Energy 36 (2011) 2716–2732

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Development of energy and emission parameters for densified form of lignocellulosic biomass

Arifa Sultana, Amit Kumar*

Department of Mechanical Engineering, 4-9 Mechanical Engineering Building, University of Alberta, Edmonton, Alberta, Canada T6G2G8

ARTICLE INFO

Article history:
Received 20 September 2010
Received in revised form
8 February 2011
Accepted 8 February 2011
Available online 21 March 2011

Keywords:
Agricultural residue
Straw
Pellet
Greenhouse gas emission
Energy assessment

ABSTRACT

The environmental performance of production and distribution of densified form of lignocellulosic biomass (i.e., agri-residue based pellets) in Western Canada in terms of energy and greenhouse gas (GHG) emission was assessed. The results show that energy usage and resulted emissions are highest in field activities especially if emission and energy are attributed to straw in farming stage where nitrogen fertilizer is the highest contributor. Significant reduction of energy use (64%) and emission (65%) are possible if the organic fertilizer is used in farming. Adopting the zero tillage option instead of conventional practice results in energy saving (10%) and emission reduction (8%). From the scenario analyses it is also evident that using biomass as an energy source during drying or no drying in pellet production stage or using alternate mode (i.e., truck and train) of transport for pellet delivery result in less than 5% reduction of the energy use and emissions compared to the base case. Agri-pellet has the potential to offset substantial amount of GHG emission compared to other fuel sources including wood pellets. The energy and emission of production chain of agri-pellets may vary between countries but overall trend compared to other fuel sources would be similar.

1. Introduction

Environmental concern and unstable fossil fuel market are main drivers for use of biomass based pellet as an energy fuel. Governmental obligation on use of biomass fuel is another predominant basis for increasing use of pellet in European countries (8 million tonnes in 2008) [1], which is not common in North America. A significant amount of pellets produced today in North America are exported to European countries [2,3]. The conversion of biomass to pellet form upgrades it's physical and chemical properties especially in terms of calorific value. In addition to the environmental advantages, biomass based pellets have other value-added opportunities, such as, increased energy density, higher bulk density, and higher heating value.

A number of studies have been performed on the life cycle analysis (LCA) of biofuels especially on ethanol from straw which have shown positive energy balance and reduced greenhouse gases [4–7]. Most of the LCA analyses were done on transportation fuels, such as, bioethanol, biodiesel, hydrogen [8–13]. Both the emission and the energy use of wood pellet have been analyzed in previous studies [1,14–18]. Mani [14] analyzed streamlined life cycle analysis approach to quantify emissions of wood pellet production. Raymer [15] quantified the amount of GHG emissions for six forms of woody biofuels including wood pellet. Hagberg et al. [16] calculated life cycle energy and emission analysis of wood pellet production in Swedish settings by considering different assumptions and methodological choices. Magelli et al. [17] mainly dealt with life cycle analysis of wood pellet production and transportation from Canada to Europe. Zhang et al. [18] investigated a life cycle analysis of wood pellet with co-firing options and compared with coal and hypothetical natural gas combined cycle. The aforementioned studies focused on pellets from woody biomasses. The life cycle analysis of pellet made of agricultural biomass (i.e., straw) is non-existent. The aim of this paper is to analyze pellet production from agricultural residue, especially from wheat straw with regard to its energy input and emission throughout its life cycle. This study uses data on Western Canada (Prairie Provinces) for life cycle analysis of pellets. The selected geographic region is endowed by large agricultural land area and large energy demand.

Canada is the sixth largest producer of wheat in the world and most of which is produced in Prairie provinces, e.g., Saskatchewan, Alberta and Manitoba. Agricultural residues are available in significant quantities in areas where growth of grain crops are concentrated [19,20]. Agricultural activities of Western Canada produce 37 million of tonnes of biomass each year [21]. The potential of recovering agricultural residues (i.e., straw from wheat,

---

* Corresponding author. Tel.: +1 780 492 7797; fax: +1 780 492 2200.
E-mail address: Amit.Kumar@ualberta.ca (A. Kumar).

0360-5442/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2011.02.012

barley and oats) after accounting for current use is about 6.2 million tonnes per annum [19]. Most of these biomass resources are wasted or underutilized. This biomass potential could be used as a feedstock for bioenergy development.

The objective of the current study was to develop a data intensive model to estimate of the energy use and GHG emission associated with production and use of agricultural biomass based pellets (or agri-pellets). The scope of the paper includes the life cycle analysis of agricultural pellet starting from wheat farming to the distribution of pellets to users taking into account all the input and output flows of energy and emission occurring along the pellet life cycle. This is a standard approach and has been applied to life cycle analysis of other biofuels from herbaceous residues. A number of scenarios have been examined to study the impacts of changing tillage system, taking organic farming option, omitting farming activities, modes of transport and drying options. The analysis also takes into account land use change aspect, i.e., effect of crop residue removal on soil organic carbon and N_2O emission.

2. Methodology

This study followed four steps to a life cycle analysis: goal definition and scoping; inventory assessment; impact assessment; and interpretation. In this paper a detailed model was developed to determine energy consumption and emission over the life cycle of biomass pellet using agricultural residues. Direct and indirect energy consumptions and emissions at each stage of life cycle of pellet production were considered in the model. Key stages of energy consumption and emission estimation included (i) crop production and harvesting, (ii) transportation of crop residue from field to the pellet plant, (iii) pellet production, (iv) transportation to user.

The agricultural residue in the form of straw has been considered as feedstock in this research because of its large availability in Western Canada. Spring wheat is the prime wheat crop in the considered region among others such as durum, winter wheat. This represents about 85% of the provincial total wheat production for the last ten years. Wheat yields have averaged 2.69 tonne/ha over the past twelve years [22]. Residue yields considered 1.1 times grain yield [19].

For life cycle analysis of energy and GHG emissions of agri-pellets, following types of energy and emission sources were considered:

- Manufacturing, distribution and application of fertilizer, herbicides, insecticides and fuel used for growing the biomass feedstock;
- Harvesting and collection of biomass residues;
- Land use change resulting from production and removal of biomass residues;
- Transportation of biomass from farm to pellet plant;
- Conversion of biomass residues to pellet;
- Transporting pellets to the user.

2.1. Goal definition

Information from existing literature was compiled for the determination of energy consumption and GHG emission from pellet utilizing the most currently available data for each unit process. For wheat farming, wheat transportation and pellet production, current technology and practices in Canada are considered. The goal of this study was to analyze agri-pellets in terms of energy and emission impact when it is used for heating purposes.

2.2. Scope

When comparing biofuel with fossil fuels, it is of utmost importance to consider the same relevant service from the various systems [23]. LCA requires the use of a functional unit for comparison, of different energy systems. The functional unit of current analysis is the 1 MJ heat produced from pellet.

Three major gaseous emissions make long term contribution to the global warming, which were included in this study, are CO_2, CH_4 and N_2O. Based on earlier studies [24,25], the 100-year time horizon was used to determine global warming potential. The CO_2 emission are described in terms of CO_{2eq}, which is the weighted sum of CO_2, CH_4 and N_2O emission considering the global warming potential values for these gaseous as 1, 21 and 310, respectively [26].

Carbon emission from biomass combustion is considered zero as all carbon released from straw during its combustion is taken up by the plant during its growth [1,15]. Fig. 1 illustrates the base-line system boundary used in this study which shows the unit processes considered in this analysis. The life cycle of natural gas includes gas extraction from well, upgrading, refining, transmission, storage, distribution and combustion. The emissions associated with each step were considered. The life cycle of coal pathways consist of coal mining, processing, coal transportation to plant and burning in coal-fired plant. The life cycle emissions of natural gas and coal have been taken from previous studies [17,18,25].

The base case is developed by considering the current and existing practices of pellet production in Western Canada. Wheat planting is included in the base case as one of the unit operations. In

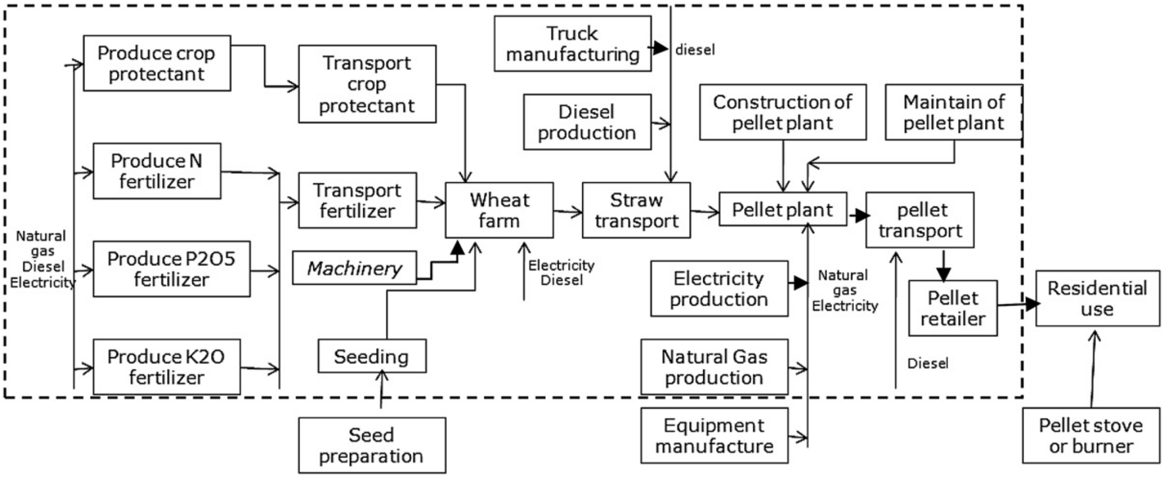


Fig. 1. System boundary for life cycle analysis of agricultural pellet production.

Table 1
Developed Life cycle analysis scenarios.

Phases	Scenario description	Scenarios
Field	*Starting point of life cycle chain* • Start from wheat farming and allocation of energy and emission between grain and straw based on mass ratio. *Fertilizer* • Synthetic fertilizer *Tillage system* Conventional tillage	Base case
Pellet plant	*Drying fuel* • Natural gas	
Pellet transport	*Mode of transport* • Truck transport	
Field	*Starting point of life cycle chain* • Consider straw as by-product; all energies and emissions before straw harvest are omitted.	Scenario 1
Field	*Fertilizer* • Organic fertilizer	Scenario 2
Field	*Tillage system* Zero tillage	Scenario 3
Pellet plant	*Drying fuel* • Biomass (straw)	Scenario 4
Pellet plant	*Drying fuel* • Without drying	Scenario 5
Pellet transport	*Mode of transport* • Truck and train combination	Scenario 6

base case, the farming practice of wheat production is considered and the energy and emission during wheat production were allocated between wheat grain and straw based on mass ratio. However a number of earlier studies do not consider emissions related to farming [27,28] because they considered wheat straw production is incidental of wheat grain production. The later concept is analyzed in one of the scenarios. The estimated economic optimum size of the agri-pellet production plant is taken from an earlier study by the authors [19]. The economic optimum size of the agri-pellet plant in Western Canada is 150,000 tonnes/year and collection radius of the biomass for the plant is 94 km [19]. Wheat straw is assumed to be collected from the field in the form of bales. These bales are transported to the agri-pellet production plants on trucks. In a pellet plant, pellet production is a combination of sequential steps including preprocessing, drying, grinding, pelleting, cooling, screening, and bagging. Different scenarios (Scenario 1–6) were developed by changing key assumptions and methodological choices while keeping other parameters and assumptions same as the base case. Scenarios are shown in Table 1.

In this study, the total energy requirement and resulted emission of the whole process is the sum of the energy requirement and emissions of unit processes respectively. The emission attributed to pellet production was evolved using existing data on emission factors and material flow input of the unit processes from published literature. Wherever data was not available, these were assumed or calculated. To develop a quantitative input estimate of energy requirement for each process, input per functional unit and energy co-efficients (MJ per unit) were used. Energy co-efficient is the energy used from primary production to end-user [29]. Data to develop energy co-efficients were taken from the published literature. In field processes, input data were usually location-specific information data. These data were estimated by developing a data intensive model which was ultimately used to estimate the total emissions for agri-pellet production.

2.3. *Inventory assessment*

2.3.1. *Agronomic input data and assumptions*

The usual practice for use of straw in Western Canada till today is either to leave it in field to rot or to collect for animal feed. If the straw is left in the field it provides some nutrient for the soil. Nutrient replacement by applying fertilizer is necessary if straw is removed. We assumed that nutrient requirement of soil due to removal of residue is compensated by application of fertilizer and therefore there would be no change in the yield of straw.

Agricultural inputs such as fuel, fertilizers, electricity, herbicides and machineries contribute to GHG emission to atmosphere. Alberta's soil contains abundance of calcium and some minerals so nitrogen, phosphorous, potassium and sulfur are the only fertilizers that need to apply in soil [30]. Agricultural practices including resource usage and emissions vary widely by location and crops [31]. The factors which influence the inputs to the soil for any crop production includes crop rotation, soil characteristics, the sequence of soil preparation and culturing steps, and type and application rate of fertilizers. Application rates of fertilizers and insecticides are region-dependent and vary due to soil types and available nutrients [32]. Nutrient uptake (total nutrient taken up by the crop) and removal value (nutrient removed in the harvested portion of the crop) are given in Table 2 based on typical nutrient concentrations and yield for good growing condition for Western Canada [33]. Actual uptake and removal may vary with time (year) and depend on crop yield, crop variety, soil fertility [33]. In this study all fertilizer, seeding, pesticides used in Western Canada were reviewed. In this region, demand is the greatest for two nitrogen-based fertilizers: urea and anhydrous ammonia [29]. Urea consumption in the prairies represents 81% of the total used fertilizers. The amount of N fertilizer required depends on the level of soil nitrate–nitrogen (NO_3–N). Less fertilizer is needed if the level of soil nitrogen is high [34]. Wheat has traditionally been grown using conventional tillage in the southern prairie of Western Canada. However, with increasing concerns about decline in soil quality, farmers have been shifting to continuous cropping system coupled with reduced or zero tillage [35]. Hence, we have considered continuous cropping of wheat with conventional tillage system in our base case analysis.

2.3.1.1. *Effect on land use change.*

The effect of removal of agricultural residues from the field is still being debated by many researchers [28]. Since straw need to be removed from soil top for agri-pellet production, an in-depth consideration of the issues including affects to soil organic matter turnover, soil erosion, crop

Table 2
Average nutrient uptake and removal by 40 bu/ac wheat crop under Western Canada conditions (derived from [33]).

Crops	N		P_2O_5		K_2O		S	
	Uptake[a]	Removal[b]	Uptake[a]	Removal[b]	Uptake[a]	Removal[b]	Uptake[a]	Removal[b]
	Kg/ha							
Spring wheat	94.72	27.46	35.87	9.53	81.27	61.65	10.09	5.05
Winter wheat	75.67	17.38	34.19	5.62	79.59	60.53	11.21	3.36
Barley	124.43	37.55	49.88	12.33	118.82	89.67	14.57	6.72
Oat	120.51	51.57	45.40	16.81	163.10	142.36	14.57	9.53

[a] total nutrient taken up by crop.
[b] nutrient removed during harvesting straw.

Table 3
Inputs and energy co-efficient for wheat production.

Operation	Input quantity				Energy co-efficient			
	Unit	Used value	Low-high	Reference	Unit	Used value	Low-high	Reference
Fuel and oil								
Diesel use					MJ/kg	45.25		[50]
Sowing	kg/ha	3.0	0.9–21.6	[51,55–57]	MJ/kg	45.25		[50]
Fertilizer and liming								
Spreading fertilizer	kg/ha	2.0	0.9–4.7	[29,45,51,58]	MJ/kg	45.25		[50]
Liming	kg/ha		1.5	[50]	MJ/kg	45.25		[50]
Plant protection								
Pesticide spraying	kg/ha	1.5	0.8–1.7	[29,45,51,58]	MJ/kg	45.25		[50]
Harvesting and baling								
Combine harvesting	kg/ha	14.0	7.0–19	[29,45,51,58]	MJ/kg	45.25		[50]
Baling and handling	kg/ha	1.5	1.3–1.7	[29,45,51,58]	MJ/kg	45.25		[50]
Transport								
Machine transport	kg/ha	0.04	0.3–0.4	[29,45,51,58]	MJ/kg	45.25		[50]
Loading and handling								
Loading and handling	kg/ha	1.3	0.3–3.8	[29,45,51,58]	MJ/kg	45.25		[50]
Electricity	kWh/ha	37.07		[50]	MJ/kWh	9.89		[50]
Gasoline	L/ha	9.35		[50]	MJ/L	43.19		[50]
LPG	L/ha	2.81		[50]	MJ/L	26.72		[50]
Natural gas	M^3/ha	0.007		[50]	MJ/m^3	40.43		[50]
Seeds and agrochemicals								
Seeds	kg/ha	125	35–175.27	[51,55–57]	MJ/kg	7.2	5.57–7.2	[29,51]
Fertilizer Urea-N (46–0–0)	kg/ha	94.72	85.19–104.25	[33]	MJ/kg	67.03	90.6–45.6	[45,46,49,50]
Ammonium nitrate (34–0–0)	kg/ha	94.72	85.19–104.25	[33]	MJ/kg	63.00	42.8–75.63	[45,49,50,59]
Phosphate (P_2O_5) (11–54–0)	kg/ha	35.87	32.51–39.23	[33]	MJ/kg	13.11	2.11–20.3	[29,45,60,61]
Potassium (k_2O) (0–0–60)	kg/ha	81.27	72.86–89.68	[33]	MJ/kg	9.85	4.6–12.35	[29,46,50,64,65]
Sulfur	Kg/ha		8.96–11.21	[50]	MJ/kg	1.12		[46,50,51]
Lime stone	kg/ha		44.83	[50]	MJ/kg	0.17		[50,51]
Pesticides	kg/ha	0.49	0.33–0.49	[50,51,62,63]	MJ/kg	308	297–474	[46,47,49]
Farm machinery								
Tractor	kg/ha	8.60		[29,45,50]	MJ/kg	158.9		[46,50]

yield, N_2O emission and others. The impact can vary from location to location with climate, soil type and crop management. The issue of land-use-change effects induced by agricultural residue collection has been partially investigated in earlier studies [28,36,37]. Agriculture soil has exclusive property that it can store C and also emit it as CO_2. The use of biomass may lead to alteration of carbon stored above and below the ground in the field [28]. Most of the life cycle analyses do not consider the changes except few [6,28,36]. Any disturbances of soil organic matter (SOM) increase the rate of decline of the SOM until equilibrium is reached. The factors which affect the soil carbon pool are very site-specific [38]. Soil characteristics, climate, agronomic practices such as tillage, crop rotation, residue management, fertilizer application affect the soil carbon pool [28]. A detailed assessment of carbon dioxide and nitrous oxide emissions and sequestration from agricultural soil in Alberta was done by Alberta Agriculture, Food and Rural development [38]. Data from this study was used in the current analysis.

Emissions associated with land use changes are mainly carbon dioxide and nitrous oxide. N_2O emission evolves from organic matter decomposition in soil and from nitrogen fertilizer. Emission is very site-specific, depends on soil type, climate, crop type, tillage method, application rate of fertilizer. The majority of the N_2O production from agricultural soil can attribute to denitrification and nitrification process. Denitrification is the major process of N_2O production which increases at moist soil conditions with low oxygen availability [38]. N_2O has higher (310 times) global warming potential than CO_2 over a 100-year period. Moreover, a part of the nitrogen fertilizer used in soil is converted to N_2O and some may run off the site [28]. The IPCC soil emission estimates are based upon linear extrapolation between N_2O emission and N fertilizer application without considering soil type and climate [38].

Soil organic carbon (SOC) is decreased in soil due to removal of straw during harvesting. Straw if not removed would otherwise decompose in soil. On average 0.75 tonne/ha stubble is kept in field for protection against wind and water erosion and for improving soil moisture conservation [19,39]. The amount of residue retained for soil conservation varies with field slope, soil texture, residue type, weather condition, soil aggregation and tillage practice [40]. About 30% of straw yield (i.e., 2.96 tonne/ha) of the loose residue is retained on the soil surface after harvesting is complete due to inefficient machine [19]. Total amount kept in soil (i.e., 1.5 tonne/ha), decomposes in soil. Similar amount is reported by in an earlier study (for Western Canada [40]). Total N content of straw is 6 kg N/tonne with 10 percent moisture [41]. Hence, total of 9 kg N is decomposed per hectare of soil when straw is harvested based on total amount of straw kept in soil. About 27.5 kg N/ha (Table 1) is removed during the harvesting from the soil [33]. The difference 18.5 kg N/ha should be adjusted by nutrient replacement. If the fertilizer requirement of wheat crop is adjusted for the removal of nutrients in the straw then there should be no wheat yield changes and thus no changes in N content of soil. It is assumed in this study that the amount of nutrient removed during harvest is compensated by applying more nutrient to the soil so net yield would not change [42]. IPCC [43] estimated a factor of 1.325% of N/kg N

Table 4
Assumptions for truck transport.

Capacity of the plant (tonnes/year)	150,000	[19]
Amount of biomass transport	157,500	
Material loss in plant	5%	[19]
Capacity of the truck (tonnes)	16.8	[67]
Distance from field to pellet plant (km)	94	[19]
Fuel consumption of a truck (full load) (L/km)	0.25	[68]
Fuel consumption of a truck (empty) (L/km)	0.20	[68]
Travel speed of heavy-duty truck in high-way of Alberta (km)	50	[66]
Life time of a truck (hours)	12,000	[44]
Steel and iron composition in truck	65%	[69]
Moisture content of straw[a]	14%	[19]

[a] Moisture content in wet basis.

fertilizer is released as N_2O. This value is more generic without considering soil texture, climate, temperature and other factors in consideration [38]. The denitrification potential and capacity to produce N_2O increase with the decomposition of straw. The manufacturing and application of additional fertilizer also takes into account energy and emission assessment. Using IPCC [43] estimate, the calculated N_2O emission was 1.619 kg N_2O/ha (or 0.0006 kg N_2O/kg of straw.)

Another effect of harvesting straw is the decrease in soil organic carbon (SOC) due to changes in soil carbon stock. Loss of soil carbon occurs through emission of CO_2. The removal of straw from the field causes a reduction of SOC to be 0.27 tonnes C/ha per year [28]. Gabrielle and Gagnaire [6] estimated SOC decrease rate of 0.15–0.75 tonnes C/ha depending on the soil and climatic condition. Sauve [38] considered similar value from 0.15 to 0.45 tonne C/ha for Alberta. In order to supply 150,000 tonnes/year of straw to the pellet production plant, 1,228,000 ha of land is required [19]. About 30% of this land is used for wheat cultivation. Based on these input values, an amount of 99.46 ktonne C/year is lost from SOC to atmosphere and hence 358 ktonne CO_2/year emission which accounts 0.159 kg CO_2/MJ of pellet.

2.3.1.2. Fertilizer. Three primary nutrients N fertilizer, P_2O_5 and K_2O are considered in the analysis. Sulfur application in the field was omitted as the amount of application rate is very low in Western Canada. Lime is usually applied to acidic soil to neutralize the excess acidity of soil which might cause reduction in yields but only 5% of the total area of Alberta lies in the acidic region so the lime application was omitted from the analyses. Different nitrogen-based fertilizer (e.g., urea (46–0–0) (i.e., urea contains 46% N), ammonium nitrate (34–0–0), ammonium sulfate (21–0–24) (i.e., ammonium sulfate contains 21% N and 24% sulfur)), anhydrous ammonium can be applied to wheat production areas. Mainly urea and ammonium nitrate are used in wheat production in Western Canada [29] and the use of urea is prevalent. The application rate of nitrogen-based fertilizer (kg/ha) and its energy co-efficient is low in North America than in Europe [4,5]. In the current analysis, GHG emissions during production of fertilizers, transportation of fertilizers and its application in the field are considered. The average transport distance of the fertilizer from production plant to the farm was taken as 500 km [44]. The application rate of fertilizer was taken from the Canadian Fertilizer Institute as shown in Table 2 [33]. The fossil fuel usages for the production of fertilizer, transportation and application of fertilizer were taken from previous studies [29,45,46]. The estimation of energy co-efficient varies considerably with the type of fertilizer, time and estimation procedure. The energy co-efficient was calculated by considering energy requirement during manufacturing of raw material for production of fertilizer. Energy required in manufacturing of machinery used for producing fertilizers was not considered. Fossil fuels used for the production of fertilizer contribute to GHG emissions. This is due to the energy requirement during processes of mineral extraction and fertilizer manufacturing. Fertilizers input in wheat production and its energy co-efficients are shown in Table 3. The 'value used' shown in Table 3 are taken based on values suitable for Western Canada.

2.3.1.3. Pesticides. The total energy input for pesticide includes energy required in manufacturing of the raw material used for pesticides and the direct energy input during making of pesticides. The energy related to packaging, transporting and application of pesticides was considered. The energy requirement in manufacturing of different fossil fuels used for these processes involved in production of pesticide were reported in literature [47–49]. The average energy requirements of 23 different pesticides listed by Green [47] were used in the analysis. The pesticides application rates were taken from Piringer and Steinberg [50] and this rate varies from 0.33 to 0.49 kg/ha. Pesticide input for wheat production and its energy co-efficients are shown in Table 3.

Fig. 2. Map of Alberta (derived from [57]).

Table 5
Capacities and fuel requirements of heavy-duty trucks (derived from [68]).

Type of truck	Gross vehicle weight (GVW) (tonne)	Payload (tonne)	Fuel requirement L/km (empty)	Fuel requirement L/km (full load)
Truck, distribution traffic	14	8.5	0.20–0.25	0.25–0.30
Truck, regional traffic	24	16.8	0.25–0.30	0.30–0.40
Tractor and semi-trailer, long-haul traffic	40	26	0.21–0.26	0.29–0.35
Truck with trailer, long-haul traffic	60	40	0.27–0.32	0.43–0.53

2.3.1.4. Seeding. The energy used for seed production, packaging and distribution was estimated based on earlier studies [29,51]. The optimum seeding rate for Alberta varies from 138 to 144 kg/ha for durum wheat and 112–135 kg/ha for spring wheat [52]. Input of seeding rate and its energy co-efficients are shown in Table 3.

2.3.1.5. Machinery. The energy requirements for manufacturing, transportation and repair of machinery were taken from Coxworth et al. [46]. The energy required for manufacturing and repair of farm equipment was considered to be 158.9 MJ/kg and for transportation of the equipment was 8.6 MJ/kg [46]. The estimation of the amount of material required for manufacture of the proportional faction of tractors and agricultural utensils used in the agricultural phase are estimated based on previous study [44].

The proportion fraction of machinery or utensils was estimated using [44]:

$$M_F = \frac{W \times T_0}{L_T} \tag{1}$$

M_F = fraction for the amount of machinery (kg/Fu) used in the field work.

Fu = functional unit selected for this paper.
W = weight of the tractor or other utensils (kg).
T_0 = operation time for each field operation (hour/Fu).
L_T = life time of tractor or utensils (hours).

2.3.1.6. Fuels and electricity. The emission from combustion of fuels and that associated with production and delivery of the fuels to the farm were considered. The estimates include field operations such as seeding, harvesting and hauling of harvested material to the roadside, application of fertilizer, herbicides and other farming operations. Application of lime was not included in the analysis. The estimate of the energy co-efficient of fuels was considered based on previous study [29]. Data for diesel emission was taken from previous studies [53]. Carbon dioxide attributed to electricity consumption is based on mix of fuel to produce electricity which comes mainly from coal (46%), gas (40%), hydro (7%), wind (5%) and biomass (2%) [54]. There are also emissions during the construction of a power plant but this is negligible when averaged over the life cycle of the power plant [27,30]. Fuel and electricity input in production of wheat and its energy co-efficients are shown in Table 3.

2.3.2. Transportation of straw bale from field to pellet plant

Straw in the form of bales are usually transported by truck [19,68]. In this analysis, bales were loaded onto a truck and transported to a pellet plant throughout the year. The weight of each bale was considered to be 500 kg (based on weights reported in earlier studies [19,66]). Bales were stacked on a flatbed trailer with payload capacity of 16.8 tonne. Assumptions considered for truck transport were shown in Table 4. Based on an earlier study by the authors [19], the highest yield area of Alberta is Census Division 5. It is considered in this study that the location of the pellet plant is at the center. Census division 5 is 138 km north from Calgary (Fig. 2 [57]). For an optimum plant capacity of 150,000 tonne per year [19] the biomass requirement for a pellet plant is 157,000 tonne per year considering the 5% loss in the plant. Optimum capacity is defined as the capacity of the plant at which the cost of production of pellets is minimum.

Different capacities of truck and trailer are shown in Table 5 [68]. For this capacity the numbers of truck trips were 17,045 per year. We considered the fuel consumption of a single fully loaded truck and empty truck are 0.25 and 0.20 L/km, respectively. The fuel requirements of trucks with different capacities are shown in Table 5. Energy consumed to haul 1 kg of straw to a distance of 94 km is 0.115 MJ considering the higher heating value of diesel is 45.25 MJ/L. We considered diesel as the fuel for truck transport since 46% of heavy-duty truck operates by diesel [69]. Table 6 gives the biomass transport forms and truck carrying capacities.

The actual load a truck can carry is limited by the weight or volume limit of the truck. Thus actual load of truck was estimated by

$$W_a = \min\{W_p,\ (b \times V)\} \tag{2}$$

Where,
W_a = actual load a truck can carry (kg);
W_p = Payload of a truck (kg).
b = bulk density of bale (kg/m^3).
V = volume capacity of a truck (m^3).

Actual fuel consumption of truck with a certain load can be estimated as [44].

$$F_c = F_0 + \left\{ \left(F_f - F_0\right) \times \frac{W_a}{W_P} \right\} \tag{3}$$

Where,
F_c = Actual fuel consumption of a vehicle with W_a load (L/km).
F_0 = fuel consumption of an empty vehicle (L/km).
F_f = fuel consumption of a fully loaded vehicle (L/km)
W_p = Payload of a truck (kg).
W_a = Actual transportable load of a truck (kg).

In Eq. (3), the fuel consumption (L per km) during hauling is F_c and fuel consumption at the time of back hauling is F_0 (L/km). The data for truck transport is shown in Table 7.

To estimate the energy and emission in manufacturing of a truck of capacity 22 tonnes the composition of truck material was considered. The material used for truck manufacturing included steel (51.29%), iron (12.98%), wrought aluminum (12.17%), rubber

Table 6
Biomass transport forms and capacity.

Forms of biomass for transport	Bulk density (tonne/m^3) (a)	Amount to be transported (tonne) (b)	Payload (tonne) (c)	Volume capacity of truck (m^3) (d)	Actual weight carry Min{c, (a × d)}	No of trucks loads
Bale	0.11	157,500	16.8	84	9.24	17,045
Chop	0.16	157,500	11	70	11	14,318
Pellet	0. 60	150,000	40	70	40	3750

(9.01%), plastic (3%) and rest covered by copper, lead and glass [69]. A reference speed of 50 km/h was considered for our analysis. The life time of a truck is typically 12,000 h and energy intensity of steel is 37 MJ/kg [44,70]. The life cycle emissions data for steel production was derived from literature [69]. The tailpipe emission from heavy-duty truck for diesel fuel and the life cycle emission analysis of diesel production was also derived from earlier studies [53,71].

2.3.3. Straw pellet production

In a pellet plant, production of pellets is a combination of sequential steps including preprocessing, drying, grinding, pelleting, cooling, screening, and bagging. All of the equipment is operated by electric motor. The power requirement for straw-based pellet production is 865 kW [19]. This electrical energy was converted to thermal energy by considering the efficiency of power plant is 35% (assumed to be for coal in case of Alberta). Unlike wood pellet production, pellet mill is the highest energy consuming equipment (34%) in straw-based pellet production followed by dryer (19%). This is different than wood pellet production where the dryer consumes the maximum portion of electricity [72] because the moisture content of woody biomass is 45–50% compared to 15–20% of agricultural biomass. The feedstock species, particle size, pellet size and moisture level are important factors in determining how much horsepower is needed. The straw pelletization requires less electrical power than pelletization of wood, even though it requires extra power for chopping compared to wood [19]. The power requirement for all the equipments used for pellet production was taken from previous study [19].

If straw is delivered to the pellet plant with moisture content lower than 12%, drying may not be required [72]. In spring harvesting moisture content of straw is 40% less than fall harvesting. The rotary drum dryer is generally used in a pellet production plant [73,74] and this was considered in this analysis. The pellet plant with capacity of 150,000 tonnes per year operates for 7200 h annually (about 24 h/day, 300 days/year, hence at a capacity factor of 85% [19]). The energy required for pellet production was estimated at be 0.15 $MJ_{thermal}$/kg of pellet. The GHG emission factors for electricity used were taken as 905 g CO_2/KWh, 0.028 g CH_4/KWh and 0.02 g N_2O/KWh [75].

In this analysis moisture content of straw was considered to be 14% [19]. Straw arriving at pellet plant typically have moisture content of 13–20% which is reduced to 8–10% using dryer. Natural gas is commonly used fuel for drying [17]. This was considered in the base case scenario. Another scenario considered for the analysis was the use of biomass straw as drying fuel. The reduction of moisture content of biomass was from 14% to 8%.

Straw requires conditioning to provide durable pellets and to minimize fines [74]. Conditioning is done with steam or hot water to soften the fibrous material of straw. The requirement of steam for conditioning purpose is approximately 4% (by mass) of total amount of dry biomass feedstock used [76]. Conditioned feedstock is then fed to the pellet mill. Steam generation for conditioning is produced by burning natural gas in a boiler. Boiler efficiency was considered to be 80% and heating value of the natural gas was 40.43 MJ/m^3 [77,78]. Thus the energy requirement for conditioning of pellet is 0.12 MJ/MJ of pellets. The assumptions considered in this study for drying and conditioning of straw is shown in Table 7.

The specific emission from combustion of natural gas was 1918 g CO_2/m^3, 0.0372 g CH_4/m^3 and 0.0332 g NO_2/m^3 [79]. The emissions during natural gas recovery including well drilling testing and processing emission were 0.1339 kg CO_2/m^3, 0.0019 kg CH_4/m^3 and 46×10^{-6} kg NO_2/m^3 [80].

2.3.4. Transportation of pellet from plant to consumer

The truck considered for transporting pellet from the plant to retailer or end-user has a capacity of 40 tonnes (70 m^3 capacity). This pellet can be used in small-scale combustor by residential users or large scale CHP plants. It is assumed that pellets are transported from plant to nearby location (e.g., Edmonton or Calgary as these two are the nearby big cities) in Alberta (Fig. 2 [54],). Two locations for the consumers were considered at distances of 140 km and 280 km between production plant and consumer. We assumed that the retailer stores are within these two cities from which residential user purchases 250 kg of pellets at a time (15 kg bag each) [1]. The distance between the retailer shop and the residence of small user was assumed to be 5–15 km in two different scenarios. The approximate radius of city of Edmonton and Calgary are 14 km and 15 km, respectively. Including suburbs the approximate radius can be increased to 54 km and 40 km respectively. Sikkema et al. [1] considered the distance of 93 km from retailer to the residential user in European setting. Assumptions considered for pellet transport are shown in Table 8.

The GHG emissions from the passenger car, which is used to transport pellets from retailer store to customer, were considered 0.258 kg CO_2/km and 8.6×10^{-4} kg N_2O/km [81]. The fuel consumption of passenger car is considered to be 0.066 L/km [81]. Pneumatic trucks are used in Europe for delivering pellet to households or medium size users and trucks are used for delivery to large scale user [82]. Unlike Europe pneumatic truck with automated loading system is not common in North America, so truck and combination of truck and train transport are used here. The average transported volume is about 0.25 tonnes/year for residential user but for users of large loads can be between 500 and 1000 kg [1]. For industrial bulk users such as CHP plants, pellets are transported through wholesale merchants or directly from the pellet plant.

2.3.5. End user

There are two main end-uses of pellet including residential and industrial. The residential pellet biomass trade in Canada is local or regional while currently industrial wood pellets are traded internationally. In case of agricultural pellet we have considered that

Table 7
Assumptions for drying and conditioning of biomass for pellet production (derived from [19]).

Drying	
Total amount of biomass for drying (tonnes/year)	157,500
Moisture reduction	14%–8%
Temperature increase (°C)	25 °C–110 °C
Specific heat of water (KJ/kg °C)	4.2
Specific enthalpy of steam at standard atmosphere (KJ/kg)	2676
Conditioning	
Percentage of water required for conditioning biomass (%)	4%
Temperature increase of water for conditioning (°C)	20 °C–100 °C
Boiler efficiency (%)	80%

Table 8
Assumptions for pellet transport from pellet plant to consumer.

Heavy-duty truck transport		
Pellet truck capacity (tonne)	40	[66]
Fuel consumption (L/km)	0.25	[68]
Highest yield area	Census division 5	
Distance from center of census division 5 to		
Calgary (km)	140	
Edmonton (km)	280	
Passenger car transport		
Distance travel by customer (km)	5	
Fuel consumption (L/km)	0.066	[81]
Pellet bag size (kg)	15	[1]

Table 9
Energy use and associated emission for straw production.

Input	Energy requirement	Emission				Sources/Comments
	MJ/MJ_{pellet}	$kg\ CO_2/MJ_{pellet}$	$kg\ CH_4/MJ_{pellet}$	$kg\ N_2O/MJ_{pellet}$	$kg\ CO_{2eq}/MJ_{pellet}$	
Base Case						
Fertilizer						
N	0.1574	0.00151 [a]	4.43×10^{-6}[b]	2.25×10^{-5} [c]	0.008575	[a]: Total carbon requirement for urea fertilizer is 1.225 kg CO_2/kg N [46]. In case of ammonium nitrate fertilizer the carbon requirement is 1.904 ± 0.275 kg CO_2/kg N [5]. [b]: Total methane requirement for nitrogen fertilizer is $3.6 \times 10^{-3} \pm 0.6$ x 10^{-3} kg CH_4/kg N [5]. [c]: Total nitrous oxide requirement for nitrogen fertilizer is 0.0183 kg N_2O/kg N [5].
P_2O_5	0.0117	0.00012 [d]	1.07×10^{-8}[e]	1.96×10^{-8}[f]	0.000124	[d]: Total carbon requirement for phosphate fertilizer is 0.253 kg CO_2/kg P_2O_5 [46]. [e]: Total methane requirement for phosphate fertilizer is 2.3×10^{-5} kg CH_4/kg P_2O_5 [5]. [f]: Total nitrous oxide requirement for phosphate fertilizer is 4.2×10^{-5} kg N_2O /kg P_2O_5 [5].
K_2O	0.0198	0.00022 [g]	2.22×10^{-8}[h]	9.92×10^{-9} [i]	0.000227	[g]: Total carbon requirement for potash fertilizer is 0.212 kg CO_2/kg K_2O [46]. [h]: Total methane requirement for potash fertilizer is 2.1x 10^{-5} kg CH_4/kg K_2O [5]. [i]: Total nitrous oxide requirement for potash fertilizer is 9.4×10^{-6} kg N_2O /kg K_2O [5].
Pesticide	0.0045	0.00004 [j]	1.10×10^{-9}[k]	9.61×10^{-9} [l]	0.000045	[j]: Total carbon requirement for pesticides (average of 23 pesticides) is 3.73 kg CO_2/kg pesticides [5]. [k]: Total methane requirement for general pesticides is 1.8×10^{-4} kg CH_4/kg pesticides [5]. [l]: Total nitrous oxide requirement for general pesticides is 1.51×10^{-3} kg N_2O /kg pesticides [5].
Seed	0.0223	0.00021 [m]	0.00000 [n]	1.62×10^{-6} [0]	0.000714	[m]: Total carbon requirement for sowing is 0.212 kg CO_2/kg seeds [51]. [n]: Total methane requirement for sowing is 2.1x 10^{-5} kg CH_4/kg seeds [5]. [o]: Total nitrous oxide requirement for sowing is 9.4×10^{-6} kg N_2O /kg seeds [5].
Fuel	0.0419	0.00035[p]	8.18×10^{-8}[q]	1.63×10^{-7} [r]	0.000399	[p]: Total carbon requirement for diesel fuel is 0.01926 kg CO_2/MJ of diesel fuel in Western Canada [5]. [q]: Total methane requirement for diesel fuel is 4.42×10^{-6} kg CH_4/MJ for diesel fuel in Western Canada [5]. [r]: Total nitrous oxide requirement for diesel fuel is 1.95×10^{-7} kg N_2O /MJ of diesel fuel in Western Canada [53].
Machinery	0.0337	0.00018[s]	1.0×10^{-8}[t]	3.78×10^{-15}[u]	0.000177	[s]: Total carbon requirement for machinery is 2.046 kg CO_2/kg steel [70]. [t]: Total methane requirement for machinery is 0.0001 kg CH_4/kg steel [70]. [u]: Total nitrous oxide requirement for machinery is 0.0027 kg N_2O /kg steel [70].
Total	**0.2914**	**0.00240**	$\mathbf{4.52 \times 10^{-6}}$	$\mathbf{1.77 \times 10^{-5}}$	**0.01026**	
Nutrient Replacement						
N	0.112	0.00204	6.0 x 10^{-6}	3.05 x 10^{-5}	0.01162	[5][46]
P_2O_5	0.009	0.00017	2.0 x 10^{-8}	2.74 x 10^{-8}	0.00017	[5][46]
K_2O	0.005	0.00010	1.0 x 10^{-6}	4.50 x 10^{-9}	0.00010	[5][46]
Total	**0.125**	**0.00231**	**0.00001**	**0.000031**	**0.01190**	
Organic Farming						
Fertilizer production	0	-	-	-	0	[63][87]
Pesticide production	0	-	-	-	0	[63][87]
Seed	0.0117	-	-	-	0.00071	[63][87]
Fuel	0.0105	-	-	-	0.00052	[63][87]
Machinery	0.0176	-	-	-	0.00017	[63][87]
Manure storage	0				0.0005	[63][87]
Total	**0.0398**				**0.00141**	

Table 10
Energy and emission during transportation and pellet production.

Operations	Energy requirement	Emissions			
	MJ/MJ_{pellet}	kg CO_2/MJ_{pellet}	kg CH_4/MJ_{pellet}	kg N_2O/MJ_{pellet}	kg CO_{2eq}/MJ_{pellet}
Transport of straw from field to pellet plant					
Truck run (95 km)[a]	0.012	0.00046	3.39×10^{-8}	6.79×10^{-8}	0.000485
Diesel production[b]	0.0003	0.00002	0.0000	9.67×10^{-8}	5.03×10^{-5}
Truck manufacture[c]	0.0023	0.0001	0.0000	0.0000	0.000179
Sub total	0.015	0.00061	4.01×10^{-8}	3.32×10^{-7}	0.000714
Pellet production					
Pelleting	0.02847	0.00716	2.21×10^{-7}	1.58×10^{-8}	0.00721
Drying[d]	0.01311	0.00062	1.2×10^{-8}	1.07×10^{-8}	0.00063
Conditioning	0.00851	2.0×10^{-5}	3.9×10^{-10}	3.4×10^{-10}	2.03×10^{-5}
Sub total	0.05009	0.00780	2.37×10^{-7}	2.68×10^{-8}	0.00786
Transport pellet from plant to the consumer					
Transport to Calgary[e]	0.002	15.93×10^{-5}	1.16×10^{-8}	2.33×10^{-8}	16.67×10^{-5}
Transport to Edmonton[e]	0.005	31.85×10^{-5}	2.33×10^{-8}	4.67×10^{-8}	33.35×10^{-5}
Car transport[f]	0.0663	5.70×10^{-9}	0	1.26×10^{-12}	6.12×10^{-9}

[a] The tailpipe emissions of diesel are 2.73 kg CO_2/L, 2.0×10^{-4} kg CH_4/L, and 4.0×10^{-4} kg N_2O/L [53].
[b] Emissions during diesel production are 0.12 kg CO_2/l, 57.0×10^{-4} kg N_2O/l [71].
[c] Emission for steel production 2.045 kg CO_2/kg, 0.0001 kg CH_4/kg, and 0.0027 kg N_2O/kg [70].
[d] Emissions from burning of natural gas are 1.918 kg CO_2/m^3, 3.72×10^{-5} kg CH_4/m^3 and 3.32×10^{-5} kg NO_2/m^3 [79].
[e] Diesel fuel emission from heavy-duty truck are 2.73 kg CO_2/L, 2.0×10^{-4} kg CH_4/L and 4.0×10^{-4} kg N_2O/L [53].
[f] Emission from passenger car are 0.258 kg CO_2/km and 8.6×10^{-4} kg N_2O/L [81].

pellet is used in CHP plants in Canada. For residential users small-scale combustor such as pellet stove or burner is considered. The efficiency of this type of combustor is usually 60% but these days high efficiency combustor of efficiency 85% are available [83]. The emissions per unit energy output from small-scale combustor are generally high due to incomplete combustion which depends on temperature during combustion, excess air and other factors [84]. In large scale plants combustion occur at high temperature and complete combustion is possible due to proper technical design and hence lower emissions per unit energy output. CO_2 emission due to combustion of pellet was considered zero because pellet is considered as a carbon neutral fuel, i.e., the amount of CO_2 released during its combustion is same as the amount taken up by plants during its growth [1,15,30]. Other GHG emission, e.g., CH_4 and N_2O are considered in the analysis. There are also GHG emissions during the construction of a power plant but that is likely to be small when averaged over the lifetime of the power plant. We have not considered the emissions during manufacturing of small-scale combustor in our analysis.

2.3.6. Introduction to scenarios

Scenario analyses were done to examine the sensitivity of different assumptions and parameters on the life cycle emission and energy of agricultural pellet production and utilization. Different scenarios were developed by changing various assumptions of the base case. The details on the scenarios are given below.

2.3.6.1. Scenario 1. The analysis starts from harvesting of straw from the field assuming that straw is the by-product of wheat production. The upstream activities of wheat farming were not taken into consideration. In the base case all emission and energy required for wheat farming were allocated to the grains and straw on mass basis. In this scenario, nutrient replacement required due to the removal of straw from the field was included. Other assumptions are same as the base case.

2.3.6.2. Scenario 2. This scenario was developed to distinguish the primary energy used and GHG emission between inorganic (or synthetic) and organic fertilizers. Recently there has been an increase in organic fertilizer usage at an annual rate of 20% [85]. Other advantages of using organic fertilizer are increased soil quality, and enhanced biodiversity [86]. Nutrient sources are different in inorganic and organic wheat but it is assumed that the nutrient requirement per kg of harvested wheat is the same [63]. It was also assumed that organic fertilizer requirements are met by manure [63]. GHG from manure may vary with manure management, storage and allocation. In the current analysis, GHG emission from manure management in wheat production system were adapted from Hoeppner et al. [87] and Meisterling et al. [63]. The yearly availability of beef cattle manure, hog manure, dairy manure in Alberta are 51.9, 2.5 and 3.9 million tonnes, respectively [88], which are sufficient for organic wheat farming in the province.

2.3.6.3. Scenario 3. Wheat has traditionally been grown using conventional tillage in the southern prairie of Western Canada. However, farmers are shifting from conventional practice to reduced or zero tillage system to retain soil quality and to reduce cost. The zero tillage is currently used for wheat production. So it was assessed in terms of GHG emissions and energy consumption in Scenario 3.

2.3.6.4. Scenario 4. Solid biomass can be used as a dryer fuel instead of natural gas [70,89]. In this scenario it was assumed that straw would be used as fuel for drying during pellet production. If biomass was used as dryer fuel, 187,000 tonne/year straw are needed annually, of which 30,000 tonne/year (20% of biomass) is used as dryer fuel and rest, 157,000 tonne of straw feedstock for making pellets.

Table 11
Emissions from pellet burning (derived from [90]).

Operations	Emission			
	g CO_2/MJ_{pellet}	g CH_4/MJ_{pellet}	g N_2O/MJ_{pellet}	g CO_{2eq}/MJ_{pellet}
Small-scale combustor	0[a]	5.01×10^{-3}	3.01×10^{-3}	1.03684
CHP plant	0[a]	1.65×10^{-3}	6.61×10^{-4}	0.23965

[a] The assumption is that the amount of CO_2 released during combustion is the same as taken up by the plant during its growth.

2.3.6.5. *Scenario 5.* Drying can be omitted if the moisture content of biomass is less than 12% [72]. Spring wheat harvesting in August–September in Western Canada can reduce moisture content by 40% so drying can be omitted. This case was evaluated in this scenario.

2.3.6.6. *Scenario 6.* Trucking is the usual means of biomass transport and this is the only transport accessed in rural areas [67]. For the considered area (from Calgary to Edmonton) biomass can be transported by train as the infrastructure is already in place. Earlier studies on LCA conclude that emissions are reduced substantially by using trains [67]. Truck transport is considerably more energy intensive than rail transport [46]. Energy required for rail and truck is 0.47 MJ/t-km and 2.0 MJ/t-km, respectively [46]. Sixty percent of the total volume of land freight shipment in Canada is by rail and the remaining by truck [67] to reduce road congestion and cost of delivery. The size of the train considered was equivalent to 100 cars with capacity 190 m^3 per car. Typical train capacity is 26.6 tonne/car [67].

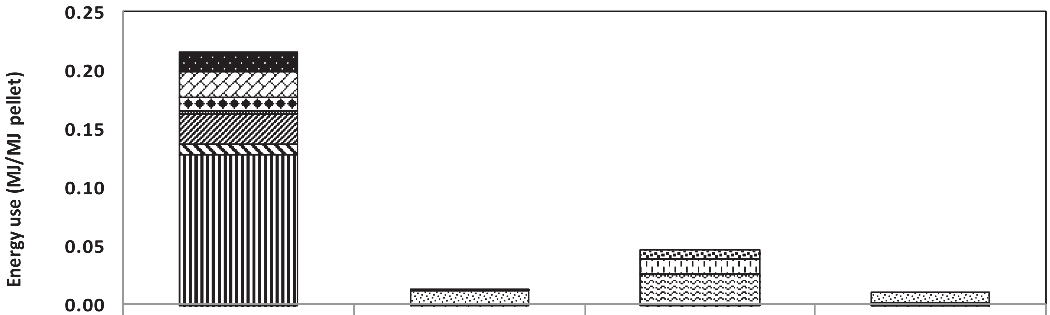
3. Impact assessment and interpretation – results and discussion

The energy requirements and associated emissions for base case are shown in Table 9. In the base case energy and emission are allocated between wheat grain and straw on mass basis. The nutrient replacement was also considered in the base case to compensate for the nutrients removed due to straw harvesting. The energy and emission due to nutrient replacement is completely assigned to straw. It is seen from Table 9 that the total energy use for the base case (after allocation to wheat and straw) is 0.21642 MJ/MJ of pellet e.g., the amount of energy used is 0.21642 MJ for 1 MJ of pellets. Field activities of wheat straw production is 21.07 gm CO_{2eq}/MJ of pellet. The highest energy use and emission comes from fertilizer production, transportation and application which is 84% of the total used energy and 94% of total emissions.

Energy use and emission in base case occurred during transport of straw (baled form) from field to the pellet plant (distance 94 km), pellet production and pellet transported to consumer is shown in Table 10. The tailpipe emission of the truck contributes 67% of the total emission by using 80% of the total energy. This operation consumes highest amount of energy compared to other operations in transportation phase. In base case, the total energy use of pellet production is 0.048 MJ/MJ of pellet and 60% of the energy is used in pelleting process. Total emission in pellet production is 7.76 gm CO_{2eq}/MJ of pellet of which 93% of emissions comes from the equipment which are operated by electric motors.

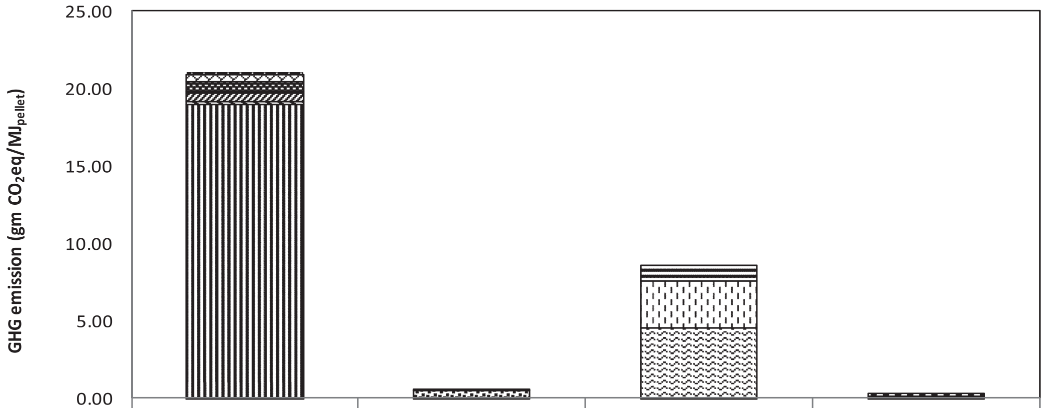
In the base case, the pellet use was considered for residential users. The pellet plant is assumed to be located in the center of census division 5 of Alberta and the pellets can be transported to the retailers in the nearby big cities such as Calgary and Edmonton. The residential users get the pellets from the retailers who are on an average a driving distance of 5 km. The energy used to transport to the retailer of Calgary and Edmonton are 0.002 MJ/MJ of pellet and 0.005 MJ/MJ of pellet, respectively. Emission due to transport to Edmonton is higher due to longer distance of transport as compared to Calgary.

Emissions from pellet burning are shown in Table 11 [90]. These results are similar to earlier studies [84,90–92]. Pellet burning in a small-scale combustor results in higher emissions than the CHP plant. This is because of the efficiency of the combustion units are lower than the CHP plants. In CHP plants, technical design of the combustor support complete combustion of fuel by controlling



	Field	Transport	Pellet production	Transport to residential user
▨ Truck + car transport	0.0000	0.0000	0.0000	0.0092
▨ Pellet conditioning	0.0000	0.0000	0.0080	0.0000
▨ Drying with NG	0.0000	0.0000	0.0131	0.0000
▨ Pellet, equipment and electricity manufacture	0.0000	0.0000	0.0263	0.0000
▨ Truck Manufacturing	0.0000	0.0000	0.0000	0.0000
▨ Diesel production	0.0000	0.0003	0.0000	0.0008
▨ Truck run including backhauling	0.0000	0.0120	0.0000	0.0000
■ Machinery	0.0176	0.0000	0.0000	0.0000
▨ Fuel	0.0220	0.0000	0.0000	0.0000
▨ seeding	0.0117	0.0000	0.0000	0.0000
▨ Pesticide	0.0024	0.0000	0.0000	0.0000
▨ K2O	0.0254	0.0000	0.0000	0.0000
▨ P2O5	0.0092	0.0000	0.0000	0.0000
▥ N	0.1280	0.0000	0.0000	0.0000

Fig. 3. Energy use for pellet production and distribution.



	Field	Transport	Pellet production	Transport to residential user
◨ Truck + car transport	0.00	0.00	0.00	0.17
⊟ Pellet conditioning	0.00	0.00	1.00	0.00
◫ Drying with NG	0.00	0.00	3.05	0.00
▨ Pellet, equipment and electricity manufacture	0.00	0.00	4.52	0.00
■ Truck Manufacturing	0.00	0.00	0.00	0.00
⊠ Diesel production	0.00	0.05	0.00	0.12
⊡ Truck run including backhauling	0.00	0.48	0.00	0.00
■ Machinery	0.18	0.00	0.00	0.00
⊠ Fuel	0.40	0.00	0.00	0.00
⊠ seeding	0.71	0.00	0.00	0.00
▣ Pesticide	0.04	0.00	0.00	0.00
▨ K2O	0.55	0.00	0.00	0.00
◪ P2O5	0.19	0.00	0.00	0.00
▥ N	18.99	0.00	0.00	0.00

Fig. 4. Emission from pellet production and distribution.

amount of air intake in combustor unit. In case of small-scale combustor, such as a pellet furnace of stove, efficiency of combustion is less due to incomplete combustion.

Energy use in the life cycle of pellet production is shown in Fig. 3. Energy use in each phase of pellet production, starting from wheat farming till delivery to the plant is shown in Fig. 3. Total energy used for pellet production and distribution is 0.286 MJ/MJ of pellet. The highest energy used is in farming (76%) especially for all fertilizer production, transportation and application. From this amount, about 62% energy is used in the production of nitrogen fertilizer, transportation and application. Similar result was also observed in an earlier study for this unit operation [27].

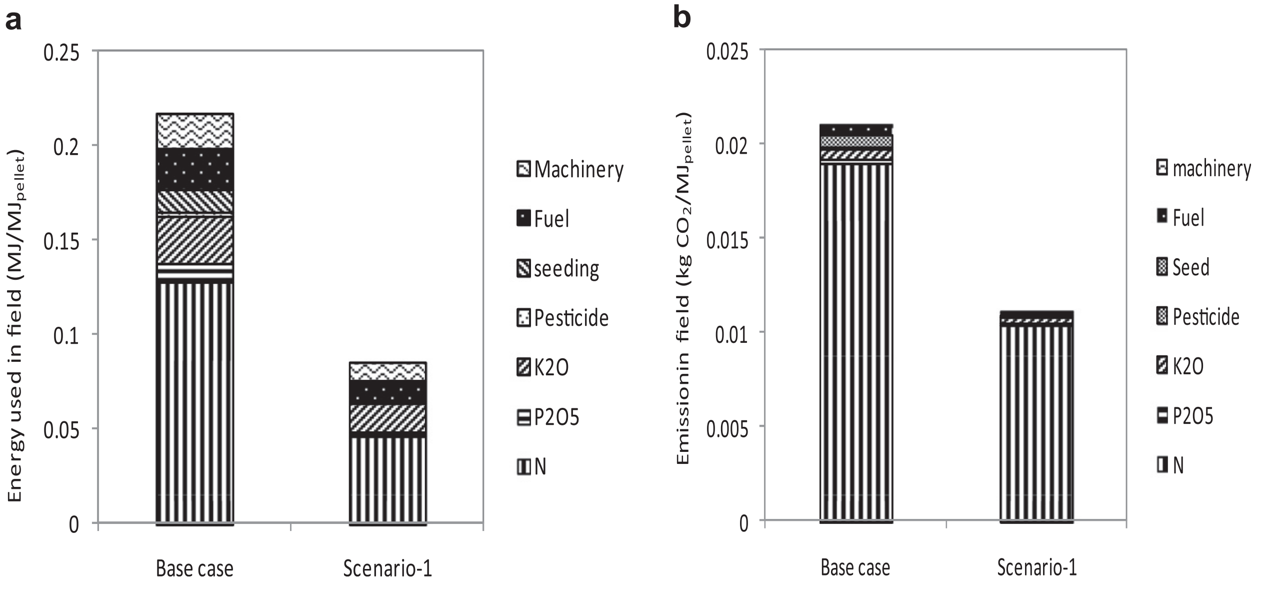


Fig. 5. Energy (a) and emission (b) from field activities in scenario 1.

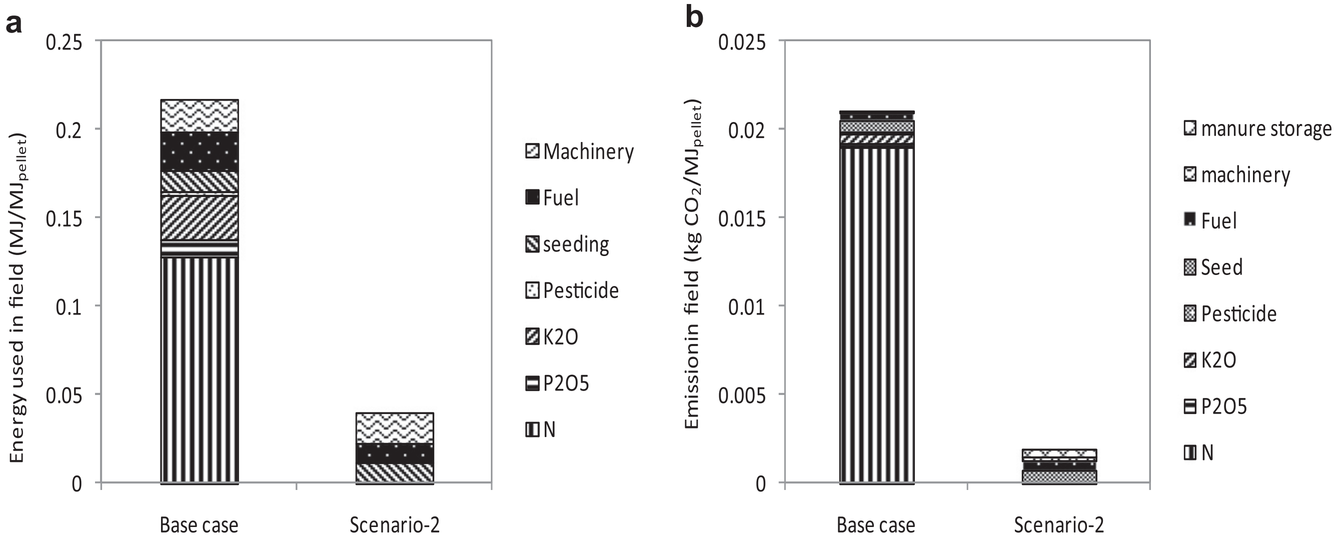


Fig. 6. Energy (a) and emission (b) from field activities in Scenario 2.

Total emission during pellet production and distribution is shown in Fig. 4, which is 30.34 gm CO_{2eq}/MJ of pellet. About 70% of the total emission occurs during field activities especially in all fertilizer production, transportation and application. About 92% from this amount came from nitrogen fertilizer production, transportation and application.

3.1. Scenario analysis

In Scenario 1, nutrient replacement was considered for removal of straw from the field. Considering straw as a by-product, this resulted in an energy consumption of 0.154 MJ/MJ of pellet production which was 46.31% lower than the base case. Life cycle GHG emission was also reduced by 64.79% compared to the base case and was 10.68 gm CO_{2eq}/MJ of pellet production (Fig. 5).

As inorganic fertilizer is the highest contributor, both for the energy usage and the resulting emission, so to reduce energy use and emission one option could be to use organic fertilizer instead of inorganic fertilizer. The energy use is generally lower if organic fertilizer is used compared to inorganic fertilizer in farming system, but the yield of straw produced is lower [58]. Hoeppner et al. [87] showed that energy use was 50% lower with organic farming than conventional farming where inorganic fertilizer was used. Production of wheat using inorganic fertilizer had the highest energy use, whereas the organic wheat production has the highest energy efficiency [58]. The assumption is that the inorganic fertilizers are produced by employing fossil energy. On the other hand, the nitrogen nutrient for the organic system is obtained from cattle manure. As the manure is used for organic farming, so energy and emission due to fertilizer production can be omitted for this type of farming. Seeding and machinery manufacturing impacts can be assumed to be the same for both organic and inorganic systems. Organic farms usually plow or till as a mechanical method of controlling weeds, instead of using pesticides [63]. So the pesticide production and transport impact is not considered in the analysis. The fuel used in farm equipment depends on the type of equipment.

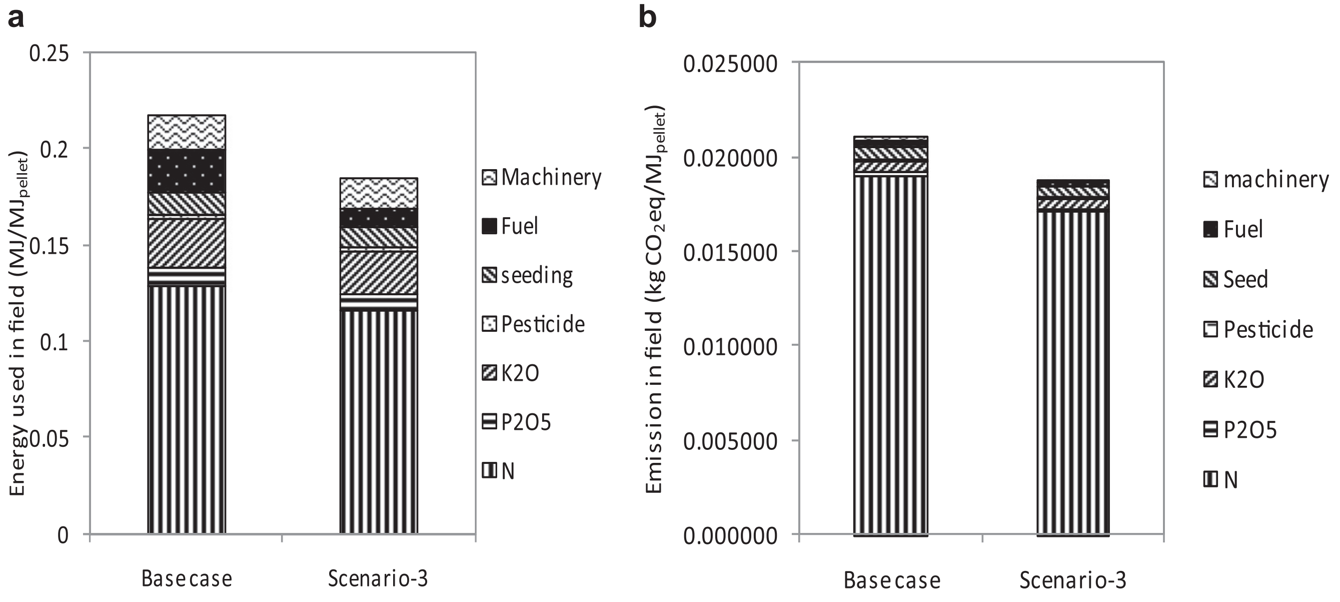


Fig. 7. Energy (a) and emission (b) in scenario 3.

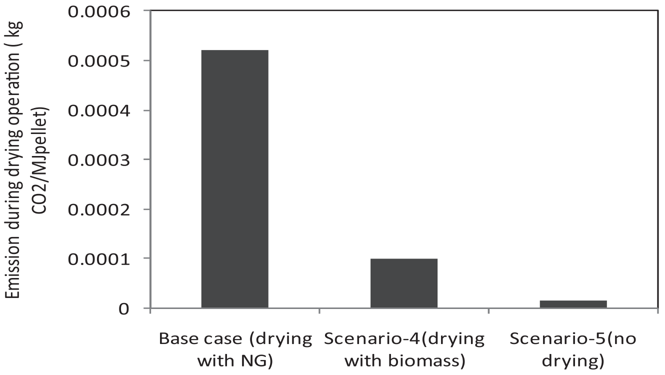


Fig. 8. Comparison of emission of scenarios 4 and 5 with base case.

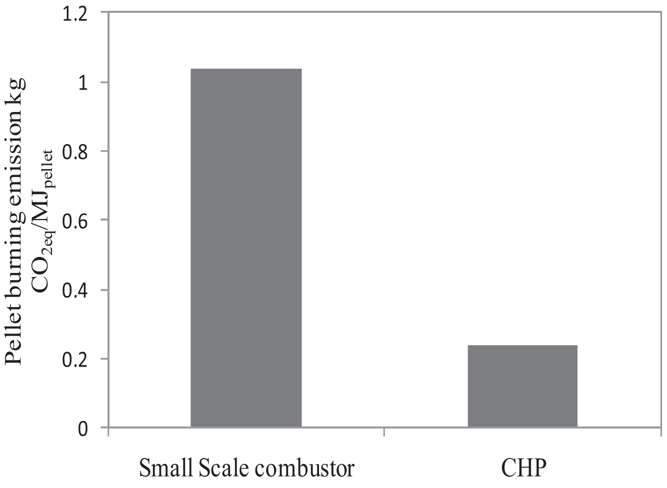


Fig. 10. Emissions in end use of pellet.

Based on Madler et al. [86] and Hoeppner et al. [87], we considered that the organic farming is less fuel intensive. Wheat yields for organic agriculture are typically lower than inorganic system [63]. Madler et al. [86] and Meisterling et al. [63] reported organic wheat yield as 80% and 75%, respectively, of the conventional wheat yield. We assumed 80% in our study. The LCA study of organic and inorganic wheat by Meisterling et al. [63] showed that the shifting from inorganic to organic fertilization can save energy of 0.61 kJ/kg of wheat production and reduce emissions by 30 g CO_{2eq}/kg of wheat production. The data for this scenario was adopted from previous studies [63,87], which are shown in Table 9. Fig. 6 shows that fertilizer contributed the most to the difference in energy input between inorganic and organic system. The energy and emissions for Scenario 2 accounted for 36% and 33% of the total energy and emission compared the base case scenario.

The tillage system has a significant effect on the yield of spring wheat [93]. Several studies reported the increase of yield due to zero tillage on average stubble, e.g., Lafond et al., 21% [93], Brandt 13% [94], Wright 12% [95], Stobbe et al. 5% [96]. In case of the fallow management practice, the yield of spring wheat is not affected [93]. In our study we have assumed that 10% of the yield change occurs due to change from conventional tillage to zero tillage. By using zero tillage system (Scenario 3), both energy use and emissions were reduced compared to the conventional tillage. This was due to less use of machinery and fuel in this scenario compared to base case. Fuel and machinery emission reductions were larger than the small increase in emissions associated with higher herbicide used in zero tillage [46]. In conventional method, multiple tillage are used for seed bed preparation, seeding, fertilizer, pesticide application and weed control, whereas, in zero tillage soil is disturbed only during planting. The life cycle energy used in zero tillage was reduced by 0.274 MJ/MJ of pellet production. The reduction of energy requirement and emissions in zero tillage were observed in previous studies [45,51]. In this study, the reduction is 4.19% of the energy requirement for pellet production compared to the base case (conventional tillage). Similarly, life cycle emission was 30.09 gm CO_{2eq}/MJ which is a reduction of 1% from the base case (Fig. 7). Farmers continue to adopt zero tillage in Alberta. The 2006 Census of Agriculture shows that 27% of farmers adopted zero tillage compared to 16.5%in 2001. Thus zero tillage acres have increased from about 5 million in 2001 to nearly 9 million in 2006 [97].

The usual practice of pellet production in Western Canada is to use natural gas as dryer fuel. By replacing this with biomass (straw) (Scenario 4), the emission was reduced (Fig. 8). In Scenario 5, the drying process was omitted assuming that moisture content of straw brought to the pellet plant has a moisture content of less than 12% [72]. The amount of moisture in straw which is harvested in August–September contains approximately 40% less moisture. A reduced life cycle emission (29.92 gm CO_{2eq}/MJ of pellet production, 4.2% less than the base case) resulted due to use of straw as the dryer fuel. Similar analysis of replacing natural gas by sawdust was

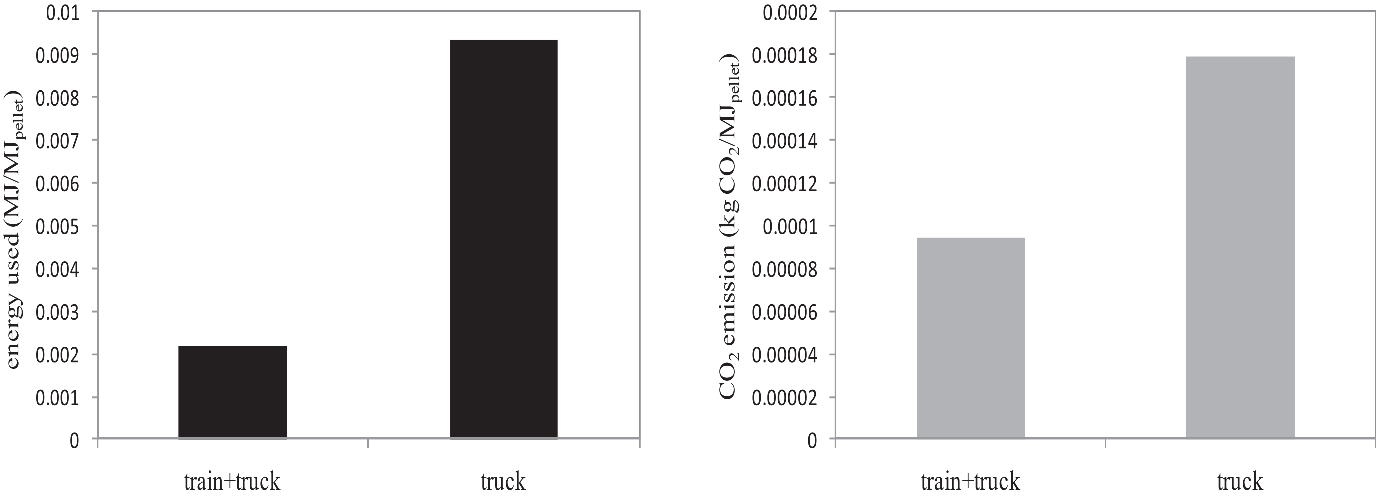


Fig. 9. Energy used and emissions for different mode of transport.

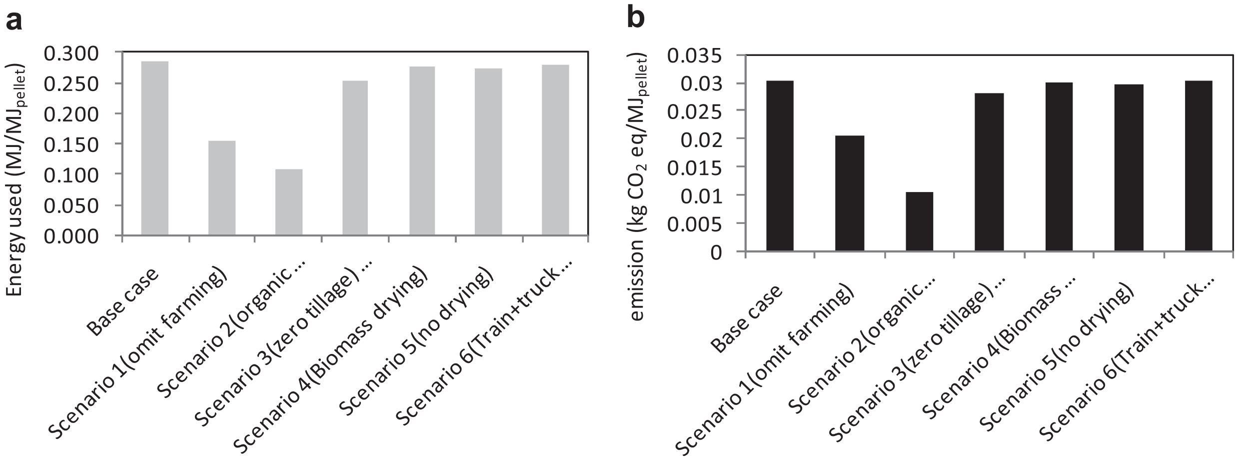


Fig. 11. Energy (a) and emission (b) comparison of Scenarios 1–6.

done by Magelli et al. [17], during making of wood pellets and found that the emission by using sawdust is far less compared to natural gas. This emission was 29.82 gm CO_{2eq}/MJ when drying operation was omitted and this is similar to using straw. The comparison of Scenario 4 and Scenario 5 with base case is shown in Fig. 8.

The truck transport is considerably more energy intensive than rail transport [46]. Energy required for rail and truck are 0.47 MJ/t-km and 2.0 MJ/t-km, respectively [46] The corresponding emission for truck transport is higher than train transport [67]. The CO_2 emissions for truck and train transport are 41.3 gm/Km-tonne and 21.8 gm/km-tonne respectively [67]. By considering 140 km total travel distance, the amount of energy for truck transport and combined train and truck transport (40 km by truck and remaining by train) in Scenario 6 is shown in Fig. 9. Thus using combined truck and train in delivery results in 2.5% and <1% reductions of energy and emission, respectively, from the base case values.

If pellet is burned in a CHP plant, the emission per MJ of pellet is reduced significantly compared to small-scale combustor because of the complete burning in CHP combustor. The resultant emissions in both cases are shown in Fig. 10 [90]. Fig. 10 shows that emission from CHP plant is 76.88% less than small-scale combustor.

If base case is compared with all other scenarios, energy used and emissions for all scenarios except Scenarios 1 and 2, are close to base case and the difference is within ±4% and ±2%, respectively. Energy use and emissions are 46.1% and 32.50% of the base case, respectively, if farming practice is omitted (Fig. 11). Organic farming (Scenario 2) provided large reduction of energy use and emission compared to base case i.e., 64% and 65%, respectively. Adopting the zero tillage option instead of conventional practice causes energy saving (10%) and curbing of emission (8%). Effects of changing either dryer fuel (Scenario 4) or omitting drying (Scenario 5) or changing tillage system (Scenario 3) or changing mode of transport (Scenario 6) are not significant on energy use and emission. In straw pellet production, drying is used to reduce moisture content from 14% to 8%. For this small reduction of moisture content, both the energy requirement and emissions are less. This is unlike the case of wood pellet production where moisture content is reduced from 40% to 10% [89], and the total emissions are 43% higher than straw pellet production [98]. The change of tillage system only reduces the machinery and fuel use but fertilizer applications are same for both tillage systems. So the alternate tillage option did not change the life cycle energy use and emission of pellet production appreciably. Finally, it can be stated that the use of organic fertilizers can reduce energy requirement and emission but the change of wheat yield due to the organic fertilizer use and its economic aspect should be taken into account.

3.1.1. *Emission and energy analysis for composite cases*

The base case considered current practices of wheat farming, biomass transport and pellet production in Western Canada. After analyzing the basic scenarios, as explained earlier, it is obvious that some additional scenarios combining potential options of basic scenarios (e.g., combining organic fertilizer, zero tillage, train

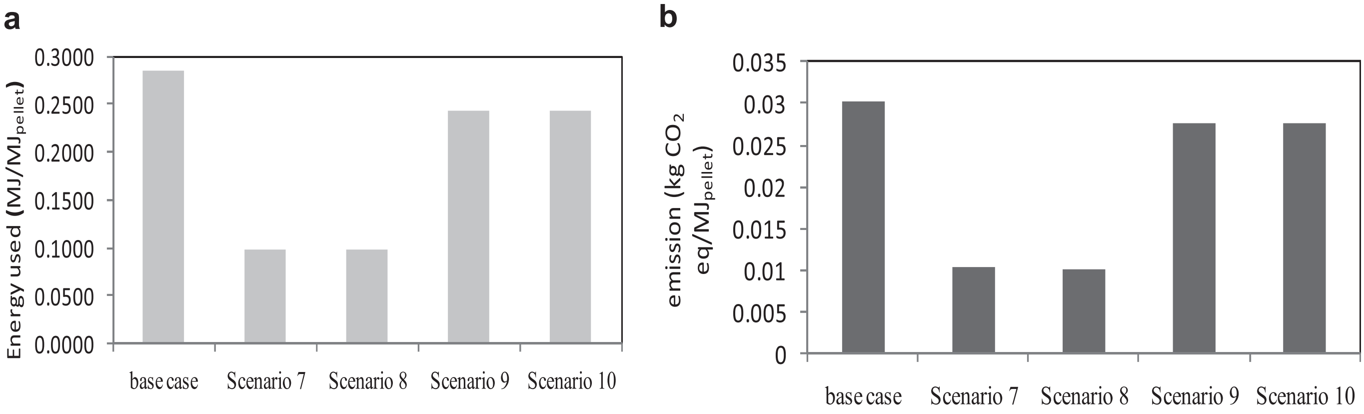


Fig. 12. Energy (a) and emission (b) for composite cases.

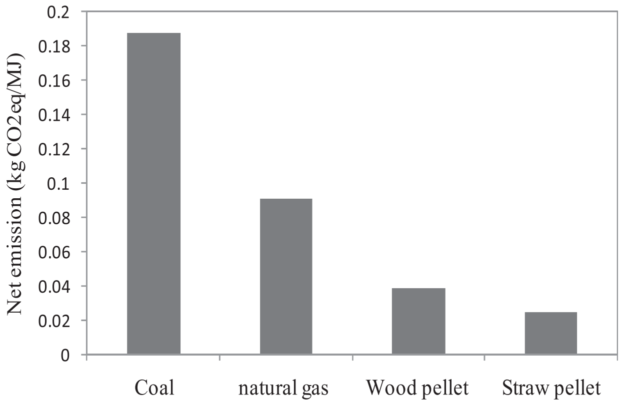


Fig. 13. Comparion of Agri-pellet with other fuel sources.

transport and no drying options) would be interesting to examine. These composite scenarios are: Scenario 7 (combining organic farming, truck transport and drying with biomass in plant); Scenario 8 (organic farming, truck transport and no drying in plant); Scenario 9 (zero tillage farming, truck transport and drying with biomass in plant); and Scenario 10 (zero tillage farming, truck transport and no drying in plant). As stated earlier, zero tillage is a potential option against conventional tillage. The spring wheat harvesting period of Western Canada is from August to September [99]. There is also a possibility of natural air drying of straw during this time in similar places [100]. As drying depends on the weather condition so the pellet plant operator may keep the option for drying of straw before pellet production. Fig. 12 shows the energy requirements and emissions for composite scenarios. It is observed that energy requirement and emission in the composite case of organic farming i.e., Scenario 7 are reduced by 2% and 1.5%, respectively, compared to basic organic fertilizer case (Scenario 2). Choosing no drying option with organic farming (Scenario 8) causes lower energy and emission but the changes are not significant (<1% of Scenario 7). If zero tillage farming is adopted with no drying option as in Scenario 10 then the energy use and emission are 84.9% and 90.6% of the base case, respectively; corresponding reductions from the basic zero tillage case (Scenario 3) are 4% and 1.5%. Another factor i.e., train transport would also influence the result favorably. Calculations based on present data in the case of Western Canada indicate that additional 1–3% lowering of the base case energy and emission could result by combining this with the appropriate composite cases.

3.1.2. *Emission comparison of agricultural pellet with other fuel sources*

Fig. 13 shows emissions for the agricultural pellet and other fuel sources which are commonly used for heating and electricity production purposes. Emission of coal, natural gas and wood pellet has been taken from previous studies [17,25]. It is obvious that the emission from biomass pellet is far less than other fuel sources.

For Western Canada, net emissions for coal, natural gas and wood pellet are, respectively, 350%, 250% and 50% higher than straw pellet. However, these numbers may vary from location to location and due to adopted technology in fuel production but the comparative emission trend is expected to be same.

4. Conclusions

The life cycle analysis of the energy use and associated emission of agri-pellets were carried out by considering field operations, transport of straw to pellet plants, operations in pellet plants and transport of pellets to the user. The energy use and emissions are the highest in field activities. Nitrogen-based fertilizer production, transportation and application are the highest contributors among the field activities. Large reductions of energy use (64%) and emission (65%) are possible if the organic farming is practiced. The next important option is switching to the zero tillage farming option from conventional tillage which could result in about 10% energy saving and 8% lower emission. The utilization of biomass as dryer fuel in pellet production or omitting the drying or adopting a combination of train and truck transport for pellet delivery causes less emission and energy use but only by less than 5%. Agri-pellets have the potential to offset substantial amounts of GHG emission compared to other fuel sources as energy source. The emission is reduced approximately by 50%, 250% and 350% if compared to wood pellets, natural gas and coal, respectively.

References

[1] Sikkema R, Junginger M, Pichler W, Hayes S, Faaj APC. The international logistics of wood pellets for heating and power production in Europe: costs, energy-input and greenhouse gas balances of pellet combustion in Italy, Sweden and the Netherlands. Biofuels Bioproducts& Biorefining 2010;4:132–53.

[2] Swan J. European wood pellet import market: the Canadian influence: 2008 PFI annual conference, July 21, Hilton head, SC. USA; 2008.

[3] Speltar H, Toth D. North America's wood pellet sector. Research paper FPL-RP-656. United States Department of Agriculture, Forest Services, Forest Products Laboratory; 2009.

[4] Punter G, Rickeard D, Larive J, Edwards R, Mortimer N, Home R, et al. Well-to-wheel evaluation for production of ethanol from wheat. Report FWG-P-04–024. UK: Low Carbon Vehicle Partnership, http://www.rms.lv/bionett/Files/BioE-2004-01%20Ethanol_WTW_final_report.pdf; 2004.

[5] Mortimer ND, Elsayed MA, Horne RE. Energy and greenhouse gas emissions for bioethanol production from wheat grain and sugar beet. Final Report. UK: British Sugar Plc., http://www.northenergy.co.uk/c/pdf/Resources_Research_Unit-Work_for_British_Sugar-2_1.pdf; 2004.

[6] Gabrielle B, Gagnaire N. Life-cycle assessment of straw use in bio-ethanol production: a case study based on biophysical modeling. Biomass and Bioenergy 2008;32:431–41.

[7] Spatari S, Bagley DM, Mcclean H. Life cycle evaluation of emerging lignocellulosic ethanol conversion technologies. Bioresource Technology 2010;101:654–67.

[8] Kim S, Dale BE. Global potential bioethanol production from wasted crops and crop residues. Biomass and Bioenergy 2004;26:361–75.

[9] Kim S, Dale BE. Life cycle assessment of various cropping systems utilized for producing biofuels: bioethanol and biodiesel. Biomass and Bioenergy 2005;29(6):426–39.

[10] Manish S, Banerjee R. Comparison of biohydrogen production processes. International Journal of Hydrogen Energy 2008;33(1):279–86.

[11] Sarkar S, Kumar A. Biohydrogen production from forest and agricultural residues for upgrading of bitumen from oil sands. Energy 2010;35(2):582–91.

[12] Quintero JA, Montoya MT, Sanchez OJ, Giraldo OH, Cardona CA. Fuel ethanol production from sugarcane and corn: comparative analysis for Columbian case. Energy 2008;33(3):385–99.

[13] Silalertruksa T, Cheewala S. Environmental sustainability assessment of bio-ethanol production in Thailand. Energy 2009;34(11):1933–46.

[14] Mani S, Sokhansanj S, Bi X. A streamlined life cycle of biomass densification process. See also, www.nt.ntnu.no; 2005.

[15] Raymer AKP. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. Biomass and Bioenergy 2006;30:605–17.

[16] Hangberg L, Sarnholm E, Code J, Ekvall T, Rydberg T. LCA calculations on Swedish wood pellet production chains – According to the renewable energy directive. Stockholm, Sweden: IVL Swedish Environmental Research Institute Ltd.; 2009.

[17] Magelli F, Boucher K, Bi HT, Melin S, Bonoli A. An environmental impact assessment of exported wood pellets from Canada to Europe. Biomass and Bioenergy 2009;33:434–41.

[18] Zhang Y, Mckechnie J, Cormier D, Lyng R, Mabee W, Ogino A, et al. Life cycle emissions and cost of producing electricity from coal, natural gas and wood pellets in Ontario, Canada. Environmental Science and Technology 2010;44:528–44.

[19] Sultana A, Kumar A, Harfield D. Development of agri-pellet production cost and optimum size. Bioresource Technology 2010;101(14):5609–21.

[20] Searcy E, Flynn PC. Processing of straw/corn stover: comparison of life cycle emissions. International Journal of Green Energy 2010;5(6):423–37.

[21] Sokhansanj S, Mani S, Stumborg M, Samson R, Fenton J. Production and distribution of cereal straw on the Canadian prairies. Canadian Biosystem Engineering 2006;48:3.39–46.

[22] Alberta Agriculture and Rural Development (AARD). Agricultural statistical yearbook 2008. URL, http://www/agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd12401#tables; 2008 [accessed on 09.01.08].

[23] Gnansounou E, Dauriat A, Villegas J, Panichelli L. Life cycle assessment of biofuels: energy and greenhouse gas balances. Bioresource Technology 2010;100:4919–30.

[24] Intergovernmental Panel on Climate Change (IPCC). Climate change 2001. Synthesis Report, http://www.grida.no/publications/other/ipcc_tar/; 2001. See also.

[25] Jungmeier G, Spitzer J. Greenhouse gas emissions of bioenergy from agriculture compared to fossil energy for heat and electricity supply. Nutrient Cycling in Agroecosystems 2001;60:267–73.

[26] Environmental Protection Agency (EPA). Inventory of U.S. green house gas emissions and sinks: 1990–2007. Report 430-R-09-004. Washington D.C. USA. April 15, http://epa.gov/climatechange/emissions/usinventoryreport.html; 2009.

[27] Hartmann D, Kaltschmitt M. Electricity generation from solid biomass via co-combustion with coal: energy and emission balances from a German case study. Biomass and Bioenergy 1999;16:397–406.

[28] Cherubini F, Ulgiati S. Crop residue as raw materials for biorefinery systems – an LCA case study. Applied Energy 2010;87:47–57.

[29] Nagy CN. Energy co-efficients for agriculture inputs in Western Canada. Canada: Federal Panel on Energy Research and Development (PERD), Natural Resources Canada (NRCan); 1999.

[30] Kumar A, Cameron JB, Flynn PC. Biomass power cost and optimum plant size in Western Canada. Biomass and Bioenergy 2003;24(6):445–64.

[31] O'Donnell B, Goodchild A, Cooper J, Ozawa T. The relative contribution of transportation to supply chain greenhouse gas emission: a case study of American wheat. Transportation Research Part D 2009;14:487–92.

[32] Fernandez-Cornejo J, Jans S. Pest management in US agriculture. In: Agricultural Handbook, vol. 717. Washington DC: Economic Research Service. US Department of Agriculture; 1999.

[33] Canadian Fertilizer Institute (CFI). Nutrient uptake and removal by field crops: Western Canada 2001. See also, http://www.cfi.ca/elibrary/; 2001.

[34] Mckenzie R. Wheat nutrition and fertilizer requirements: nitrogen. Edmonton, Alberta: Alberta Agriculture and Rural Development; 2001.

[35] Bryan R. Beneficial management practices: environmental manual for crop producers in Alberta – Tillage and seeding practice. Edmonton, Alberta: Alberta Agriculture and Rural Development; 2004.

[36] Lal R. Carbon emission from farm operations. Environment International 2004;30:981–90.

[37] Lal R, Follett RF. Soil carbon sequestration and the greenhouse effect. Madison, WI: SSSA Spec. Publ.; 2008.

[38] Sauve JL. A preliminary assessment of carbon dioxide and nitrous oxide emissions from agricultural soils in Alberta. Alberta: AESA Soil Quality Committee; 2000.

[39] Stumborg MM, Townley S, Coxworth E. Sustainability and economics issues for cereal crop residue export. Canadian Journal of Plant Science 1996;76:669–73.

[40] Saskatchewan Agriculture. Best management practices when harvesting surplus cereal straw. See also, http://www.agriculture.gov.sk.ca/Default.aspx?DN=9d0653b7-9839-42e5-9a72-c5f678834165; 2008.

[41] Hartman M. Estimating the value of crop residues. Direct seeding. Agdex 519–25. Edmonton, AB, Canada: Alberta Agriculture and Rural Development; 2008.

[42] Levelton Engineering Ltd. Assessment of net emissions of greenhouse gases from ethanol-blended gasolines in Canada lignocellulosic feedstock. Report R-2000-2. Agriculture and Agri-Food Canada, http://www.oregon.gov/ENERGY/RENEW/Biomass/docs/FORUM/GHG_Lig.PDF; 2000.

[43] IPCC. Agriculture, Forestry and other land use. Geneva, Switzerland. In: Guidelines for national greenhouse gas inventories, vol. 4; 2006.

[44] Gasol CM, Gabarrell X, Anton A, Rigoli M, Carrasco J, Ciria P, et al. Life cycle assessment of a *Brassica carinata* bioenergy cropping system in Southern Europe. Biomass and Bioenergy 2007;31:543–55.

[45] Zenter RP, Stumborg MA, Campbell CA. Effect of crop rotations and fertilization on energy balance in typical production systems on the Canadian Prairies. Agriculture, Ecosystems and Environment 1989;25:217–32.

[46] Coxworth E, Entz MH, Henry S, Bamford KC, Schoofs A, Ominski PD, et al. Study of the effects of cropping and tillage systems on the carbon dioxide released by manufactured inputs to Western Canadian agriculture: Identification of methods to reduce carbon dioxide emissions. Final Report, Volume 1. Agriculture and Agri-Food Canada, http://www.usask.ca/agriculture/caedac/Document/coxworth.doc; 1995.

[47] Green MB. Energy in pesticide manufacture distribution and use. In: Helsel ZR, editor. Energy in plant nutrition and pest control. New York: Elsevier; 1987.

[48] Bhat MG, English BC, Turhollow AF, Nyangito HO. Energy in synthetic fertilizers and pesticides: Revisited. Oak Ridge National Laboratory (ORNL), ORNL/Sub/90–99732. Oak Ridge, TN, USA: Department of Energy; 1994.

[49] Audsley E, Stacey K, Parsons DJ, Williams AG. Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use. Hampton, Peterborough, UK: Crop Protection Association; 2009.

[50] Piringer G, Steinberg LJ. Reevaluation of energy use in wheat production in the United States. Journal of Industrial Ecology 2006;10(1–2):149–67.

[51] West TO, Marland G. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agriculture, Ecosystems and Environment 2002;91:217–32.

[52] Dunn R, Mckenzie R. Seeding practices for irrigated cereals and canola. Edmonton, AB, Canada: Alberta Agriculture Food and Rural Development; 2006.

[53] GHG Registries. Inventories of greenhouse gas emission methodologies. See also, www.registries.ca/registries/out/CO159-COE-ATT1.pdf; 2010.

[54] Alberta Electric System Operator (AESO). Alberta a unique player in the electricity world. Powering Albertans 2010;4(1):9–11.

[55] Ali MB. Characteristics and production costs of U.S. wheat farms. Statistical bulletin 974–5. Washington, DC: USDA (U.S. Department of Agriculture) Economic Research Service; 2002.

[56] Tompkins DK, Fowler DB, Wright AT. Water use by no-till winter wheat influence of seed rate and row spacing. Agronomica Journal 1991;83:766–9.

[57] Alberta Agriculture and Rural Development (AARD). Agricultural statistical yearbook. See also, http://www/agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd12401#tables; 2006.

[58] Dalgaard T, Halberg N, Porter JR. A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. Agriculture, Ecosystems and Environment 2001;87:51–65.

[59] Boerma H, Gimby M, Coxworth E. A study of energy consumption of different practices in Saskatchewan. Year III. Tech. Report No. 103, Publ. No. C-185-1-b-80. Saskatoon, Sask: Saskatchewan Research Council, http://www.src.sk.ca/html/publications/annual_reports/index.cfm; 1980.

[60] Graboski MS. Fossil energy use in the manufacture of corn ethanol. Report to the National Corn Growers Association. Golden, CO: Colorado School of Mines, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.170.7995&rep=rep1&type=pdf; 2002.

[61] U.SDepartment of Energy (DOE). Energy and environmental profile of the U.S. chemical industry Washington. USA: DOE, Office of Industrial Technologies D.C; 2000.

[62] Gianessi LP, Marcelli MR. Pesticide use in U.S. crop production 1997. National summary report. Washington, DC: National Center for Food and Agricultural Policy, http://cipm.ncsu.edu/croplife/nationalsummary1997.pdf; 2000.

[63] Meisterling K, Samaras C, Schweizer V. Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. Journal of Cleaner Production 2009;17:222–30.

[64] Sheehan J, Carnobreco V, Duffield J, Graboski M, Shapouri H. Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. Report No. NREL/SR-580–24089. Golden, CO. USA: National Renewable Energy Laboratory.U.S. Department of Agriculture and the U.S. Department of Energy, http://www.nrel.gov/docs/legosti/fy98/24089.pdf; 1998.

[65] Statistics Canada. Non-metal mines. SIC 062. Report No. 26-224-XIB. Ottawa, Canada: Manufacturing, Construction and Energy Division, Statistics Canada, http://dsp-psd.pwgsc.gc.ca/Collection/Statcan/26-224-XIB/0009726-224-XIB.pdf; 1997.

[66] Sokhansanj S, Mani S, Tagore S, Turhollow AF. Techno-economic analysis of using corn stover to supply heat and power to a corn ethanol plant – part 1: cost of feed stock supply logistics. Biomass and Bioenergy 2010;34:75–81.

[67] Mahmudi H, Flynn PC, Chackel MD. Life cycle analysis of biomass transportation: train vs. trucks. SAE International; 2005 ISSN: 0148-7191.

[68] Volvo Truck Corporation. Emissions from volvo trucks. See also, www.volvotrucks.com; 2006.

[69] Gaines L, Stodolsky F, Cuenca R, Eberhardt J. Life-cycle analysis for heavy vehicles. Annual Meeting. San Diego, California: Air and Waste management Association; June 1998.

[70] Markas Engineering Service. Cradle-to-gate life cycle inventory: Canadian and US steel production by mill type. Ottawa, Canada: Athena Sustainable Materials Institute; 2002.

[71] Furuholt E. Life cycle assessment of gasoline and diesel. Resources, Conservation and Recycling 1995;14:251–63.

[72] Pastre O.EUBIA –; Pellets for Europe. Analysis of the technical obstacles related to the production and utilisation of fuel pellets made from agricultural residues. ALTENER 2002;2002-012-137-160. See also, www.pelletcentre.info.

[73] Campbell KA. A feasibility study guide for an agricultural biomass pellet company. USA: Agricultural Utilization Research Institute; 2007.

[74] Karwandy J. Pellet production from sawmill residue: a Saskatchewan perspective. Forintek Canada Corp. Report No. 2006-29, http://www.saskforestcentre.ca/index.php?f=content&c=177; 2007.

[75] Environment Canada. National inventory Report. Greenhouse gas sources and Sinks in Canada. 1990–2007. Bonn, Germany: United Nations Framework Convention on Climate Change, http://www.ec.gc.ca/Publications/default.asp?lang=En&xml=B77E6264-D0E3-45B5-BE56-5A395C0B7653; 2009.

[76] Thek G, Obernberger I. Wood pellet production costs under Austrian and in comparison to Swedish framework condition. Biomass and Bioenergy 2004;27:671–93.

[77] Dias J, Costa M, Azevecto JLT. Test of a small domestic boiler using different pellets. Biomass and Bioenergy 2004;27:531–9.

[78] Kristensen EF, Kristensen JK. Development and test of small-scale batch fired straw boiler in Denmark. Biomass and Bioenergy 2004;26:561–9.

[79] National Energy Technology Laboratory (NETL). Development of baseline data and analysis of life cycle greenhouse gas emissions of petroleum-based fuels. Report DOE/NETL-2009/1346. USA: U.S. Department of Energy, http://www.netl.doe.gov/energy-analyses/pubs/NETL%20LCA%20Petroleum-based%20Fuels%20Nov%202008.pdf; 2008.

[80] Ipcc Nggip. Good practice Guidance and Uncertainity management in National greenhouse Inventories. Kangawa, Japan: National Greenhouse Gas Inventories Programme; 2003.

[81] Environmental Protection Agency (EPA). Average annual emissions and fuel consumption for passenger cars and Light truck. EPA420-F-00–013 and EPA420-F-97-037; 2000.

[82] Senechal S, Grassi G. Logistic management of wood pellets: data collection on transportation, storage and delivery management. Belgium: EUBIA – European Biomass Industry Association; 2009.

[83] US. Department of Energy. Wood and pellet heating. Energy efficiency and renewable energy; 2010.

[84] Johansson LS, Tullin C, Leckner B, Sjovall P. Particle emissions from biomass combustion in small combustors. Biomass and Bioenergy 2003; 25:435–46.

[85] ERS. Recent growth patterns in the US. Organic foods market. Econ Research Service. US Department of Agriculture; 2002.

[86] Madler P, Fliessbach A, Dubois D, Gunst L, Fried P, Niggli U. Soil fertility and biodiversity in organic farming. Science 2002;296(3573):1694–7.

[87] Hoeppner JW, Entz MH, McConkey BG, Zentner RP, Nagy CN. Energy use and efficiency in two Canadian organic and conventional crop production systems. Renewable Agriculture and Food Systems 2005;21(1):60–7.

[88] Navartnasamy M, Koberstein B, Jones J. Biogas energy potential in Alberta. Agri-facts. Agdex 2008;768-3:1–5.

[89] Mani S, Sokhansanj S, Bi X, Turhollow A. Economics of producing fuel pellets from biomass. Applied Engineering in Agriculture 2006;22(3): 421–6.

[90] Jungmeier G. Personal Communication. Austria: Joanneum Research, Institute of Energy Research; 2010.

[91] Kjallstrand J, Olsson M. Chimney emissions from small-scale burning of pellets and fuelwood – examples referring to different combustion appliances. Biomass and Bioenergy 2004;27:557–61.

[92] Caserini S, Livio S, Giugliano M, Grosso M, Rigamonti L. LCA of domestic and centralized biomass combustion: the case of Lombardy. Biomass and Bioenergy 2010;34:474–82.

[93] Lafond GF, Loeppky H, Derksen DA. The effect of tillage systems and crop rotations on soil water conservation, seeding establishment and crop yield. Canadian Journal of Plant Science 1992;72:103–15.

[94] Brandt SA. Zero till vs. conventional tillage with two rotation: crop production over the last two years. In: Proc. of soil and crop workshop. Saskatoon: University of Saskatchewan; 1989.

[95] Wright T. General overview of conservation tillage. In: Lafond GP, Fowler DR, editors. Crop management for conservation. Saskatoon, SK: Division of Extension, University of Saskatchewan; 1990.

[96] Stobbe EH, Donaghy D, McMillan A, Townsend J. Comparison of conventional and zero tllage on wheat, barley, flax and rape production. Weed Control Conference Proceedings 1970;25.

[97] Gamache P. Direct seeding statistics in Alberta. Reduced tillage Linkage. See also, http://www.reducedtillage.ca/print_friendly.aspx?a=359; 2007.

[98] Samson R, Lem CH, Stamler SB, Dooper J. Developing energy crops for thermal applications: optimizing fuel quality, energy security and GHG mitigation. In: Pimentel D, editor. Biofuels, solar and wind as renewable energy systems. Springer Science-Business Media; 2008.

[99] Edwards NM, Hatcher DW, Marchylo BA. Quality of Western Canadian wheat. Canadian Grain Commission. 1498–9654, http://dsp-psd.pwgsc.gc.ca/collection_2009/agr/A92-23-2007E.pdf; 2007.

[100] University of Saskatchewan. Harvesting, grain drying and storage. Winter wheat production manual [Chapter 23]. D. B. Fowler Publications, http://www.usask.ca/agriculture/plantsci/winter_cereals/Winter_wheat/CHAPT23/cvchpt23.php; 2002.