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Development of agri-pellet production cost and optimum size

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ABSTRACT

Minimum production cost and optimum plant size were determined for pellet plants using agricultural biomass residue from wheat, barley and oats. Three scenarios involving minimum, average and maximum yields of straw were considered for developing a techno-economic model. The life cycle cost of producing pellets in Western Canada was estimated. The economically optimum size of production plant for the three yield scenarios in tonne year^{-1} were 70,000, 150,000 and 150,000, respectively. The corresponding costs of production per tonne are $170.89, $129.42 and $122.17, respectively. However, the cost of pellets does not change much for capacities over 70,000 tonne year^{-1} for both the average and maximum yields. The optimum size is same for both average and maximum yield cases. Sensitivity analyses have showed that the total cost of pellet production is most sensitive to field cost followed by transportation cost. Currently, the cost of energy from agri-pellets is higher than that of energy from natural gas.

1. Introduction

Energy security, global warming and utilization of local resources are the driving factors for using biomass as an alternative energy source. Biomass is nearly carbon neutral, hence its utilization for fuel helps mitigate greenhouse gas emissions. Studies have estimated the amount of agricultural residue (e.g. wheat and barley straw) available in Western Canada (Sokhansanj et al., 2006). Currently large amounts of these agricultural residues are left in the field to rot, ultimately releasing carbon dioxide to the atmosphere. This biomass could be used to produce pellets which is a form of fuel. Biomass, including agricultural residue, is not competitive with fossil fuel (e.g. coal) for large scale power production in Western Canada (Kumar et al., 2003). It can compete only if supported by carbon credits (Kumar et al., 2003). The value of carbon credits required to make biomass competitive as fuel production depends on the type of biomass and the technology for its conversion to fuel (Kumar et al., 2003).

Biomass has low energy density (MJ m^{-3}) and low yield per unit area (dry tonnes ha^{-1}) (Kumar et al., 2003). These two key factors result in a high cost of biomass delivery, which increases the total biomass-processing cost. Densified biomass, especially pellets has drawn attention due to its superiority over raw biomass in terms of its physical and combustion characteristics (Obernberger and Thek, 2004). Like other biomass feedstocks, pellets are carbon neutral, i.e., the carbon emitted during their combustion is taken up in the re-growth of the biomass used to produce them. Moreover, pellets have other value-added advantages over raw biomass. Pelletization reduces moisture content, increases energy content (MJ kg^{-1}), enhances combustion efficiency, and produces greater homogeneity of composition as compared to raw biomass (Obernberger and Thek, 2004). The bulk density of biomass pellet is 4–10 times that of 'as received biomass' (Karwandy, 2007). This makes for easier handling and transport. All these factors make pellets one of the more attractive forms of biomass-based energy.

Wood-based pellets are produced commercially around the world (e.g. USDA, 2009) but there is limited production of agricultural biomass-based pellets. Few studies have reported results on the economics of pellet production. Mani et al. (2006a) estimated the cost of producing pellets from sawdust, reporting that these pellets could be economically produced at a cost of $51 tonne^{-1} for a plant with a capacity of 45,000 tonne year^{-1}. The production cost could be further reduced by using larger plants to gain benefits of economy of scale. Thek and Obernberger (2004) did a detailed study of sawdust pellet production in a European setting. Urbonowski (2005) derived the capital cost estimate from this study and used in designing a Canadian pellet plant. Hoque et al. (2006) estimated the economics of wood pellet production for export market. Other studies such as NEOS (1995) and Williams and Lynch (1995) have worked on the cost of wood pellet production. Samson and Duxbury (2000) estimated the cost of switchgrass pellets for commercial purposes. Pastre (2002) analyzed the economics of straw and wood pellets from a European perspective and overviewed some technical problems related to the production and utilization of pellets made from agricultural residue. Campbell (2007) estimated the cost of straw pellets at different capacities.

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Fasina et al. (2006) estimated the cost of pelleting switchgrass, peanut hull and poultry litter for heating greenhouses. There is little data, however, on the details of producing agricultural biomass-based pellets and how the cost of these varies according to the scale of the production plants.

The economics of biomass-processing facilities is different from that of fossil-fuel-based energy facilities. For the latter, larger plants are more cost effective, whereas, in the case of biomass-processing facilities, there is a trade-off between the cost of transporting biomass to the facility and the capital cost of the facility. The cost of transportation of biomass increases as the size of the processing facility increases, because the area for collecting field-sourced biomass increases. The capital cost per unit of output decreases as the size of the facility increases, because there economies of scale benefits. As a result of the trade-off between the two costs, there is a size of facility at which the cost of processing biomass is minimal. This is the economically optimum size of the biomass utilization facility. The development of pellet production plants of this size reduces the total cost of producing of pellets. This concept has been applied to the production of fuels and electricity from biomass (Larson and Marrison, 1997; Dornburg and Faaij, 2001; McIlveen-Wright et al., 2001). Kumar et al. (2003) estimated the optimal size for power plants using three biomass sources: straw, whole forest and forest residue. Jenkin (1997) estimated the optimal size for biomass utilization facilities under constant and variable costs. Nguyen and Prince (1996) determined the optimal size for bio-ethanol plants processing sugarcane and sweet sorghum. Walla and Schneeberger (2008) estimated the optimal size of a biogas plant. Other studies have assessed biomass economics from a general perspective (Overend, 1982; Larson and Marrison, 1997; Dornburg and Faaij, 2001; McIlveen-Wright et al., 2001). However, none of these studies estimated the optimal size for an agricultural biomass-based pellet production plant. There is very little information available on the economically optimum size for facilities producing agricultural biomass-based pellets.

The key objective of this research is to develop a data intensive techno-economic model for assessing the economic viability of using agricultural residue for pellet production. Specific objectives include:

- Estimation of pellet production cost ($ per tonne of pellets) from agricultural biomass (e.g. wheat, barley and oat straw) in Western Canada.
- Determination of the optimum size of the pellet production plant based on agricultural biomass.
- Development of cost curves to study the variation in pellet production cost as the size of the pellet production plant varies.

The scope of this research is to conduct a techno-economic assessment for developing a straw pellet plant operating for 30 years using wheat, barley and oat straw. This includes estimating the cost of all operations including harvesting and collection, handling, storage, transportation, and pellet production.

2. Current technology for pellet production

Pellet production is a combination of sequential steps including preprocessing, drying, grinding, pelleting, cooling, screening, and bagging. These processes play an important role in the techno-economic analysis. A detailed review is provided elsewhere in the literature (e.g. NEOS, 1995; Williams and Lynch, 1995; Samson and Duxbury, 2000; Pastre, 2002; Thek and Obernberger, 2004; Hoque et al., 2006; Mani et al., 2006a; Wolf et al., 2006; Campbell, 2007; Karwandy, 2007).

Usually straw for processing into pellets comes in the form of round or rectangular bales. Chopping of straw to reduce its length is the first step. The length of the straw is reduced to 2.5–10 cm (Jannasch et al., 2001) using a tub grinder or shredder. If straw has a high moisture content, drying is used to reduce the feedstock moisture to a level suitable for pelleting. The average received moisture content of straw before the drying process is 15%; after drying it is 8–10% (Campbell, 2007). Dryer size should be appropriate; over-sizing can increase capital and operating costs significantly. If straw is delivered to the pellet plant with moisture content lower than 12% drying may be bypassed (Campbell, 2007). The rotary drum dryer is the one most commonly used in pellet production plants (Campbell, 2007; Karwandy, 2007). There is an additional cost for the associated hopper, bin, and handling system if the biomass fuel requires drying.

The output of the dryer and tub grinder or shredder is then ground in a hammer mill to a small uniform size of 3.2 mm or less (Mani et al., 2006b). In other words, particle size reduction for pelletization is a two-step process: chopping by tub grinder or shredder and then grinding by a hammer mill. The particle size is controlled through the hammer mill's changeable screen. Small particles increase the density and hardness of the pellets but very finely ground feedstock loses its fibrous characteristic (NEOS, 1995). Grinding straw requires more energy than grinding woody biomass, and therefore costs more.

The lignin content of wood is high and generally sufficient to bind wood pellets properly, but straw requires conditioning to achieve enough strength to provide durable pellets and minimize fines (Karwandy, 2007). Conditioning, which can be done with steam or hot water to soften the fibrous material in straw, and may require the inclusion of binder material. Usually the conditioning system is an integral part of pellet mill. The requirement of steam for conditioning purpose is approximately 4% of total amount of biomass feedstock used (Thek and Obernberger, 2004). At times binders such as starch, molasses, paraffin, or lignin sulphate are added to increase the pellet durability. Conditioned feedstock is fed into a pellet mill where rollers extrude it, forcing it to pass through die holes which effectively compress it into pellets. Adjustable knives attached to the pellet mill cut the pellets into desired length. A pellet mill has different feed rates over its die life. For example, a new pellet mill may run at a rate of 4.5 tonnes h^{-1}, but, when half worn, it may need to run at 3.5 tonnes h^{-1}, to maintain the required pellet quality (Wright, 2008). Straw has a higher mineral content and is therefore more abrasive than wood. The pellet mill configuration including the effective die length, feed rate and rotating speed is set up differently for straw than for wood pellets. Operating parameter including die temperature, pressure, and die/roller configuration determine pelleting efficiency (Campbell, 2007). Pellets leaving the pellet mill at a high temperature and with excess moisture are then cooled and dried using forced air over a screen to gently cool the hot fragile pellets from 95–100 to 25 °C. This results in increased hardness and durability of the pellets, and removes fines. The final moisture content is typically in the range of 5–8%.

Screening is required to separate residual fines from the finished pellets before bagging. Fines and fragments collected from screening are returned to the dryer or pelletizer. If fines exceed 3% of the product issuing from the screening process there is a problem with feedstock or the pelleting process which needs to be corrected (Campbell, 2007). The last step of the pelleting process is to fill the appropriate (typically 18 kg) amount of pellets into bags and seal them. The bagging system may be manual, semi-automatic or fully automatic depending on the size of the plant.

3. Methodology of techno-economic analysis and optimization

Detailed data collection was carried out for the development of a data intensive techno-economic model of agricultural biomass pellet production. Various parameters were developed for the pellet production plants and also taken from the existing literature. The determination of cost was based on data taken from the literature, on personal communication with pellet plant manufacturers, equipment suppliers, and experts, and author developed data.

The techno-economic model was developed for a straw pellet plant operating for 30 years. All life cycle costs of the pellets were considered, including the cost of obtaining the straw, transporting to pellet plant, and producing pellets. Costs incurred by the plant for the production of pellets include capital cost, energy cost, employee cost, and consumable cost. To develop the model, yields of wheat, barley and oats were considered. The biomass procurement area was determined to estimate the transportation cost. The scale factors for all the equipment related to pellet production were determined based on the data of previous studies. All costs associated with pellet production were added to the field and transportation costs to obtain the total cost of pellet production. Iterations were carried out to obtain the minimum cost of producing pellets. The capacity corresponding to the minimum cost of pellet production is the optimal size of the processing plant. The optimum size of the plant was determined for average, maximum and minimum biomass yields. The following sections demonstrate the application of this methodology of techno-economic assessment and optimization to agricultural pellet production in Western Canada.

4. Assessment of availability of straw

Considering the variability of production and crop supply, the annual volume of straw that potentially could be procured in a particular region can be assessed. The actual amount depends on many factors which include biomass species, biomass yield, location, climate, time of harvest, and the technology used for the harvesting and collection of the biomass. The yield of residue is an important parameter for determining the capacity and location of a bioenergy facility. It eventually affects the production cost.

The year-to-year supply availability of net crop residue (straw) is an important consideration for the development and operation of any bioenergy facility. The lifespan of a typical bioenergy facility is 25–30 years which requires continuous and constant supply of feedstock. This is particularly true for facilities which depend on annual crop production.

In Western Canada (Alberta), the total average production of wheat, barley and oats over the last 12 years (1997–2008) has been 6.8, 6.3 and 0.72 million tonnes year^{-1}, respectively. Since straw yield is not measured by farmers, the available straw production volumes are typically determined by measuring and applying straw to grain mass ratios. The average yields of wheat, barley and oats are 2.66, 3.03 and 2.49 green tonnes ha^{-1}, respectively. Different levels of straw to grain mass ratios were recommended in different studies (Stumborg et al., 1996; Klass, 1998; Levelton et al., 2000; PAMI, 2001; PFRA, 2003; Sokhansanj et al., 2006; Sokhansanj and Fenton, 2006; Liu, 2008). After an extensive analysis of all the values, the ratios adopted in this study for estimating crop residue for wheat, barley and oats are 1.1, 0.8 and 1.1, respectively. To determine the net yield of straw, additional factors have been taken into consideration. Some residue is retained for soil conservations, some is left on the field in accordance with the removal efficiency of the harvesting machine, and some is needed for livestock feeding, bedding and mulching. There is a small amount of straw lost through handling, transport and storage. The quantity of straw is further reduced in accordance with its moisture content. A portion of available straw must remain on the field to prevent soil erosion and maintain soil health and fertility. Previous studies estimated different amounts of straw for soil conservation (Lindstorm et al., 1979; Stumborg et al., 1996; Campbell and Coxworth, 1999; Kline, 2000; Sokhansanj et al., 2006; Liu, 2008). Considering all the estimated values from the literature, an amount of 0.75 tonne ha^{-1} was allocated to soil conservation in this study. Some of the residues are used for livestock feeding, bedding and mulching. Based on Sokhansanj et al. (2006), Alberta's annual straw requirement for livestock is considered to be 3.2 Mt for 4.85 ha of land. In this study, the amount for livestock feeding and bedding was 0.66 tonne ha^{-1}. The total yield was further reduced by a number of factors, such as the portion of straw that a harvesting machine is capable of removing. Several earlier studies have reported the harvest losses (e.g. Sheehan et al., 2003; Perlack et al., 2005; Sokhansanj and Fenton, 2006; Liu, 2008). Based on all the available data a conservative estimate of 30% was used for harvest loss in this study. Based on previous studies (Perlack and Turhollow, 2002; Hamelinck et al., 2005; Liu, 2008), the storage and transportation loss was assumed to be 15%. Of this, field loss was 3%, handling loss was 5% (Liu, 2008) and storage loss was 7% (3.5% for each storage) (Hamelinck et al., 2005). All these losses are shown in Table 1.

In this study, the assumed moisture content of the straw was 14%, wet basis. After considering all the factors mentioned above, the average net yields of wheat, barley and oat straw over twelve years (1997–2008), are shown in Fig. 1. Gross yields refer to the total yield of residue without any reduction in yield due to the various factors mentioned. The net yields take into account all the factors which affects the yields. A wide variability was observed in the net yields of straw over the years. To develop our techno-economic model, we have considered three cases: the average yield, the maximum yield, and minimum yield. Fuel and residue properties of the three kinds of straws are shown in Table 2.

5. Input data and assumptions for development of cost estimates

The production of pellets from agricultural residue involves harvesting and collection, handling, storage, transportation and pellet production. Cost factors are developed for each element and are discussed in detail in subsequent sections. Total cost incurred from straw harvesting to pellet production can be divided into three main components:

(1) Field cost, all costs incurred in the field.
(2) Cost of transportation from field to pellet plant.
(3) Pellet production cost.

All cost figures are given in $US, base year 2008. The inflation rate is assumed to be 2.0%.

5.1. Field cost

The estimated price of biomass can vary from producer to producer and from plant to plant (Brechbill and Tyner, 2008). The field cost of agricultural residue consists of the cost of: harvesting and collection, on-farm storage, nutrient replacement, and farmer's premium. It is assumed that fuel consumption in collecting straw involves single pass, i.e. grain harvesting and stalk collection are done at the same time. All costs were estimated based on the application of existing technologies and practice, therefore the cost of harvesting biomass was based on current farming practice. As a result, no tillage management practice was considered for estimating the straw recovery, and round bales were considered because they

Table 1
Calculation of net yield for wheat, barley and oat straw.

Crop	Average yield grain (green tonne ha^{-1})	Straw to grain ratio	Gross yield (green tonne ha^{-1})	Level of straw retained for soil conservation (green tonne ha^{-1})	Fraction of straw harvest machine can remove (%)	Fraction removed for animal feeding and bedding (green tonne ha^{-1})	Fraction of straw loss from harvest area to pellet plant (%)	Net yield (green tonne ha^{-1})	Moisture in straw (%)	Net yield (dry tonne ha^{-1})
Wheat straw	2.66	1.1	2.93	0.75	70	0.66	15	0.73	14	0.63
Barley straw	3.03	0.8	2.42	0.75	70	0.66	15	0.48	14	0.38
Oat straw	2.49	1.1	2.74	0.75	70	0.66	15	0.78	14	0.54

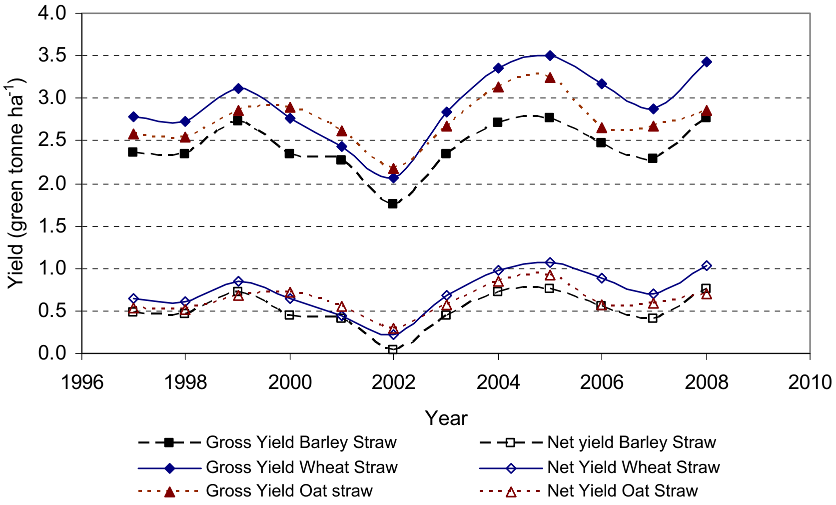

Fig. 1. Gross and net yield of wheat, barley and oat straw.

Table 2
Residue properties.

Characteristic	Wheat straw	Barley straw	Oat straw	Source
Moisture content (%)	15.9	13.6	17.2	Verhegyi et al. (2009)
Heating value (GJ/odt)	17.8	19.20	18.10	Bailey-Stamler et al. (2007) and Chico_Santamarta et al. (2009)
Bulk density (kg/m^3)	79.0	82.0	85.0	Bailey-Stamler et al. (2007)
Nutrient content (%)				
Nitrogen	0.66	0.64	0.64	Kumar et al. (2003) and Bailey-Stamler et al. (2007)
Phosphorus	0.09	0.05	0.10	
Potassium	1.60	2.5	2.4	
Sulfur	0.17	0.19	0.16	
Ash	8	8	7	Bailey-Stamler et al. (2007)

are more prevalent. Bale weights vary in the range of 360–500 kg (Liu, 2008). It was assumed that all farmers are willing to sell their straw to a bioenergy facility.

5.1.1. Harvesting and collection cost of straw

The capital costs for harvesting equipment are not estimated in this paper. It was determined that the pellet plant operators contract out the straw harvesting. It was therefore assumed that farmers harvest the straw and deliver it to the roadside in the form of large bales which they cover with tarp to limit the ingress of moisture. The pellet plant operator is responsible for arrangement of bales pick-up. Another option could be assigning all activity to an intermediary party (a custom harvester) who harvests, collects and delivers the straw to the biofacility as needed. This type of intermediary party is called a third party logistic (3PL) provider. This type of concept is now becoming popular. After farmers finish their harvest, custom harvesters harvest and bale the straw, putting the bales near the edge of the field for collection and delivery to the pellet plant. The hauling of the bales from the farmer's field to the pellet plant can be done by the custom harvester or a commercial trucking company. Custom harvesters' rates are based on the equipment they use in harvesting but a typical rate is about \$10.50 bale^{-1} (\$21.00 tonne^{-1} for 500 kg bales) and \$3.25 bale^{-1} (\$6.5 tonne^{-1} for road siding) (Campbell, 2007).

Where straw is stored depends on the type of procurement system used to collect it. There are three storage options available, including at the end-of-field, intermediate (central depot), and plant storage. In winter if the roads are impassible, end-of-field storage might not be useful. However, from an economic perspective end-of-field storage is a good option because it provides accessibility to both the farmer and the transporter. Intermediate (central depot) storage is feasible if the market matures for agricultural pellets and other biomass products, creating many buyer and suppliers (Campbell, 2007). In most situations, storage at the plant will be the most expensive option. Some companies needing high quality feedstock, may choose plant storage in order to have better control over the quality of their input feedstock and avoid spoilage and shrinkage (Liu, 2008).

5.1.2. Bale wrapping cost

The type of wrap for the bales depends on the length of time of its storage. The loss of dry matter during storage depends on how long bale are stored and what type of wrapping is used. Sometimes it also depends on the type of the baler. Three types of bale wrapping are available – twine, net wrap, and plastic wrap. If the bales are stored for a short time, twine is useful, though losses will be high. If bales have to be stored for a long time, extra protection is required in order to reduce dry matter loss. In this situation, plastic wrapping is useful because it is the most protective of the three options. Over 6 months storage time the dry matter loss for twine is 18.8%, for net wrap it is 8.4% and for plastic wrap it is 6.15% (Brechbill and Tyner, 2008). In this study, it is assumed that bales are wrapped with twine.

5.1.3. Storage cost

The quality of biomass and its cost depend on the type of storage. In an enclosed storage structure, quality remains good due to less dry matter loss, but this is the most expensive option. The costs for various storage facilities include: on-field storage at \$0.9–\$1.8 tonnes^{-1}, outside on a crushed rock base at \$2.0–\$2.7 tonne^{-1}, open structure (under a roof) on a crushed rock base at \$5.4–\$7.2 tonne^{-1}, and enclosed structure with a crushed rock base at \$9–\$13.5 tonne^{-1}. The associated losses are 10–20%, 5% and 2%, respectively (Liu, 2008; Craig, 2008). In this study, bales are stored in the field in open condition.

5.1.4. Nutrient replacement cost

In Western Canada the soil's carbon level remains high in spite of repetitive straw recovery because plant roots and the residue retained in the field, decompose in the soil (Kumar et al., 2003). Alberta soil has an abundance of calcium and some minerals (Kumar et al., 2003; AARD; 2009). Nitrogen, phosphorous, potassium and sulfur are the only fertilizers that need to be applied to the soil (Kumar et al., 2003). Fertilizers containing these nutrients are spread over the crop for replacement of the nutrients removed when straw is removed. The cost associated with these fertilizers is considered a nutrient replacement cost. Farmers usually apply fertilizer to their crops, so the nutrient payment is for incremental fertilizer only and does not include the cost of application. The cost of nutrient replacement is shown in Table 3.

5.1.5. Premium to the farmer

To ensure a constant supply of biomass throughout the year, a premium should be paid to the farmer to encourage participation in biomass collection and selling. This cost is also shown in Table 3.

5.1.6. Storage premium cost

This is the payment for the opportunity cost for the land on which the bales are stored. If the bales are kept on the edge of the field for a long time, the land is not available for planting a crop. Table 3 shows the storage premium cost.

5.2. Transportation cost

It is assumed in this analysis that the area from which feedstock is drawn is circular. The center of the circular area can be a pellet plant or an intermediate storage area from which biomass is transported to a pellet plant. It is assumed that biomass distribution is uniform within the circular area. Straw transport is done over existing publicly maintained roads. Pellet plants are located near existing consumers adjacent to the transmission lines and biomass is transported from field to pellet plant by trucks.

The average radius of a circular area is $r_{av} = \frac{2}{3}r$, where r is the length of the radius of the circular area. As all the transportation is not necessarily in straight line, a tortuosity factor of 1.27 is considered in this study (Overend, 1982; Sarkar and Kumar, 2009). Perlack and Turhollow (2002) considered a tortuosity factor of 1.3.

For the Province of Alberta, the fraction of the total harvest area used to grow wheat, barley and oats to total harvest area is 30% (Statistics Canada, 2008). This land is located mainly in southern Alberta which is a highly agriculturally intensive area. This study assumes that the storage of big round bales is at the roadside

Table 3
Production and delivery cost of biomass.

Factor	Value (\$ tonne^{-1})	Source/comments
Harvesting cost		
– Shredding	3.67	Brechbill and Tyner (2008)
– Raking	2.31	Brechbill and Tyner (2008)
– Baling	3.65	Brechbill and Tyner (2008)
Bale wrap		
– Twine	0.49	Brechbill and Tyner (2008)
– Net wrap	1.77	Brechbill and Tyner (2008)
– Plastic wrap	2.48	Brechbill and Tyner (2008)
Bale collection		
– Bale picker	0.67	Liu (2008)
– Tractor	3.58	Liu (2008)
Bale on-field storage cost		
– On-field storage	1.80	Campbell (2007)
– Storage premium	0.10	Brechbill and Tyner (2008)
Farmer premium cost	5.50	Kumar et al. (2003)
Nutrient replacement cost	22.62	Kumar et al. (2003)
– Nitrogen cost	1260	Four years (2005–2008) average data has been taken. The nutrient replacement is determined by multiplying by the amount of nutrient per unit of fertilizer. K_2O is 83% potassium. P_2O_2 is 44% phosphorous Pauly (2008) and Jensen (2008)
– P_2O_5 cost	1240	
– K_2O cost	440	
– Sulfur cost	520	

and the bales are covered with tarp, and also the pellet plant contracts the straw transportation to trucking firms. Trucks are contracted year round and have self-loading equipment. The straw bales are stored at field's edge and transported on public roads. The road allowances are large in North America (Mahmudi and Flynn, 2006). If roads are impassible due to weather conditions then storing is done in the plant. We assume at least 3 months storage at the plant for the season when the roads are impassible. Although, 'just in time' delivery reduces feedstock storage requirements, operational disruptions resulting from unreliable delivery may cost the pellet company more than was saved in the capital budget (Campbell, 2007).

Transportation cost has two components irrespective of its mode, i.e. truck, rail or pipeline. The fixed component of the cost of truck transportation is the cost of loading and unloading cost ($ tonne^{-1}). The variable component of the cost of truck transportation includes cost of wages for the driver, fuel, and maintenance ($ $\text{tonne}^{-1}\ \text{km}^{-1}$). These variable costs are proportional to the distance travelled and changes with transportation distance. The typical loading and unloading cost for truck transportation in North America is $5.45 green tonne^{-1} (Kumar et al., 2003; Campbell, 2007; Searcy et al., 2007). The straw truck variable transportation cost is $0.22 green $\text{tonne}^{-1}\ \text{km}^{-1}$ (Campbell, 2007; Liu, 2008).

The size of the pellet plant determines the biomass draw area, thus the total cost of transportation increases as pellet plant capacity increases. Fig. 2 shows the correlation between transportation cost and capacity. The transportation distance is proportional to the square root of the capacity of the plant; and this is reflected by the curve in Fig. 2. Considering all the unit operation costs, straw delivery at the plant gate costs $95.33 tonne^{-1} for a plant having capacity of 150,000 dry tonnes year^{-1}.

5.3. Pellet production cost

A techno-economic assessment model was developed to assess the cost of production of pellets including various cost components. These cost components include:

- Capital cost.
- Employee cost.
- Energy cost.
- Consumable cost.

Employee, energy and consumable costs are considered as operating costs. The input data and assumptions for the techno-economic model are summarized in Table 4.

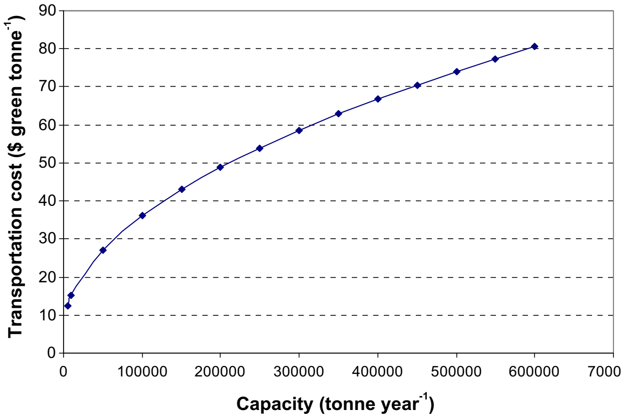

Fig. 2. Delivered cost of straw as a function of pellet plant size.

Table 4
Input data and assumptions for techno-economic model.

Factors	Value
Plant life (years)	30[a]
Inflation	2.0%[b]
Internal rate of return	10%[c]
Material loss during pelleting process	5%[d]
Plant operating factor[e]	
Year 1	0.70
Year 2	0.80
Year 3 and onward	0.85
Spread of capital cost during construction[f]	
Year 1	20%
Year 2	35%
Year 3	45%
Cost of additional equal sized pellet plant unit relative to the first	0.95[g]
Other costs such as tax, insurance etc. are assumed to be a percentage of capital cost	0.5%
Power requirement for different equipment for pellet production[h,i]	(KW)
Primary grinder	112
Dryer	120
Hammer mill	75
Boiler	75
Pellet mill	300
Cooling	5
Bagging	40
Other	40
Lighting and heating	112

[a] Plant life for the pellet plant is assumed based on the other biomass-processing facilities. There is large number of studies which assumes similar number Kumar et al. (2003) and Sarkar and Kumar (2009).

[b] This is the average inflation over 12 years Kumar et al. (2003) and Sarkar and Kumar (2009).

[c] Assumed.

[d] Derived from earlier studies on pellet production.

[e] Solid handling plants have a start-up profile. These values are assumed based on operating factors reported in earlier studies on biomass handling facilities. Kumar et al. (2003) and Sarkar and Kumar (2009).

[f] Taken from earlier studies and values reported on the investment profile. Kumar et al. (2003) and Sarkar and Kumar (2009).

[g] Kumar et al. (2003) and Sarkar and Kumar (2009).

[h] Campbell (2007).

[i] Pastre (2002).

5.3.1. Capital cost

Capital cost includes the cost of process equipment and utility and its installation. It also includes capital cost of land, storage, buildings, and other infrastructure. The capital cost of different equipment has been collected from equipment suppliers, pellet manufacturer and the literature. The maintenance cost of the equipment in this study is 2.5% of the equipment capital cost except for the hammer mill and pellet mill (Thek and Obernberger, 2004). These mills cost more to maintain than the other equipments. In this study, the annual maintenance cost of the hammer mill and pellet mill are assumed to be 18% and 10% of the installed equipment capital cost, respectively (Thek and Obernberger, 2004). The mechanical and electrical installation of the equipment cost 32% and 20% of the equipment's capital cost, respectively. Freight and sales tax is 4% of the equipment's capital cost (Campbell, 2007). All equipment prices are adjusted to 2008 US dollar value by using inflation factor.

5.3.2. Scale factor

The power function is an acceptable way of estimating capital cost at various capacities within a typical range of up to 10 times the calculated costs. It can increase more or less proportionately with plant capacity depending on the parameters (Gallagher et al., 2005). This exponent for adjusting the cost of equipment from one capacity to another is given in Eq. (1).

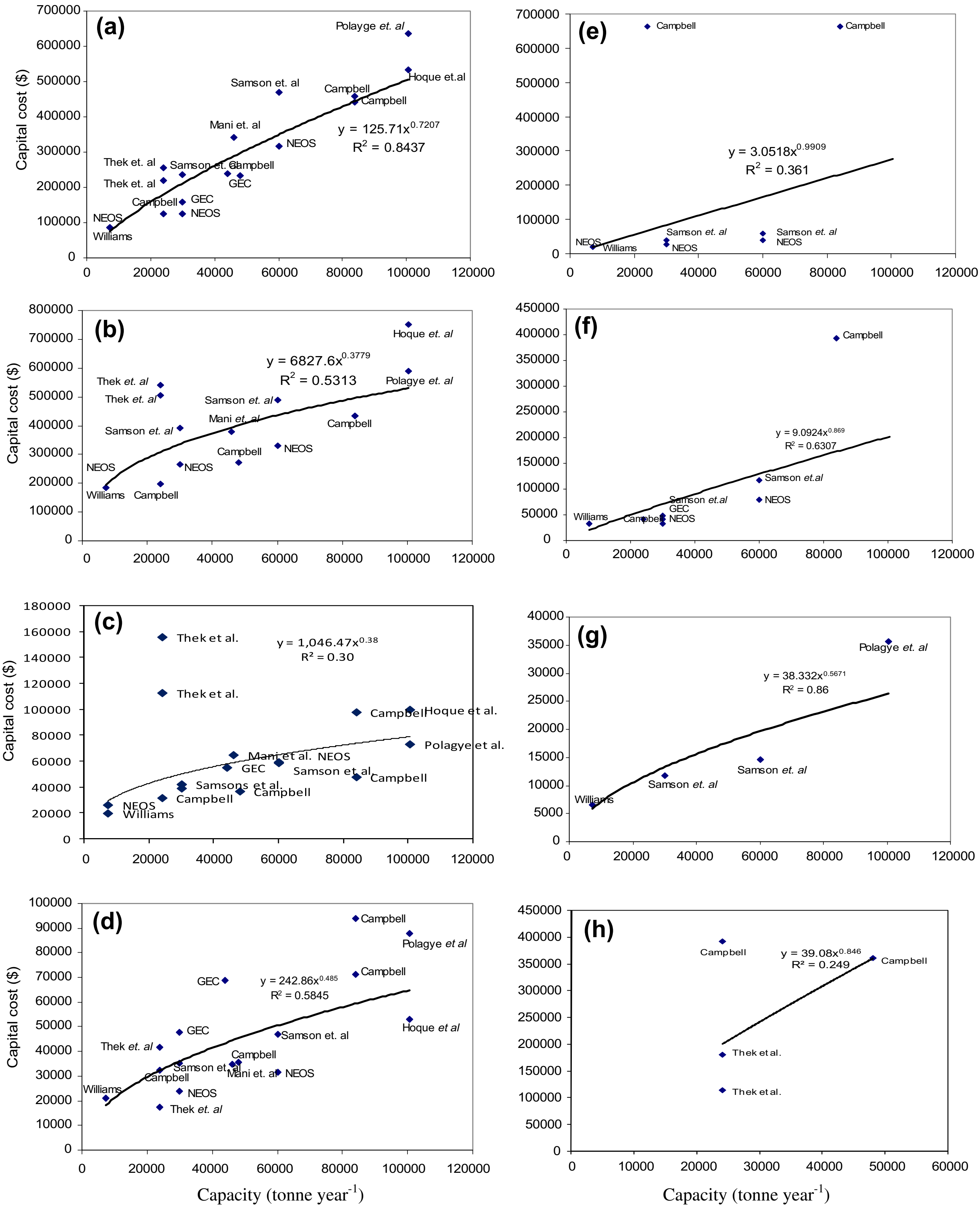

Fig. 3. Scale factors: (a) pellet mill; (b) dryer; (c) hammermill; (d) cooler; (e) primary grinder; (f) bagging system; (g) feeder; and (h) storage.

$$\mathrm{Cost}_2 = \mathrm{Cost}_1^* \left(\frac{\mathrm{Capacity}_2}{\mathrm{Capacity}_1}\right)^{\text{Scale factor}} \tag{1}$$

If the scale factor = 1, means capital cost increases proportionately with capacity. This indicates there is a constant rate to scale. A scale factor <1, means the capital cost increases at a rate less than the capacity, so, there is an increasing return to scale. For biomass-processing equipment, there is an economy of scale benefit as plant size increases. Capital cost per unit of output decreases as plant capacity increases. Mani et al. (2006) and Hoque et al. (2006) both considered a scale factor of 0.6 for estimating cost of wood pellet processing equipment. A scale factor of 0.6 means that one percent increase in the plant size, increases capital cost by 0.6%. There is a range of scale factor for biomass-processing facilities. For dry mill ethanol plants it was reported to be 0.836 (Larson and Marrison, 1997), which suggests that capital cost increases more rapidly with capacity for these plants than for processing plants having a scale factor of 0.6. Nguyen and Prince (1996) considered a scale factor of 0.7 for capital, administrative, and operating costs. Boerrigter (2006) reported different scale factors (0.5–0.7) for different scale plants. Lower scale factors for small scale plants and higher scale factors for larger plants. Other studies gave different scale factors for different biomass-processing equipment (Hamelinck and Faaij, 2002; Spath et al., 2005). Remar et al. (1998) used three types of indices (scale factor, location index and inflation index) in the same calculation to adjust for size, geography and time (Remar et al., 1998; Remar and Mattos, 2003).

In this study the scale factors for the main equipment in a pellet production plant were derived from the values of capital cost reported in the literature for different equipment, such as pellet mill, dryer, hammer mill, cooler, pellet shaker, boiler, grinder, bagging system, and feeder; as well as storage bins and the building. The scale factors for all these equipment and infrastructure were used to estimate the overall scale factor for an agricultural pellet production plant. The scale factors are discussed below. Fig. 3(a) shows the capital cost of pellet mills at various capacities, as reported in the literature (NEOS, 1995; Williams and Lynch, 1995; Thek and Obernberger, 2004; GEC, 2006; Hoque et al., 2006; Mani et al., 2006; Campbell 2007; Polagye et al., 2007). Based on these figures, the derived scale factor for pellet mills is 0.84.

Fig. 3(b) shows the capital cost of dryers at different capacities reported in the literature (NEOS, 1995; Williams and Lynch, 1995; Thek and Obernberger, 2004; GEC, 2006; Hoque et al., 2006; Mani et al., 2006; Campbell 2007; Polagye et al., 2007). The scale factor for dryer derived from Fig. 3(b) is 0.53. This estimate is lower than that found in different literature. Hamelinck and Faaij (2002) considered it to be 0.8 and Spath et al. (2005) gave it a value of 0.75.

Fig. 3(c) shows the capital cost of hammer mills at different capacities (NEOS, 1995; Williams and Lynch, 1995; Thek and Obernberger, 2004; GEC, 2006; Hoque et al., 2006; Mani et al., 2006; Campbell 2007; Polagye et al., 2007). Based on Fig. 3(c), the estimated scale factor for hammer mills is 0.38. The scale factor reported in other studies is 0.6 (Hamelinck and Faaij, 2002; Spath et al., 2005). The main reason for this large variation in values reported by different studies is that costs were estimated for different countries setting and at different times. The range of capital costs for coolers is shown in Fig. 3(d) (NEOS, 1995; Williams and Lynch, 1995; Thek and Obernberger, 2004; GEC, 2006; Hoque et al., 2006; Mani et al., 2006; Campbell 2007; Polagye et al., 2007). The scale factor derived from Fig. 3(d) is 0.49. The scale factor derived for the primary grinders considered for this paper is 99%. Fig. 3(e) shows the capital cost of grinders of different capacities (NEOS, 1995; Samson and Duxbury, 2000; Campbell, 2007). The scale factor derived for the bagging system is 0.87. This is based on the capital cost data for bagging system given in Fig. 3(f) (NEOS, 1995; Williams and Lynch, 1995; Samson and Duxbury, 2000; Hoque et al., 2006). Based on the capital cost data in Fig. 3(g) the scale factor for feeding systems is 0.57 (Williams and Lynch, 1995; Samson and Duxbury, 2000; Polagye et al., 2007). This value is less than the value used in Hamelinck and Faaij (2002). The estimated scale factor for storage is 0.85. This is based on capital cost values at various capacities as shown in Fig. 3(h) (Thek and Obernberger, 2004; Campbell, 2007). The scale factor for conveyors considered in this study is 0.80, based on a previous study (Hamelinck and Faaij, 2002). Some of the scale factors derived in this study are not same as those considered in previous studies because estimation of costs was done in different countries and at different times.

In the base case, the pellet plant has a production capacity of 6 tonnes h^{-1} with an annual production capacity of 44,000 tonnes. The plant operates for 7200 h annually, which is about 24 h day^{-1} and 300 days $year^{-1}$ (capacity factor of 85%). The selection of equipment size or capacity depends on the type of feedstock, particle size and moisture level. It takes less energy to create 8 mm

Table 5
Capital cost of equipments and employee costs of pellet production plant (base case 6 tonne h^{-1}).

Plant equipment	Scale factor	Capital cost – base case ($)	Maximum size of equipment (tonne $year^{-1}$)	Source
Capital cost				
Primary grinder	0.99	650,000	105,000	Campbell (2007) and Polman (2008)
Dryer	0.6	430,000	100,000	Hamelinck and Faaij (2002) and Campbell (2007)
Hammer mill	0.6	150,000	108,000	Wright (2008) and Polman (2008)
Feeder	0.57	44,700	50,000	Campbell (2007) and Polman (2008)
Boiler	0.7	51,000		Campbell (2007) and Kumar et al. (2003)
Pellet mill (with conditioner)	0.85	350,000	50,000	Wright (2008) and Polman (2008)
Pellet cooler	0.58	170,000	216,000	Wright (2008) and Polman (2008)
Screener/shaker	0.6	18,300	100,800	Campbell (2007) and Polman (2008)
Bagging system	0.63	450,000	100,800	Campbell (2007) and Polman (2008)
Conveyor tanks etc.	0.75	1130,00	84,000	Campbell (2007) and Polman (2008)
Hourly-wage employee	Hourly rate	Worker shift	Annual hours	Source
Cost of hourly-wage employee				
Supervisor	21.00	1	7200	Hoque et al. (2006)
Maintenance worker	18.00	On-call	2080	Hoque et al. (2006)
Machinery operator	16.00	2	7200	Campbell (2007)
Packaging	15.00	2	7200	Campbell (2007)
Forklift operator	15.00	1	7200	Hoque et al. (2006)
Salary labor		Salary ($ $year^{-1}$)	Payroll tax benefit	Source
Cost of permanent employee				
General manager		100,000	45%	Hoque et al. (2006)
Financial manager		75,000	45%	Hoque et al. (2006)
Supervisor		60,000	45%	Campbell (2007)
Secretary		40,000	45%	Campbell (2007)

pellets than it does to make 6 mm pellets. A 12 mm pellet requires even less horsepower. The smaller the particle size, the larger the capacity of the equipment and the horsepower required for processing (Wright, 2008). Softwood requires equipment with lower horsepower and capacity compared to hardwood (Wright, 2008). The capacity of coolers is based on the volume of air flow, ambient temperature, and design particulars (Wright, 2008). Table 5 lists the equipments, its capital cost and the maximum possible size available today.

In this study, the assumed maximum sizes for the equipment are given in Table 5. To provide any capacity over maximum size, two or more identical sized units can be purchased. The maximum capacity of the pellet mill is 50,000 tonnes year^{-1}. However, pellet manufacturers prefer smaller units in order to avoid unnecessary full shut down for maintenance. Large pellet mills are limited (Macarthur, 2008). The larger the diameter of die and roller, the greater the force that is exerted on a given area and the risk of causing metal fatigue. There is also a problem with peripheral speed. With larger diameters, the dies or rollers turn more slowly. For these reasons high capacity single unit pellet mills are not available on the market (Polman, 2008; Macarthur, 2008). There are some other costs associated with pellet production such as site preparation, plant and office building, feedstock storage, pellet storage, wheel loaders, forklifts and office materials. The capital costs of these items were taken from a previous study (Campbell, 2007). Fig. 4 shows how the of unit capital cost of the whole plant changes with capacity.

Capital cost of the pellet production plant per unit of output decreases with increase in capacity, due to economy of scale. For plant capacities higher than 100,000 dry tonnes year^{-1}, the change in unit capital cost is not significant.

5.3.3. Employee cost

Another major cost component is the employee cost, which includes the cost of personnel in production, marketing and administration. Two types of employee are usually involved in a pellet production process i.e., permanent employees and hourly-wage employees. In the production process, seven hourly-wage employees and four permanent employees are required for an entire 44,000 tonne year^{-1} production plant. This is based on the literature and in discussions with the pellet plant operators (Campbell, 2007; Macarthur, 2008). The labor cost does not increase linearly with the capacity of plant; there is an economy of scale here too. For example, large pellet plants do not have higher labor costs per tonne of produced pellets; nearly the same number of worker is required, to operate a half capacity plant. There are break-points at some production level above which another worker is required (Campbell, 2007). Handling the feedstock and finished pellets is more labor-intensive than the production process. Three workers are required for bagging if it is done manually for the base case plant. The total number of workers required in any pellet plant is largely determined by the loading, unloading, handling and storing of feedstocks and pellets. The employee and administrative costs of a 44,000 tonne year^{-1} plant are given in Table 5. Payroll taxes and fringe benefits are considered to be 25% of the hourly wages (Wright, 2008).

5.3.4. Energy cost

5.3.4.1. Electricity cost. All pellet plant equipment needs electricity, which is a significant part of pellet production cost. Of all the equipment required for straw pellet production, the pellet mill consumes the most electricity, followed by the dryer (Pastre, 2002). In contrast, the dryer consumes the most electricity in wood pellet production (Pastre, 2002). If an equipment of the proper size is not installed, an overly large unit will waste electricity. The feedstock species, particle size, pellet size and moisture level all play an important part in determining how much horsepower is needed. Hardwood is more difficult to pelletize than softwood and requires additional horsepower. Pellets can be produced at a rate of 4 tonnes per h for softwood and 2–3 tonnes h^{-} for hardwood using the same machine (Wright, 2008). Similarly, straw pelleting requires less power than pelleting of softwood, but requires extra power for chopping than does wood. It takes less power to create an 8 mm pellet than it does to make a 6 mm pellet (Wright, 2008). Table 4 shows the power requirement for all the equipment used for pellet production. The data in Table 4 were derived from studies by Campbell (2007) and Pastre (2002).

In this study, the allowance for idle hours includes 5% for warming up a machine, shutting down, running without products etc. (Campbell, 2007). Thus there are 6840 annual full-time production hours. The energy charges considered for this study amount to \$0.122 kW h^{-1} month^{-1}. Table 4 shows that pellet mill is the highest (34%) power consuming unit followed by dryer (19%).

5.3.4.2. Natural gas cost. Natural gas is used to reduce the moisture content of feedstock in a dryer and, as a boiler fuel, to produce steam. It is assumed in this study that the moisture content of the feedstock was reduced from 14% to 10%. This use of natural

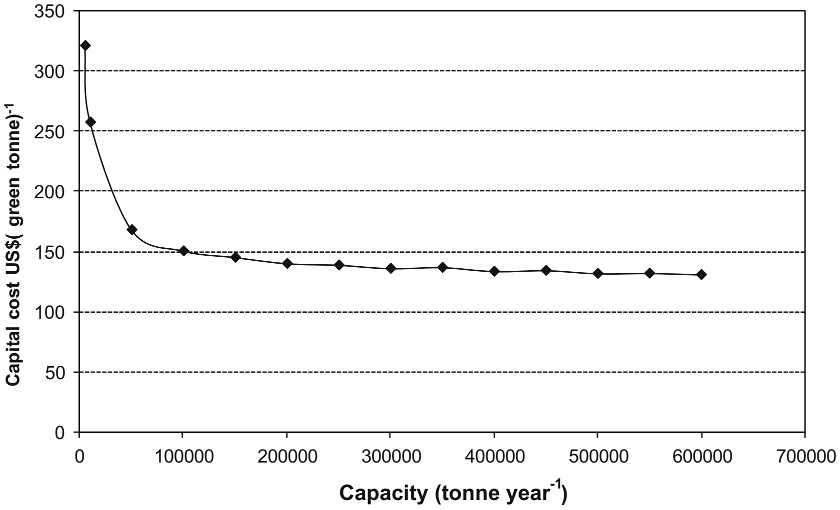

Fig. 4. Change of unit capital cost of pellet production plant with capacity.

gas costs \$1.00 tonne^{-1}. The steam required to condition feedstock before it enters the pellet mill is 4% of the total weight of the feedstock (Thek and Obernberger, 2004). The boiler efficiency considered for steam production is 80% (Dias et al., 2004; Kristensen and Kristensen, 2004). Assuming a gas price of \$5.94 GJ^{-1}-based on the 2008 price of natural gas (Energy shop, 2009; Direct Energy, 2009), the gas for drying costs \$1.27 tonne^{-1}.

5.3.5. Consumables cost

In pellet production dies and rollers are considered consumable items. Their useful life depends on the physical characteristics of the feedstock. Straw is more abrasive than wood so dies wear out more easily (Pastre, 2002). Similarly, if pellets are made out of bark, dies need to be changed 3–4 times, due to abrasion (Wright, 2008). The cost of rollers, blades and screens is \$2.75 tonne^{-1} (Campbell, 2007). Pellet bags are another consumable item and costs \$0.15 bag^{-1}. Assuming the capacity of 50 bags to be 1 tonne, the cost of bags is \$7.50 tonne^{-1} (Campbell, 2007). A 110 horsepower wheel loader uses 18.65 l of diesel per hour at full load (Campbell, 2007). If the diesel costs \$1.43 gal^{-1} (NRCan, 2009) the cost of fuel for the wheel loader is \$1.27 tonne^{-1}.

6. Results and discussion

The techno-economic model developed in this study estimates the cost of producing agricultural biomass-based pellets and the economically optimum plant capacity using the cost and technical parameters provided in earlier sections. The costs and technical parameters were considered for each unit operation from feedstock harvesting to pellet storage. The model considered straw yield, field costs such as straw acquisition, nutrient replacement and farmer premium along with the cost of transportation and maintenance, and operating costs such as labor, energy and consumable items.

The cost of producing pellets from biomass is highly dependent on the size of the plant. The optimum size for a pellet plant is a trade-off between the cost of transporting biomass, which increases as plant capacity increases and capital cost per unit of output that, due to economy of scale, decreases as plant capacity increases. As a result of this trade-off, there is a particular capacity at which production cost is minimal; this is the optimum size for the production plant. Table 6 shows the optimum sizes in the average, maximum and minimum yield scenarios for agricultural biomass-based pellet production plant. It gives, as well, the area from which straw is drawn and the agri-pellet production cost.

The cost of biomass transportation increases in proportion to the square root of capacity, whereas per unit capital cost decreases with capacity. Fig. 5 shows the variation in the production cost of agri-pellets with the capacity of the plant. The pattern of the curve is similar for the average and maximum yield scenarios. For the minimum yield scenario, the pattern of the curve is different after 70,000 tonnes year^{-1}. Fig. 5 shows two regions. For the average and maximum yield scenarios and plants with capacities less than 70,000 dry tonnes year^{-1}, the production cost rapidly increases as the size of the agri-pellet production plant decreases. Above 70,000 dry tonnes year^{-1}, the cost of production is almost flat. The reason is that the benefit in the plant's capital cost per unit output due to economy of scale is offset by the increased cost of transporting the

Table 6
Economic optimum size of agriculture biomass-based pellet production plant.

	Average yield	Maximum yield	Minimum yield
Straw yield (dry tonnes ha^{-1})	0.50	0.78	0.08
Optimum size (tonnes year^{-1})	150,000	150,000	70,000
Project area from which straw is drawn (km)^2	1228,737	782,917	3492,837
Agri-pellet cost (\$ tonne^{-1})	129.42	122.17	170.89
– Capital recovery	7.61	8.76	5.22
– Maintenance cost	2.41	2.47	2.71
– Field cost	47.61	47.61	47.61
– Transportation cost	47.72	39.32	76.27
– Employee cost	8.23	8.23	17.63
– Energy cost	5.92	5.92	11.37
– Consumable item cost	9.86	9.86	10.10

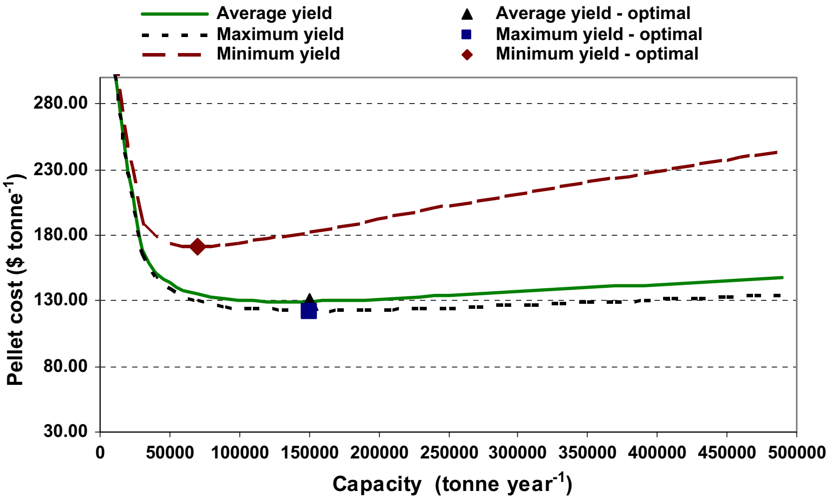

Fig. 5. Pellet cost as a function of capacity for three cases of straw yield.

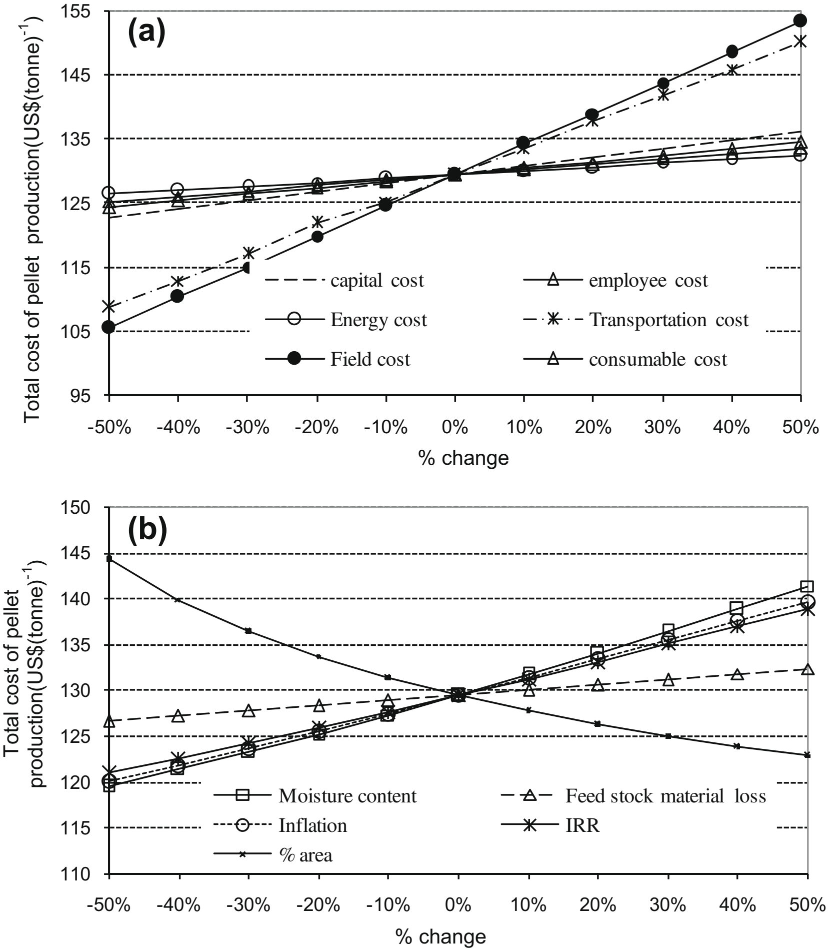

Fig. 6. Sensitivity analysis of (a) cost factors and (b) technical factors.

Table 7
Impact of cost factors and technical factors on optimal size (in tonne year^{-1}) for average yield (base case 150,000 tonne year^{-1}).

% Change	50% Lower	40% Lower	30% Lower	20% Lower	10% Lower	10% Higher	20% Higher	30% Higher	40% Higher	50% Higher
Cost factors										
Field cost	No change	No change	No change	No change	No change	No change	No change	No change	No change	No change
Transportation cost	Increase 40,000	Increase 40,000	Increase 40,000	No change	No change	Decrease 20,000	Decrease 20,000	Decrease 60,000	Decrease 60,000	Decrease 60,000
Capital cost	Decrease 20,000	Decrease 20,000	No change	No change	No change	No change	No change	No change	No change	No change
Employee cost	Decrease 60,000	Decrease 60,000	Decrease 20,000	Decrease 20,000	No change	No change	No change	No change	No change	No change
Energy cost	Decrease 20,000	Decrease 20,000	Decrease 20,000	Decrease 20,000	No change	No change	No change	No change	No change	No change
Consumable item cost	No change	No change	No change	No change	No change	No change	No change	No change	No change	No change
Technical factors										
Moisture content	No change	No change	No change	No change	No change	No change	No change	Decrease 20,000	Decrease 20,000	Decrease 20,000
Material loss	No change	No change	No change	No change	No change	No change	No change	No change	No change	No change
Inflation	Decrease 20,000	Decrease 20,000	No change	No change	No change	No change	No change	No change	No change	No change
IRR	No change	No change	No change	No change	No change	No change	No change	No change	No change	No change
% Area for biomass	Decrease 60,000	Decrease 20,000	Decrease 20,000	Decrease 20,000	No change	No change	No change	No change	No change	No change

agricultural biomass. Thus, in this region agricultural biomass-based pellet plants can be built over a wide range of capacities without significant cost penalties. For example, the economically optimum size of plant for the average yield case is 150,000 tonnes year^{-1}, but agri-pellet production cost remains within 10% of the optimum value from 70,000 tonnes year^{-1} to more than 500,000 tonnes year^{-1}. While the calculated optimum size is 150,000 tonnes year^{-1}, it is more likely that the plant would be built to handle 70,000 tonnes year^{-1} in order to minimize risk. For the minimum yield scenario, above 70,000 tonnes year^{-1}, any increase in capacity will increase the cost of production considerably. In this case, an increase in transportation cost outweights the reduction of capital cost per unit of output. Above 70,000 tonnes year^{-1}, reduction in capital cost is 5% for the minimum yield case, but the biomass must be collected from a very widespread area. The minimum yield scenario is based on yields obtained in the drought years which were observed 2 years out of the 12 years of data collection. The agri-pellet plant can be built at a capacity of 70,000 tonnes year^{-1} which will result in pellet production cost of \$130–\$132 tonne^{-1}. It is evident that agri-pellets (at \$7.2 GJ^{-1}) are still not economical as a fuel today compared to fossil fuel (i.e. natural gas at \$6.5 GJ^{-1}).

Table 6 shows the different cost components of producing straw-based pellets. From Table 6 it can be seen that transportation contributes the most to total cost, followed by field cost. Transportation alone contributes almost 40% of the total cost. The main reason for the cost of transportation being high is that the biomass feedstock is very dispersed due to low yield. Straw harvesting requires nutrient replacement, which is a significant field cost in all cases.

Plant capacity and the agri-pellet production cost associated with it depend on crop yield and the distance between where the biomass is collected and the plant is built. In Alberta, one of the western Canadian provinces, the net yield of straw is 0.50 tonne ha^{-1} whereas, in other prairie provinces, such as in Manitoba, the net yield is 0.65 tonne ha^{-1}. Economic optimum size are larger when yields are higher.

7. Sensitivity analysis

The sensitivity of the cost factors and technical factors were studied for the average yield case. This sensitivity analysis was carried out by changing the values for different costs and technical factors from −50% to +50% in steps of 10% for each case. Cost factors such as field, transportation, capital, employee, energy, and consumable costs were included in the analysis. Technical factors, including moisture content, feedstock material loss, inflation, internal rate of return (IRR), and percentage of area used for wheat, barley and oat production were considered. Fig. 6 shows the results of the sensitivity analysis done on cost factors, and technical factors.

It can be seen from Fig. 6(a) that the cost of agri-pellet production is most sensitive to field cost, followed by transportation cost. A variation of about ±50% of field cost can change the pellet price from \$153.33 to \$105.52 tonne^{-1}. The agri-pellet production cost changes from \$150.05 to \$108.79 tonne^{-1} given a change of ±50% in transportation cost. Table 7 shows that variation in field cost does not affect optimum plant size, however, variation in transportation cost changes the optimum size from 190,000 to 90,000 tonnes year^{-1}. As transportation cost increases, the optimal size of the agricultural pellet production plant decreases. The opposite result is observed when the cost increases. With a change from +50% to −50% in capital cost, the cost of production changes by \$13.36 tonne^{-1}. Other costs, such as employee cost, energy cost and consumable cost, do not change the total cost of production significantly.

It can be concluded from Fig. 6(b) that changes in moisture content and IRR have nearly the same impact on the total production cost. An increase in the moisture content, IRR, inflation and loss of feedstock material in the plant contribute to increase in the pellet production cost. Higher inflation and increase of the production area for wheat, barley and oats reduces the cost of pellets. Pellet production cost is most sensitive to changes in moisture content. With a −50% to +50% change in moisture content, the cost increases by \$21.92 tonne^{-1}. An increase of moisture content adversely affects the heating value of fuel. The percentage of area used for wheat, barley and oat production changes the total cost significantly. A slightly nonlinear pattern is observed for the impact of the amount of area used for wheat, barley and oat production. This is due to the fact that the cost of producing pellets depends on the radius of the circle from which agricultural residue is collected. The variation in optimum size (Table 7) has to do more with percentage of change in this area than with the moisture content. The impact that values for cost and technical factors have on optimal plant size are shown in Table. 7.

8. Conclusions

A techno-economic model was developed for estimating the cost of producing pellets and the optimum size of pellet plants based on agricultural biomass. Agricultural residue, including wheat, barley and oat straw, were considered at average, maximum and minimum yield cases. The total cost was calculated from the harvest of straw to pellet production. The techno-economic model was applied to Western Canada. For average and maximum yield cases, cost curves are quite flat for a wide range of plant sizes over 70,000 tonnes year^{-1}. This implies that plants smaller than the economically optimum size can be built with only minor cost penalty. From the sensitivity analysis it can be concluded that total cost of production of pellet is most sensitive to field cost followed by transportation cost.

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