacturing (percentage)

Shown in Table 4, producing one MSF of OSB in the southeastern US region requires a total cumulative energy of 3680 MJ. Though OSB production in this region requires large amounts of energy, 57% of which is derived from combustion of wood fuel, consisting of bark, OSB dust, fines and trimmings generated from manufacturing processes (Kline, 2004). The remaining energy is derived from combustion of fossil fuels. In addition, 17.8% of this cumulative energy is primarily in the form of electricity utilized in the production processes within manufacturing. Natural gas is the next primary source of energy; though the consumption is relatively smaller, this is mainly used "for back-up or secondary heat generation, providing up to 12% of heating requirements" (Kline, 2004). Following natural gas is liquid propane gas, which is used in small volumes as the fuel is used by forklifts mainly in the finishing process and heat generation in the manufacturing process. In general, fossil fuel requirement is very low. Aside from its use in forklifts and log handling, fossil fuel is only used in emission control activities. Figure 6 exhibits the proportion of various fuel sources used across the unit processes of OSB manufacture.

Electricity

Utilization of primary energy sources for the generation of electricity in the Southeastern region

	Percentage Share, 1998[1/]												
Fuel Source	AL[2]	AR	FL	GA	KY	LA	MS	NC	SC	TN	TX	VA	Avg
Coal	59.5	50.7	34.6	60.6	95.7	23.2	34.1	56.9	37.1	56.4	37.4	43.6	49.2
Petroleum	0.2	0.3	21.6	0.6	0.1	0.7	15.7	0.2	0.4	0.7	0.0	3.7	3.7
Gas	2.0	8.1	16.7	1.5	0.6	31.6	16.4	0.8	0.5	0.6	33.9	3.0	9.6
Nuclear	23.9	28.7	16.4	27.2	0.0	18.3	26.7	31.9	55.9	29.0	10.9	37.7	25.6
Hydro	8.8	6.8	0.1	4.4	3.6	0.0	0.0	3.4	2.9	9.6	0.4	0.4	3.4
Non utility	5.5	5.4	10.6	5.7	0.0	26.2	7.1	6.8	3.3	3.7	17.4	11.6	8.5

1/ *Source*: Energy Information Administration/State Electric Profiles 2000, Department of Energy. http://www.eia.doe.gov/cneaf/electricity/st_profiles/toc.html
2/ Abbreviations of Southeastern States

Figure 7: Utilization of primary energy Sources for the generation of electricity in the Southeastern Region US

From Figure 5, a total of 654 MJ of electricity is used to produce 1 MSF of OSB. However, the importance is not the amount of electricity used; the focus is the fuel source used to generate the electricity. Consumed up to 49.2%, coal is the dominating fuel source followed by nuclear energy, natural gas, petroleum and hydro. Analyzed with SimaPro 5 and the FAL database, significant environmental impacts have been shown to have been strongly correlated with coal, nuclear and as well as petroleum combustion (Kline, 2004). Natural gas, however, has relatively less impact on the environment (Kline, 2004).

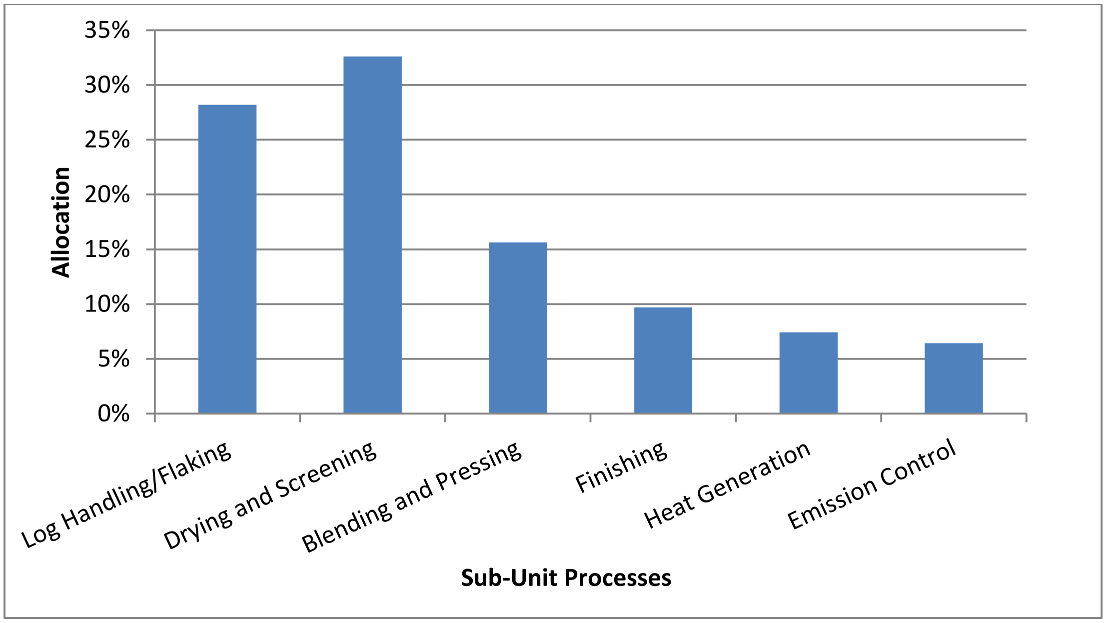
Electricity allocated to each sub-unit process

Sub-Unit Process	Original Survey	Allocation[1/]	Allocation
	%	%	KWh/MSF
1-Log Handling/Flaking	25.5	28.2	51.2
2-Drying and Screening	29.5	32.6	59.2
3-Blending and Pressing	14.1	15.6	28.4
4-Finishing	8.8	9.7	17.6
5-Heat Generation	6.7	7.5	13.5
6-Emission Control	5.8	6.4	11.7
Other Utilities (overhead)	9.6	---	---
Total:	**100.0**	**100.0**	**181.6**

1/Weighted allocation of overhead electrical load to all sub-unit processes.

Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Table 4: Southeastern electricity allocation along the sub-unit processes of manufacturing for 1MSF 3/8-inch basis of OSB



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.*
Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Figure 8: Sourtheastern electricity allocation along the sub-unit processes of manufacturing

As shown in Figure 6, the processes of log handling, drying, and screening have the most electricity demand at 25.5% and 29.5% respectively. Though this data is surveyed only from one mill, the data is still representative of all OSB mills as "similar types of equipment" (Kline, 2004) are used in the manufacturing process, with exceptions to emission systems. Table 4 displays the percentage and as well as absolute values of electricity allocated in the sub-unit processes of manufacturing.

Log Handling/Stranding

Electricity is the most demanded energy, as displayed in Figure 6. Though this huge demand is necessary, as powerful motors are needed to handle and cut green logs into strands.

Drying and Screening

Throughout the entire OSB production, drying and screening are the processes that demands energy to the highest degree. This demanded energy comes in the form of electricity and heat generated from the combustion of wood residues produced earlier in the log handling process (Kline, 2004). Entire 59.2 kWh of electricity and 2.17 BTU of heat are used to process 712 kg of green strands into 608 kg of dry strands of roughly 5% MC for every MSF of OSB (Kline, 2004).

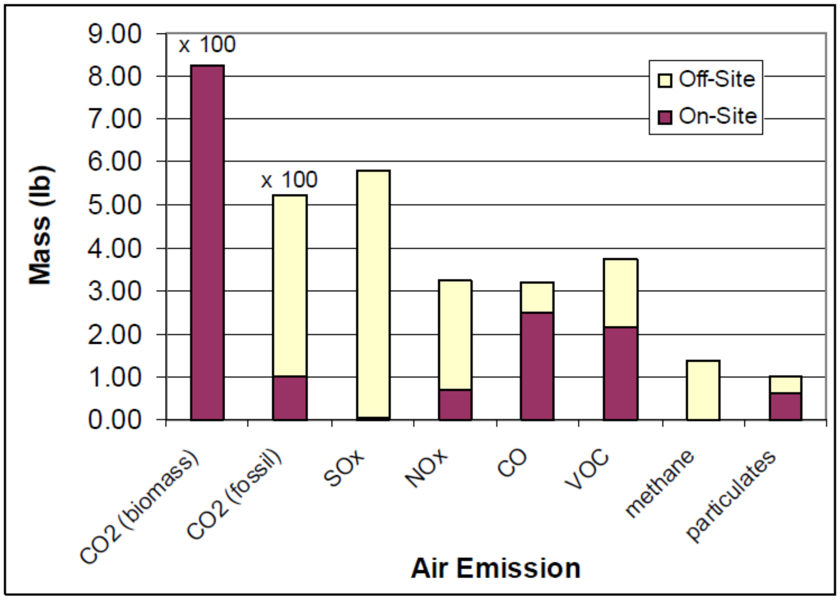
Blending and Pressing

Although there is relatively less energy consumed in this process, blending and pressing are some of the relatively more energy demanding processes after drying and screening (Kline, 2004). A total of 28.4 kWh of electricity and 0.57 million BTU of self-generated heat are needed to mix 608 kg of dry strands with wax and resin and press them into 640 kg of OSB (Kline, 2004).

Finishing

Only small amounts of energy are utilized in this process as 640 kg of OSB mat is trimmed to its final dimension of 572 kg in mass (Kline, 2004). As a result of trimming, 63.5 kg of OSB scrap is produced per MSF (Kline, 2004). The scrap would re-enter the manufacturing process as fuel supply for heating energy (Kline, 2004).

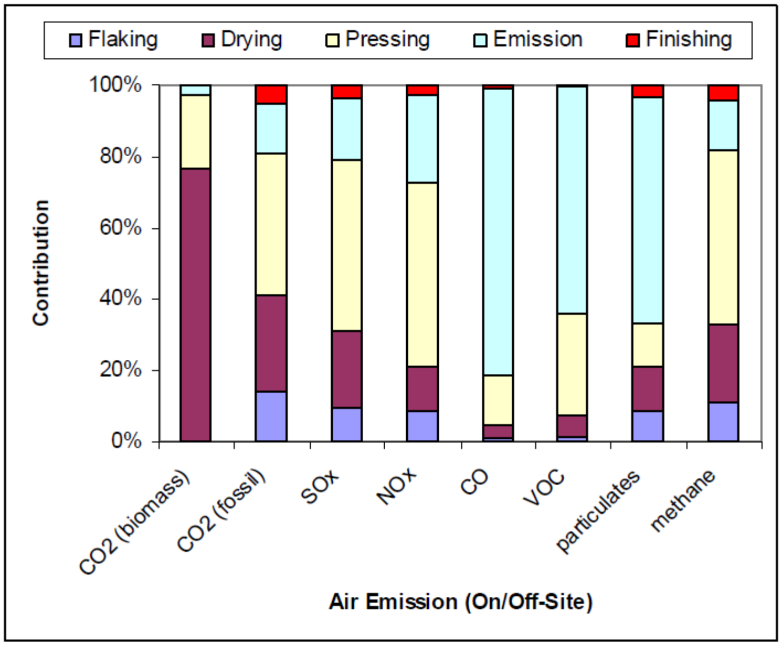
Global Warming Potential



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

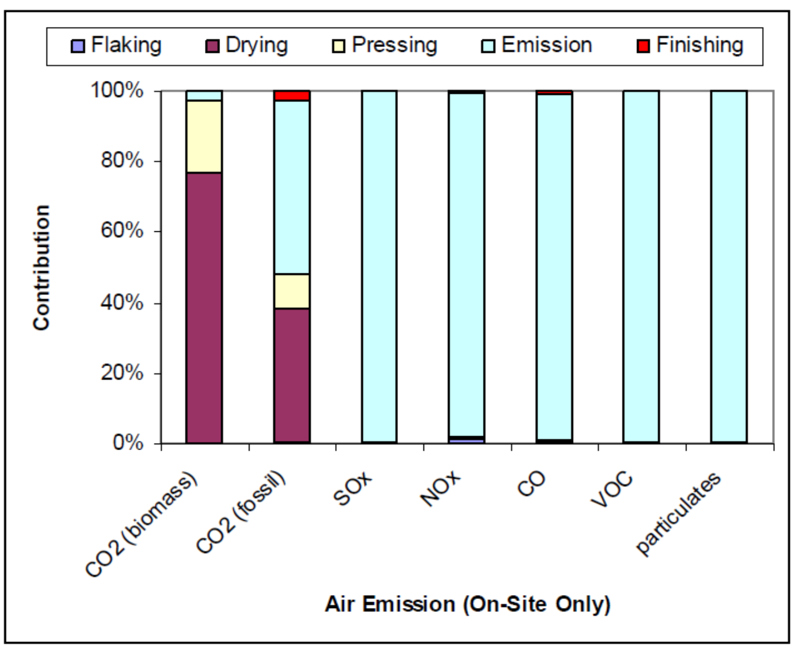
Figure 9: Air Emissions Generated On-site and Off-site during the manufacturing of 1 MSF 3/8-inch basis of OSB

Air emission analysis is categorized into on-site (restricting scope of emissions released only from within the plant) and off-site (enlarging the scope to emissions contributed from production to "delivery of fuels, resin, wax and electricity" (Kline, 2004). All air emissions including CO_2, CO, VOC and particulates are produced on-site, whereas methane, SO_x, CO_2 from fossil fuel combustion and NO_X emissions are produced off-site, as Figure 7 displays. A close look into CO_2 emission in both on-site and off-site reveals that 61% is released from biomass, and in term of on-site emissions, the biomass released CO_2 accounts to 89% (Kline, 2004).



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Figure 10: Air emissions generated both On-Site and Off-Site during the manufacturing of 1 MSF 3/8-inch basis of OSB

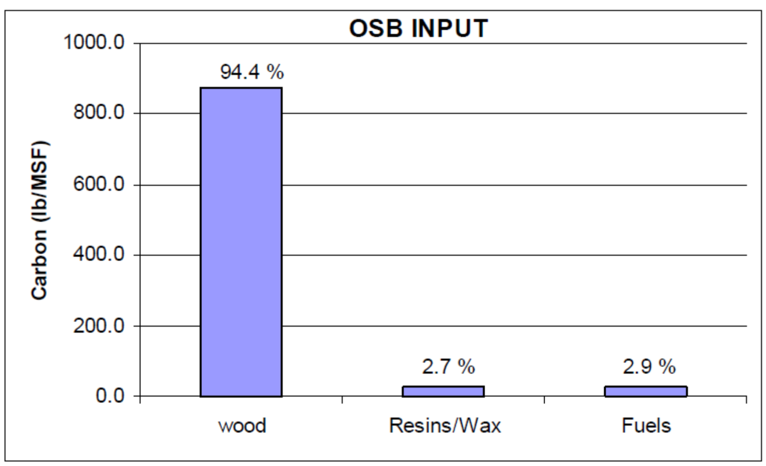


Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Figure 11: Air emissions generated On-Site during the manufacturing of 1 MSF 3/8-inch basis of OSB

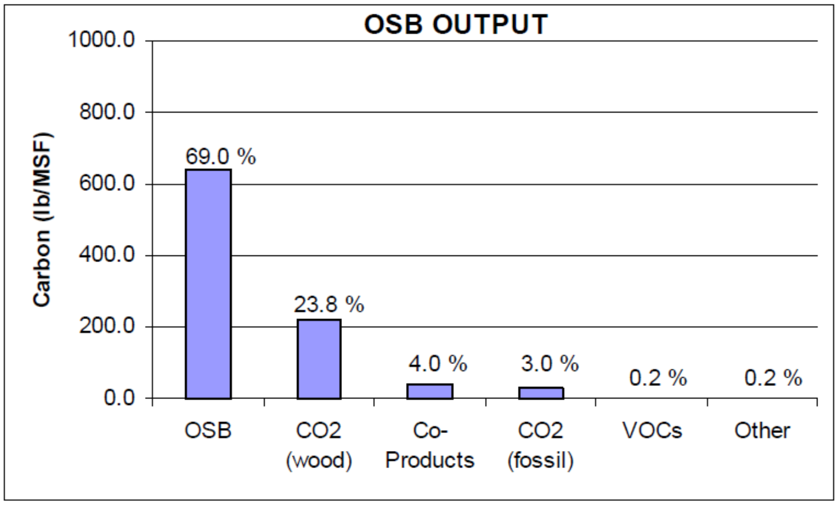
The release of air emissions in percentage from "only on-site" and "on-site and off-site" is displayed in Figures 8 and 9. From Figure 9 (on-site), drying is the primary contributor for emitting biomass CO_2, but as for fossil fuel released CO_2, the drying process released less than half of the total emission. Emission control system emitted half of all fossil fuel CO_2 and as well as the majority of all other emissions. Seen from Figure 8 (on-site & off-site), every production process is involved with emission of each pollutant, because of the off-site impact that is included. Similarities shared in both figures are that emission control is primarily responsible for air emission across various air pollutants (Kline, 2004). Flaking and finishing processes have the least air emissions, and majority of CO_2 emissions from fossil fuel and biomass is released by the drying process.

Carbon Balance



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Figure 12: Input of Carbon Raw Material for 1 MSF 3/8-inch basis of OSB



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Figure 13: Carbon Output per MSF 3/8-inch basis of OSB

Figure 8 shows carbon content assumptions of various material and fuel inputs associated. Throughout the entire manufacture of one MSF of OSB, roughly 423 kg of total carbon from material and fuel is consumed (Kline, 2004). Of this carbon sum, 396 kg of carbon originates from wood raw material. Another 11.4 kg and 12.3 kg of carbon are from the input of resin, wax and fuel respectively (Kline, 2004). As for carbon output shown in figure 9, 273.3 kg of carbon is within the MSF of OSB panel itself. Co-products contain the other 4% of carbon, while the remaining carbon output is emitted to the atmosphere as CO_2, VOCs and other emissions.

Other Air Emissions

Figure 9 displays the percentage of air emission from each substance that is produced on-site. Carbon monoxide and VOC are the next primary air emissions following carbon dioxide. Emission of VOC accounts to 0.23%, 0.06 kg and NOx follows with emission of 0.08%, 0.02 kg (Kline, 2004). PM_{10} and SO_2 are emitted 0.06% and 0.01% respectively (Kline, 2004).

Emission Control Analysis

Emission	Reported Emissions (lb/MSF)				NCASI Emissions (lb/MSF) [2/]	
	Mill 1 (wet ESP + RTO)	Mill 2 (wet ESP)	Mill 3 (RTO)	Mill 4 (wet ESP)	RTO	Wet ESP
Total HAP[1/]	NA	NA	NA	**1.8850**	**0.0582**	**1.3797**
Acetaldehyde	NA	NA	NA	0.3100	0.0102	0.2168
Acrolein	NA	NA	NA	0.1100	0.0000	0.1564
Formaldehyde	NA	NA	NA	0.2660	0.0205	0.4101
Methanol	NA	NA	NA	0.9390	0.0046	0.4874
Phenol	0.0000	0.0333	0.0334	0.0297	0.0567	0.0152
Total VOC	**2.9600**	**2.7400**	**0.5980**	**5.1600**	**0.0782**	**8.8639**
Particulates	**0.7700**	**0.7150**	**0.5240**	**0.9290**	NA	NA
CO	**3.4900**	**3.2400**	**0.7150**	**5.8500**	**0.3782**	NA
THC [3/]	NA	NA	NA	NA	**0.4203**	**10.068**

1/ Hazardous Air Pollutants (HAP) as defined by NCASI, 1999. Highest top 5 HAP individual compounds listed.
2/ Average NCASI (1999) VOC emissions measured after RTO and wet ESP treatments
3/ Total Hydrocarbons (THC) is a total organic VOC analysis measured based on the molecular weight of Carbon (NCASI 1999).

Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Table 5: Analysis of different emission systems used in US OSB mills

From Table 5, the mills participating in this survey employed RTO, wet ESP or combination of RTO and wet ESP emission systems. This variation in employment of emission systems is the result of "Maximum Achievable Control Technology" (Kline, 2004), which is a regulation that was used at the time of this study. Thus, data inconsistency on air emissions and certain assumptions are evident in this section. Indicated in Table 5 is the comparison of reported emission values from the four participating mills with NCASI emission data. Mill 3 displays lowest emissions, and indeed "falls within the range found in NCASI data for RTO methods" (Kline, 2004). Mill 1 employs both wet ESP and RTO emission systems, but the emissions are significantly greater than the NCASI reported RTO emission data. Though both Mills 3 and 4 employ wet ESP, Mill 4 emissions are almost doubled. This can only be assumed that both mills have different input portions of hardwood and softwood raw material.

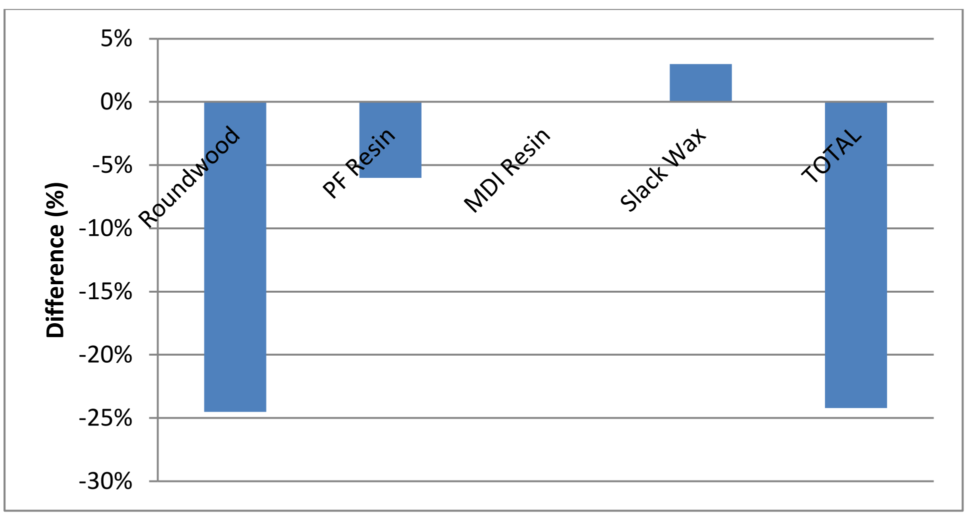
2.4 Contrast between Canadian and US mills

2.4.1 Material Input

Material Inputs	Canadian Mills	US Mills	Difference (%)
Roundwood (kg)	626	780	-24.5%
PF Resin (kg)	18.1	19.2	-6.01%
MDI Resin (kg)	0	3.7	
Slack Wax (kg)	9.02	8.75	2.99%
TOTAL	653	811	-24.2%

Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Table 6: Average material inputs in Canadian mills versus US mills for 1 MSF of 3/8 inch OSB



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Figure 14: Average material inputs in Canadian mills versus US mills for 1 MSF of 3/8 inch OSB

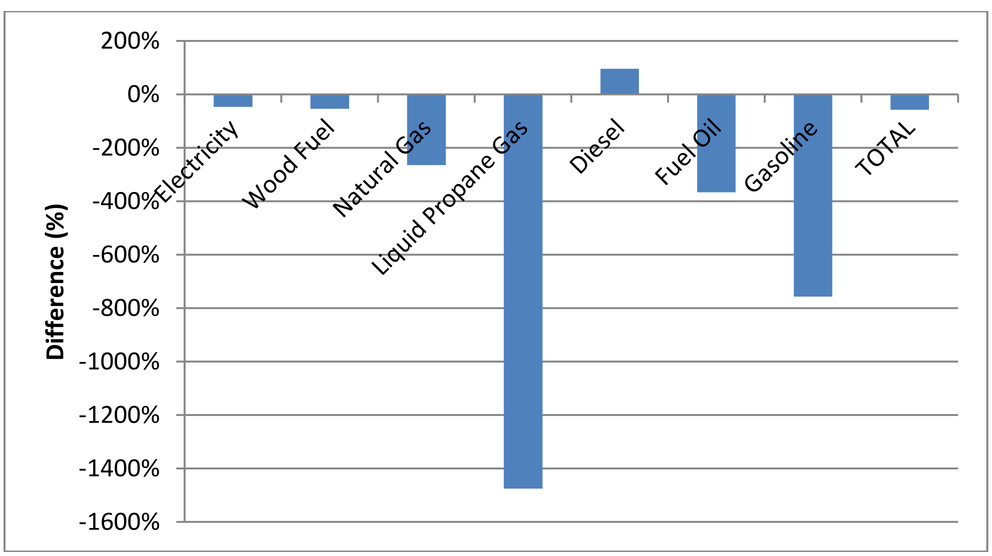
Material inputs are generally higher in Canadian mills. These inputs include roundwood input at 5%, wax at 3% and the significantly higher usage of water at 57% (Kline, 2004). Though some inputs are less utilized in Canadian mills, US mills have overall used greater amounts of total resin and wax at 26% (Kline, 2004). Canadian mills only use PF resin, whereas US mills use PF and MDI resins (Kline, 2004).

2.4.2 Energy

Energy Inputs	Canadian Mills	US Mills	Difference (%)
Electricity (MJ)	445	655	-47.1%
Wood Fuel (MJ)	2050	3158	-54.1%
Natural Gas (MJ)	65.5	240	-266%
Liquid Propane Gas (MJ)	4.2	66.2	-1476%
Diesel (MJ)	50.7	2.52	95.0%
Fuel Oil (MJ)	6.45	30.1	-367%
Gasoline (MJ)	0	1.05	-757%
TOTAL	2622	4153	-58.4%

Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Table 7: Average energy inputs in Canadian mills versus US mills for 1 MSF of 3/8-inch of OSB



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Figure 15: Average energy inputs in Canadian mills versus US mills for 1 MSF of 3/8-inch of OSB

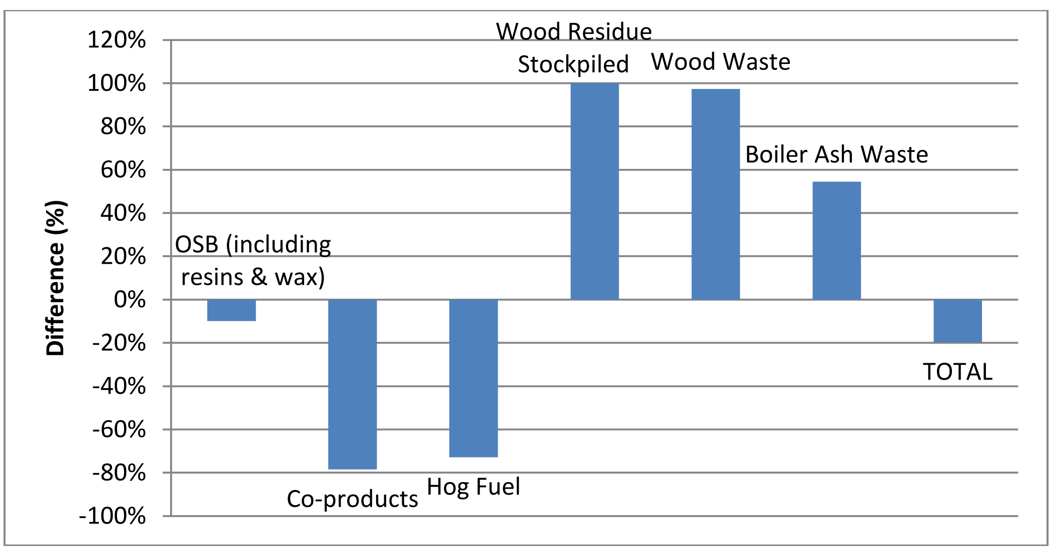
Energy inputs of various sources are generally higher in the southeastern US mills. The surveyed US mills have evidently greater input of electricity, wood fuel and natural gas by 47%, 54% and 266% respectively (Kline, 2004). Though consumption of wood fuel is greater in US mills, the difference should be smaller when wood density differences are accounted for (Athena Sustainable Materials Institute, 2008). Use of natural gas is significantly higher in US mills, which is a result of employing RTO (Kline, 2004).

2.4.3 Material Output

Material Outputs	Canadian Mills	US Mills	Difference (%)
OSB (kg)	522	574	-10.0%
Co-products (kg)	18.4	32.9	-78.5%
Hog fuel (kg)	102	176	-72.8%
Wood residue (kg)	7.2	0	100%
Wood Waste (kg)	1.9	0.05	97.4%
Boiler Ash Waste (kg)	4.2	1.91	54.5%
TOTAL	656	786	-19.8%

Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Table 8: Average material outputs in Canadian mills versus US mills for 1 MSF of 3/8-inch of OSB



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Figure 16: Average material outputs in Canadian mills versus US mills for 1 MSF of 3/8-inch of OSB

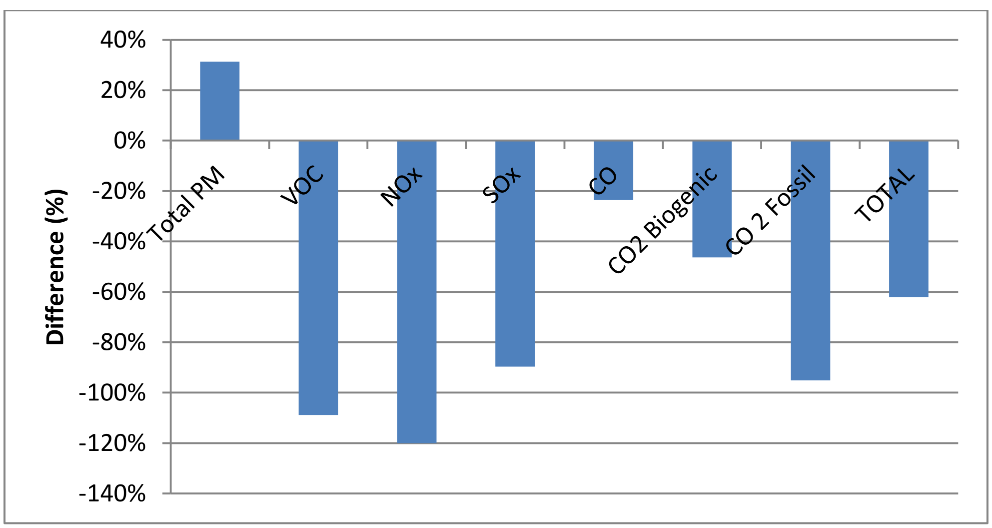
Quantities of OSB product, co-products and hog fuel production are higher in the US, but "some of this difference is (...) due to raw fibre density differences between the two regions" (Athena Sustainable Materials Institute, 2008). As for boiler ash waste, US mills produce only half of production from Canadian mills.

2.4.4 Emission

Substances	Canadian Mills	US Mills	Difference (%)
Particulate matter (kg)	0.67	0.46	31.3%
VOC (kg)	1.13	2.36	-109%
NOx (kg)	0.677	1.49	-120%
SOx (kg)	1.35	2.56	-89.6%
CO (kg)	1.19	1.47	-23.5%
CO2 Biogenic (kg)	261	382	-46.4%
CO2 Fossil (kg)	124	241	-95.1%
TOTAL	390	631	-62.1%

Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Table 9: Average main air emissions generated in Canadian mills versus US mills for 1 MSF of 3/8-inch of OSB



Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

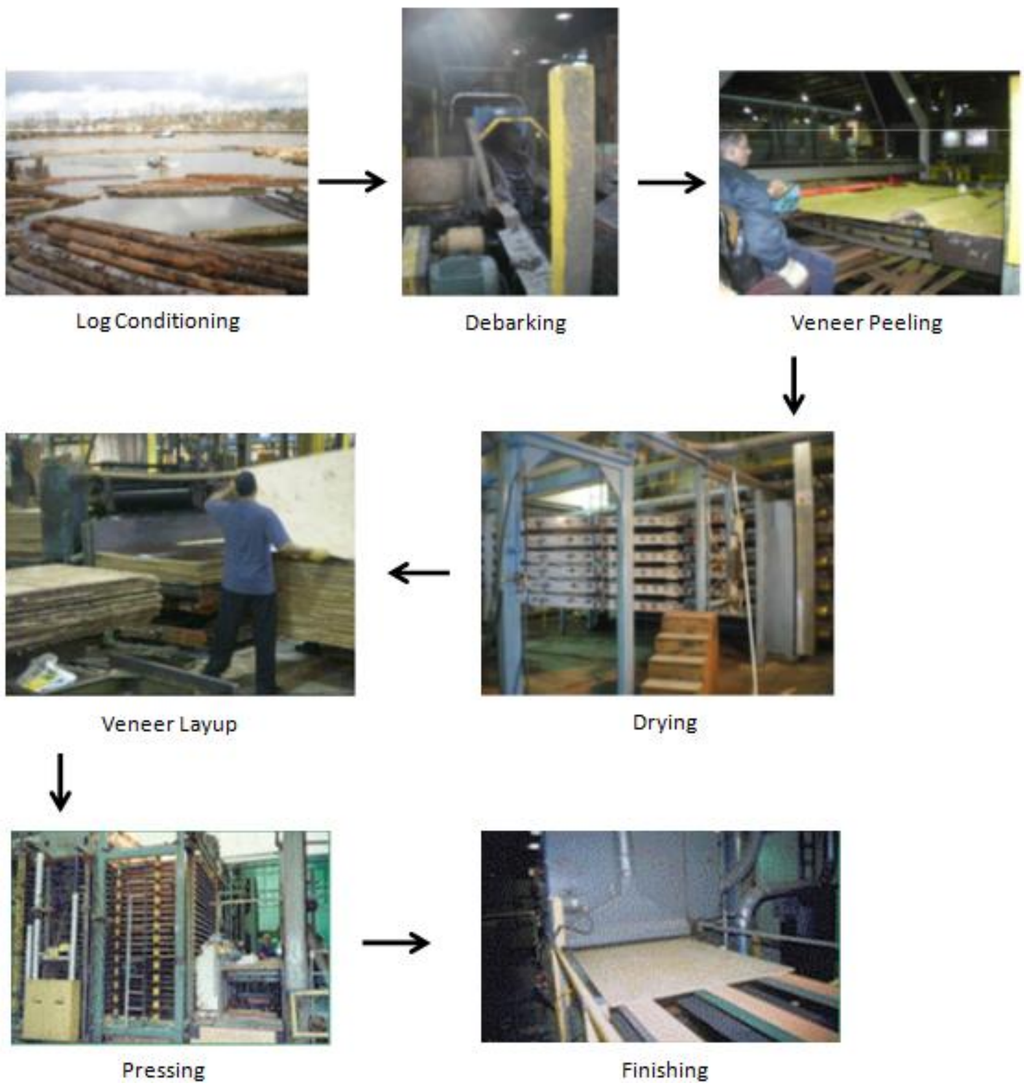
Figure 17: Average main air emissions generated in Canadian mills versus US mills for 1 MSF of 3/8-inch of OSB

Use of different emission systems in the mills across the continent reflects the difference in air pollutant extraction efficiencies. Emission equipment used by Canadian mills is less efficient and this is displayed by higher particulate matter release (by 32%) in Canada (Kline, 2004). Interestingly, VOC including methane emissions are at least twice as low from Canadian mills, despite the use of RTO in the mills of southeast US. Emissions of NOx and CO, as well as biogenic and fossil CO_2 are both lower in Canadian mills, which is a result of consuming less "biomass and thermal fossil fuels" (Athena Sustainable Materials Institute, 2008) in manufacturing.

3 Canadian and US Softwood Plywood Study

3.1 Plywood Manufacturing Process

The following section provides a brief description of the manufacturing processes and the subsequent emissions involved in the production of OSB.



Source: Smith, G. (2012). WOOD 487. Vancouver, British Columbia, Canada. Retrieved April 10, 2012

Figure 18: Plywood manufacturing process

3.1.1 Green process, debarking

Upon the arrival of logs to the plywood mill, the green logs are stored in a pond storage or cold deck, where the logs are sprayed with water (US EPA, 1983). After which, the logs are debarked and "cut into specifically sized blocks" (US EPA, 1983). The bark generated is usually used as fuel.
By-products generated from debarking are generally too coarse to emit into the atmosphere, although some finer particles such as PM_{10} (US EPA, 2011) may be emitted during its transportation on conveyor systems (US EPA, 1983).

3.1.2 Green process, log conditioning and veneer peeling

Utilizing spray chambers or hot water vats, the logs are conditioned via heat and moisture (US EPA, 1983). The conditioned logs are then cut into veneers with a veneer lathe. Afterwards, with a veneer clipper, the pieces of veneer are "cut to size" (US EPA, 1983). Furthermore, the veneer is sorted based on size, species, grade, heartwood and sapwood (US EPA, 1983).

3.1.3 Veneer drying

Through the drying process, the moisture content of green veneers is reduced to its target moisture content ranging approximately between 1% to 15% (US EPA, 2011). There are essentially two types of dryers employed in the industry, longitudinal veneer dryer that "circulates air parallel to the veneer" (US EPA, 1983) and jet dryers that use "direct hot, high velocity air (...) to create (...) a turbulent flow of air" (US EPA, 1983) on the veneer surface. Two types of heat generation are available in veneer dryers, direct-fired or indirect-heated. Direct-fired dryers generate heat through the combustion of "gas or wood" (US EPA, 1983) in a boiler to produce hot gases. For indirect gas dryers, steam coils warm the air circulating on the veneer surface. Alternatively, mills may also employ veneer kilns to dry veneers (US EPA, 1983) as well.

Drying is the main process primarily responsible for air emissions. Through the combustion of fossil fuel or wood residue, both PM and PM_{10} are released into the atmosphere (US EPA, 2011). Two types of organic compounds, condensable and volatile, are also emitted in this process as well (US EPA, 2011). When these condensable compounds cool after its emission, it combines "with water vapor to form aerosols [that] can cause blue haze" (US EPA, 2011).

3.1.4 Veneer layup and pressing

Through resin applicators such as curtain coaters or roll spreaders, the commonly used phenol formaldehyde (exterior applications) and urea-formaldehyde (interior applications) resins are spread along one side of a veneer (US EPA, 2011). Depending on the end product, the three or five veneers will be symmetrically and grain alternating laid into one panel before it's sent to the hot press. Pressing temperatures typically range between 132°C and 165°C for softwood plywood and 107°C and 135°C for hardwood plywood (US EPA, 2011). These high pressing temperatures are needed to activate the thermosetting resins.

The thermal process taken place is a source of both PM and PM_{10} and hazardous air pollutant emissions as well (US EPA, 2011).

3.1.5 Finishing

Lastly, the panels are trimmed to final dimensions and finished to customer preference. Automated sanders along with pneumatic dust collectors are employed for the finishing process (US EPA, 1983).

3.2 Life Cycle Assessment of Plywood

The following is a summary of energy utilization and air emissions released from the manufacturing process of plywood production in Canada.

3.2.1 System Boundaries

Three BC softwood plywood mills that represent "25% of all [Canadian] plants" (Athena Sustainable Materials Institute, 2008) participated in this LCA study. The combined production of these mills is 675 MMSF 3/8" basis of softwood plywood, which is approximately "25% of the industry's annual production" (Athena Sustainable Materials Institute, 2008). The annual production of the participating mills is approximately between "152 to 257 MMSF 3/8-inch basis annually" (Athena Sustainable Materials Institute, 2008).

3.2.2 LCA Results

The following paragraphs display results of environmental impacts generated from the manufacturing of OSB.

Total Primary Energy

Energy Source	Resource Harvesting (MJ)	Resource & Material Transportation (MJ)	Manufacturing (MJ)	Total (MJ)
Non-renewable, fossil	408	189	1,649	2,246
Non-renewable, nuclear	3.3	1	7	11
Renewable (SWHG)	2.8	0	500	503
Renewable (biomass)	0.006	0.028	1,713	1,713
Feedstock, fossil	0	0	297	297
Feedstock, biomass	0	0	13,289	13,289
Total Primary Energy	414	190	17,455	18,059

Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

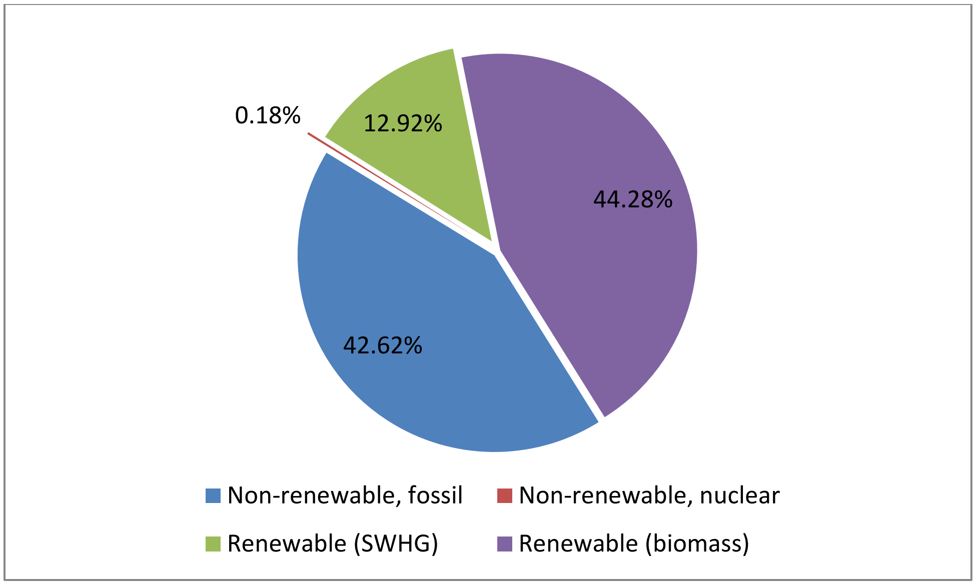
Table 10: Energy Utilization in production of 1 MSF 3/8-inch basis of plywood (Absolute Value)

Energy Source	Resource Harvesting	Resource & Material Transportation	OSB Manufacturing	Total
Non-renewable, fossil	18.2%	8.4%	73.4%	100.0%
Non-renewable, nuclear	30.0%	6.4%	63.6%	100.0%
Renewable (SWHG)	0.6%	0.0%	99.4%	100.0%
Renewable (biomass)	0.0%	0.0%	100.0%	100.0%
Feedstock, fossil	0.0%	0.0%	13.2%	100.0%
Feedstock, biomass	0.0%	0.0%	100.0%	100.0%
Total Primary Energy	2.3%	1.1%	96.7%	100.0%

Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Table 11: Energy Utilization in production of 1 MSF 3/8-inch basis of plywood (Percentage)

The entire product of plywood is categorized into three system processes, resource harvesting, resource and material transportation and plywood manufacturing (Athena Sustainable Materials Institute, 2008). Amongst these three unit processes, the manufacturing process is primarily responsible for the overall environmental impact. The total primary energy requirement of the entire production from cradle to gate accumulates to 18 GJ per MSF of plywood (Athena Sustainable Materials Institute, 2008). Although this energy sum includes a significant amount of feedstock energy of 13.6 GJ (75.2%) within the raw material and phenol formaldehyde resin as well, and with this feedstock energy disregarded from the equation, the total energy requirement reduces to 4.5 GJ per MSF. As for fossil feedstock energy, it is entirely used to in the production of phenol formaldehyde resin (Athena Sustainable Materials Institute, 2008).



Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Figure 19: Energy utilization within OSB manufacturing

As shown in Figure 19, within the 4.5 GJ of manufacturing energy requirement, almost 50% is derived from non-renewable fuel sources. This energy is mainly fossil fuel derived, while the remaining 50% is derived from renewable sources, primarily biomass, thus, with the significantly high utilization of biomass, production of plywood is 49.5% "energy self-sufficient" (Athena Sustainable Materials Institute, 2008).

Global Warming Potential

Substances	Resource Harvesting	Resource & Material Transportation	OSB Manufacturing	Total
Acidification (kg SO2)	408	189	1,649	2,246
Eutrophication (kg N)	3.3	0.7	7	11
Smog (kg ethylene)	2.8	0	500	503
Global Warming (kg CO2)	0.006	0.028	1,713	1,713
HH Air- Mobile (kg PM2.5)	0	0	13,289	13,289
Total Emissions	414	190	17,158	17,762

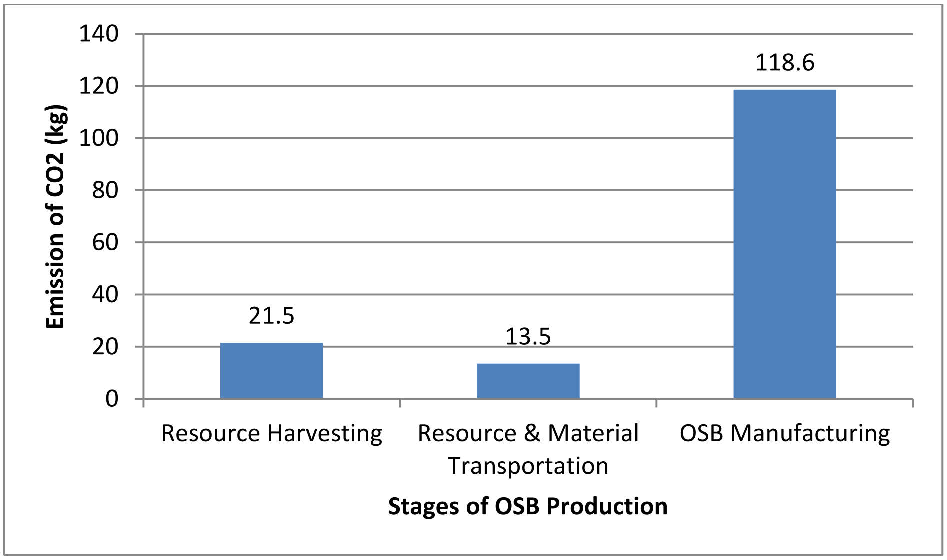
Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Table 12: Air emissions generated in the production of 1 MSF 3/8-inch basis of plywood (Absolute Value)

Substances	S1: Resource Harvesting	S2: Resource & Material	S3: OSB Manufacturing	Total
Acidification (kg SO2)	18.17%	8.41%	73.4%	100%
Eutrophication (kg N)	30%	6.36%	63.6%	100%
Smog (kg ethylene)	0.56%	0%	99.4%	100%
Global Warming (kg CO2)	0.0003%	0.0012%	76.3%	100%
HH Air- Mobile (kg PM2.5)	0%	0%	100%	100%
Total Emissions	2.33%	1.07%	96.6%	100%

Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Table 13: Air emissions generated in the production of 1 MSF 3/8-inch basis of plywood (Percentage)



Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Figure 20: Emission of CO_2 in the production of 1 MSF 3/8-inch basis of plywood

In terms of global warming potential, only human related fossil carbon is considered. For the production of each MSF of plywood, a total of 118.6 kg of CO_2 is produced (Athena Sustainable Materials Institute, 2008). The manufacturing process mainly emits the majority of CO_2 of up to 66.1%, 78.4 kg, as resource harvesting and transportation processes only contribute 22.2% and 11.6% respectively (Athena Sustainable Materials Institute, 2008).

Carbon Balance

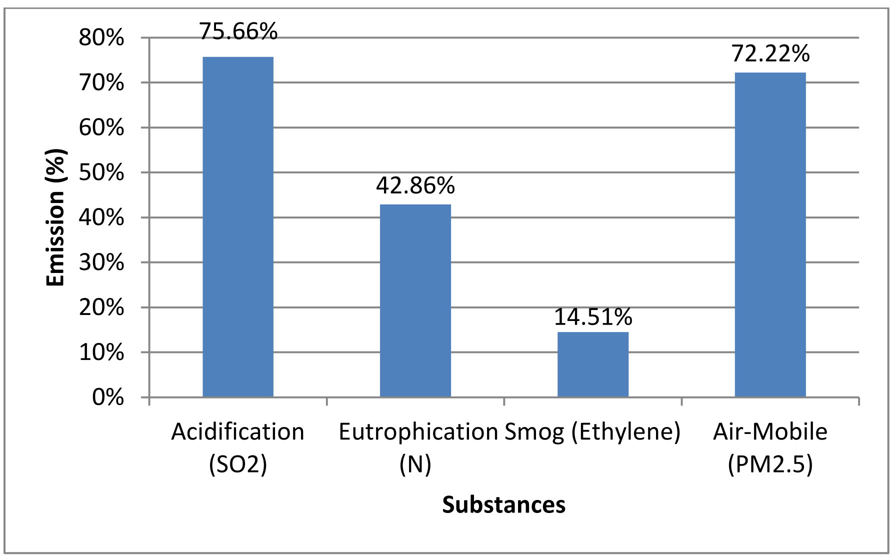
Each MSF of a plywood panel has 119 kg of CO_2 emitted during production (Athena Sustainable Materials Institute, 2008). This emission is offset by 696 kg of CO_2 that is already sequestered within the plywood, resulting to a positive net carbon balance of 577 kg of CO_2 (Athena Sustainable Materials Institute, 2008).

Other Air Emissions

	Resource Harvesting	Resource & Material Transportation	OSB Manufacturing	Total
Acidification (Kg of SO_2)	0.35	0.11	1.43	1.89
Eutrophication (Kg of N)	0.003	0.001	0.003	0.007
Smog (Kg of Ethylene)	0.25	0.08	0.056	0.386
Air-Mobile (Kg of $PM_{2.5}$)	0.03	0.02	0.13	0.18

Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Table 14: Acidification, Eutrophication, Smog and Air-Mobile Emissions



Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Figure 21: Acidification, Eutrophication, Smog and Air Mobile Emissions in manufacturing of plywood

Measuring on the basis of SO_2 emissions, acidification potential is generally "a function of fossil fuel combustion" (Athena Sustainable Materials Institute, 2008). As shown in table 11 majority of SO_2 emissions, 75.6% are released from the combustions taken place within the manufacturing process.

Resource harvesting and manufacturing processes both contribute evenly at 44.3% and 45.9% respectively to the eutrophication impact potential (Athena Sustainable Materials Institute, 2008). This is the result of both fertilization in the forest and fossil fuel emissions in manufacturing (Athena Sustainable Materials Institute, 2008).

The total smog impact from producing one MSF of plywood is the emission of 0.89 kg of ethylene (Athena Sustainable Materials Institute, 2008). The majority of this ethylene emission, two-thirds, is released from the manufacturing process, though almost one-third of ethylene emission is contributed from resource harvesting.

The overall human health criteria impact is 0.18 kg of particulates at 2.5 micron in diameter (Athena Sustainable Materials Institute, 2008). A significant portion, 72.1%, of $PM_{2.5}$ is generated in manufacturing, while the process of resource harvesting produces 19.2% and transportation produces 8.8% (Athena Sustainable Materials Institute, 2008).

3.3 Life Cycle Inventory of plywood

The following is a summary of energy utilization and air emissions released from the manufacturing process of plywood production in both Pacific Northwest and Southeastern US.

3.3.1 System Boundaries

The LCI data presented in the following paragraphs are provided by a survey completed by five plywood manufacturers in the Oregon and Washington states, Northwestern region of US. The combined annual production of the five participating manufacturers 1,233,424 MSF 3/8-inch basis plywood annually, representing 26% of the production from the region and 27% of the entire US plywood production (Wilson, 2004).

Another five plywood manufacturers also participated from the states of "Alabama, Georgia, Louisana, Mississippi, Florida, Arkansas, and Texas" (Jim Wilson, 2010), Southern region of US. The combined production of these five manufacturers represents 14% of the plywood production from the Southern region (Jim Wilson, 2010). The total annual production of these participating manufacturers accumulates to 1,383,642 MSF 3/8-inch basis (Jim Wilson, 2010).

3.3.2 LCI Results

The following paragraphs display results of environmental impacts generated from the manufacturing of plywood.

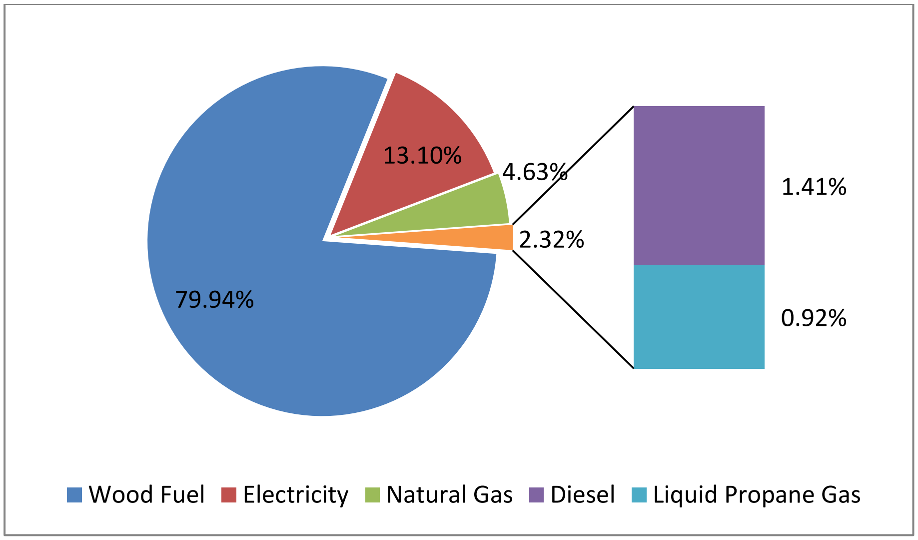
Total Primary Energy

Energy Utilization

Energy Source	Manufacturing (MJ)	Percentage
Wood Fuel	3053	79.9%
Natural Gas	177	4.63%
Liquid Propane Gas	35.0	0.92%
Diesel	53.8	1.41%
Electricity	500	13.1%
Total Primay Energy	3818	100%

Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Table 15: Energy utilization per MSF 3/8-inch basis within softwood plywood manufacturing



Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Figure 22: Energy utilization per MSF 3/8-inch basis within softwood plywood manufacturing (percentage)

The entire plywood manufacturing process in the Northwestern region of US requires a total of 3820 MJ of energy (Jim Wilson, 2010). Shown in Table 15 are the proportions of "electricity, diesel, liquid propane gas, bark-hogged fuel and steam" (Wilson, 2004) utilized in manufacturing. Electricity is a widely used form of energy, accounting to 13.1% of the total manufacturing energy, in every process of plywood manufacturing. Its usage in the operations of manufacturing includes "the debarker, bucker, lathe, pneumatic and mechanical conveying equipment, fans, hydraulic pumps, saws, and a radio-frequency redryer" (Wilson, 2004). Diesel is the next primary source of energy that is mainly used to power "log loaders" (Wilson, 2004) for debarking operations. As for its fossil fuel counterpart, liquid propane gas is only needed in relatively smaller quantities, as it is typically used to operate forklifts (Wilson, 2004).

Electricity

Percentage Share, 1998[1]			
Fuel Source	OR	WA	Average
Coal	9.1	6.5	7.8
Petroleum	0.0	0.1	0.05
Natural Gas	1.1	6.8	4.0
Nuclear	6.8	0.0	3.4
Hydro	77.8	77.2	77.5
Renewable	0.3	0.0	0.2
Non Utility	4.8	9.4	7.1

[1] Source: Energy Information Administration/State Electric Profiles 2000, Department of Energy (2000).

Table 16: Utilization of primary energy sources for the generation of electricity in the PNW region

In producing each MSF of 3/8-inch basis plywood, an overall 500 MJ of electricity is consumed in all of the processes of manufacturing (Jim Wilson, 2010). Various fuel sources are utilized to generate electricity in the US Northwestern region, and displayed in Table 15 are the proportions of these fuel sources utilized. Hydro energy is the chief source of energy that accounts to 77.5% of all fuel sources utilized. In addition, impact analysis from the SimaPro software did not reveal any environmental impact related to hydro-generated electricity (Wilson, 2004). Though consumed at much lesser quantity, coal is the next chief source of energy accounting utilization of 7.8%, and non-utility follows at 7.1%. Unlike hydro source, coal combustion contributes "significant impact values" (Wilson, 2004).

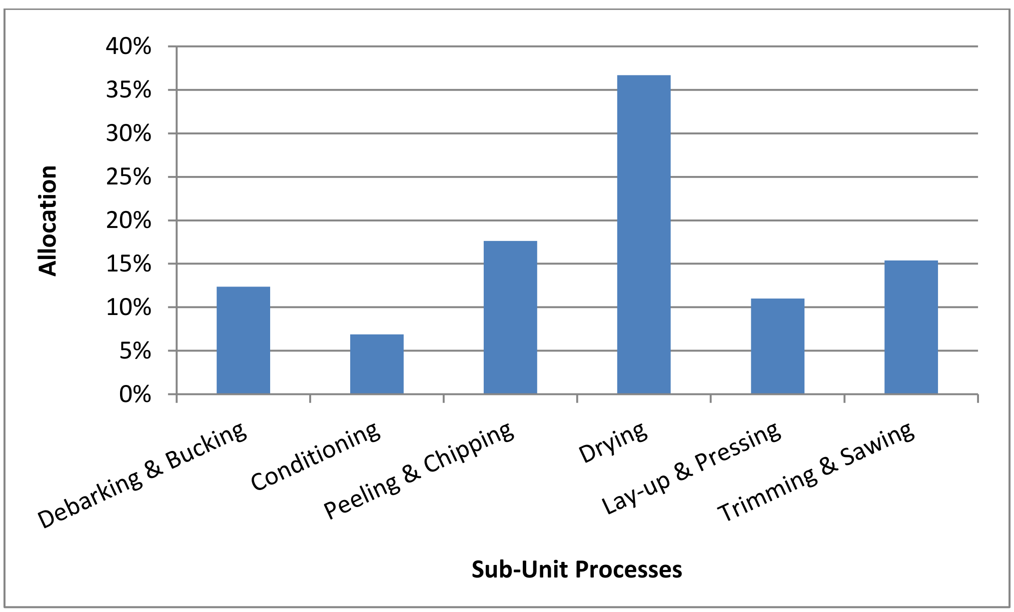
Electricity allocation

PNW electricity allocation along the manufacturing processes

Sub-unit Process	KWh MSF 3/8-in basis	Allocation Percentage[1]
Debarking & Bucking	17.2	12.4
Conditioning	9.6	6.9
Peeling & Clipping	24.5	17.6
Drying	51.0	36.7
Lay-up & Pressing	15.3	11.0
Trimming & Sawing	21.4	15.4
Total	138.9	100

[1] Source: Ferrari, C.J., 2000. Life Cycle Assessment: Environmental modeling of plywood and laminated veneer lumber manufacturing. Table 24, Appendix D., page 111 – Distribution of electricity use by sub-unit processes.

Table 17: PNW electricity allocation along the sub-unit processes of plywood manufacturing for 1 MSF 3/8-inch basis

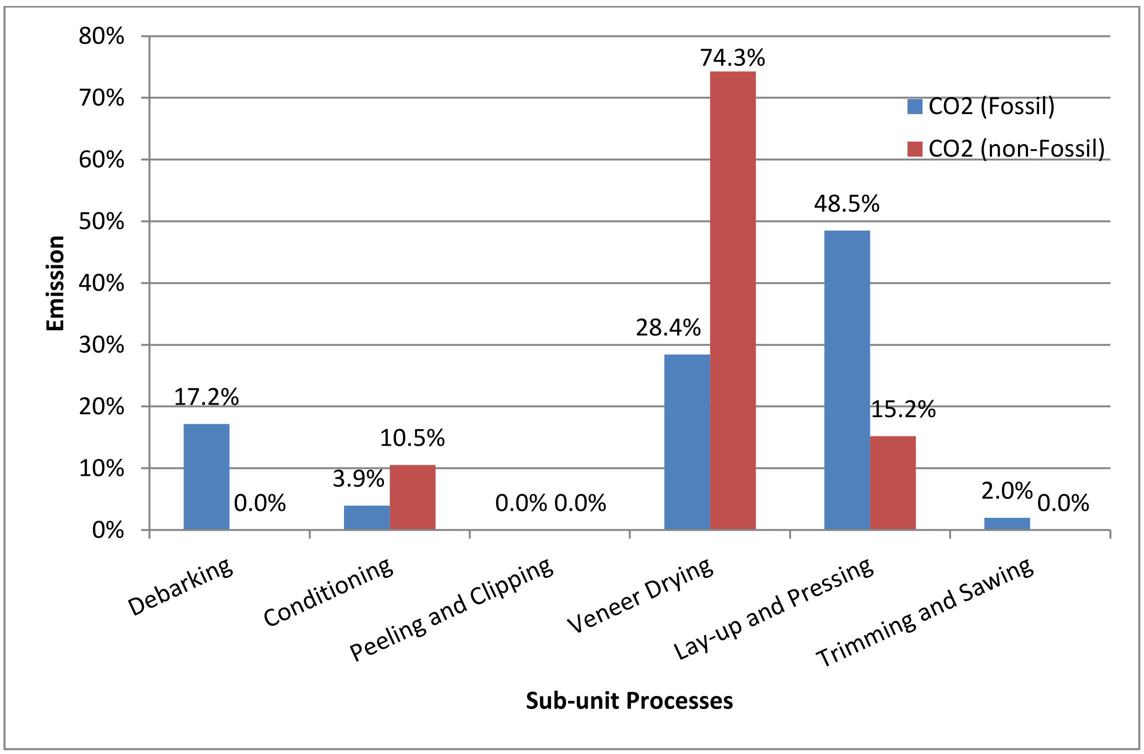


Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Figure 23: PNW electricity allocation along the sub-unit processes of plywood manufacturing for 1 MSF 3/8-inch basis (Percentage)

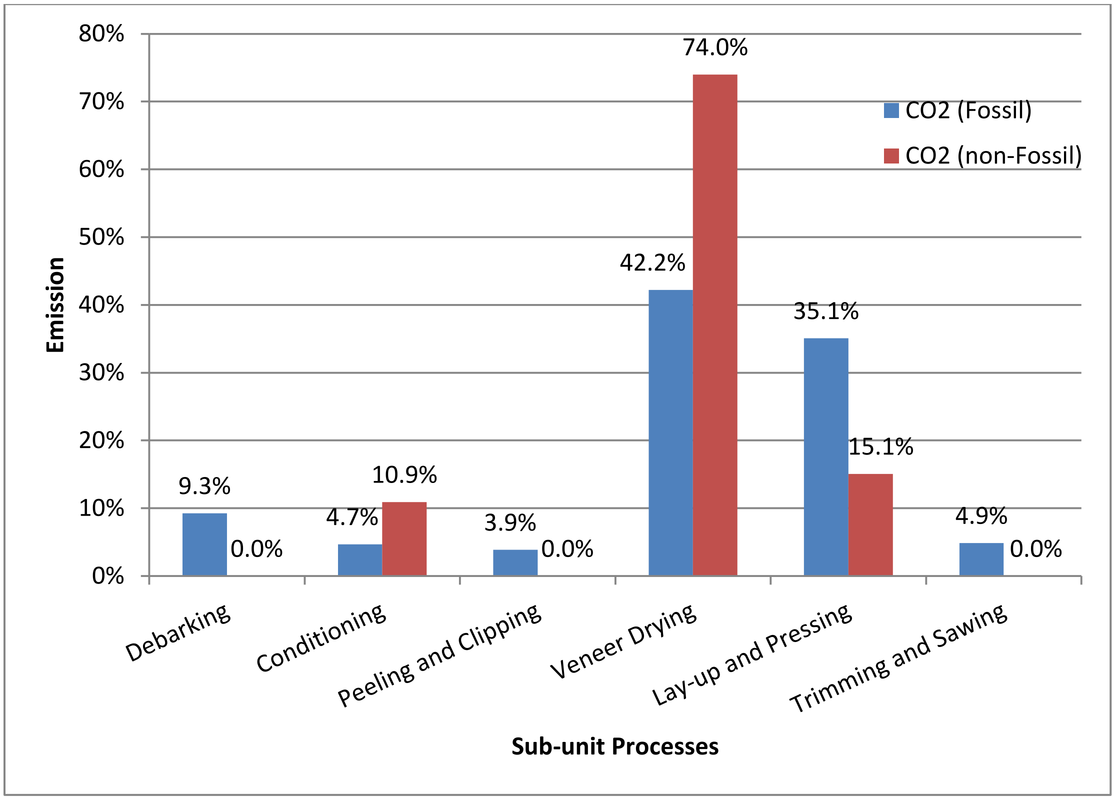
Displayed in Table 16, drying is the primary process in electricity consumption due to the operations to "increase (...) heat and mass transfer rates during drying" (Jim Wilson, 2010). These operations include the use of "high velocity fans (...) in longitudinal, cross-flow and jet dryers (Jim Wilson, 2010). Each of the remaining sources utilizes about 15% electricity, with exceptions to conditioning, where only 6.9% of electricity is allocated (Jim Wilson, 2010).

Global Warming Potential



Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Figure 24: CO_2 emissions (percentage) per MSF 3/8-inch basis of plywood from sub-unit processes of manufacturing in the PNW region



Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Figure 25: CO_2 emissions (percentage) per MSF 3/8-inch basis of plywood from sub-unit processes of manufacturing in the SE region

In Pacific Northwestern plywood mills, non-fossil fuel associated CO_2 emission is almost 6 times greater than emissions of CO_2 associated with fossil fuel. Shown in table 16 proportions of non-fossil fuel CO_2 emissions are greatest at almost 75% in the veneer drying process. Combustion of hogged fuel that consists of bark produced from debarking, wood residues created from various manufacturing processes and "some purchased hogged fuel" (Jim Wilson, 2010), is the source of non-fossil fuel CO_2 emissions. Along with non-fossil fuel CO_2 emissions, almost 30% of fossil fuel $C0_2$ is emitted during drying as natural gas is also combusted as well. This large scale of fuel consumption makes veneer drying the process releasing almost 70% of CO_2 emissions.

As for the mills in the Southern US region, similar CO_2 emission trend is also evident. However, there are exceptions to the quantity of emission as Southern mills release greater amounts of CO_2. Southern mills release 56.5 kg and 34.3 kg of non-fossil fuel and fossil fuel associated CO_2 emissions than mills from of PNW, a result of higher wood waste and natural gas consumption in the Southern mills (Jim Wilson, 2010). Veneer drying and pressing processes are also the primary sources of CO_2 emissions.

Carbon Balance

PNW Plywood - Inputs

Raw Materials	Carbon %	Carbon (kg)	Percentage
Round wood	51.2	415	93.2%
Bark	51.2	23	5.16%
Purchased			
Dry veneer	51.2	1.50	0.34%
Green veneer	51.2	3.31	0.74%
Hogged fuel	51.2	2.56	0.57%
Total	51.2	446	100%

Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Table 18: Carbon input per MSF 3/8-inch basis of plywood produced in the PNW region

PNW Plywood - Outputs

Air Emissions	Carbon (kg)	Percentage
HAP	0.033	0.0076%
Other	0.14	0.0329%
CO	0.38	0.0871%
CO2 (biofuel)	35.2	8.14%
Particulates	0.087	0.0201%
PM 10	0.052	0.0120%
VOC	0.30	0.0702%
Soliid Output		
Plywood	218	50.4%
Co-products	176	40.6%
Waste	2.76	0.64%
TOTAL	432	100%

Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Table 19: Carbon output per MSF 3/8-inch basis of plywood produced in the PNW region

SE Plywood - Inputs			
Raw Materials	Carbon %	Carbon (kg)	Percentage
Round wood	51.2	508	91.7%
Bark	51.2	30.2	5.45%
Purchased			
Dry veneer	51.2	1.96	0.35%
Green veneer	51.2	2.54	0.46%
Hogged fuel	51.2	11.2	2.01%
Total	51.2	554	100%

Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Table 20: Carbon input per MSF 3/8-inch basis of plywood produced in the SE region

SE Plywood - Outputs		
Air Emissions	Carbon (kg)	Percentage
HAP	0.026	0.0046%
Other	0.148	0.026%
CO	0.558	0.10%
CO2 (biofuel)	52.6	9.15%
Particulates	0.137	0.024%
PM 10	0.026	0.0044%
VOC	0.131	0.023%
Solid Output		
Plywood	263	45.7%
Co-products	254	44.3%
Waste	4.23	0.74%
TOTAL	575	100%

Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Table 21: Carbon output per MSF 3/8-inch basis of plywood produced in the SE region

The 2010 LCI plywood report on PNW and SE region mills does not provide carbon balance data, therefore, the data from 2004 LCI plywood report are used for analysis instead. However, the 2004 LCI report only reported the carbon data for hogged fuel, other sources of fuel, resins and waxes utilization are not provided. This section is written with the assumption that only hogged fuel is used for manufacturing of plywood both in the PNW and SE regions. For every MSF 3/8” basis of plywood panel, a total of approximately 446 kg of carbon is generated, and 443 kg and 2.56 kg of this cumulative carbon sum are produced from wood raw material and hogged fuel respectively in the PNW mills (Kline, 2004). Up to 50.4% (218 kg) of carbon is sequestered within the plywood product, while the remaining 40.6%, (176kg), resides within various co-products. As for air emissions, biofuel CO_2 is the primary source of carbon emission at 8.14%, which is 35.2 kg of carbon (Jim Wilson, 2010). Carbon monoxide and VOC are the next primary sources, releasing 0.9% (0.38 kg) and 0.7% (0.3 kg) of carbon respectively.

In contrast, both carbon inputs and outputs are higher in plywood manufacturing mills from the Southeastern mills. A cumulative carbon sum of 554 kg is required for 1 MSF of plywood (Kline, 2004). Up to 543 kg of carbon from this total is stored in the input of wood materials, while 11.2 kg of carbon is contributed by hogged fuel (Kline, 2004).

The plywood product sequesters 263 kg of carbon, 44.9 kg greater than the carbon sequestered within plywood produced from Pacific Northwestern mills, though this difference may be the result of different wood species used (Kline, 2004). Higher masses of carbon are also evident in the co-products, as 254 kg of carbon (44.3%) is stored. Carbon air emissions are greater in the SE mills as well (Kline, 2004). Biofuel carbon dioxide, carbon monoxide and VOC emissions account to 52.6 kg, 0.56 kg and 0.13 kg of carbon released to the atmosphere respectively (Kline, 2004).

Other Air Emissions

Air Emission	Debarking	Conditioning	Peeling and Clipping	Veneer Drying	Lay-up and Pressing	Trimming and Sawing	Total
CO	1.44%	9.57%	0%	72.09%	16.91%	0%	100%
Dust (PM10)	0%	0%	1.71%	95.33%	0.48%	2.48%	100%
Particulates	2.99%	0.90%	2.20%	65.39%	26.55%	1.96%	100%
Methane (CH4)	3.19%	4.81%	2.27%	30.88%	56.76%	2.09%	100%
Nitrogen Oxides	18.48%	4.45%	0.54%	31.83%	44.21%	0.49%	100%
SO2	0%	0%	0%	99.49%	0.51%	0%	100%
Sox	4.48%	4.81%	1.65%	31.41%	56.18%	1.48%	100%
VOC	0%	0%	0%	70.28%	29.72%	0%	100%
HAP	0.99%	0.37%	0.0%	26.87%	71.77%	0.0%	100%
TOTAL	4.24%	5.59%	0.54%	59%	30%	0.52%	100%

Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Table 22: Air emissions per MSF 3/8-inch basis generated from the production of plywood in the PNW region (percentage)

Air Emission	Debarking	Conditioning	Peeling and Clipping	Veneer Drying	Lay-up and Pressing	Trimming and Sawing	Total
CO	0.83%	10.13%	0.07%	71.31%	17.49%	0.16%	100%
Dust (PM10)	0%	0%	4.25%	19.16%	0.12%	76.46%	100%
Particulates	2.41%	1.35%	0.87%	19.31%	30.63%	45.42%	100%
Methane (CH4)	5.19%	5.93%	4.13%	35.66%	43.89%	5.19%	100%
Nitrogen Oxides	11.14%	5.00%	1.49%	35.43%	45.09%	1.85%	100%
SO2	0%	0%	0%	99.34%	0.66%	0%	100%
Sox	5.28%	0%	3.54%	38.39%	48.31%	4.47%	100%
VOC	0%	0%	0%	23.31%	76.69%	0%	100%
HAP	0.83%	0.62%	0.001%	4.93%	93.62%	0%	100%
TOTAL	3.47%	6.03%	1.10%	50.3%	33.1%	6.03%	100%

Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Table 23: Air emissions per MSF 3/8-inch basis generated from the production of plywood in the SE region (percentage)

Methane CH4

Plywood pressing and veneer drying are the primary contributors to methane emissions in the Pacific Northwestern mills. The pressing process releases the most methane emissions of 56.88%, while veneer drying releases 30.88% (Jim Wilson, 2010). Higher methane emission within pressing is the result of increased use of natural gas.

In comparison, Southern mills release almost double the methane emissions produced from Pacific Northwestern mills. Increased methane emissions are the result of higher natural gas consumption in every manufacturing process, especially within plywood pressing, where natural gas consumption is 50% higher in Southern mills than in PNW mills (Jim Wilson, 2010).

Nitrogen Oxides

Nitrogen oxide emissions are higher in pressing than in veneer drying. The pressing process contributes 44.2% of NO_X emissions, whereas drying contributes 30.9% of the emission (Jim Wilson, 2010).

Southern mills produce higher nitrogen oxide emissions than mills of PNW by 30% due to increased combustion of natural gas (Jim Wilson, 2010).

SO_2, VOC, CO and Particulates

The veneer drying process is the chief contributor to the emissions of SO_2 and VOC. Though emission of $S0_2$ is mainly higher with the combustion of natural gas (Jim Wilson, 2010), it is highest in the drying process at 99.49%, while the remaining 0.51% of SO_2 emission is released from pressing. As for VOC, CO and particulate emissions, 70%, 72% and 65% are released from the veneer drying process respectively.

In comparison to emissions of CO and particulates from Southern mills, PNW mills have lower emissions at approximately 29% and 31% respectively. However, SO_2 and VOC emissions much greater in PNW mills than in Sothern mills, as displayed in table 17.

Emission Control

Though emission control values are not provided in the LCI study, the typical emission control systems employed in plywood mills are identified in the following paragraphs.

PM emissions

Emission systems used to remove particulate emissions generated during veneer drying are absorption systems, electrified filter beds, wet electrostatic precipitators and oxidation systems (US EPA, 2011).

VOC emissions

Either regenerative thermal oxidizers or regenerative catalytic oxidizers are used to control VOC emissions from veneer drying (US EPA, 2011).

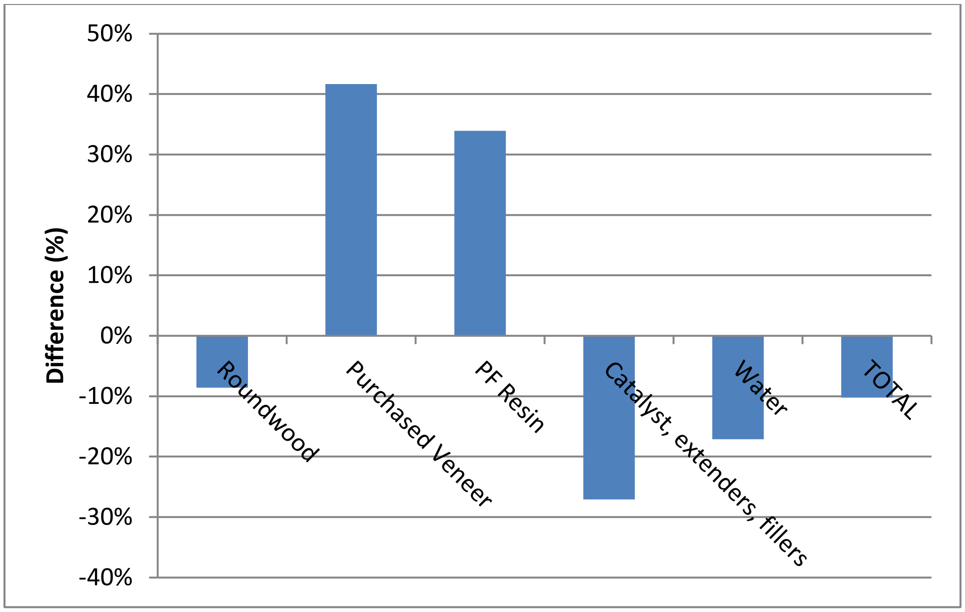
3.4 Contrast between Canadian and US mills

3.4.1 Material Input

Material Inputs	Canadian Mills	US Mills	Difference (%)
Roundwood (kg)	749	813	-8.56%
Purchased veneer (kg)	16	9.34	41.7%
PF Resin (kg)	10.9	7.21	33.9%
Catalyst, extenders, fillers (kg)	3.58	4.55	-27.1%
Water (L)	364	426	-17.1%
TOTAL	1143	1260	-10.2%

Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Table 24: Average material inputs in Canadian mills versus US mills for 1 MSF 3/8-inch of plywood



Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Figure 26: Average material inputs in Canadian mills versus US mills for 1 MSF of 3/8 inch of plywood

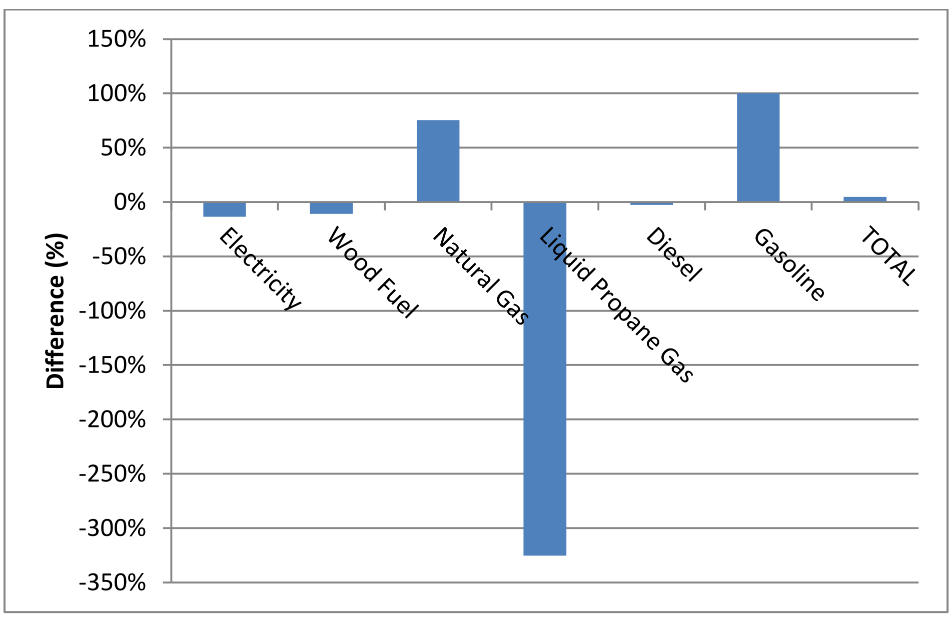
Information is provided by the Athena report in 2008, therefore the 2004 CORRIM report is used for this comparison. Canadian plywood mills generally have higher material inputs than their US counterpart. Purchased veneer and PF resin are the noticeably higher inputs at 42% and 34% difference respectively (Athena Sustainable Materials Institute, 2008). Roundwood input is also higher in Canadian mills, though the difference is very small at 5% (Athena Sustainable Materials Institute, 2008). As for catalyst, extenders and fillers and as well as water, US mills utilized much greater inputs at a difference of 27% and 17% respectively (Athena Sustainable Materials Institute, 2008).

3.4.2 Energy Input

Energy Inputs	Canadian Mills	US Mills	Difference (%)
Electricity (MJ)	440	500	-13.7%
Wood Fuel (MJ)	1535	1701	-10.8%
Natural Gas (MJ)	496	123	75.3%
Liquid Propane Gas (MJ)	7.9	33.6	-325%
Diesel (MJ)	52.5	53.9	-2.74%
Gasoline (MJ)	1.05	0	100%
TOTAL	2532	2412	4.77%

Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Table 25: Average energy inputs in Canadian mills versus US mills for 1 MSF of 3/8-inch of softwood plyood



Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Figure 27: Average energy inputs in Canadian mills versus US mills for 1 MSF of 3/8-inch of softwood plywood

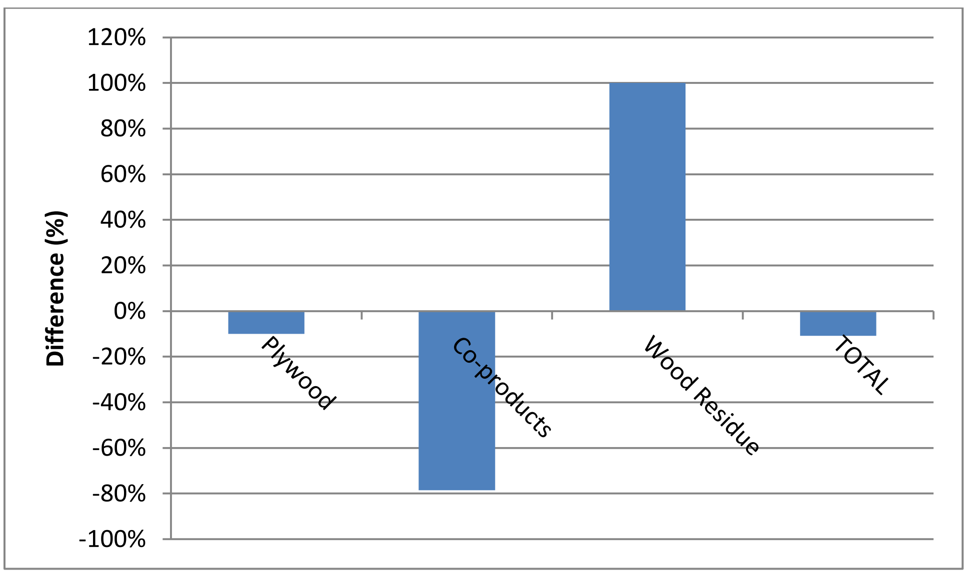
Overall energy inputs are lower in Canadian mills. Electricity, wood fuel and diesel inputs are all lower in Canadian mills, though the diesel input difference is very small. Natural gas input, however, is substantialy greater in Canadian mills due to the on-site heat requirements of their thermal processes (Athena Sustainable Materials Institute, 2008).

3.4.3 Material Output

Material Outputs	Canadian Mills	US Mills	Difference (%)
Plywood (kg)	392	450	-14.6%
Co-products (kg)	277	350	-26.3%
Wood residue (kg)	19.9	0	100%
TOTAL	689	799	-16%

Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Table 26: Average material outputs in Canadian mills versus US mills for 1 MSF of 3/8-inch of softwood plywood



Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Figure 28: Average material outputs in Canadian mills versus US mills for 1 MSF of 3/8-inch of softwood plywood

Both plywood products and co-products output are higher in US mills, although "some of this difference is due to raw fibre density differences between the two regions" (Athena Sustainable

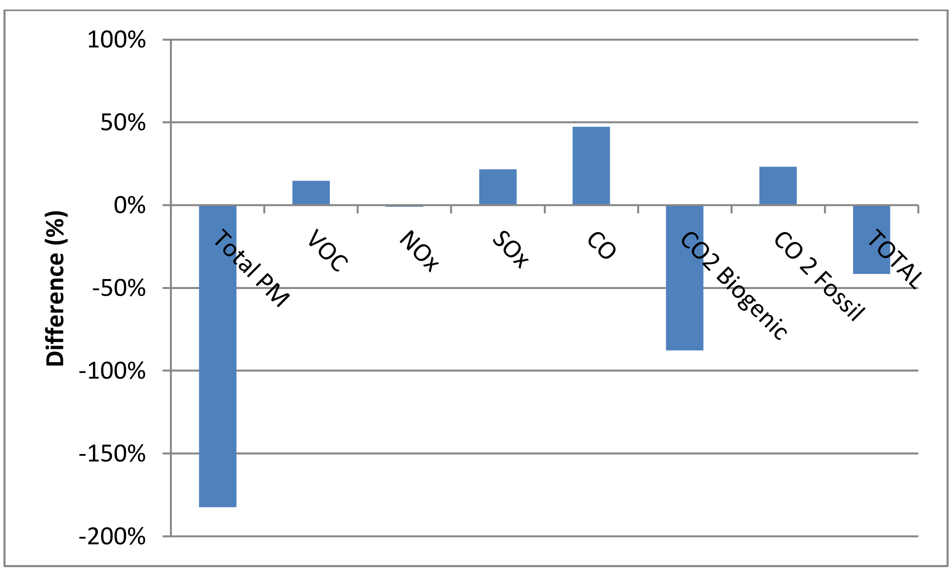
Materials Institute, 2008). While Canadian mills produce 19.9 kg of wood residue, their US counterparts do not produce them at all.

3.4.4 Emission

Substances	Canadian Mills	US Mills	Difference (%)
Particulate matter (kg)	0.199	0.562	-182%
VOC (kg)	0.696	0.594	14.7%
NOx (kg)	0.572	0.577	-0.87%
SOx (kg)	1.2	0.941	21.6%
CO (kg)	3.5	1.846	47.3%
CO2 Biogenic (kg)	135	253	-87.8%
CO2 Fossil (kg)	89.9	69.1	23.2%
TOTAL	231	327	-41.5%

Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Table 27: Average main air emissions generated in Canadian mills versus US mills for 1 MSF of 3/8-inch of softwood plywood



Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Figure 29: Average main air emissions generated in Canadian mills versus US mills for 1 MSF of 3/8-inch of softwood plywood

Because actual emission control systems employed in US mills are not provided in the LCI report, inferences cannot be made on emission differences between mills of Canada and US. Particulate matter emission is significantly lower in Canadian mills at a difference of 182% (Athena Sustainable Materials Institute, 2008). Volatile organic compound, SO_2 and as well as CO emissions are higher in Canadian mills than in US mills at 15%, 22% and 47% respectively (Athena Sustainable Materials Institute, 2008). On the contrary, NOx emissions are lower, which may be the result of lower usage of biomass fuel in the manufacturing process of Canadian mills. Biogenic CO_2 emission is lower in Canadian mills by 88% (Athena Sustainable Materials Institute, 2008). However, fossil CO_2 emission is higher at 23% for Canadian mills (Athena Sustainable Materials Institute, 2008). This is due to the increased use of natural gas and lower use of hog fuel in thermal processes of Canadian mills (Athena Sustainable Materials Institute, 2008), although this may also be the result of a natural gas intensive Canadian mill that swayed the average (Athena Sustainable Materials Institute, 2008).

4 Analysis

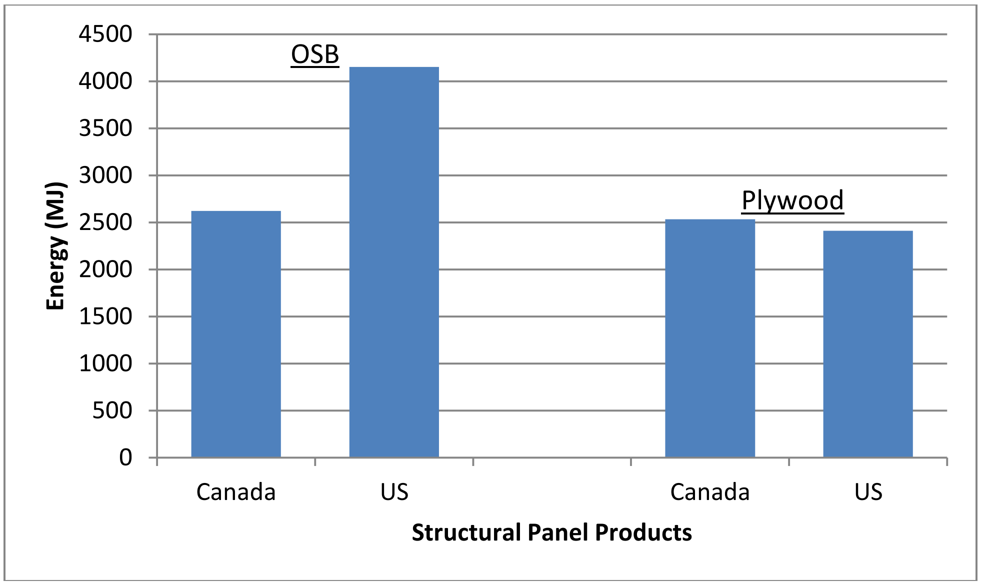
4.1 Structural Panel Comparison

Categories	Unit	OSB		Plywood	
		Canada	US	Canada	US
Energy	MJ	2622	4153	2532	2412
Greenhouse Gases (CO2)	kg	385	623	225	322
Acidification (SOx)	kg	1.35	2.56	1.2	0.941
Eutrophication (NOx)	kg	0.677	1.49	0.572	0.577
Total Particulate	kg	0.67	0.46	0.199	0.562
VOC	kg	1.13	2.36	0.696	0.594

Sources: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.
Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Table 28: Sustainability comparison between OSB and softwood plywood for 1 MSF 3/8-inch basis

4.1.1 Energy

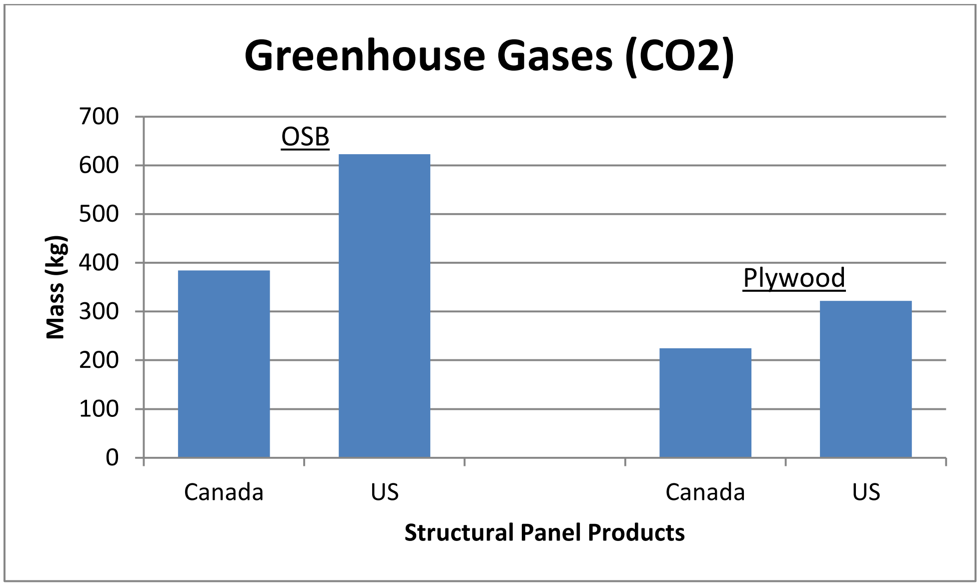


Sources: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.
Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Figure 30: Comparison of energy utiliztion between OSB and softwood plywood for 1 MSF 3/8-inch basis

As displayed in Figure 30, the overall energy utilization in the manufacturing of OSB is greater than that of plywood. The contrast in energy utilization between OSB and plywood manufactured in Canada is relatively minor with approximately 90 MJ (3.4%) difference. On the contrary, the difference in energy utilization between US manufactured OSB and plywood is much more significant at approximately 1740 MJ (42%) greater in the manufacture of OSB.

4.1.2 Greenhouse Gases

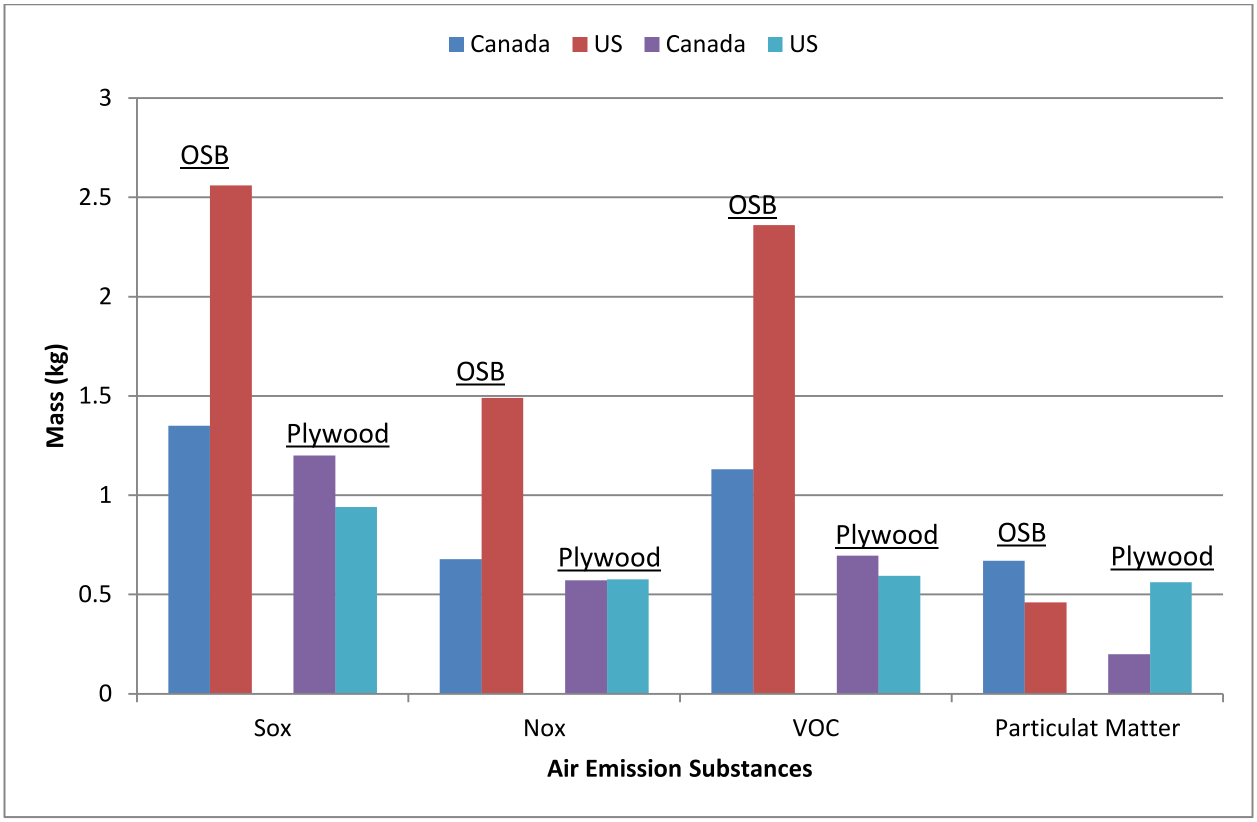


Sources: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.
Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Figure 31: Comparison of CO_2 emissions between OSB and softwood plywood for 1 MSF 3/8-inch basis

Shown in Figure 31, the manufacturing of OSB generates greater quantities of greenhouse gas emissions than the manufacturing of plywood. Although the CO_2 generated in the Canadian manufacturing of OSB is relatively greater than the CO_2 generated from plywood manufacturing at about 160 kg (42%), this difference is relatively insignificant in comparison to the difference of CO_2 generated between US manufactured OSB and plywood. The CO_2 produced from US manufactured OSB is 300 kg (48%) greater than the carbon dioxide produced from the manufacturing of plywood in US.

4.1.3 Other air emissions



Sources: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.
Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Figure 32: Comparison of SOx, NOx, VOC and particulate matter emissions between OSB and softwood plywood for 1 MSF 3/8-inch basis

Emission of SOx

Release of SOx emissions is higher in the manufacture of OSB than plywood, as displayed in Figure 32. The difference between US manufactured OSB and plywood is significantly greater than the difference between Canadian panel products. The Canadian manufacturing of OSB releases 0.15 kg (11%) more SOx emissions than that of plywood, whereas, US manufactured OSB releases 1.62 kg (63%) more than the manufacturing of plywood.

Emission of NOx

From Figure 32, emissions of NOx are generally higher in the manufacturing of OSB than plywood. For Canadian panel products, the manufacture of OSB releases slightly more NOx emissions than the manufacture of plywood by approximately 0.11 kg (16%). As for US panel products, the NOx emission difference is much greater with the manufacture of OSB releasing 0.913 kg (61%) more than the manufacturing of plywood.

Emission of VOC

As displayed in Figure 32, the manufacturing of OSB releases higher volatile organic compound emissions than that of plywood. VOC emissions are greater in the manufacture of OSB than plywood by 0.434 kg (38%) for Canadian panel products. In contrast, for US panel products, the VOC emission difference is considerably greater in the manufacture of OSB than plywood by 1.77 kg (75%).

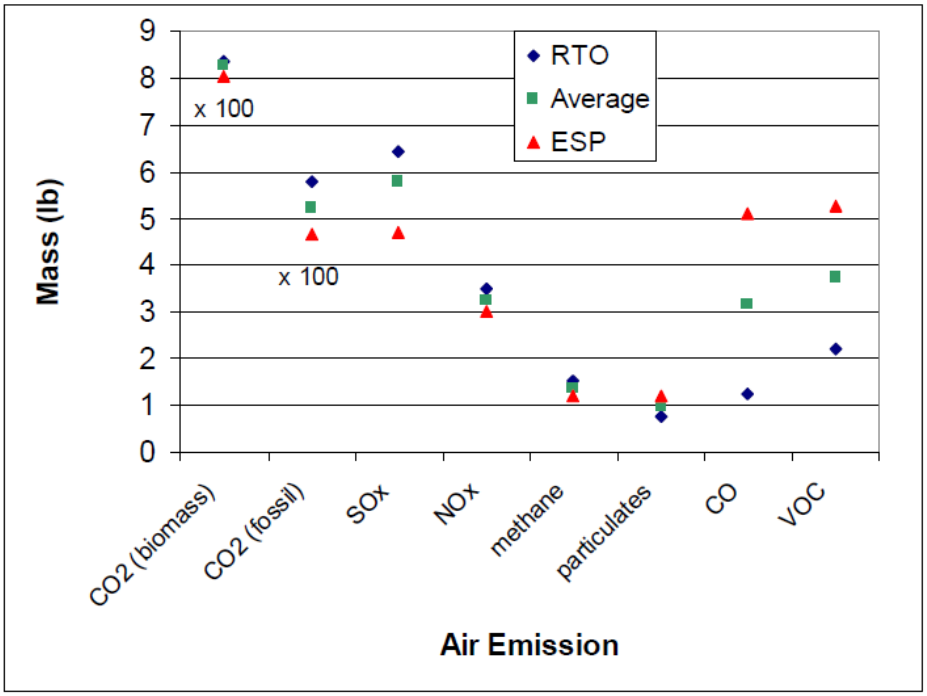
Emission of Particulate Matter

From Figure 32, the overall release of total particulate matter is greater in the manufacture of OSB than plywood. Specifically speculating Canadian panel products, manufacturing of OSB emits higher particulate matter than the manufacture of plywood by a significant difference of 0.471 kg (70%). However, in the US panel products, PM emissions released from the manufacture of OSB is lower than that of plywood by 0.10 kg (22%).

4.1 Emission Control System

4.1.1 Oriented Strand Board

4.1.2 Emission Control Systems Utilized in US



Source: Wilson, J. B. (2004). *Softwood Plywood Manufacturing.* Corvallis: CORRIM.

Figure 33: Combined on-site and off-site emissions produced in the manufacturing of 1 MSF 3/8-inch basis of OSB

The four southeastern plants participating in this study mainly employed two types of emission control systems, two plants used wet or dry Electro-Static Precipitator, ESP, and the other two used Regenerative Thermal Oxidizers, RTO (Kline, 2004). Figure 29 above displays the comparison between the results of air emissions in both on-site and off-site scenarios for each of the emission control systems. RTO is shown to be more effective than ESP at removing emissions of particulate, CO, and VOC by "34.1%, 75.8% and 57.9%" (Kline, 2004) respectively. On the contrary, the efficiency of RTO is countered by its increase of greenhouse gas emissions due to its utilization of natural gas. As a result, RTO has much greater "biomass CO_2, fossil fuelCO_2, SO_X, NO_X and methane emissions" than its counterpart by "4.0%, 24.7%, 36%, 16.7% and 26.2%" (Kline, 2004) respectively.

4.1.3 Emission Control Systems used in Canadian and US mills

Though the manufacturing process is the same, Canadian and US OSB mills typically employ different dust extraction systems. In Canadian mills, "electrified filter bed, Wet Electrostatic Precipitator, baghouse, multicyclone and dust collection" (Athena Sustainable Materials Institute, 2008) systems are used to remove particulates created in the manufacturing process. Conversely, US mills employ regenerative thermal oxidizers to extract particulates, CO and volatile organic compounds, and wet and dry Electrostatic Precipitator to collect particulates (Athena Sustainable Materials Institute, 2008).

The use of different systems in mills of both countries leads to different extraction efficiency, as well as different energy utilization. With the use of RTO, Southeastern US mills have higher demand for energy in the form of fossil fuels, wood, purchased electricity, and natural gas (Athena Sustainable Materials Institute, 2008). In contrast, Canadian OSB mills consume less energy with 45% lower in electricity purchase, 73% lower in biomass fuel consumption and 2.5 times lower in the usage of natural gas (Athena Sustainable Materials Institute, 2008). However, lower energy consumption in Canadian mills came with the compromise of air emissions. On average, Canadian mills have 32% higher release of particulates than their US counterparts (Athena Sustainable Materials Institute, 2008). Fortunately, other air emissions are not compromised as the release of methane and VOC is 2 times lower and emissions of NOx and CO are lower than US mills, which may be the result of lower consumption of "biomass and thermal fossil fuel" (Athena Sustainable Materials Institute, 2008) in the manufacturing process in Canadian mills. There are 46% and 95% lower releases of biogenic and fossil fuel carbon dioxide respectively from the lower usage of "biomass and fossil fuels in the manufacturing combustion process" (Athena Sustainable Materials Institute, 2008) in Canadian mills.

4.1.2 Softwood Plywood

4.2.1 Emission controls reported by the US EPA

Stated in the US EPA report, the commonly employed VOC control system is the regenerative thermal oxidizer, but regenerative catalytic oxidizers are also used as well (US EPA, 2011). In an RTO, the temperature of preheated emissions is increased to a range between 778^{O}C and 871^{O}C (US EPA, 2011). This incineration process takes place in a "combustion chamber with sufficient gas residence time to complete the combustion" (US EPA, 2011).

Although both RCOs and RTOs remove VOCs in similar fashion, RCOs have catalytic media in the heat recovery beds (US EPA, 2011). The catalyst in the catalytic media increases the "rate of VOC oxidation" (US EPA, 2011). With the rate of oxidation increased, VOCs can be destroyed in temperatures lower than that of RTOs, "typically between 315 ^{O}C and 538^{O}C" (US EPA, 2011). As a result, fuel consumption is also reduced.

4.2.2 Emission Control Systems used in Canada and US

Canadian plywood mills typically use a wet or dry ESP, multicyclone, and round and square bag house. Emission systems are not discussed in US reports, therefore brief inferences are only drawn on emission control systems reported in the US EPA report on emission factors in plywood manufacturing.

5 Recommendation

5.1 Sustainable Structural Panel Product

In comparing the LCI profiles of both Canadian and US produced OSB and plywood products, manufacturing of the latter structural panel product from both regions is considerably more sustainable. Displayed in Table 28 are the major differences in energy utilization and air pollutant emissions of SOx, NOx, VOC and particulate matter generated in the manufacture of both panel products. Though the energy difference between the Canadian panel products is relatively minor, the energy utilized in the manufacture of OSB and plywood in the US differs by a significant amount of 1740 MJ. In addition, emissions of SOx, NOx and VOC are lower in the manufacture of plywood than OSB. The magnitude of these emissions differences is especially significant between the structural panel products manufactured in US with the manufacture of plywood releasing 1.62 kg, 0.913 kg and 1.77 kg less respectively. As for the emissions of particulate matter in the US manufacture of panel products, the manufacturing of plywood releases more PM emissions than the manufacturing of OSB. However, the opposite occurs in the Canadian manufacture of panel products, as the manufacture of plywood produces less PM emissions by 0.471 kg.

Products	**Average Canadian Plywood Outputs**		**Average US Plywood Outputs**	
	Mass (kg)	Percentage	Mass (kg)	Percentage
Plywood	379	49.8%	482	25.2%
Co-products	383	50.2%	448	23.4%
Waste	0	0%	23.4	1.2%
TOTAL	762	100%	953	49.8%

Source: Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.
Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing.* Ottawa: Athena Institute.

Table 29: Comparison of average output between Canadian and US softwood plywood manufacturing for 1 MSF 3/8-inch basis

Products	**Average Canadian OSB Outputs**		**Average US OSB Outputs**	
	Mass (kg)	Percentage	Mass (kg)	Percentage
Plywood	498	79.3%	546	37.2%
Co-products	127.76	20%	119	17.9%
Waste	1.93	0.31%	0	0%
TOTAL	627	100.0%	665	100%

Sources: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.
Athena Sustainable Materials Institute. (2008). *A Cradle-to-Gate Life Cycle Assessment of Canadian Oriented Strand Board.* Ottawa, Ontario: Athena Institute.

Table 30: Comparison of average output between Canadian and US OSB manufacturing for 1 MSF 3/8-inch basis

Aside from lower energy utilization and air emissions, plywood has considerably lower product yield than OSB, which leads to poorer wood fibre utilization in the product (Smith G. , 2012). Displayed in Tables 29 and 30 are the percentages of product yield for both panel products. Amongst the panels manufactured in US, OSB panel yields approximately 29.8% more than plywood, while a similar difference is also evident in the panels manufactured in Canada with OSB yielding approximately 29.6% more than plywood. Though product yield is much lower in the manufacturing of plywood, almost 50% of the solid outputs are generated into co-products across both regions. These co-products include hog fuel, veneer, peeler cores and pulp chips that are sold for profit (Athena 2010). As for wastes, the difference in the amount of waste generated in the manufacturing of both panel products is minor at 0.31% and 0.76% for OSB and plywood respectively.

5.2 Emission Control System

Canadian panel mills typically release higher quantities of particulate matter (from OSB manufacturing), VOC, NO_x, SO_X and CO (from plywood manufacturing) into the atmosphere, whereas US panel mills generally have greater CO_2 emissions. Release of particulate matter has a significant impact on human health that can potentially damage "the human respiratory system" (Athena Sustainable

Materials Institute, 2008). The overall impact of the remaining substances is environmentally associated. Volatile organic compound, NO_X and CO emissions are contributors to smog, which can also potentially damage the human respiratory system (Athena Sustainable Materials Institute, 2008). As for SO_X, high concentrations can lead to aquatic acidification, which impacts human health and fresh water within the affected region (Athena Sustainable Materials Institute, 2008). Lastly, the release of CO_2 emission contributes to global warming that contributes to the increase in the average temperature of the Earth and may eventually leads to global climatic changes. Overall, considering the associated environmental and health impacts, the global warming impact from CO_2 emission is relatively more gradual than the various impacts caused by VOC, NO_X, SO_X and CO emissions. Therefore, the impacts on human health criteria, smog and aquatic acidification should be considered before global warming potential. As a result, the removal of VOC, NO_x, SO_X and CO emissions should be the main concern in the structural panel manufacturing industry.

Using of regenerative thermal oxidizers in panel manufacturing mills is theoretically preferable in removing VOC, NO_x, SO_X and CO emissions. Thermal oxidizers can "destroy VOCs and condensable organics by burning them at high temperatures" (US EPA, 2011), thus having the ability to achieve VOC removal efficiency of 99% (McFarlane, 2012). In addition, thermal oxidizers also lower CO emission via the process of complete combustion by oxidizing CO to CO_2 in the "direct fired dryer exhausts" (US EPA, 2011). However, its counterpart, the regenerative catalytic oxidizer has a significant advantage over the use of RTO. The RCO generally functions in similar fashion as RTO, but the catalytic media in the heat recovery bed of the RCO increases the VOC oxidation rate, thus enabling the destruction of VOC at lower temperatures of typically between 316^{O}C to 538^{O}C (US EPA, 2011). The lower heat requirement of the RCO allows for reduced fuel utilization, a significant advantage over RTO. Although RCOs still have disadvantages that include "excessive downtime" (McFarlane, 2012) from plugged exchanger beds caused by buildup of residual ash, "higher maintenance cost" (McFarlane, 2012) from rapid deterioration of the catalyst and relatively higher CO_2 emission from increased fuel utilization, the latter disadvantage can be compensated with an emission trading legislature. An "economically efficient allocation mechanism" (McFarlane, 2012), emission trading can help redirect the available capital of panel manufacturers "towards more efficient projects via a market price for emissions" (McFarlane, 2012). Even though there is "difficulty in attaining uniform performance" (McFarlane, 2012) with RCO, the use of regenerative catalytic oxidizer in combination with the emission trading legislature is theoretically preferable.

6 Conclusion

The influential trend of sustainable construction will indeed continue to change and innovate in single family homes from the overall design to the construction practice and choice of material. Even though, OSB and softwood plywood products are decreasing in demand since 2006, nevertheless these are essential products used as sheathing material and web of I-joist, which shall help increase the demand of OSB and softwood plywood with the growth of sustainable construction. Although the manufacturing of these products has utilized great amounts of hogged fuel and wood residue to improve carbon balance, there still are volatile and particulate emissions released from the manufacturing process. Aside from carbon dioxide, emissions of VOC, NO_x, SO_X, CO and particulates are the primary air pollutants mainly released from the processes of drying and pressing in the manufacturing of both structural panel products. Particulates specifically impact human health, while the remaining substances impact both health and the environment.

When contrasting OSB with plywood on the basis of sustainability, plywood is a more sustainable structural panel product between the two. Throughout the entire manufacturing process in

Canada and as well as in the US, production of plywood utilizes lower energy and generates fewer air pollutant emissions of CO_2, SOx, NOx, VOC and particulate matter.

Structural panel mills of both regions typically employ different emission control systems. Canadian mills mainly employ wet or dry electrostatic precipitators, multicyclones, round and square bag houses, electrified filter beds and dust collection equipments (Athena Sustainable Materials Institute, 2008), whereas US mills generally use regenerative thermal oxidizers and wet and dry electrostatic precipitators (Athena Sustainable Materials Institute, 2008). Overall, the systems used in the Canadian panel manufacturing mills are less efficient in removing air pollutants and produces lower CO_2 emission. Conversely, the emission systems used in the US mills are significantly more efficient at air pollutant removal, but produce higher CO_2 emission.

Closely comparing the various emission control systems employed over the two regions, the combination of using regenerative catalytic oxidizer and emission trading legislature is theoretically preferable to lower the overall environmental impact generated from the OSB and softwood plywood manufacturing processes. In a world competing for sustainability, reducing environmental impacts of OSB and plywood will likely aid the Canadian panel manufacturers in gaining North American market shares of structural panels.

7 Appendix

Substance	OSB kg	Dust Scrap kg	Bark kg	Screen Fines kg	Total kg
CO	1.44	0.0011	0.0004	0.0142	1.46
CO2 (Fossil)	225	1.7	0.939	1.66	229
CO2 (biomass)	375	2.83	0	3.94	381
CO2 (non-fossil)	0.0889	0.0007	0.0004	0.0006	0.091
CO2	11.6	0.088	0	0	11.7
Dust (PM10)	0.304	0.002	0.0002	0.0034	0.310
Particulates	0.132	0.001	0.0009	0.0011	0.135
Methane (CH4)	0.626	0.005	0.002	0.0037	0.636
NOx	1.47	0.011	0.0036	0.0082	1.49
SO2	0.108	0.0008	0	0.0003	0.109
SOx	2.52	0.019	0.007	0.0156	2.56
VOC	0.975	0.073	0	0.0112	1.06
HAP	0.605	0.003	1.77E-06	0.0037	0.611
TOTAL	619	4.74	0.9534117	5.65	631

Source: Kline, D. E. (2004). *Southeastern Orieted Strandboard Production.* Virginia Polytechnic Institute and State University. Blacksburg: CORRIM.

Table 31: Air emissions (per MSF 3/8-inch basis) generated from the manufacture of OSB on-site and off-site in the SE region

Substance	Debarking	Conditioning	Peeling and Clipping	Veneer Drying	Lay-up and Pressing	Trimming and Sawing	Total
	kg	kg	kg	kg	kg	kg	kg
CO	0.0196	0.131	0	0.984	0.231	0	1.37
CO2 (Fossil)	5.13	1.17	0.000644	8.48	14.5	0.594	29.8
CO2 (non-Fossil)	0.00129	19.8	0	140	28.6	0	188
Dust (PM10)	0	0	0.00218	0.121	0.00060781	0.00315	0.127
Particulates	0.00685	0.00206	0.00503	0.15	0.0608	0.0045	0.229
Methane (CH4)	0.00205024	0.00309	0.00146	0.0199	0.0365	0.00135	0.0643
Nitrogen Oxides	0.0866	0.0209	0.00252	0.149	0.207	0.0023	0.469
SO2	0	0	0	0.000476	2.4313E-06	0	0.000479
Sox	0.015	0.0161	0.00553	0.105	0.188	0.00494	0.335
VOC	0	0	0	0.27	0.114	0	0.385
HAP	0.00124	0.000465	7.67E-09	0.0336	0.0899	6.76E-09	0.125
TOTAL	5.26	21.2	0.0174	150	44	0.61	221

Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Table 32: Air emissions (per MSF 3/8-inch basis) generated from the manufacture of softwood plywood in the PNW region

Substance	Debarking	Conditioning	Peeling and Clipping	Veneer Drying	Lay-up and Pressing	Trimming and Sawing	Total
	lb	lb	lb	lb	lb	lb	
CO	0.0146	0.178	0.0012	1.25	0.307	0.0029	1.76
CO2 (Fossil)	5.94	3.01	2.48	27.1	22.5	3.13	64.1
CO2 (non-Fossil)	0.0018	26.7	0	181	36.9	0	245
Dust (PM10)	0	0	0.0021	0.0095	0.0001	0.0378	0.0495
Particulates	0.0073	0.0041	0.0026	0.0581	0.0921	0.137	0.3
Methane (CH4)	0.0064	0.0073	0.0051	0.0442	0.0544	0.0064	0.124
Nitrogen Oxides	0.068	0.0305	0.0091	0.216	0.275	0.0113	0.611
SO2	0	0	0	3.72E-05	2.46E-07	0	3.74E-05
Sox	0.0297	0	0.0199	0.216	0.272	0.0251	0.562
VOC	0	0	0	0.0345	0.113	0	0.148
HAP	0.0008	0.0006	6.38E-07	0.005	0.0953	0	0.102
TOTAL	6.07	29.9	2.52	210	60.6	3.35	312

Source: Jim Wilson, M. P. (2010). *Softwood Plywood - Pacific Northwest and Southwest.* CORRIM.

Table 33: Air emissions (per MSF 3/8-inch basis) generated from the manufacture of softwood plywood in the SE region

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