BIOMASS AND BIOENERGY 33 (2009) 434–441

Available at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

An environmental impact assessment of exported wood pellets from Canada to Europe

Francesca Magelli[a], Karl Boucher[b], Hsiaotao T. Bi[b,*], Staffan Melin[c], Alessandra Bonoli[a]

[a]Department of Chemical and Mineral Engineering (DICMA), University of Bologna, Italy
[b]Clean Energy Research Centre, University of British Columbia, 2360 East Mall, Vancouver, BC, Canada V6T 1Z3
[c]Delta Research Corp., Delta, Canada

ARTICLE INFO

Article history:
Received 9 November 2006
Received in revised form
12 August 2008
Accepted 29 August 2008
Published online 29 October 2008

Keywords:
Wood pellets
Fuel consumption
Fossil fuel content
Greenhouse gas emissions
Air emissions
Life cycle analysis
Impact assessment

ABSTRACT

There have been increased interests on exporting wood pellets from Canada to Europe to meet the increased demand on biofuels in European countries. The wood pellet industry in Canada, especially in the west coastal region, has grown at an annual rate of more than 20% averaged over last 5 years due to the steady supply of wood residues. This paper attempted to analyze the fuel consumption and air emissions associated with the wood pellet production in British Columbia and export to Sweden based on a streamlined life cycle analysis, starting from tree harvesting for wood residue production to the shipping of wood pellets from Vancouver to Stockholm in Sweden. The results showed that about 7.2 GJ of energy is consumed for each tonne of wood pellets produced and shipped to Europe, representing about 39% of the total energy content of the wood pellets. Among those energies consumed over the life cycle, about 2.6 GJ is associated with long-distance ocean transportation. The ocean transportation is also the major contributor to environmental and health impacts, followed by the pellet production processes. The fossil fuel content, which quantifies the amount of fossil fuel consumed over the life cycle, for exported wood pellets ranged from 19% to 35%, depending on whether natural gas or wood residue is used in the drying operation during the wood pellet production stage. To reduce the fossil fuel content and the environmental impacts, wood residues should be used in the drying operation and, if possible, local market should be explored to reduce the energy consumption associated with wood pellet transportation over long distances.

1. Introduction

The European Commission decided to double the financial contribution to renewable energy from current 6% to 12% in 2010 [1]. This increase, if effected, could result in a reduction of CO_2 equivalent emissions of about 230–260 million metric tonnes (8% more reduction than the target set by the Kyoto Protocol). Stimulated by the incentives and tax credits, biomass utilization for the production of electricity and for the residential and district heating has been growing very rapidly in Europe, at an annual increase rate of about 25% [2,3].

Densification of wood residues into pellets for space and water heating has been practiced in Europe since the 1970s [2]. Pelletization creates a clean burning, convenient and energy-concentrated fuel from bulky fibrous waste such as sawdust and wood shavings. Wood pellet heating systems are considered as an essential component of European plans to reduce GHG emissions and are targeted by incentive programs

* *Corresponding author*. Tel.: +1 604 822 4408; fax: +1 604 822 6003.
E-mail address: xbi@chml.ubc.ca (H.T. Bi).
0961-9534/$ – see front matter
doi:10.1016/j.biombioe.2008.08.016

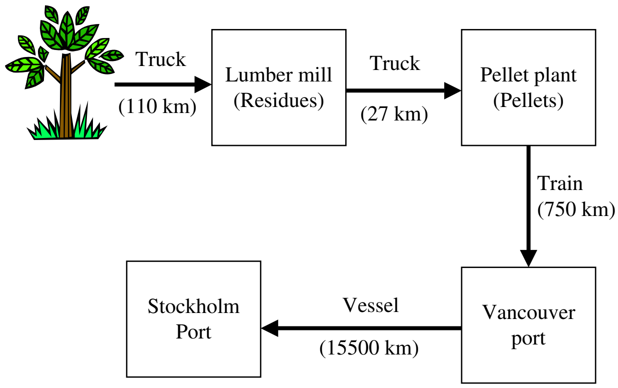

Fig. 1 – Production and transportation logistics of wood pellets from the Canadian forest to the European market.

in countries such as Germany, Norway and Sweden [3]. In North America there are an estimated 500,000 pellet burning stoves and furnaces with a total of about 650,000 tonnes of annual wood pellet consumption [4].

Canada is richly endowed with significant biomass resources. For example, the estimated thermal energy content of the annual biomass harvested in Canada is 5.1×10^9 GJ. This annual harvest is equal to 62% of the thermal energy derived from fossil fuels in Canada [5]. The development of this biomass resource, not just for energy but also for a variety of end uses, presents to Canada an opportunity to not only develop new and innovative industries but also sustainable energy and raw material supplies to reduce Canada's reliance on non-renewable fuels and greenhouse gas emissions. The production of wood pellets has become a fast growing industry in Canada in recent years. Currently there are about 19 pellet manufacturing plants with an annual production capacity just over 1,000,000 tonnes of pellets, with most plants located in the east coast and west coast regions. Contrary to USA where almost all 800,000 tonnes of wood pellets produced there are consumed domestically, more than 80% of wood pellets manufactured in Canada are exported to Europe because the demand of wood pellets in Europe is much higher than what can be produced there (1,800,000 tonnes of wood pellets are produced in Europe annually) and the production of wood pellets in Canada is more than what is consumed locally. The transportation logistics of exported pellets from Canada to Europe is thus one of the important issues in the study of production and consumption of wood pellets in view of the important role played currently by the wood pellet exported from Canada on the global wood pellet market.

The purpose of this work is to analyze the net benefits of exporting wood pellets from Canada to Europe with the consideration of environmental impacts not only associated with the production of wood pellets but also with the transportation. In view of the fact that the emissions of greenhouse gases and air pollutants come not only from pellets burning but also from the production and transportation processes, one needs to conduct a streamlined life cycle analysis in order to determine whether biomass utilization via pelletization and exportation still remains sustainable.

In the current study, we focus on wood pellets produced in British Columbia located in the west coast of Canada because more than 2/3 of Canadian wood pellets are produced in this region. Furthermore, the production site selected for analysis is located in Prince George of British Columbia, where most pellet plants are situated in the close proximity. The port for ocean shipping to Europe is located in Vancouver of British Columbia. The Canadian wood pellets are shipped to Sweden, Netherlands, Belgium and all the countries in the north of Europe. However, this work considers only the port in Stockholm, which represents the most popular destination.

For a wood pellet plant located in Prince George, the whole wood pellet production and transportation process is illustrated in Fig. 1. Trees are harvested from the forest and then transported for an average of 110 km to the lumber mill where wood residues, including both shavings and sawdust, are collected and transported by trucks for an average distance of about 27 km to the pellet plant where wood residues are densified into wood pellets. After the production and packaging, the wood pellets, either in bulk or in bags, are transported from the plant to the Vancouver port by train, over a total average distance of

Table 2 – Total energy consumed for the production of sawdust in sawmills.

Type of energy	MJ tonne^{-1} wood pellets
Electricity	140.3
Natural gas	86.15
Heavy fuel oil	9.680
Middle distillates	14.46
Propane	0.2967
Steam	2.732
Wood waste	131.4
Total	385.0

Table 1 – Emissions from tree harvesting.

Pollutant	g tonne^{-1} wood pellets
CO	63
CO_2	1177
CH_4	2.9
N_2O	1.6
NO_2	294
VOC	4.6
PM	20.4
SO_x	27.9

Table 3 – Emission factors for HDV (GHGenius 3.2).

Pollutant	g GJ^{-1} fuel used	g tonne^{-1} km^{-1}
CO_2	67,667	108
CO	383	0.61
CH_4	5.90	0.009
N_2O	0.95	0.0015
NO_x	794	1.26
SO_x	65.97	0.10
PM	40.09	0.06
VOC	58.95	0.09

Table 4 – Existing pellet mills in British Columbia, their locations and raw material transportation distance.

Pellet mills	Raw material		Mill location	
	% of raw materials	Distance from mills (km)	Nearest city	Distance to railhead (km)
Pacific Bio Energy	15	75	Prince George	At railhead
(to be installed)	40	2		
	45	1		
Premium Pellet	60	On-site (pipeline)	Vanderhoof	At railhead
	40	50		
Westwood Fiber	80	4	Kelowna	5
	20	100		
Princeton Co-Gen	100	1	Kelowna	150
Pinnacle Pellet	100	10	Quesnel	At railhead
Pinnacle Pellet	100	1	Williams Lake	At railhead

750 km. The wood pellets are then loaded to ocean vessels and shipped from North America to Europe over a distance of about 15,500 km.

2. Audit and inventories of energy consumption and emissions

2.1. *Harvesting and wood residues' production*

The first step in this process is the harvest of wood, with the residues from the wood lumber processing being used as the raw material for wood pellets. The common operation of harvesting depends on the technology used, which is often affected by management procedures and market demands.

The wood resource may be a natural forest or an established forest. An established forest is composed of three stages: seedling, site preparation and planting. Maintenance of the stand follows two stages: thinning and fertilization. In this work, only harvesting of wood from natural forest will be analyzed, excluding the re-forestation. The harvesting process is divided into five steps: felling trees, skidding trees to landing area, processing trees to logs (debarking, topping, bucking, de-limbing and cutting to length), loading and transportation to the process point (hauling). In this work the average distance for the hauling to the sawmill is estimated to be 110 km.

The emissions and energy consumptions associated with tree harvesting in British Columbia are taken from a paper from Sambo [6], which reported an energy consumption of 273 MJ m^{-3} of harvested wood. By assuming that all the energy comes from diesel fuel in consideration that the other sources of energy are negligible compared to the quantity of diesel fuel used, the emissions associated with the harvesting are estimated using the emission factors from US EPA's AP-42 database. In the calculation, the energy consumption and emissions are partitioned between the lumber and the sawdust based on their weight ratios, rather than the value of the product because it is difficult to assign a realistic value to the sawdust, a wood residue. The emission factors for each tonne of sawdust from a selected harvesting system in British Columbia are shown in Table 1. To calculate the emissions for each tonne of wood pellets produced, it is assumed that 7.8 tonnes h^{-1} sawdust at 40% moisture content is required for a 5 tonnes h^{-1} pellet plant [7].

Data for emissions and energy consumption of the sawmills in Canada were taken from a recent report by the Canadian Industrial Energy End-use Data and Analysis Centre (CIEEDAC) [8]. The given total annual energy consumption and lumber production from all sawmills were used to derive an average energy consumption for 1 m^3 wood residues. To convert the unit from GJ m^{-3} sawdust to GJ $tonne^{-1}$ pellet, an average sawdust density of 150 kg m^{-3} is used. It is seen from Table 2 that about 0.385 GJ of energy is consumed to harvest and collect wood logs, transport them over an average distance of 110 km and then converted into 1 tonne sawdust.

2.2. *Transportation of wood residues from sawmills to the pellet mill*

To study the environmental impact and the total transportation cost, it is necessary to have the information on the fuel consumption, the emission factors and the energy consumed for each kilometer of transportation by truck.

To estimate the fuel consumption from a heavy-duty diesel (HDV) engine, a life cycle analysis software called GHGenius developed by Natural Resources Canada over the past 6 years is used. GHGenius is capable of estimating life cycle emissions of the primary greenhouse gases and the criteria pollutants from combustion sources.

The energy required for a truck to transport 1 tonne of goods over 1 km is 1590 kJ $tonne^{-1}$ km^{-1} on average. The

Table 5 – Total emissions from wood residue transportation from sawmills to pellet plants.

Pollutant	g $tonne^{-1}$ wood pellets
CO_2	18,100
CO	431
CH_4	21.4
N_2O	1.0
NO_x	63.2
SO_x	7.7
PM	20.7
VOC	1.9

Table 6 – Emissions from biomass densification operation [9].

Air pollutant	Wet sawdust as fuel (kg $tonne^{-1}$ pellets)	Natural gas as fuel (kg $tonne^{-1}$ pellets)
CO_2	27.8	193
CO	0.222	0.239
SO_x	0.127	0.209
NO_x	0.482	0.514
CH_4	0.0053	0.924
NH_3	0.0	0.0038
PM	0.0142	0.0226
N_2O	0.00018	0.0030
VOC	0.0048	0.220

average weight of a truck with both payload and fuel is around 30,000 kg. Subtracting the non-payload elements, the payload or the average weight of goods one truck can transport is around 20 tonnes for each truck.

The emission factors are estimated using GHGenius, with the results shown in the second column of Table 3. Using the fuel consumption rate, emission factors are then converted from g GJ^{-1} to g $tonne^{-1}$ km^{-1}, with the results shown in the third column of Table 3.

To estimate the average distance for truck transportation of wood residues, data for existing main pellet mills in British Columbia were collected and shown in Table 4. Normally, the pellet mill is situated in close vicinity to sawmills in order to keep raw material transportation cost low. The table also shows the percentage of raw materials transported from a certain distance to different pellet mills. The distance from the production site (pellet plant) to the railhead is also shown.

The average distance covered by truck for each tonne of sawdust or wood pellets (only from the plant to the railhead) is calculated as the summation of the distance multiplied by the fraction of raw materials used in each plant. The average distance that each tonne of raw material (sawdust) has to be trucked in British Colombia from the sawmill to the plant is thus found to be around 28 km.

The total energy consumed by truck to transport 1 tonne of wood residues from the sawmill to the pellet mill can now be calculated by

$$1591\left(\frac{\text{kJ}}{\text{tonne km}}\right) \times 27.84(\text{km}) = 44,293\left(\frac{\text{kJ}}{\text{tonne of wood residues}}\right)$$

In summary, the total energy consumed to transport 1 tonne raw materials by truck for an average distance of about 28 km is around 0.044 GJ. For every tonne of wood pellets to be produced 1.56 tonnes of raw material are needed. Therefore, 0.07 GJ of energy is used for the truck transportation.

Combining the emission factors given in Table 3 with the average fuel consumption for transporting each tonne of sawdust and pellets, emissions associated with the truck transportation of 1 tonne wood residues and wood pellets from the sawmills to the pellet plant are calculated with the results shown in Table 5.

Table 8 – Freight train emission factors in g per litre [10].

	NO_x	CO	HC	PM	SO_2	CO_2	CO_2 equiv.
1990–2000	54.69	10.51	2.73	1.30	2.54	2709	3050
2001–2002	58.81	10.51	2.73	1.30	2.54	2709	3050
2002–2003	53.17	10.81	2.34	1.19	2.37	2709	3050
2003–2004	52.54	7.22	2.99	1.85	2.30	2730	3074

2.3. *Wood pellet production*

A densification process consists of three unit operations: drying, size reduction (grinding) and densification (pelleting). In the first step, wet sawdust is dried in a rotary drier. Green woodchips arriving at the mill typically contain about 50–65% of moisture. This high moisture is reduced to about 10% by drying.

After drying, a hammer mill is used to reduce the biomass to a particle size suitable for pelleting. A hammer mill screen size of 6.4 or 3.2 mm is normally used for size reduction of biomass. The hammer mill is powered by an electric motor. Part of the energy from the hammer mill is converted into heat, which is helpful for further extracting moisture from the raw material. The dry ground biomass is finally compacted in the press mill to form pellets.

Wood pellets coming out of the pelleting machine usually have a temperature of about 70–90 °C, due to the frictional heat generated during extrusion and material pre-heating. It is necessary to cool the pellet down to a temperature of about 25 °C to harden and stabilize the wood pellet and to maintain the quality of the product during storage and handling. The cooled pellets are conveyed from the cooler to storage areas using mechanical or pneumatic conveying systems. Normally the pellets are bagged automatically in 25 kg bags or stored in a silo.

Mani [9] analyzed a typical densification process for several scenarios using different fuels. The fuels compared are natural gas, coal, dry and wet sawdust, and ground wood

Table 7 – Total energy used for biomass densification [9].

Energy	Wet sawdust (MJ $tonne^{-1}$ pellet)	Natural gas (MJ $tonne^{-1}$ pellet)
Electrical energy	404	404
Fuel Energy	3168	2364
Diesel Energy	206	206
0.5		
Total	3778	2974

Table 9 – Emission factors for freight trains.

Pollutant	g $tonne^{-1}$ km^{-1}	g $tonne^{-1}$
CO_2	16.38	12,785
CO	0.043	33.56
HC	0.018	14.05
PM	0.011	8.59
SO_2	0.014	10.93
NO_x	0.315	245.9

Table 10 – Emission factors (in g kg^{-1} of fuel) for underway ocean-going vessels.

Pollutants	Emission factors (g kg^{-1} fuel)	Data source	Emission factors (kg $tonne^{-1}$ wood pellets)
CO_2	3635	Lloyd, 1995 [15]	206.4
CO	7.4	Lloyd, 1995 [15]	0.42
NO_x	93	Lloyd, 1995 [15]	5.28
SO_x	49	Lloyd, 1995 [15]	2.78
VOC	2.4	Lloyd, 1995 [15]	0.14
PM	7.6	Lloyd, 1995 [15]	0.43
CH_4	0.4	IPCC, 1997 [16]	0.023
N_2O	0.09	IPCC, 1997 [16]	0.005
NH_3	0.1118	IPCC, 1997 [16]	0.006

pellets. In this study, two scenarios, which have been commonly practiced in the industry, will be considered: wet sawdust and natural gas as fuels. Based on the work of Mani [9], total emissions for the two scenarios are shown in Table 6. Energy consumptions are given in Table 7. It is seen that the energy used to produce 1 tonne wood pellets is around 3.8 GJ using wet sawdust as the fuel for drying, and around 3 GJ when natural gas is used for drying.

2.4. *Ground transportation of wood pellets*

To transport the product from Prince George to Vancouver, wood pellets are loaded onto a CN (Canadian National) train, and then transported to New Westminster before arrive at the Vancouver Port using the BNSF railway connection. From Prince George to New Westminster the distance of the rail is 763 km, and from New Westminster to Vancouver Port is 18 km, giving a total distance from Prince George to Vancouver Port of 781 km.

According to the 2004 Locomotive Emissions Monitoring Program from Environment Canada [10], the total revenue tonne-kilometers (RTK) are 343.23 billion tonne-kilometers in 2004 in Canada. Here RTK are defined as the total weight (in tonnes) of revenue commodities handled multiplied by the distance (in kilometers) transported, excluding the tonne-kilometers involved in the movement of railway materials or any other non-revenue movement. Overall fuel consumption for all freight train and switching operations in 2004 was 2084.46 million litres in Canada. An average freight traffic fuel efficiency, defined as the amount of fuels consumed per 1000 RTK transported, is thus calculated to be 6.07 litres per 1000 RTK in 2004.

Emission factors for each of the Criteria Air Contaminants (CAC), i.e. NO_x, CO, HC, PM and SO_x, produced from locomotive operations depend on the type of engines in various throttle notch settings applied to the duty cycle for the locomotive operation. These factors were derived originally from tests performed in the early 1990s by the Association of American Railroads (AAR), Southwest Research Institute (SwRI) and the locomotive manufacturers. Realizing that the profile of the Canadian fleet had changed since 1995, the emission factors were reviewed in 2001 and revised accordingly. Since then, there have been further emission testing of locomotives at SwRI for the US EPA and Transport Canada. Also, since 2003, the emission factors have been updated annually to reflect the rising number of locomotives in the Canadian fleet now meeting the stringent US EPA Tier 0 and Tier 1 emission standards. Table 8 shows how the emission factors for freight train operations have been revised since 2001 to reflect changes in the composition of locomotive fleet.

Using the freight fuel consumption rate of 6.07 litres per 1000 RTK, emission factors in Table 8 for the year 2004 are converted into the desirable format, in g $tonne^{-1} km^{-1}$, with the results shown in Table 9. Given the transportation distance, fuel efficiency of trains and the emission factors, the total emission factors for the ground transportation of wood pellets from Prince George to Vancouver Port are estimated and shown in the third column of Table 9.

Energy consumption from rail transportation of wood pellets is estimated to be 0.336 MJ $tonne^{-1} km^{-1}$ using the GHGenius program, which is in close agreement with the fuel consumption rate for freight trains from this study (i.e. 6.07 litres per 1000 RTK). Note that rail transportation, in general, consumes approximately about 2.2 times more energy than transportation by boats. For the transportation

Table 11 – Summary of emission factors for each process in g $tonne^{-1}$ wood pellets.

Energy and pollutant	Harvest	Truck	Production		Train	Ocean vessel
			Sawdust as fuel	Natural gas as fuel		
Energy consumed	0.53	0.07	3.78	2.97	0.26	2.60
CO_2	29,850	4675	27,800	193,000	12,785	206,440
CO	494	26.5	222	239	33.6	420
CH_4	24.3	0.39	5.3	924	n.a.	23
N_2O	2.6	0.062	0.177	3.01	n.a.	5
NO_x	357.2	54.7	482	514	246	5280
VOC	6.5	3.9	4.84	220	14.05	140
PM	41.1	2.61	14.2	22.6	8.59	430
SO_x	35.6	4.34	127	209	10.9	2780
Aldehyde	n.a.	1.73	n.a.	n.a.	n.a.	n.a.
NH_3	n.a.	n.a.	0	3.81	n.a.	6

n.a., not available.

Table 12 – Total emission factors in g $tonne^{-1}$ wood pellets.

Pollutant	Production with sawdust as fuel	Production with natural gas as fuel
CO_2	281,550	446,750
CO	1196	1213
CH_4	53.0	972
N_2O	7.8	10.7
NO_x	6420	6452
VOC	169	384
PM	496	505
SO_x	2958	3040
Aldehyde	1.7	1.7
NH_3	6.0	9.8

from Prince George to Vancouver (781 km), the total energy consumed is found to be about 0.26 GJ $tonne^{-1}$.

2.5. *Ocean transportation of wood pellets*

The international shipping trade is an important part of the global economy. Ships are also an efficient means for goods transportation. However, until recently, air pollution from ships went largely unregulated, with regulatory and advocacy focus on more visible land-based sources. Reflecting the lack of meaningful regulation, the permitted rates of SO_2, NO_x and PM emissions from diesel marine engines are much greater than that from almost any other category of mobile sources. US EPA's current regulations permit new coastal and harbor craft diesel marine engines to emit NO_x and PM at rates between 2 and 27 times higher than new non-road land-based heavy-duty diesels. In Europe, as of the end of 2004, cargo vessel emissions exceeded heavy truck emissions of PM by 4–6 times, SO_2 by about 30–50 times, and NO_x emissions by about 2 times (comparing emissions expressed in terms of units per tonne-kilometer). These disparities became greater in 2005 when the sulfur content of road-vehicle diesel fuel was reduced from 350 ppm to 50 ppm, and in 2005 and 2008 when NO_x emission standards for trucks are tightened.

This study will consider the transportation from Vancouver, BC (Canada) to Stockholm (Sweden). The distance between the two cities is 15,490 km (9626 miles). The travel is very long, with the only possible pathway via Panama Canal. The average load for each travel of wood pellets is around 40,000 tonnes. The assumed underway speed for a bulk carrier of such a size is around 10 miles per h (8.7 knots) and the voyage takes more than 40 days. Due to its long transportation distance, it is important to estimate the total emissions and energy consumptions associated with the ocean transportation.

Concerning with the greenhouse gas (GHG) emissions from ocean-going vessels, United Nations Framework Convention on Climate Change (UNFCCC) had requested the International Maritime Organization (IMO) to estimate the emissions quantitatively. In the document of the Ocean Policy Research Foundation the annual total volume of ocean transport using bulk carrier is 9.992×10^{12} tonne km, and the total annual fuel consumption is 3.7×10^7 tonnes [11].

The average fuel consumption for ocean vessels is thus estimated to be 0.0037 kg fuel $tonne^{-1}$ km^{-1}. For each tonne of wood pellets to be transported from Vancouver to Stockholm over a distance of 15,400 km, the total fuel used is calculated to be 56.8 kg fuel $tonne^{-1}$ pellets. Using the high heating value (HHV) of diesel fuel of 45.9 MJ kg^{-1}, the energy consumption is found to be 2.6 GJ $tonne^{-1}$. This means that for each tonne of wood pellets to be shipped from Vancouver to Stockholm, about 2.6 GJ of energy will be consumed.

In 2002 the Policy and Planning Department of Greater Vancouver Regional District with the Environmental Canada Pacific and Yukon Region prepared a document on ''Marine Vessel air Emissions in the Lower Fraser Valley'' [12]. The emission factors from that document for underway ocean-going vessels in North Western America are shown in Table 10, and are used for the estimation of air emissions in this study. By multiplying the emission factors with the fuel consumption, air emissions associated with the transportation of 1 tonne wood pellets from Vancouver to Stockholm are obtained, with the results shown in the fourth column of Table 10.

2.6. *Total emissions over the entire process*

Table 11 shows the emission factors estimated for each stage in the whole process. By adding up all emission inventories associated with each stage of the process ranging from raw material acquisition, wood pellet production to land and ocean transportations, the total emission inventories are obtained, as given in Table 12.

3. Impact assessments

Once the total inventories of the pollutants and energy consumptions are obtained for the whole wood pellet production and transportation process, total energy consumption and environmental impacts on global warming, acid rain formation,

Table 13 – Environmental and health impacts for each stage of the process in g $tonne^{-1}$ pellets.

Energy and pollutant	Harvest	Truck	Production		Train	Ocean vessel
			Sawdust as fuel	Natural gas as fuel		
Energy consumed	0.53	0.07	3.78	2.97	0.26	2.60
GWP (CO_2 equiv.)	32,200	7014	47,973	238,839	22,720	422,449
ARP (SO_2 equiv.)	100	42.7	464	576	183	6487
HTP (dichlorobenzene equiv.)	72.1	67.3	619	684	299	7240
SFP (org. equiv.)	14.9	8.5	8.7	229	14.6	147

smog formation and human health are evaluated in this section.

The Global warming potential (GWP) indices based on the 2001 IPCC reports are used to assess the global warming impact, with the results given in tonnes of CO_2 equivalent. Acid rain formation impact is assessed using the acid rain formation potential indices in which sulfur dioxide (SO_2) is taken as the benchmark compound, with the acid rain potential (ARP) of other acid forming chemicals being expressed relative to SO_2 based on the number of moles of H^+ created per number of moles of the compound emitted.

Under certain climatic and weather conditions, air emissions from industry and transportation can be trapped at ground level, where they react with sunlight to produce photochemical smog which causes adverse health impacts. A major component of smog is ozone, which is not emitted directly, but rather produced through the interactions of volatile organic compounds (VOCs) and oxides of nitrogen (NO_x). While NO_x availability ultimately limits the production of ozone, the reactivity of the VOC determines the rate at which ozone is produced. Thus, when attempting to quantify smog potential, not only must the reactivity of the VOC be considered but also the environmental conditions. In this study, the smog formation impact is assessed based on the maximum incremental reactivity indices [13].

The impact on human health depends on the toxicity of the emitted compounds and the human exposure to them. Due to the lack of information on the human exposure, human health impact is assessed using the human toxicity potential (HTP) method [14].

Using the data in Table 11, the environmental and health impacts associated with emissions for each stage of the process are estimated using the impact indices for each impact category, with the calculated results given in Table 13. Table 14 shows the impacts from the whole process for both cases with sawdust and natural gas as the fuel for drying operation, respectively. It is seen that the impacts in all categories are generally higher when natural gas is used as the fuel, especially for the global warming impact because the combustion of sawdust is considered as CO_2 neutral in the calculation. Compared to fossil fuels commonly used for heating and combustion, the use of Canadian wood pellets in Europe can lead to more than 50% reduction in net CO_2 emissions, as shown in Table 15. The differences in other impact categories are not significant, as seen in Table 14.

The total energy consumptions over the whole process are calculated to be 7.2 GJ $tonne^{-1}$ pellets when sawdust is used as the fuel for drying and 6.4 GJ $tonne^{-1}$ pellets when natural gas is used as the fuel for drying. This is mainly because the natural gas combustion efficiency is higher than the sawdust combustion. It is also seen from Table 13 that the pellet production stage consumed most of the energy, followed by the ocean transportation and harvesting and wood residue production in sawmills. The energy consumption associated with trucking and rail transportation of wood residue is quite low.

For an average high heating value (HHV) of wood pellet of 18.5 GJ $tonne^{-1}$, the percentage of energy consumed for each tonne of Canadian wood pellets produced in Prince George and shipped to Sweden is about 39% when wood residues are used as the drying fuel. This means that for each tonne of wood pellets sold in Europe, an additional 39% net energy has been consumed during the production and transportation process. Of the total 7.2 GJ $tonne^{-1}$ energy, 3.5 GJ $tonne^{-1}$ are from fossil fuel sources, which gives a fossil fuel consumption rate or fossil fuel content of 18.7%. For the process with natural gas as the fuel for drying operation, the percentage energy consumption is about 35% and all of them come from fossil fuel sources.

Figs. 2 and 3 show the different indices and energy consumption over the whole process. It is seen that the ocean transportation is the main contributor to the environmental and health impacts due to the long transportation distance, although the ocean transportation is the most economical and less energy intensive option among the three transportation modes.

The production stage also consumes a large amount of energy. Both the drying and pelletization of wood residues consume a very large amount of energy, although these are essential steps for wood densification in order to transform the bulky wood residues into a useful and clean energy resource and to ease long-distance transportation. The differences between sawdust and natural gas as drying fuel

Table 14 – Environmental and health impacts for the whole process in kg $tonne^{-1}$ pellets.

Pollutant	Sawdust as fuel	Natural gas as fuel
GWP (CO_2 equiv.)	532	723
ARP (SO_2 equiv.)	7.28	7.39
HTP (dichlorobenzene equiv.)	8.30	8.36
SFP (org. equiv.)	0.19	0.41

Table 15 – Comparison of net CO_2 emissions from various fuel sources.

	Coal	Heating oil	Natural gas	Wood pellets
HHV (MJ kg^{-1})	33	42	48	18.5
Net CO_2 intensity (kg GJ^{-1})	90	75	57	29 (sawdust for drying) 39 (natural gas for drying)

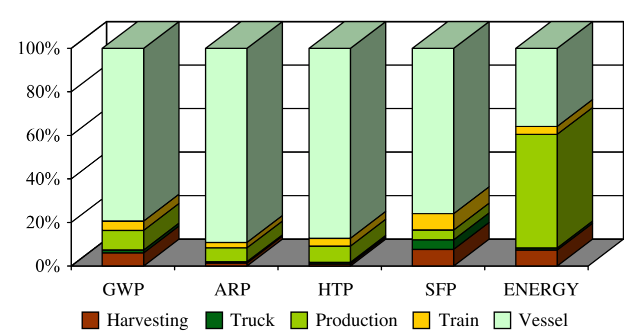

Fig. 2 – Percentage contributions from each life cycle stage with sawdust as drying fuel for the production of wood pellets.

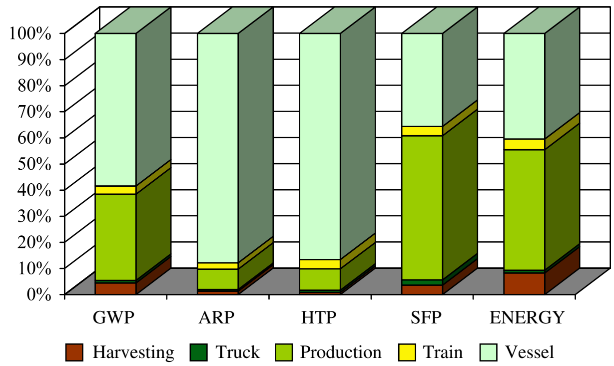

Fig. 3 – Percentage contributions from each life cycle stage with natural gas as drying fuel for the production of wood pellets.

for the production of wood pellets mainly lie in the increased quantity of greenhouse gas emissions and cost when natural gas is used.

One possible alternate way to send the wood pellets from British Columbia to Europe is to transport pellets from the west coast to the east coast of Canada by train, followed by ocean shipping from the east coast sea port (e.g. Port of Halifax) to Europe. In doing so, the distance covered by the ocean vessel could be reduced significantly, but the train transportation will be increased. This could be an interesting option to reduce the environmental and health impacts. However, because of the high cost for the train transportation, this option seems to be not viable economically.

The results also show that more than one-third of the total energy consumption over the entire process is caused by the ocean transportation for exportation. Only 4.6 GJ of energy (or 25% energy content) is consumed for each tonne of wood pellets from harvesting, truck and train transportation and production, if the wood pellets are to be used domestically.

4. Conclusions

A streamlined life cycle analysis of wood pellet production and transportation from British Columbia of Canada to Sweden showed that up to 40% energy is consumed in producing and transporting wood pellets from Canada to Europe. Major fuel consumption is associated with pellet production and ocean transportation. The total fossil fuel content for Canadian wood pellets in the European market is about 35% if natural gas is used in the drying operation, and is about 19% when the wood residues are used in the drying operation. The analysis on environmental and health impacts showed that most air pollutant emissions and their impacts are associated with the ocean transportation of wood pellets. To reduce fuel consumption and wood pellets' cost, the energy efficiency for both wood pellet processing and transportation needs to be improved in the future. Improvement in pellet production and transportation is equally important in reducing the environmental and health impacts associated with wood pellets' production and export.

Acknowledgements

The authors are grateful to Dr. Shahab Sokhansanj, Dr. Mozammel Hoque and Dr. Sudhagar Mani of the Biomass and Bioenergy Research Group at the University of British Columbia for valuable discussions during the course of this study.

REFERENCES

[1] Blok K. Renewable energy policies in the European Union. Energy Policy 2006;34:251–5.
[2] Vinterback J. Pellets 2002: the first world conference on pellets. Biomass and Bioenergy 2004;27:513–20.
[3] Malisius U, Jauschnegg H, Schmidt H, Nilsson B, Rapp S, Strehler H, et al. Wood pellets in Europe. Industrial network on wood pellets. A-3100 St. Poelten, Schiessstattring: UMBERA GmbH; 2000.
[4] Pellet Fuel Institute (PFI). Available from: <www.pelletheat.org/2/index/index.html>; 2006 [accessed 10.05.06].
[5] BIOCAP Canada Foundation. Available from: <www.biocap.ca>; 2006 [accessed 10.05.06].
[6] Sambo SM. Fuel consumption for ground-based harvesting systems in western Canada. Advantage July 2002;3(29).
[7] Mani S, Sokhansanj S, Bi XT, Turhollow A. Economics of producing fuel pellets from biomass. Applied Engineering in Agriculture 2006;22:421–6.
[8] Nyboer J. A review of energy consumption and greenhouse gas emissions in the Canadian wood product industry: 1990 to 2005. Vancouver, BC: Canadian Industrial Energy End-use Data and Analysis Centre, Simon Fraser University; March 2007.
[9] Mani S. A systems analysis of biomass densification process, Ph.D. thesis. Vancouver, Canada: University of British Columbia; 2005.
[10] Environment Canada and Railway Association of Canada. Environmental protection series: Locomotive Emissions Monitoring Program 2004; December 2005.
[11] Ocean Policy Research Foundation. A report on research concerning the reduction of CO_2 emission from vessels; August 2000.
[12] Quan RG, Cheng KC, Trask TC, Meilleur RA. Marine vessel air emissions in the lower Fraser Valley for the year 2000. Policy and Planning Department of Greater Vancouver Regional District, Environment Canada and Levelton Engineering Ltd; 2002.
[13] Carter WPL. Development of ozone reactivity scales for volatile organic compounds. Journal of the Air and Waste Management Association 1994;44:881–99.
[14] Huijbregts MAJ, Thissen U, Guinee JB, Jager T, Kalf D, van de Meent D, et al. Priority assessment of toxic substances in life cycle assessment. Part I: calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES ± LCA. Chemosphere 2000;41:541–73.
[15] Lloyd's Register of Shipping, Marine Exhaust Emissions Research Programme, 1995.
[16] IPCC/UNEP/OECD/IEA Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Cooperation and Development, International Energy Agency, 1997.