A Streamlined Life Cycle Analysis of Biomass Densification Process

Sudhagar Mani[1], Shahab Sokhansanj[1,2], Xiaotao Bi[1]
[1]Department of Chemical and Biological Engineering, University of British Columbia, 2360 East Mall, Vancouver, BC Canada V6T 1Z3.
[2]Environmental Sciences Division, Oak Ridge National Laboratory, P.O. Box -2008, Oak Ridge, TN 37831

Abstract

Mechanical densification is a process of transforming loose biomass into dense pellets. In this study, a wood pelleting plant was chosen to evaluate the total energy consumption, environmental emissions and cost of pellet production using different alternative fuels for the drying process. The fuels compared were natural gas, coal, dry and wet sawdust, and ground wood pellets. The process models were developed and applied to predict the energy consumption and emissions during combustion process. A streamlined life cycle analysis approach was used to quantify emissions. Average emission factors from published literature were used to estimate the emissions of trace metals and toxic pollutants. The environmental impacts of the emissions were evaluated based on greenhouse gases, acid rain formation, smog formation and human toxicity impact potentials. A detailed engineering cost analysis was conducted to estimate the pellet production cost using different process options and fuel sources. Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) was used to rank fuel alternatives. The best fuel source was selected based on four main criteria – energy, environmental impacts, economics and fuel quality. The results showed that wood pellet or dry sawdust might be the best alternative when compared to natural gas followed by coal and wet sawdust, when all the criteria were weighed equally. If the weighting factor for cost was doubled, coal ranked highest followed by dry sawdust, wet sawdust, wood pellet and natural gas, respectively.

Keywords: wood pellets, life cycle analysis, impact assessment, cost analysis, PROMETHEE.

Introduction

Transforming loose biomass into dense pellets involves a series of operations – drying, size reduction, densification, and cooling. Drying consumes energy in the form of heat while size reduction, densification, and cooling operations require electric power input. Due to the recent increase in natural gas price, there is a need to search for alternative fuels for the dryer. A life cycle assessment (LCA) approach quantifies energy, emissions and cost of the entire densification process (Burgess and Brennan, 2001a and b). LCA provides support information for decision makers, who may have opportunities to improve the existing systems (Sonnemann et al., 2004). The Life cycle assessment of various crop and animal feed production systems have been studied by many researchers to evaluate the environmental burdens using the concept of life cycle assessment method (Lewandowski and Heinz, 2003; Brentrup et al., 2004a,b; Skodras et al., 2004; van der Werf et al., 2005; Basset-Mens and van der Werf, 2005).

A methodological framework of LCA is applied to the production of pellets, but the methodology is streamlined within the confines of the system. The streamlined version of LCA calculates total input and output streams of materials and energy from and to a system and quantifies the emissions in each step of the processes for the assessment of environmental impacts in a holistic manner. The simplified or streamlined LCA (SLCA) has been described by Curran (1996); Todd and Curran (1999). The main intent of SLCA is to preserve the concept of LCA and produce credible results, while at the same time to meet the economic, scientific and logistical constraints that are present in the analysis (Graedel et al., 1995). The methodology of SLCA comprises of four stages: goal and scope definition, inventory analysis, impact assessment and interpretation. The description of the methodology can be obtained from Fava et al. (1991) and Consoli et al. (1993).

The results obtained from the SLCA can be used to compare and rank different alternatives. Comparison and selection of alternatives may be performed based on the criteria set for each alternative. If a system deals with more than one criterion, it is difficult to compare and select the best alternative. For example, selection of the best fuel for biomass densification system depends on the fuel quality, cost of the fuel, environmental impacts and energy consumption. Since many criteria are involved in selecting the best alternative, a multi-criteria decision-making tool may be used.

Several multi-criteria decision making tools are reported in the literature for outranking different alternatives (Albadvi, 2004; Pohekar and Ramachandran, 2004). Among them, Preference Ranking Organization METHod for Enrichment and Evaluation (PROMETHEE) is one method used in the development of decision making analysis (Brans et al., 1986; Al-Rashdan et al., 1999; Haralambopoulos and Polatidis, 2003). PROMETHEE is simple method for both quantitative and qualitative analysis of different alternatives. It performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteria. Aquino and Tan (2004) used the streamlined life cycle assessment tool to compare different packaging materials of industrial system and outranked the materials using PROMETHEE. The PROMETHEE is also extensively used in energy planning (Goumas and Lygerou, 2000), impact analysis of energy alternatives (Siskos and Hubert, 1983), building products design (Teno and Marseschal, 1998) and many other fields. In the present study, the PROMETHEE ranking method is used to select the best alternative fuel for the biomass densification process.

The main objectives of this study are: a) to identify and quantify energy, emissions and economics of the biomass densification process with five fuel sources – pellets, wet sawdust, dry sawdust, coal and natural gas; and b) to compare and rank the different fuel options based on the energy use, environmental impacts, economics and fuel quality using PROMETHEE. A simplified life cycle analysis (SCLA) method is used for calculating cost, total energy consumption and environmental impact of each fuel alternative.

System boundary

The scope of this study is to perform a gate-to-gate analysis of biomass densification process based on the energy models presented by Mani (2005). The system boundary for the present study is shown in Figure 1. The wood pellet production plant located in Princeton, BC, was considered as a representative process system in this analysis. The equipment type, size and power data were taken from the plant for energy, emissions and economic analyses. In this system, wet sawdust at 40% moisture content was used as an input material. In the drying process, a single pass rotary dryer was used to dry sawdust. All the solid fuels were burned using a cyclonic burner and the flue gas generated were diluted to supply dryer inlet gas temperature of about 255^{o}C. The burner system was modified when natural gas was used. The alternative fuels used in the systems were wet sawdust, dry sawdust, wood pellets and bituminous coal. Except coal, all other alternative fuels were supplied within the system. However, in the environmental impact study, each fuel category was considered separately for impact assessment and system outranking. Size reduction of sawdust was performed using a hammer mill powered by an electric motor. Similarly, the pellet mill, cooler fan, packing machine, screw conveyors, screw feeder and other accessories were operated using electric motors. A front-end loader was used to feed sawdust to the dryer. The raw material (sawdust) was supplied to the plant by a heavy-duty truck unit. The sawdust was collected from the sawmill plant, located closer to the pelleting plant and the sawdust was transported by dump trucks. The pellet plant has a sawdust buffer storage facility to feed the plant for up to three weeks.

Energy, emissions and economic analyses

Heat energy, electricity consumption, different fuel requirement and diesel fuel requirement for a typical biomass densification plant were calculated based on the overall mass and energy balances and plant operating parameters. The energy data were converted to corresponding emission components using emission factors published by Environmental Protection Agency (EPA) and published literatures. Emissions contributed from different fuels, and electricity was calculated based on the life cycle analysis of the fuels and electricity. Electricity production was based on the local mix, i.e. 90% from hydropower and 10% from natural gas power plants in British Columbia. Cost analysis of a biomass densification plant was conducted to calculate the processing cost of wood pellet using various fuel sources. The total annual cost of any processing operation includes fixed (capital) cost and operating cost. Emission factors for different fuel sources, electricity generation systems and detailed engineering cost analysis are given in Mani (2005).

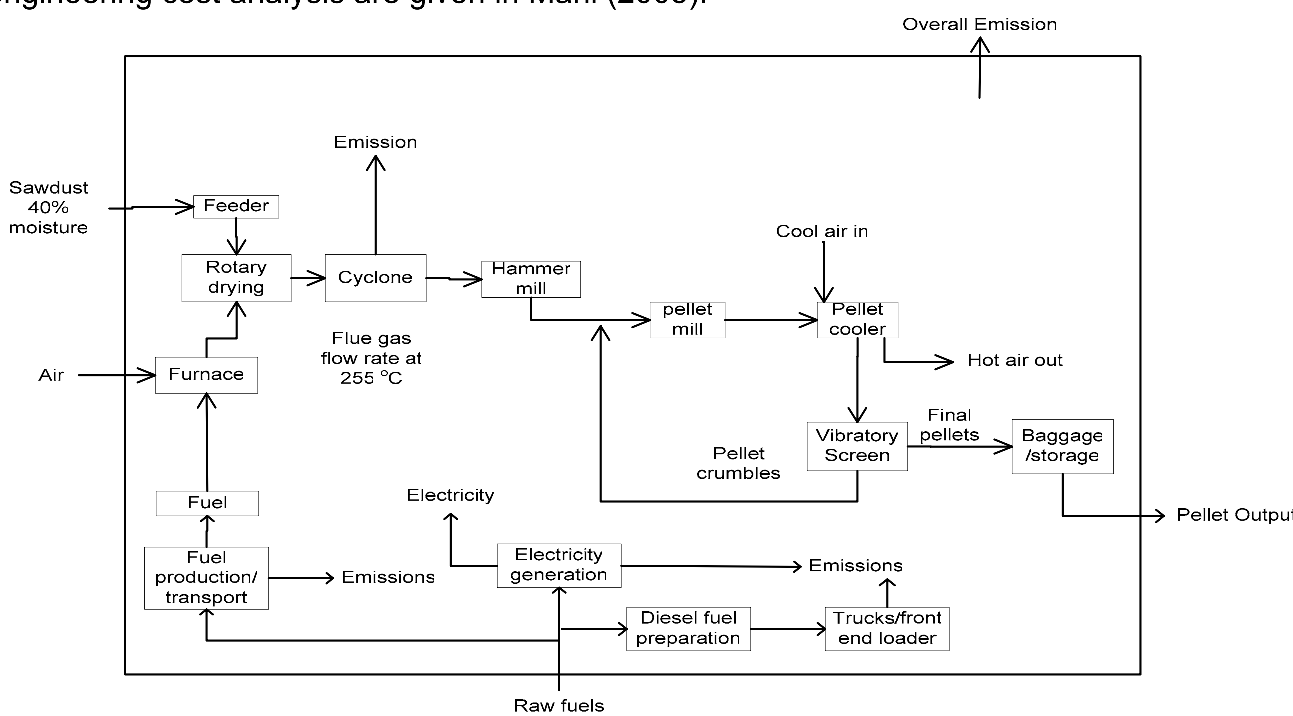

Figure 1 Process flow diagram of biomass densification plant and system boundary.

Environmental impact assessment

The environmental impact assessment can be local, regional and global environmental issues. Global warming and stratospheric ozone depletion are problems with potential global implications for a large proportion of the earth's population. Smog formation and acid rain formation deposition are regional problems that can affect areas in size ranging from large urban basins up to a significant fraction of a continent. A health impact on human is due to the emission of toxic pollutants in the air. Emission inventories for the densification process were classified into four main impact categories- greenhouse gas potentials, smog formation potentials, acid rain formation potentials and human toxicity potentials to assess the environmental and human toxicity impacts. Within the biomass densification system boundary, major air pollutants were particulates, CO_2, CO, NO_x, SO_x, CH_4, TOC and VOC.

Ranking of different fuel options

Different fuel options considered in this study were pellets, wet sawdust, dry sawdust, coal and natural gas. Each fuel option was considered as one scenario, which had different energy, environmental impact and cost data. In order to rank the best fuel source for the densification plant, a multi-criteria decision support tool, called Preference Ranking Organization Method for Enhanced Enrichment (PROMETHEE) was used. The four criteria were energy consumption, environmental impacts, economics of pellet production and fuel quality. Fuel quality is the only qualitative criteria used in the ranking procedure. A detailed description of PROMETHEE ranking procedures can be obtained from Mani (2005).

Results and Discussions

Table 1 shows the complete heat and mass balance for all the scenarios considered in this study. It can be observed that the electrical energy and diesel energy data were constant in the first five scenarios. However, the heat energy consumption varied widely depending on the fuel used. The highest heat energy was consumed by scenario 2, which used wet sawdust as a fuel with low combustion efficiency and thus required high heat energy input. In the case of scenarios 1 and 3, the heat energy was high, because large amount of sawdust was dried in order to meet the constant production rate. The densification plant itself supplied the fuels to the burner for scenarios 1 and 3.

Table 1 Material and energy balances for different biomass densification scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Input					
Raw material (t/h)	9	7.8	9	7.8	7.8
Feed moisture (% (wb))	40	40	40	40	40
Fuel type	Wood pellet	Wet sawdust	Dry sawdust	Coal	Natural gas
Dryer inlet temp. (ºC)	280	255	280	255	255
Fuel rate (kg/t)	152.6	264	179.6	97	44.6
Total electricity use (kWh/t)	119.53	112.17	119.53	112.17	112.17
Diesel use (l/h)	5.56	5.29	5.56	5.29	5.29
Energy (MJ/t pellet)					
Electrical energy	430.31	403.80	430.31	403.80	403.80
Fuel energy	2746.80	3168.00	3053.20	2813.00	2363.80
Diesel energy	205.73	205.73	205.73	205.73	205.73
Total	3382.84	3777.53	3689.24	3422.53	2973.33
Output					
Pellet production (t/h)	5	5	5	5	5

All the air emissions were analyzed based on the four impact categories previously discussed and were assessed based on global, regional and local issues (Table 1). The impact categories for each scenario were used to rank different alternatives. Figure 2 shows the greenhouse gas emissions from wood pellet production scenarios. The CO_2 equivalent for scenario 4 (coal) was the highest among all the scenarios followed by scenario 5 (natural gas). Figure 3 shows the acid rain formation, smog formation and human toxicity potentials of the different wood pellet production scenarios. Terpene emissions during the drying process contributed to the highest value of smog formation potential for all the scenarios. It can be concluded that scenario 4 has the highest environmental and health impacts among the scenarios considered in this analysis

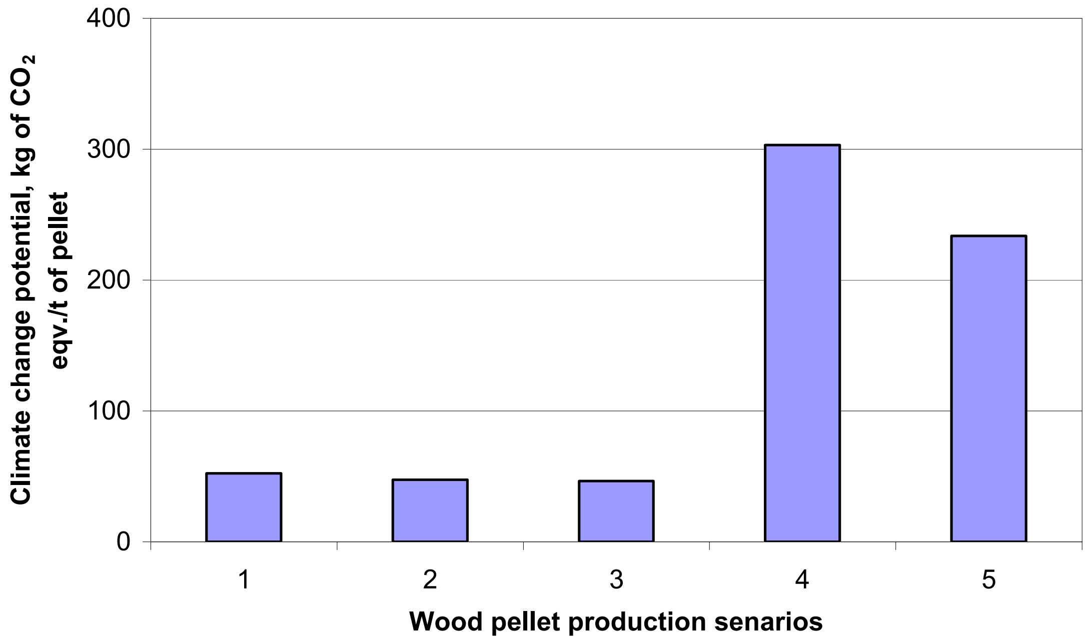

Figure 2 Comparison of wood pellet production scenario with climate change.

Figure 4 shows the breakdown of the cost of producing wood pellets from different densification systems. For scenario 5, the capital cost was slightly less due to natural gas burner. All other scenarios (1-4) used the same solid fuel burner for fuel combustion. Pellet production cost depended on plant capacity and hours of operations, which accounted for the operating cost of the plant. From the five scenarios, the operating cost for scenario 5 (natural gas) was the highest (US$ 71/t) followed by scenario 1, which used wood pellets as a fuel. This was mainly due to the high fuel cost. The pellet production cost may be reduced, if coal or sawdust is used as a fuel.

In order to rank alternative fuels for biomass densification, the Decision Lab 2000 software (Visual Decision, 2003) was used. The ranking was performed based on the PROMETHEE method as described in Brans et al. (1986). The criteria used for the decision process were: 1) total energy consumption; 2) environmental and human impacts; 3) pellet production cost; and 4) fuel quality. In the initial decision making process, equal weighting factors were assigned with all the criteria. PROMETHEE II provided a complete ranking of all selected scenarios without any comparable scheme. If the decision maker or a stakeholder decides to double the weighting factor for the pellet production cost, the PROMETHEE II outranking changes into: 1) coal; 2) dry sawdust; 3) wet sawdust; 4) wood pellet; and 5) natural gas.

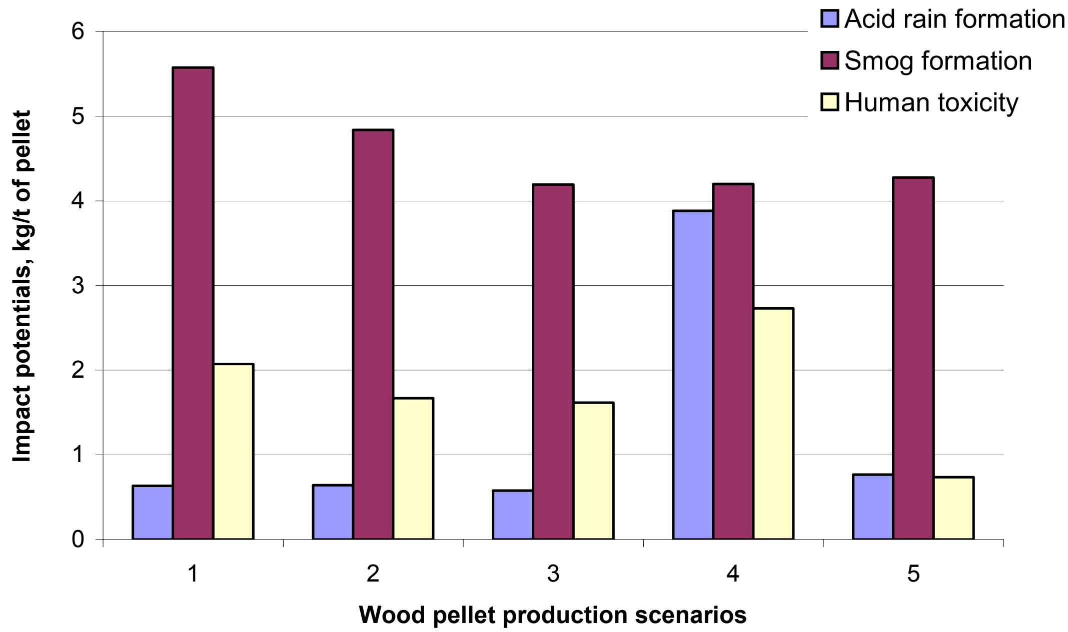

Figure 3 Comparison of pellet production scenarios with local and regional impact categories.

Figure 4 Pellet production cost for different scenarios.

Conclusions

The biomass densification process has been analyzed using the streamlined life cycle assessment tool to evaluate energy, emissions and economics of wood pellet production with different fuel options. From the energy consumption data, more than 80% of the energy was supplied for the drying process, which results in high energy cost of pelleting operation. Based on the emission inventory data, environmental impacts namely climate change, acid rain formation, smog formation and human toxicity was calculated for the best selection of alternatives. The environmental burden for the densification process is the highest if coal is used as a fuel among all other alternative fuels. Pellet production cost is high if natural gas or wood pellets is used as a fuel. The best fuel source was selected based on the four main criteria – energy, environmental impacts, economics and fuel quality. The results showed that wood pellet or dry sawdust might be the best alternative when compared to natural gas followed by coal and wet sawdust, if all the criteria were weighed equally. If the weighting factor for cost was doubled, coal ranked highest followed by dry sawdust, wet sawdust, wood pellet and natural gas, respectively.

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