Techno-economic Assessment of Pellets Produced from Steam Pretreated Biomass Feedstock

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Abstract.

Minimum production cost and optimum plant size are determined for pellet plants for three types of biomass feedstock – forest residue, agricultural residue, and energy crops. The life cycle cost from harvesting to the delivery of the pellets to the co-firing facility is evaluated. The cost varies from 95-105 \$ t^{-1} for regular pellets and 146-156 \$ t^{-1} for steam pretreated pellets. The difference in the cost of producing regular and steam pretreated pellets per unit energy is in the range of 2-3 \$ GJ^{-1}. The economic optimum plant size (i.e., the size at which pellet production cost is minimum) is found to be 190 kt for regular pellet production and 250 kt for steam pretreated pellet. Sensitivity and uncertainty analyses were carried out to identify sensitivity parameters and effects of model error.

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1.0 Introduction

Fossil fuels have long been a source of energy worldwide. However, fossil fuels are used faster than they are generated, as the world's population is growing faster than the generation and extraction of fossil fuels [1]. In addition, fossil fuels have long been considered non-environmentally friendly since burning them produces large amounts of greenhouse gases (GHGs), which contribute to global warming. An 80% increase in fossil fuel use will increase GHG emissions by 70% [2]. This could have significant impact on the environment globally. All these factors have led to the focus on the use of renewable energy sources, and biomass-based energy production is a key component of this. Biomass-based energy and fuels are considered nearly carbon neutral [3].

Biomass-based facilities face a number of challenges that has limited their development. The quality and quantity of the biomass produced from various feedstocks vary significantly, and this is one of the key factors affecting their large-scale practical use in a biomass-based facility. Typically, biomass has low calorific value, density, and yield (i.e., amount produced per unit area), all of which increase biomass delivery cost, which in turn increases biomass conversion costs [3]. Biomass pre-processing helps to reduce some of these barriers.

Pelletization is a biomass pre-processing method. The pelletization process starts with biomass collection. Forest residues are then chipped; wheat straw and switchgrass are chopped. The chipped/chopped biomass is then transported to a pellet mill to be pelletized. Biomass is dried before it is comminuted and pelletized [4, 5].

Regular pellet production refers to the production of pellets without steam pretreatment. While pelletization improves the bulk density and calorific value of the fuel, the bulk density and calorific value need to be improved significantly in order to co-fire the pellets with coal [6, 7]. Steam pretreatment, is a non-chemical pretreatment that exposes biomass to high pressure and high temperature steam in the range of 1 to 3.5 MPa and 180-240^{0}C, respectively [6, 7]. Steam pretreatment of biomass pellets can make it feasible to use pellets for co-firing. Steam pretreatment, moreover, is essential to ensure high energy output and improve thermal efficiency [6].

Steam pretreatment prior to bioconversion has been proposed by Lam [6] and Tooyserkani [7] as a means of improving the mechanical strength, hydrophobicity, and calorific values of the bio-fuels produced from biomass. These improvements can reduce biomass storage costs, thereby reducing the cost of fuel production from biomass. Steam pretreatment also improves the bio-chemical conversion, which leads to higher yield. However, this research focused specifically on improving biomass pellet energy density through steam pretreatment.

Previous studies have evaluated the economics of biomass-based energy from the perspective of generic models [2, 8-13]. The cost of producing pellets from sawdust has been reported by Mani et al. [14], who found that pellets can be produced from sawdust at a cost of 51 \$ t^{-1} at a plant capacity of 45 kt. A European pellet production scenario has been reported by Thek and Obernberger [15, 16], they predicted the production cost of sawdust-based pellets in a European setting. They reported a production cost of 95.56 \$ t^{-1} of pellets at a plant capacity of 24 kt [16]. Urbonowski [17] used their study to evaluate the capital cost of a regular pellet production plant. Other researchers evaluated the production cost of pellets in Europe and elsewhere [18-21]. However, little research evaluates the production costs of steam pretreated pellets or compares production costs of regular and steam pretreated pellets. In addition, there is limited focus on the effects of the economic optimum size of the feedstock on both processes. While life cycle analyses have been carried out by many researchers, to date there has been no techno-economic assessment of steam pretreatment processes. There is a need to evaluate the economics of pretreated biomass-based pellets.

The overall objective of this research is to determine the costs of steam pretreated pellet production from three feedstocks – forest residue, wheat straw, and switchgrass – and compare them with the costs of regular pellet production. The key objectives for the study are:

- To develop a data-intensive techno-economic model to evaluate the costs of steam pretreated biomass-based pellet production.
- To estimate the costs on a mass and energy basis of steam pretreated biomass-based pellet production for three feedstocks (forest residues, wheat straw, and switchgrass).
- To evaluate the economic optimum production plant size for steam pretreated biomass-based pellets from all three feedstocks.
- To determine the effect of various parameters on the cost of production through a sensitivity analysis.

2.0 Biomass sources, yields, and properties

2.1 Forest residues

Forest residues are a by-product of the pulp and lumber industry and may be available as an alternative fuel source in the bio-fuel industry. The limbs and tops of trees are left by the side of the road but can be collected and used. These are the residues considered in this study. Although costs are incurred through collection and delivery, existing logging roads are used and hence do not add to construction costs. [3].

2.2 Agricultural residues

Agricultural residues form the largest concentration of field-based residues in western Canada. A recent study estimated the amount of agricultural wheat straw available in Alberta to be more than 6 Mt of dry biomass [10]. It is possible to generate 2000 MW of power from the available uncollected wheat straw; this shows the value of available wheat straw [3].

2.3 Energy crop

The energy crop considered in this study is switchgrass (*Panicum vigratum, L.*). Switchgrass is a hot weather perennial grass native to North America. The grass can grow in dry weather and is suitable for marginal land. The above-ground biomass yield reported by Vogel et al. [23], is from 3 to 30 t ha^{-1}. This yield is dependent upon soil fertility, location, variety, and number of harvests per season [13, 22]. The yield considered for the purpose of this research is 3 t ha^{-1}; this figure is low because the weather in western Canada is mostly cold and the warm season lasts only 4 months.

The feedstock properties and yields data for all three feedstocks considered here are listed in Tables 1 and 2, respectively.

Table 1

Table 2

3.0 Methodology

3.1 Techno-economic analysis and optimization

A data-intensive techno-economic model was developed for the production of pellets from three different steam pretreated feedstocks. The focus of this study is to apply a specific cost number methodology to feedstocks in western Canada. Region-specific data are available for the delivered cost of different feedstocks in western Canada. However, limited work has been done to evaluate the cost of pellet production in western Canada. This study used the region-specific delivered cost of biomass to evaluate the cost difference between regular and steam pretreated pellet production. Figure 1 shows the process from biomass collection to pellet transportation.

Fig. 1

Cost parameters were developed based on a detailed literature review, in consultation with experts, and modeling, and are specific to western Canada. Costs are mainly from feedstock harvesting and transportation and pellet production. Costs associated with processing within the plant are capital cost, energy cost, employee cost, and consumable cost. The model was created based on the yields of three different feedstocks. Feedstock yield affects the delivered cost of the feedstock, specifically the transportation cost. The cost numbers developed focus on the effects of the energy requirement for steam pretreatment but do not consider the effect on cost through changes in pellet quality after steam pretreatment. In addition, material flow issues related to different feedstocks and the addition of additives are not considered. The plant life considered in this model is 30 years based on previous studies [3, 10]. The pellet production cost is the sum of the delivered feedstock cost and the pellet plant's production costs. A present value (PV) analysis was carried out for the plant for a 30-year period, and a macro-based "Goal Seek" Excel function was used to evaluate the production cost based on a net present value (NPV) of 0.

The economic optimum pellet plant size is the capacity at which the pellet production cost is lowest. This research compared cost and cost sensitivity of steam pretreated pellet production from different feedstocks. The resources considered for this research are located in western Canada and produce sufficiently large quantities of biomass to support bio-fuel production. These sources are forest residues from lumber and pulp operations, agricultural residues from agricultural crops, and energy crops like switchgrass.

We evaluated a uniform end use of biomass, based pellets, which allows us to assess the three feedstocks' relative value and evaluate an optimum pellet production size. Following work by Arifa et al. [8] and Kumar et al. [3], we considered the throughput to be the same. The optimum production size is fuel-specific and varies depending on feedstock type and quality. In pellet production, cost parameters vary, unlike in conventional fuels like coal. The cost of biomass feedstock per unit capacity depends on the size of the pellet plant. The cost of biomass fuels is directly related to the biomass transportation cost. Thus, biomass-based pellets have a significant variable cost component, which in turn affects the economic optimum size of the pellet plant [3, 9, 11, 12].

In our research we evaluated the economic feasibility of steam pretreatment, which has received limited attention. The focus of this research is to quantify the economic benefits of pellet quality and supply chain improvements through steam pretreatment on overall production costs and to compare the production costs of steam pretreated and regular pellets.

Details on the different cost parameters and the techno-economic model are given in the following sections.

3.2 Input data and assumptions for the development of cost estimates

Note: All currency figures are in US$ and the base year is 2015. An inflation rate of 2% has been assumed. The exchange rate for the Canadian dollar against the U.S. dollar is considered here to be 1.27 according to Bank of Canada on January 30, 2015. In the base case, the pellet plant is assumed to run at 6 t h^{-1} with an annual production capacity of 44 kt. This size is based on earlier studies on pellet plants [10]. The cost parameters considered for the model development are given in Tables 3-5.

Table 3

Table 4

Table 5

Cost factors considered for the model are as follows:

- *Biomass field costs*: Biomass price can vary from producer to producer and from plant to plant [10, 24]. Field costs in general for all feedstocks consist of harvesting and collection, chipping/chopping and nutrient replacement (through a premium to farmers). All forms of biomass are chipped/chopped before being transported to a pellet plant. It was assumed that farmers harvested and baled, then left the feedstock by the roadside. The other field cost is storage cost. This model assumes that the biomass feedstock is stored without any fixed structure, and hence storage cost is low since there is no capital cost for a storage facility [10]. Nutrient replacement is in the form of payment to farmers to replenish nutrients after biomass harvesting. Nutrient replacement is considered for wheat straw and switchgrass, but not for forest biomass. Nutrient replacement mainly consists of the fertilizer required for wheat and switchgrass cultivation [10]. Forest residues, currently burned to prevent forest fires, require no nutrient replacement and hence no costs are incurred. [12].

- *Transportation costs of biomass to a pellet plant*: Biomass from agricultural residues and energy crops is transported over existing roads. Forest harvest residues are also transported on existing roads, those built for the pulp and lumber industry [3]. As noted above, biomass transportation costs vary with the bio-fuel facility's capacity. The reason for this is that the area from which biomass is harvested is directly related to plant capacity, and the transportation distance is proportional to the square root of the harvested area [3]. Thus, overall pellet production capacity is sensitive to changes in harvest area and transportation distance. A higher yield ensures sustainable pellet production. This effect is explored further in the sensitivity section. Changes in transportation cost with capacity are shown in Fig. 2.

Fig. 2

- *Capital cost, power plant capital cost index, and scale factor*: The capital cost is made up of the costs of pellet process equipment and installation. The pellet plant cost used in this model is based on costs developed in an earlier study by Sultana and Kumar [10], and the steam pretreatment capital cost is from McAloon and Taylor's work [25]. The maintenance cost considered for the model is 2.5% of the equipment cost. All equipment prices are adjusted to the 2015 dollar using the power plant cost index (PCCI) factor [26]. Changes in capital cost with capacity are shown in Fig. 3.

Fig. 3

The PCCI is an indicator considered for the construction of power generation projects in North America. The bio-fuels produced in pellet plants are usually used in boilers to produce heat and power. The PCCI factors are maintained by Information Handling Systems Inc. (IHS) and date back to 2000 [26]. The PCCI varies with changes in equipment cost, facilities, materials, and manpower. Inflation is not used to adjust the capital cost since this cost can increase with increases in the price of steel, cement, and construction materials. Hence, using inflation to adjust the base year price is not sufficient and instead the PCCI is used.

The scale factor used in this study is calculated based on equation 1 [3, 10], where

$$\mathrm{Cost}_2 = \mathrm{Cost}_1 \times (\mathrm{Capacity}_2/\mathrm{Capacity}_1)^{\text{Scale factor}} \quad (1)$$

The scale factor considered for this model is based on work by Sultana et al. [10] and is less than 1. This means that capital cost increases at a rate lower than plant production capacity. For bio-fuel facilities, there is always an economy of scale benefit associated with increased production capacity.

- *Maximum unit size*: The study considers the maximum unit size for equipment (see Table 4). The maximum capacity of the pellet plant limits the optimum size as well as economies of scale. The largest manufactured single unit pellet plant reported in the literature is 50 kt y^{-1} [10]. The capital cost per unit capacity decreases as the plant size increases up to 50 kt y^{-1} plant capacity. For capacities beyond 50 kt y^{-1}, the capital cost per unit production increases with the increase in capacity. This has an impact on the economic optimum size of a production plant.
- *Operating cost:* The operating cost considered for the model consists of labour cost, energy cost, and consumable cost.

1. Labour cost: Labour cost is a major cost component in pellet production. Two types of employees are considered for this study: permanent and hourly. 7 hourly employees and 4 permanent employees are required for regular pellet production at a base case production of 44 kt y^{-1}. Two additional hourly employee operators are considered for the steam pretreatment unit for steam pretreated pellet production [10]. The labour cost has an important role in determining the economic optimum size since this cost does not change linearly with production capacity. The number of employees required depends upon the pellet plant's operations.
2. Energy cost: The energy costs considered for the model are made up of electricity and natural gas costs. The electricity cost is based on equipment wattage information from an earlier study [18]. The equipment type and wattage vary with the quality and type of feedstock used. For example, wheat straw pellets require less energy to produce than softwood pellets and more energy for grinding [27]. However, the model assumes the electricity demand to be the same for the three feedstocks since no additional equipment specific to the feedstocks has been considered.

Natural gas is required for feedstock drying and steam pretreatment. The natural gas requirement is based on the energy requirement of the unit operations and is calculated from the simulation developed in Aspen Plus for both regular and steam pretreated pelletization. The details of the simulation process modeling are given in an earlier study by the authors [27]. The gas price considered is 4.68 \$ GJ^{-1} [10].

3. Consumable cost: Consumable cost is also considered for this study. It consists mainly of bags and fuels required for pellet collection and running the plant machinery.

- *Plant reliability and start-up profile*: Biomass facilities have frequent plant outages due to solids blockages [3]. The plant reliability factor considered for this study is 0.85. The start-up of most biomass facilities is smooth, and facilities are considered to start at 70% of their rated production capacity and reach their maximum capacity of 85% in year 3.
- *Return*: Pellet cost is evaluated at a pre-tax return on an investment of 10%. The impact of Return on Investment (ROI) on the pellet production cost is evaluated in the sensitivity analysis.

4.0 Results and Discussion:

Production costs and the economic optimum size of production for the three sources of biomass considered in this study are shown in Fig. 4. As expected, the production cost and economic optimum size depend on the pellet production process and the feedstock used.

- *Profile of production cost vs. capacity*: The profile of production cost vs. capacity shows a flat trend. This can be explained in the following manner. For biomass projects, there is a trade-off between two cost parameters. The project transportation cost increases with the square root of the project capacity. However, the capital cost per unit capacity of the project decreases with the project capacity. Because the variable cost of transportation increases with the capacity of the bio-fuel plant, the pellet production cost remains fairly unchanged with changes in capacity as this is balanced by the economy of scale benefits in the capital cost. This is unlike the cost vs. capacity of conventional fuel, wherein the total cost of energy production decreases with capacity due to economies of scale. Hence, transportation distance plays a role in pellet plant production capacity. Thus, there is an economic optimum size for biomass-based plants. This concept has been explored earlier for different biomass conversion pathways [3, 8, 9, 12, 14, 28, 29]. The optimum plant size for regular pellet production is 150-190 kt y^{-1}, while for steam pretreated pellet production it is 230-270 kt y^{-1}. The production costs vs. capacity profile, in cost per unit mass and cost per unit energy, is presented in Fig. 3.

Fig. 4

- *The assumption that maximum unit size will impact production cost*: The largest pellet plant size reported in the literature is 50 kt y^{-1}. The maximum unit size is a guiding factor in creating small pellet plants. It is observed from the model that at every interval of 50 kt y^{-1}, pellet production costs increase. Thus, a small increase in production capacity beyond every increment of 50 kt y^{-1} leads to an increase in production cost, up to 190 kt y^{-1} for regular pellets and 270 kt y^{-1} for steam pretreated pellets. Beyond this, the economy of scale is no longer effective since the increase in transportation cost is not compensated for by the decrease in capital cost per unit capacity. The production costs increase beyond this capacity for both regular and steam pretreated pellets, hence 190 kt y^{-1} and 270 kt y^{-1} are considered optimum production scales for regular and steam pretreated pellet production.
- *The composition of pellet production cost*: Table 6 shows the delivered costs of pellet production for three feedstocks and two processes. The major cost component is the delivered cost of the feedstock, which is more than 50% of the delivered cost of the pellet production. The delivered cost of the feedstock consists of transportation and field costs. Thus, improving processes and technologies and reducing biomass field cost and transportation cost will significantly improve the optimum pellet plant size. The effect of delivered cost is significant for wheat straw and switchgrass feedstocks since harvesting

costs are high; for forest residue feedstock, a by-product of forest logging operations, delivered costs are low. Thus, agricultural pellets cost more than forest residue pellets.

Table 6

- *Effect of steam pretreatment on pellet production costs*: Steam pretreatment significantly increases pellet production costs because of the capital costs of boilers and steam pretreatment units. The plant operating cost further increases with the extra natural gas required to operate the steam pretreatment unit. As observed from the simulation and modeling results of the steam pretreatment process, the drying process uses a large amount of natural gas, which significantly increases the energy requirement [27]. Table 6 shows that the difference between steam pretreated and regular pellet production costs is 50-60 $\$ t^{-1}$. However, the optimum size for a steam pretreatment pellet plant is higher than a regular pellet plant due to the economy of scale benefits of a steam pretreatment unit. However, the economic optimum size varies due to the material losses during steam pretreatment. These material losses occur as high pressure steam breaks the biomass and reduces its solid content. Higher material losses have been predicted for switchgrass than for wheat straw and forest residue [4, 5] and thus, steam pretreatment under current practices will not solve the issues related to biomass co-firing in a coal power plant. However, improving the drying energy requirement and steam pretreatment will significantly improve the overall biomass co-firing process.
- *Cost per unit mass vs. cost per unit energy variation*: As explained in the introduction, steam pretreatment increases the calorific value of the fuel by 8-10% (see Table 2). This is the primary motivation for the steam pretreatment of biomass feedstock prior to pelletization. However, the increase in calorific value is overshadowed by the increased

energy requirement, which creates a bottle-neck in the process. Thus, under current operating conditions steam pretreated pellet production is not justifiable. The change in cost per unit energy capacity shows the same flat trend and the same economic optimum size (see Fig. 4). However, the striking difference is the reduced gap in the cost per unit energy value for steam pretreated and regular pellets. Figures 5 (a) and (b) show that the difference in cost to produce regular and steam pretreated pellets is within 2 - 3 $\$$ GJ^{-1}. Hence pellet production costs, in terms of the fuel's energy value, improve through steam pretreatment.

Fig. 5

- *Effect of bulk density*: Bulk density is also improved through steam pretreatment (see Fig. 6). However, improving bulk density does not create a large difference in the delivered cost of pellets to power-producing plants as it does not significantly improve the load carried by the trucks and hence does not affect the variable cost of transporting pellets.

Fig 6

- *Effect of feedstock type on production cost*: Of the three feedstocks considered, the delivered cost is lowest for forest residues. The delivered cost is a major portion of the overall production cost of wood pellets, and the lower cost of wood pellet production is reflected by the cost per unit mass value of the cost of production: 91 $\$$ t^{-1} for wood vs. 96 $\$$ t^{-1} for wheat straw, the highest among the feedstocks considered. The production cost is lowest for switchgrass, which has both a higher yield and lower field cost than wheat straw (see Table 6).

  The steam pretreatment of pellets has a different effect on the cost per unit mass value of the production cost for the three feedstocks. The cost per unit mass is highest for switchgrass since steam pretreatment leads to material loss, and this loss is highest for switchgrass (see Table 2). The economic optimum plant size is lower for switchgrass than for the other feedstocks for this same reason. Both field cost and transportation cost are related to biomass harvested, and the high mass loss in switchgrass increases field and transportation costs, which cannot be offset by reducing the capital cost. Hence switchgrass has a smaller optimum plant size than the other feedstocks studied here.

5.0 Sensitivity Analysis

A sensitivity analysis of cost and technical factors was conducted for the base case scenario by varying these factors by ±20%. Cost factors include field, transportation, capital, employee, energy, and consumable. Technical parameters are moisture mass fraction, material loss, inflation, return, and biomass harvesting area.

The results of the sensitivity analysis are shown in Fig. 7. Field and transportation costs are the most sensitive factors and range from 8-16 $\$ t^{-1}$ for changes of ±20%. This variation shows that a high yield (i.e., reducing transportation cost) and process improvement (i.e., reducing operating cost) will improve the overall cost of production. The technical parameters show that changes in moisture mass fraction, IRR, and biomass yield lead to production costs of 5-8 $\$ t^{-1}$. Hence, cost factors are more sensitive to variation than technical factors.

Fig. 7

Steam pretreatment sensitivity models show that the model outputs are sensitive to the material loss parameter, which changes the biomass required to produce the same quantity of pellet. Switchgrass shows more sensitivity since, of all the feedstocks studied here, it has the highest material loss in steam pretreatment. The sensitivity analysis also shows that a high material yield during steam pretreatment can improve the cost of producing pellets from steam pretreatment.

A sensitivity analysis was also carried out to understand the effect of variations in capacity factor and capacity on production costs for both regular and steam pretreated pellets. Table 7a shows the effects of changes in capacity factor on production costs for steam pretreated pellets from forest residue, wheat straw, and switchgrass. Table 7b shows the effects of variations in capacity on production costs of regular and steam pretreated pellets from wheat straw and switchgrass. Production costs increase with a decrease in capacity and an increase in capacity factor.

Table 7

6.0 Uncertainty Analysis:

The lack of exact representative data for different cost parameters is a limitation of the modelled cost of production. When there are no accurate data available, researchers use assumptions for their models, which lead to uncertainty. A Monte Carlo simulation was carried out that assumed greatest volatility in the values of drying and steam pretreatment energy required. A Monte Carlo analysis is a well-known method that deals with a number of variables and quantifies the uncertainty in the final output. The number of iterations used for our model is 10000. The simulation was carried out using Model Risk software [30]. Uncertainties are considered for transportation cost, field cost, and material loss during steam pretreatment with a variation of 40% based on the sensitivity analysis result, and a variation of 20% is considered for the capital cost.

The production costs generated from the Monte Carlo simulation are shown in Fig. 8. The Monte Carlo simulation results for the base case scenario variations for different feedstocks for regular pellet production show a production cost of 98-109 $ t^{-1}$ with a standard deviation of 2.3-3.1 $ t^{-1}$ at 95% confidence and 153-164 $ t^{-1}$ with a standard deviation of 3.7-4.9 $ t^{-1}$ at 95% confidence for the base case scenario for steam pretreated pellets.

Fig. 8

7.0 Conclusions

A techno-economic model was developed to estimate pellet production costs and optimum pellet plant size based on three feedstocks. Agricultural residue, forest residue, and energy crops were considered for two pelletization processes, regular and steam pretreated. The total cost was calculated from biomass harvesting to pellet production. The techno-economic model was applied to western Canada. For the base case scenario, the model shows an economic optimum plant size of 190 kt for regular pellets and 250 kt for steam pretreated pellets. From the sensitivity analysis it can be concluded that pellet production cost is most sensitive to field cost followed by transportation cost. The model's uncertainty analysis shows that there is greater variation with steam pretreatment than with regular pellet processing because additional energy is required for steam pretreated pellet production. In conclusion, steam pretreatment leads to additional costs, which can be minimized by improving drying and steam pretreatment efficiency.

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Table 1: Feedstock properties

Characteristic	Wheat Straw	Forest Residue	Switc h grass	Source
Moisture mass fraction (%)	14	45	14	[3, 10, 13]
Regular pellet HHV (MJ kg^{-1})	17.8	19.2	18.1	[25]
Steam pretreated pellet HHV (MJ kg^{-1})	19	19.5	19	[25]
Regular pellet bulk density (kg m^{-3})	780	800	660	[22]
Steam pretreated pellet bulk density (kg m^{-3})	1086	1112	834	[22]

Table 2: Calculation of net yield for wheat straw and switch grass

Crop	Yield Grain/ straw (t ha^{-1})[a]	Grain ratio	Gross yield (t ha^{-1})[a]	Level of straw retained for soil conservation (t ha^{-1})[a]	Mass fraction of straw harvest machine can remove (%)	Mass fraction removed for animal feeding and bedding (t ha^{-1})[a]	Mass fraction of straw loss from harvest area to pellet plant (%)	Moistur mass fraction (%)
Wheat straw	2.66	1.1	2.93	0.75	70	0.66	15	14
Switch-grass	-	-	3.5	0.75	70	0.66	15	14

[a] Calculated on 'as received' basis i.e. actual wet yields of the biomass.

[b] Calculated on dry basis i.e. actual wet yields are adjusted to zero moisture mass fraction.

Table 3: Reference input data for the techno-economic model

Items	Values/formulae	Comments/sources
Forest Residue		
Biomass yield (t ha^{-1})	0.24	Assumed yield based on hardwood and spruce yield in Alberta [3, 8, 9, 28, 29]. Dry basis [a].
Biomass chipping cost ($ t^{-1})	7.42	The cost of chipping consists of forwarding and piling [3, 8, 9, 28, 29]. Dry basis.
Chip loading, unloading, and transportation cost ($ m^{-3})	$0.5973\times(2.30+0.0257\,D)$	D is the round-trip transportation distance between in-bush chipping and a centralized bio-fuels production plant [3, 8, 9, 28, 29].
Tortuosity factor	1.27	Increases feedstock transportation distance for geographical conditions such as swamps, hills, and lakes in the biomass site [8].
Straw		
Yield (t ha^{-1})	0.52	Dry basis. [3, 8, 9, 10]
Straw harvesting cost ($ t^{-1})	34.65	The harvesting cost consists of shredding, raking, baling, collection, storage and nutrient replacement [10]. Dry basis.
Straw loading and unloading cost ($ t^{-1})	4.72	The cost is calculated based on the moisture mass fraction of the feedstock [10]. As received basis [b].
Straw transport cost ($ t^{-1} km^{-1})	0.142	As received basis [10]

Switch grass Yield (t ha^{-1})	3	Dry basis. [13, 22]
Field cost (\$ t^{-1})	17.81	Dry basis. [13, 22]
Distance fixed cost (\$ t^{-1})	9.75	Dry basis. [13, 22]
Distance variable cost (\$ t^{-1} km^{-1})	0.0866	Dry basis. [13, 22]

[a] For all biomass, the reported yields or weights are on dry weight basis, except as noted, i.e. actual wet yields are adjusted to zero moisture mass fraction. Estimated actual moisture mass fraction is 45% for forest residue, 14% for wheat straw and switchgrass. The estimated actual moisture mass fractions were used in calculating transportation costs.

[b] As received basis refers to the actual wet yields of the biomass.

Table 4: Pellet production plant costs (base case 6 t h^{-1})

Plant equipment	Scale factor	Capital cost - base case (M $)	Maximum size of equipment (kt y^{-1})	Source
Primary grinder	0.99	0.512	105	[10]
Dryer	0.6	0.339	100	[10]
Steam pretreatment unit	0.75	23.072	660	[25]
Hammer mill	0.6	0.118	108	[10]
Feeder	0.57	0.035	50	[10]
Boiler	0.7	0.040		[10]
Pellet mill (with conditioner)	0.72	0.276	50	[10]
Pellet cooler	0.58	0.134	216	[10]
Screener/shaker	0.6	0.014	100	[10]
Bagging system	0.63	0.354	100	[10]
Conveyor tanks, etc.	0.75	0.890	84	[10]

Table 5: General Assumptions

Factors	Value	Sources
Operating life (years)	30	Assumed based on similar bio-fuels studies [6, 10]
Inflation	2.0%	Assumed 2% based on average inflation of the last 12 years [6, 10]
IRR	10%	Assumed
Pelletization mass loss	5%	Based on experiment [27]
Plant capacity factor		Account for the production profile of the plant [6, 10]
Year 1	0.7	
Year 2	0.8	
Year 3 and onward	0.85	
Capital cost spread		Taken from earlier studies [6, 10]
Year 1	20%	
Year 2	35%	
Year 3	45%	
Other costs such as tax, insurance, etc., are assumed to be a percentage of capital cost.	0.50%	[6, 10]
Equipment power used for energy calculation (kW) :		[10]
Primary grinder	112	
Dryer	120	

Hammermill	75	
Boiler	75	
Pellet mill	300	
Cooling	5	
Bagging	40	
Light and heat	112	

Table 6: Economic optimum size and components of production cost of pellet production from three feedstocks

	Straw		Forest residue		Sw
	Regular	**Steam pretreated**	**Regular**	**Steam pretreated**	**Regular**
Optimum size (kt y^{-1})	190	250	190	290	190
Pellet cost ($\$$ t^{-1})	96.09	148.30	91.35	144.20	91.50
-Capital recovery	7.53	12.06	8.53	16.02	10.82
- Maintenance cost	2.08	2.90	1.84	2.83	2.03
-Field cost	41.21	46.26	22.20	25.26	20.13
-Transportation cost	26.69	33.85	29.17	39.56	35.73
-Premium	0.00	0.00	5.03	4.33	4.20
-Employee cost	5.72	6.18	5.18	5.32	5.72
-Energy cost	4.26	38.51	11.61	42.35	4.26
-Consumable item cost	8.61	8.55	7.80	8.54	8.61
Pellet transportation	4.96	4.33	4.88	4.29	5.35
Total pellet cost ($\$$ t^{-1})	101.06	152.63	96.23	148.50	96.85

Table 7: (a) Effect of variations in capacity factor on the production cost (\$ t^{-1}) of steam pretreated pellets

Capacity factor	Forest residue	Wheat straw	Switchgrass
0.7	143.39	146.93	151.02
0.8	144.33	147.56	151.50
0.85	145.20	148.50	152.68

(b) Effect of change in capacity on production cost (\$ t^{-1}) of regular and steam pretreated pellets.

	Wheat Straw		Switchgrass	
Change in capacity	Regular	Steam pretreatment	Regular	Steam pretreatment
0%	96.38	147.48	92.05	152.36
-10%	96.93	148.74	92.76	153.39
-20%	97.95	149.45	93.23	154.02

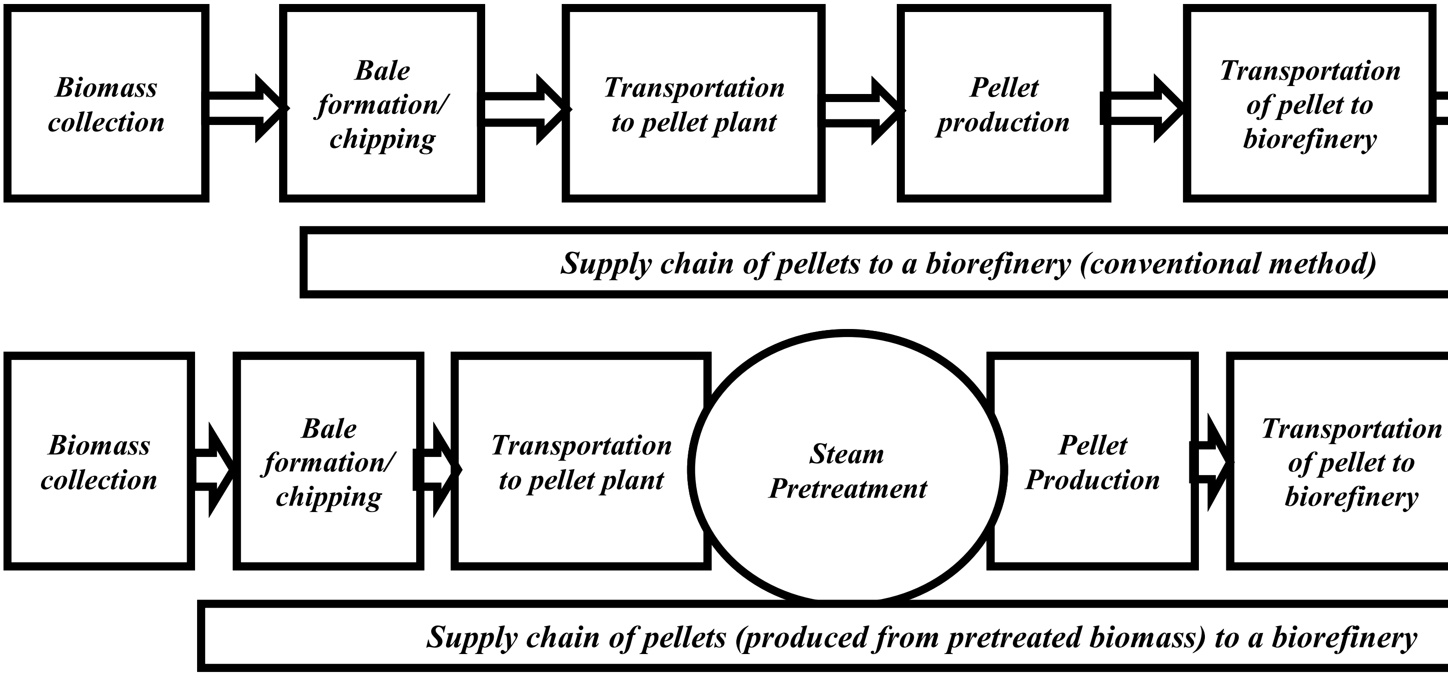


Fig. 1: Process flowchart showing collection of biomass to pellet production

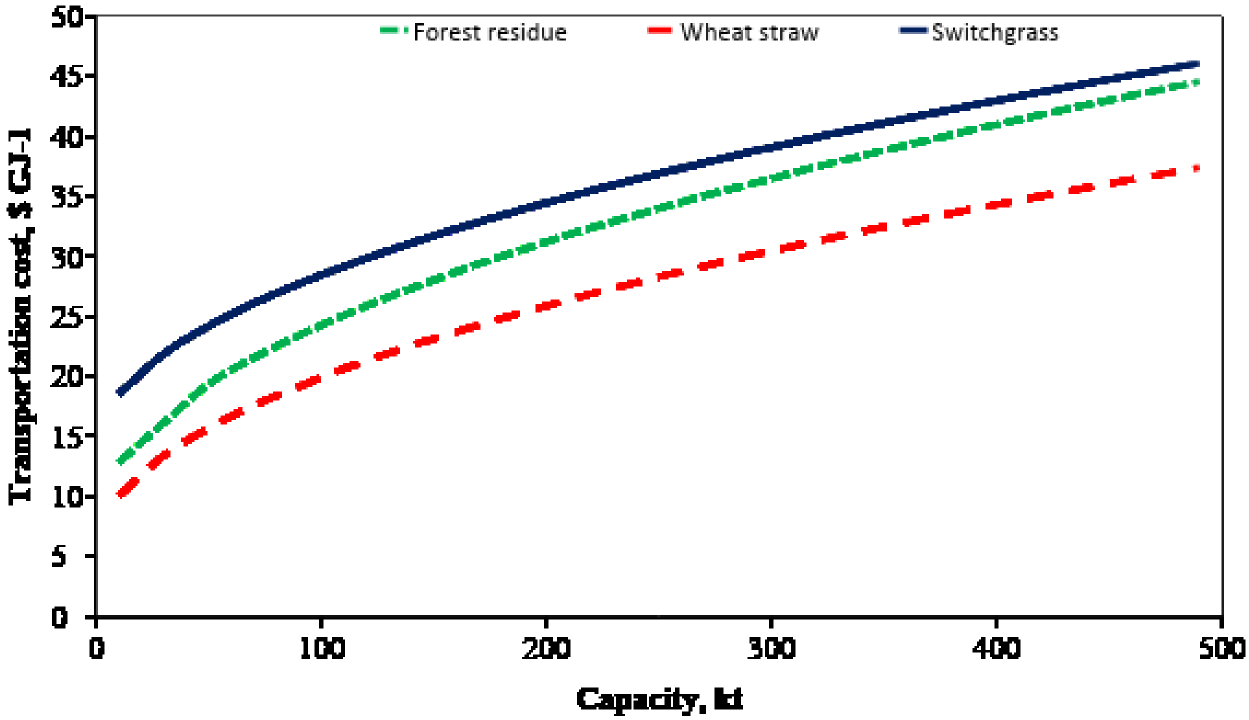


Fig. 2: Transportation cost of straw as a function of pellet plant capacity

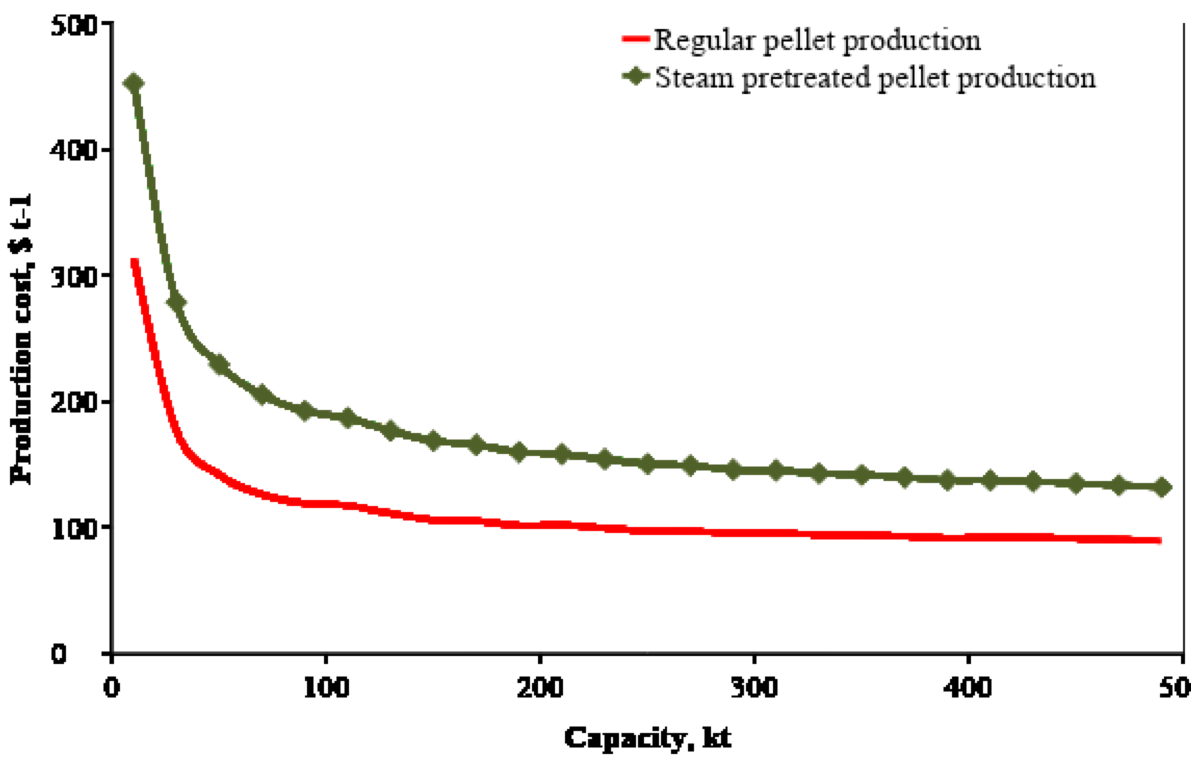
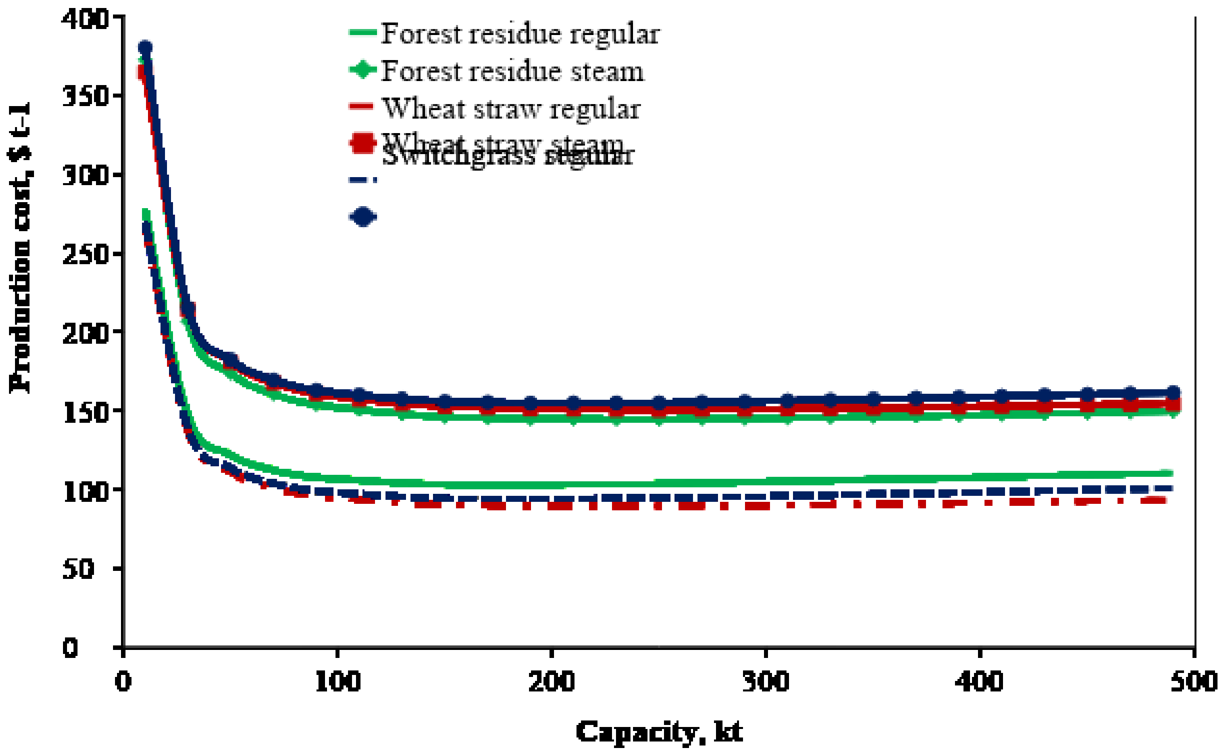


Fig. 3: Change of unit capital cost of pellet production plant with capacity

(a)



(b)

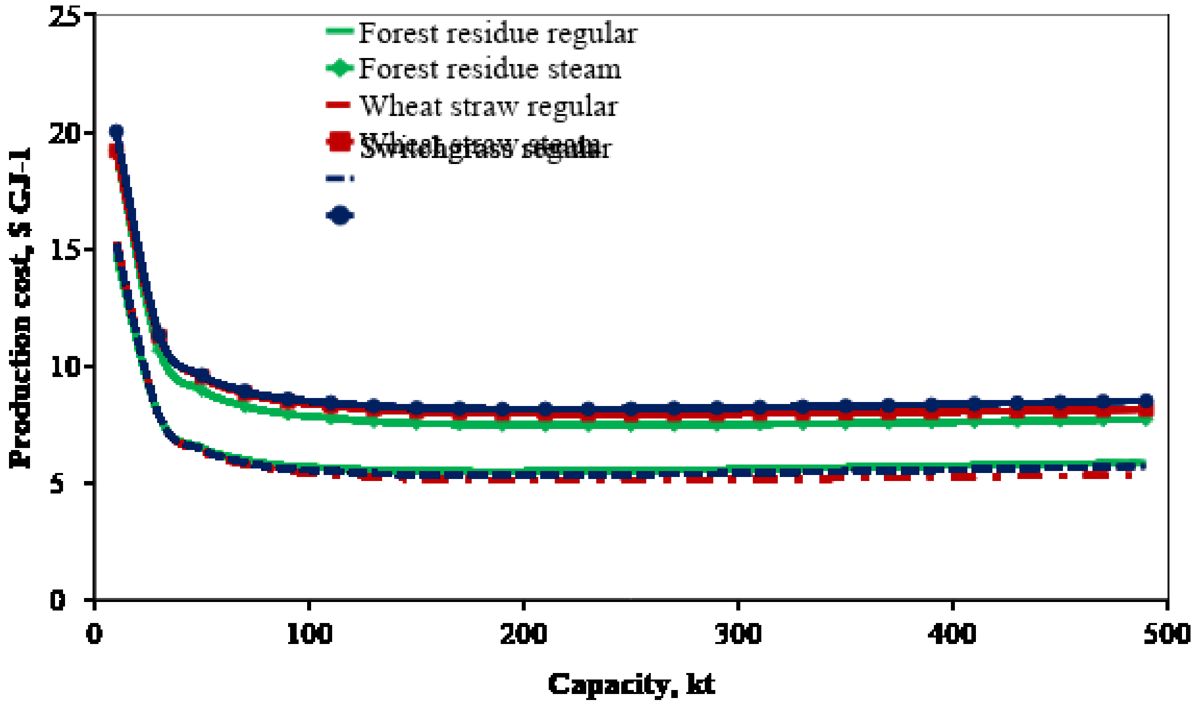
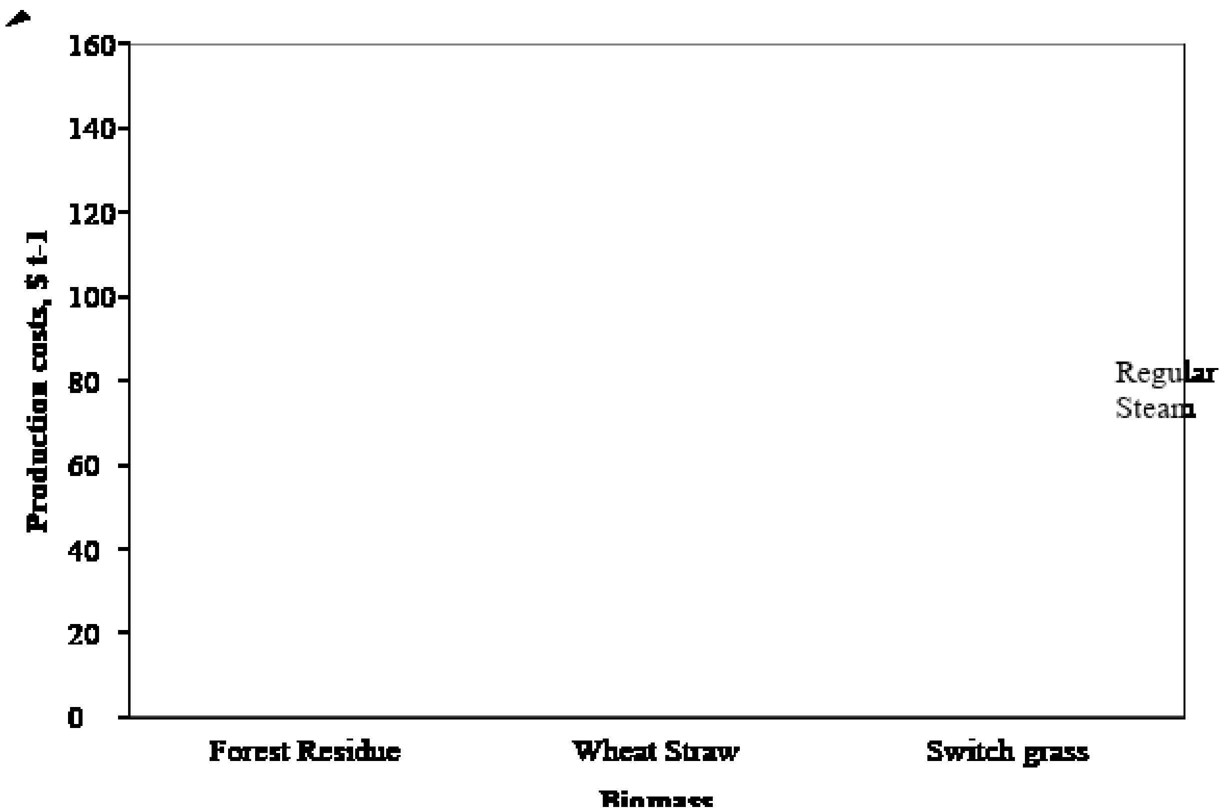


Fig. 4: Pellet production costs for the three feedstocks in (a) $ t^{-1} (b) $ GJ^{-1}

(a)



(b)

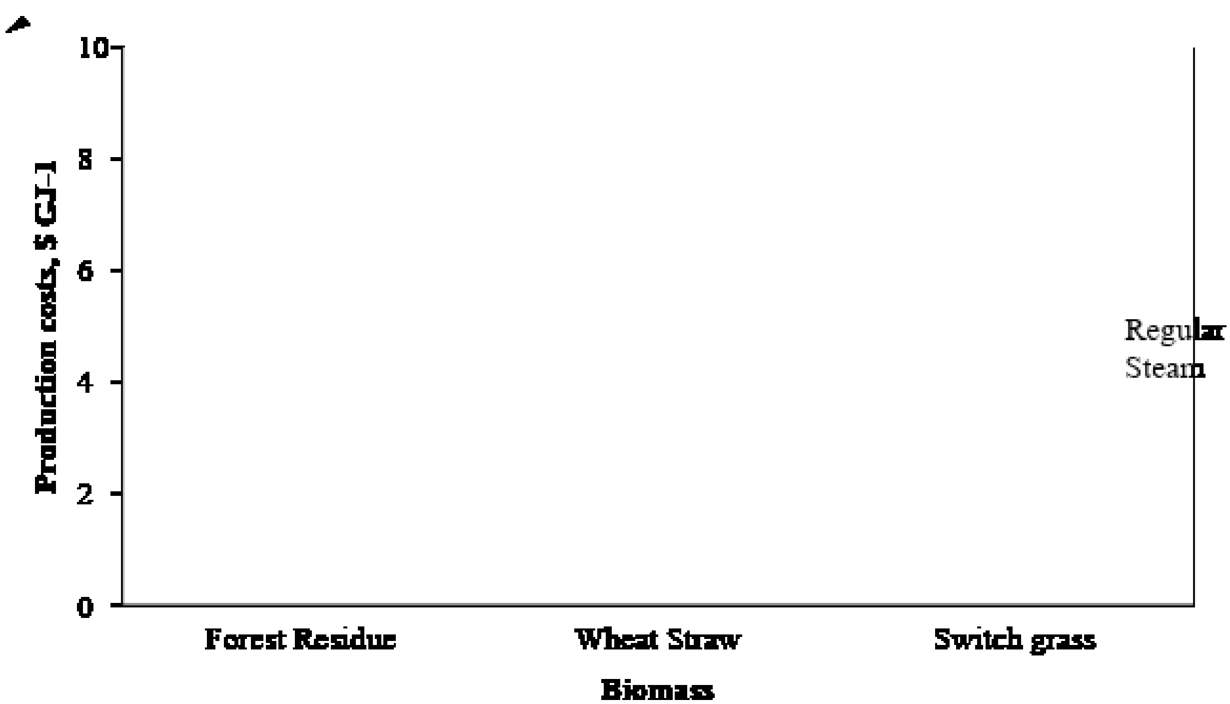


Fig. 5: Comparative analysis of production costs for the base case in (a) \$ t^{-1} (b) \$ GJ^{-1} for the three feedstocks

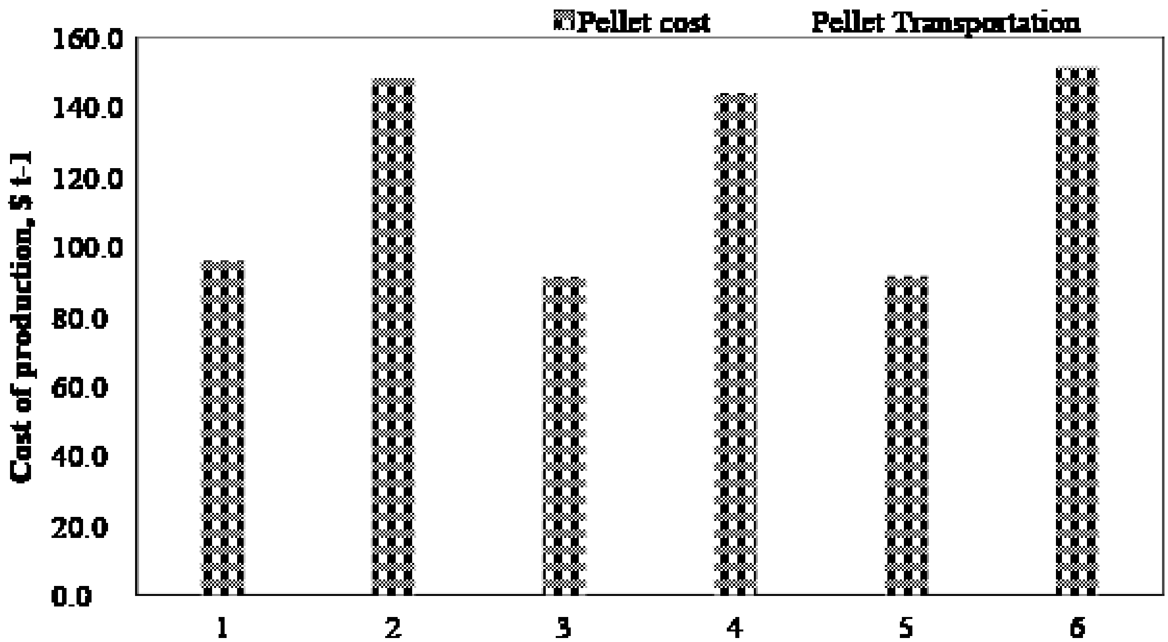


Fig. 6: Effect of bulk density on pellet transportation cost

Regular pellet

Steam pretreated pellet

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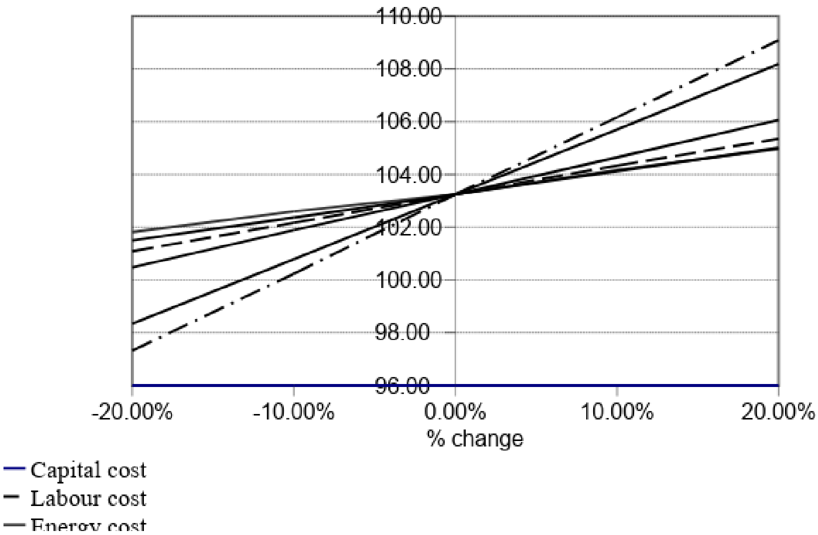

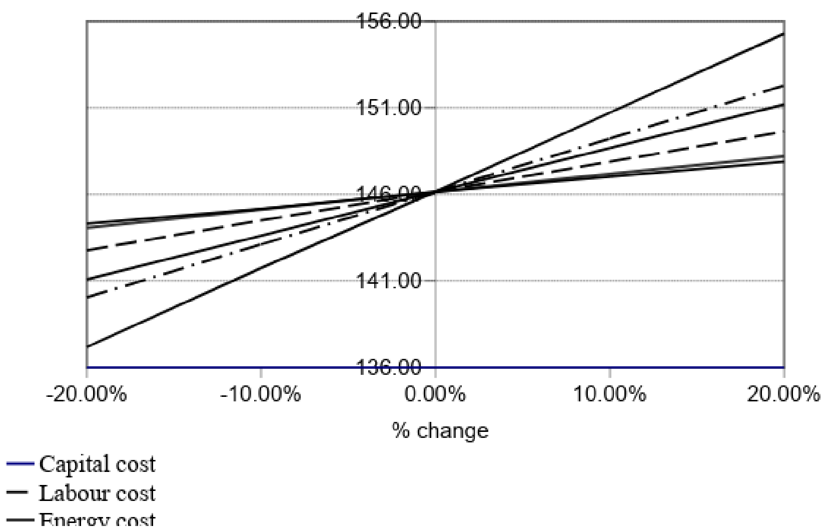

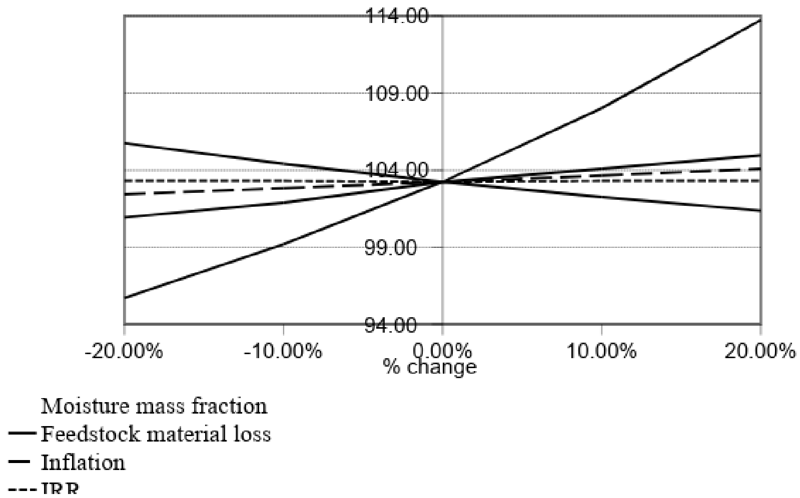

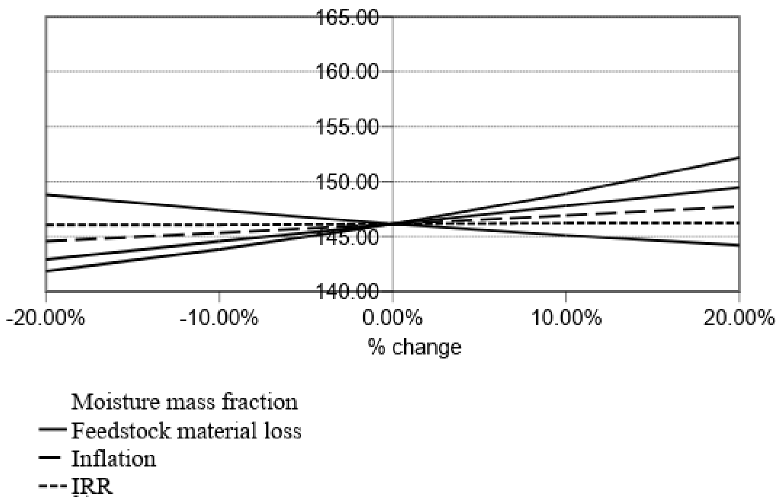

(a). **Forest residue**

Regular pellet Steam pretreated pellet

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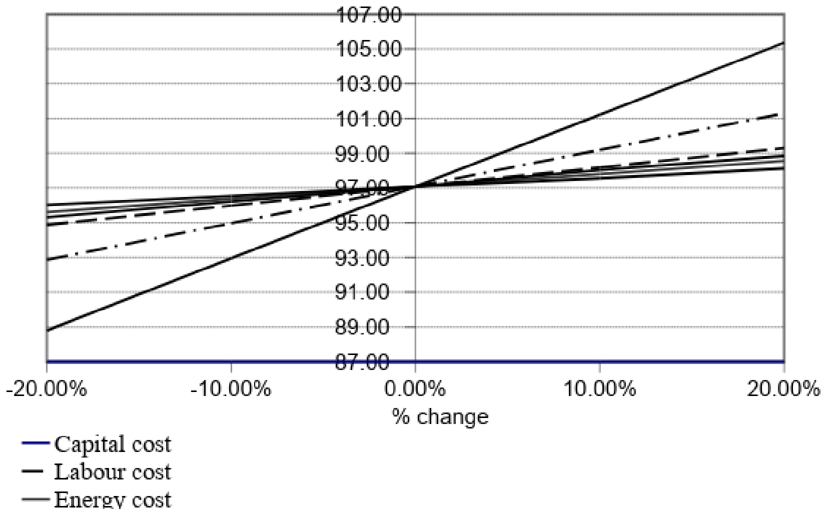
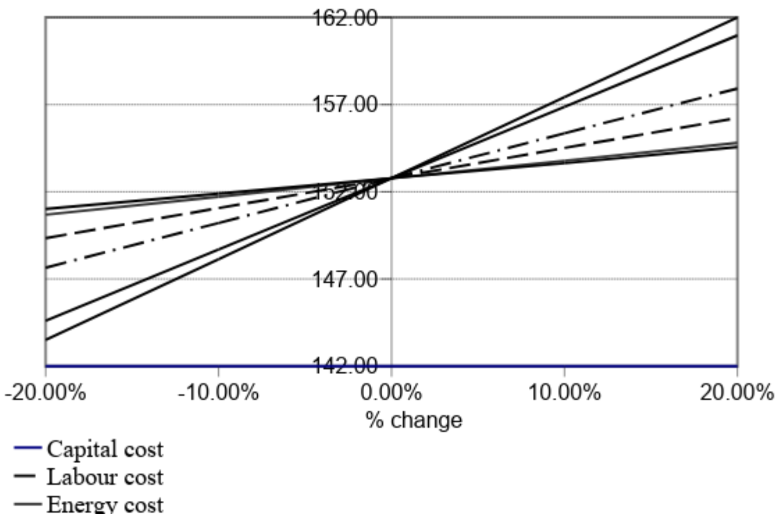
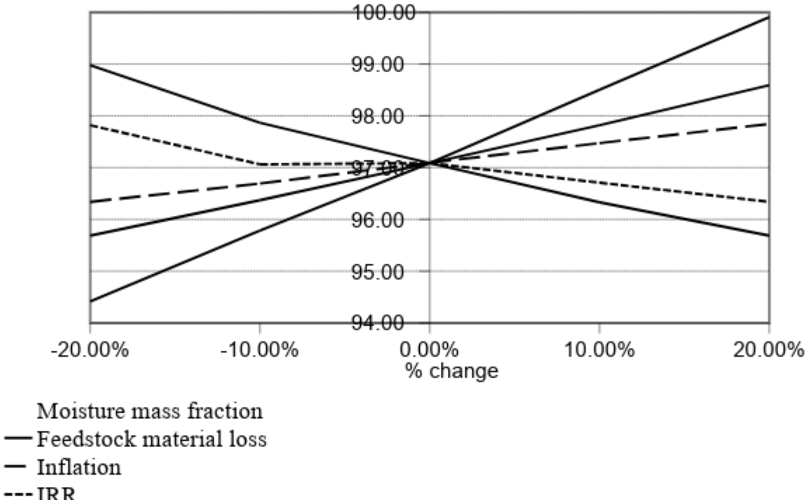
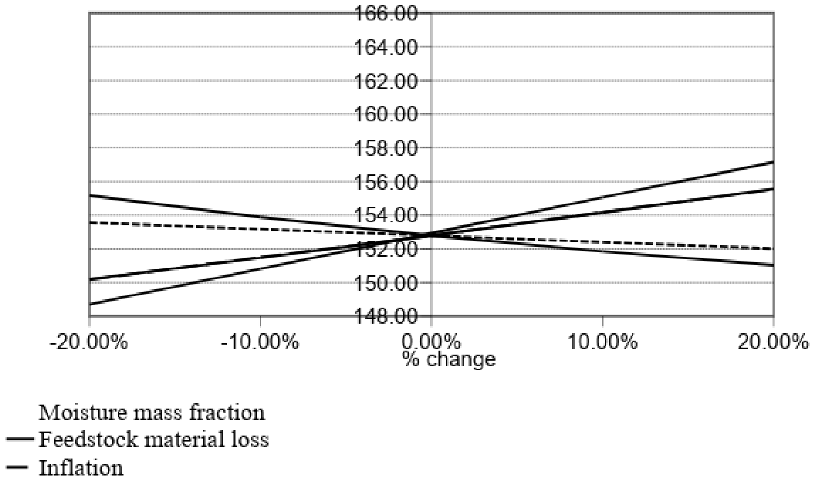

107.00
105.00
103.00
101.00
99.00
97.00
95.00
93.00
91.00
89.00
87.00
-20.00%
-10.00%
0.00%
10.00%
20.00%
% change
Capital cost
Labour cost
Energy cost


162.00
157.00
152.00
147.00
142.00
-20.00%
-10.00%
0.00%
10.00%
20.00%
% change
Capital cost
Labour cost
Energy cost

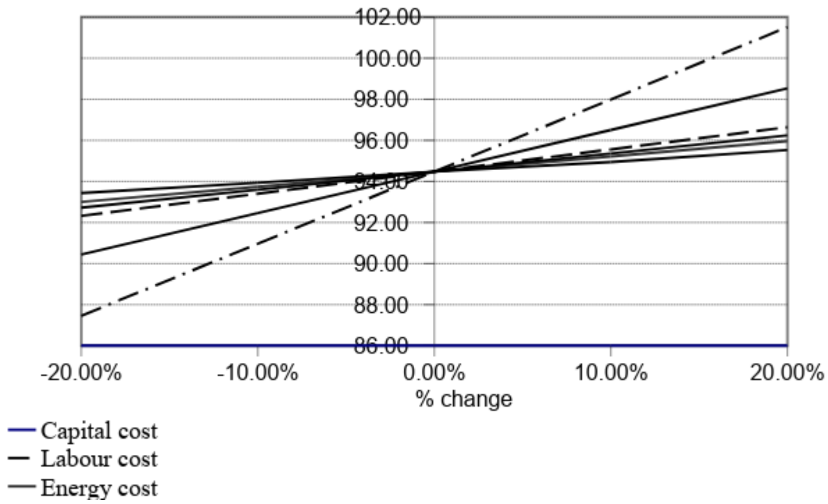


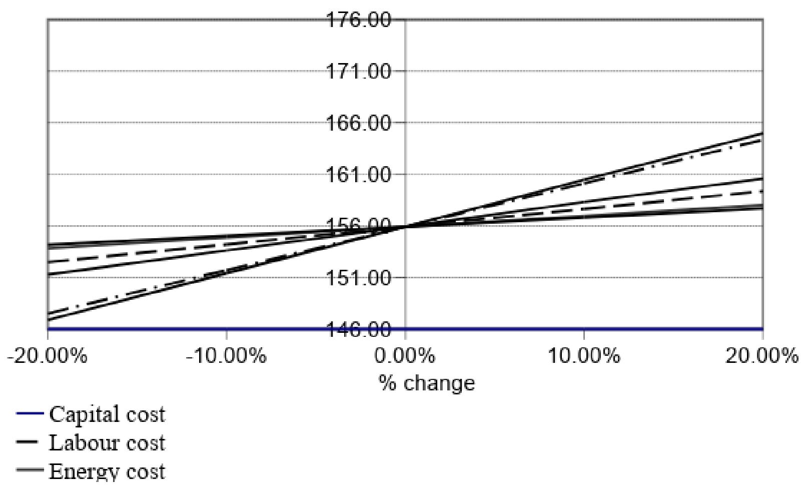


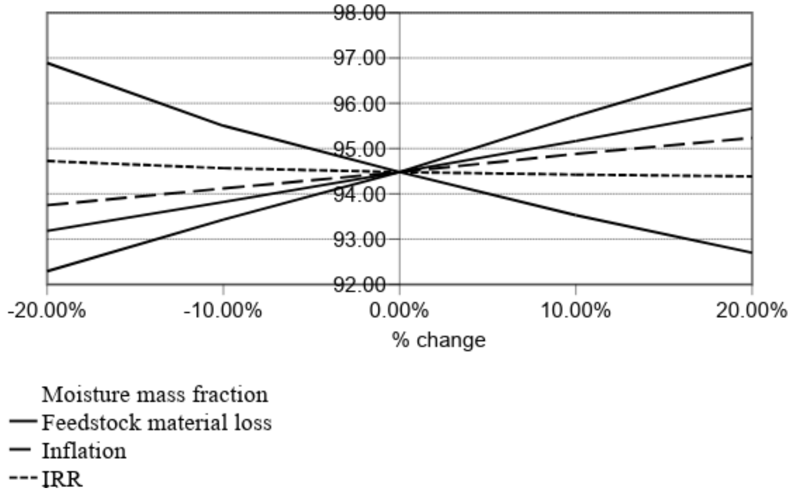
(b). **Wheat straw**

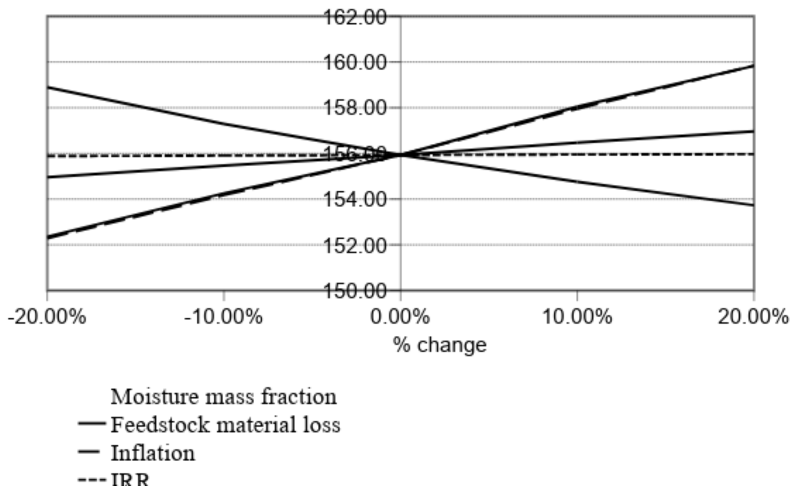
Regular pellet Steam pretreated pellet

Total cost of pellet production ($


102.00
100.00
98.00
96.00
94.00
92.00
90.00
88.00
86.00
-20.00%
-10.00%
0.00%
10.00%
20.00%
% change
Capital cost
Labour cost
Energy cost


176.00
171.00
166.00
161.00
156.00
151.00
146.00
-20.00%
-10.00%
0.00%
10.00%
20.00%
% change
Capital cost
Labour cost
Energy cost



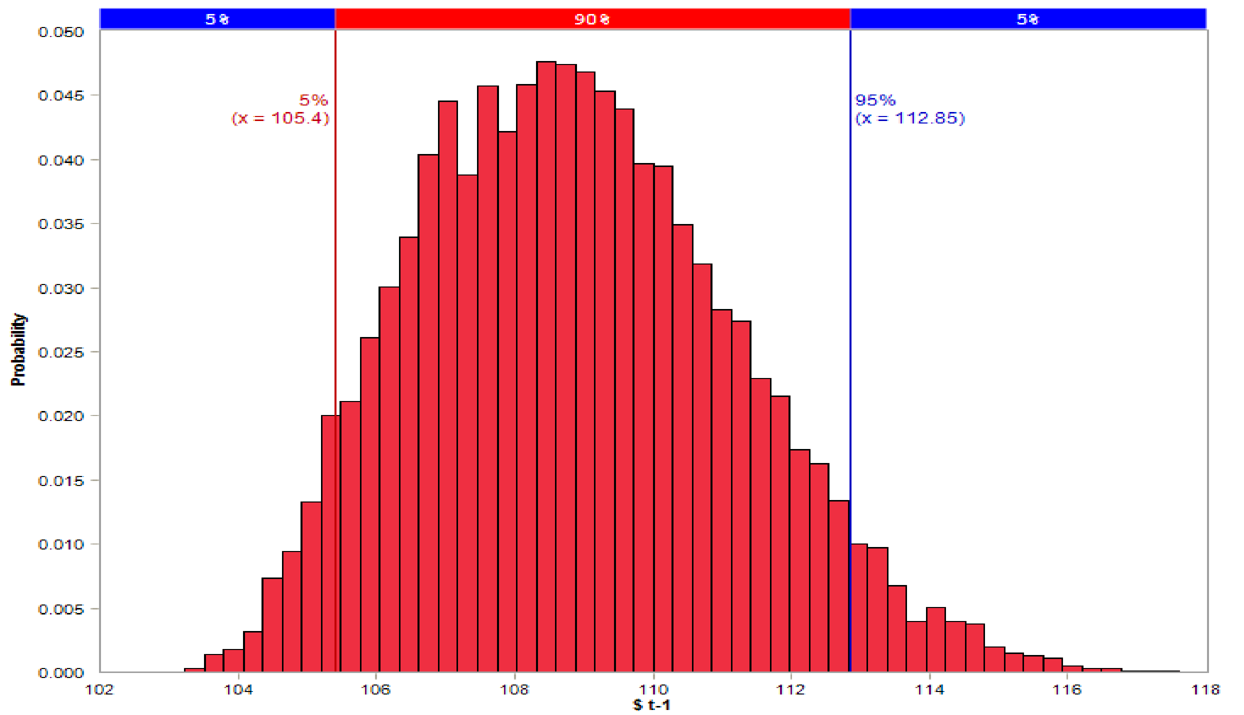


(c). Switchgrass

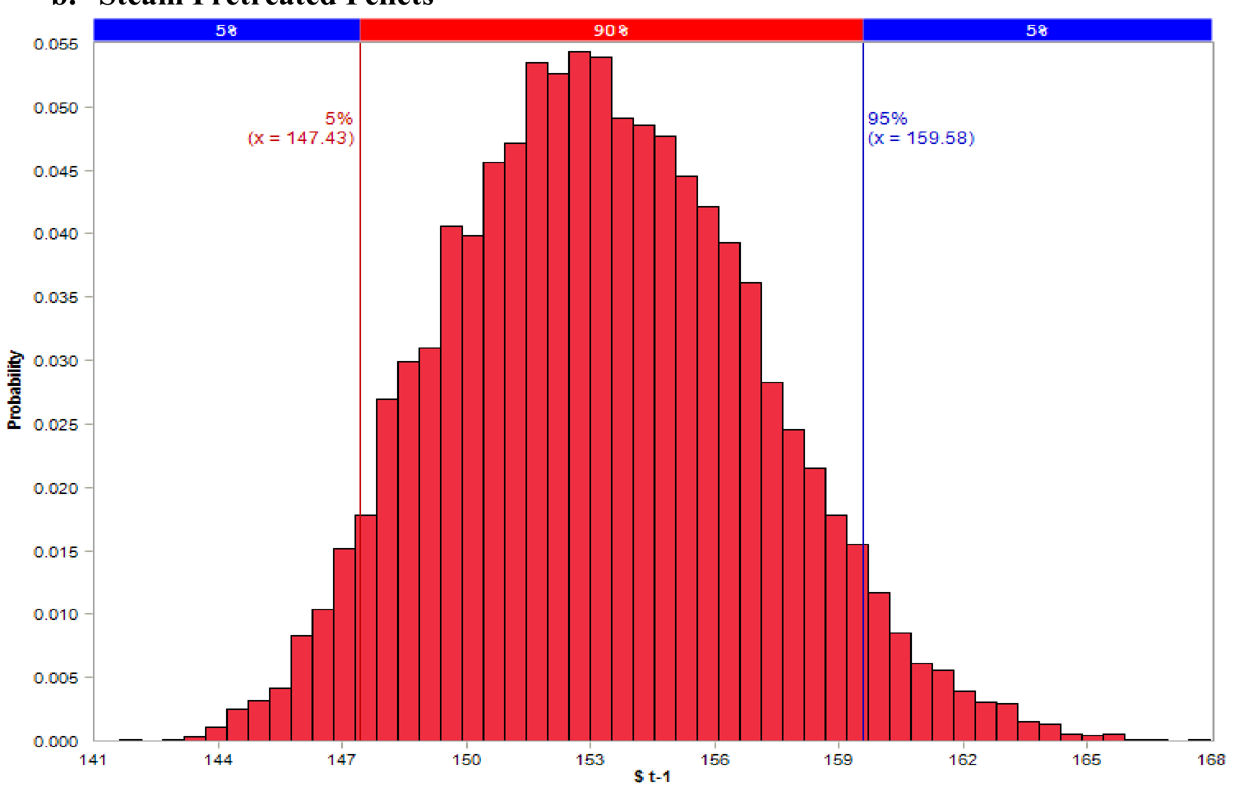
Fig. 7: Sensitivity analysis of regular and steam pretreated pellet

1. Forest Residues

a. Regular Pellets

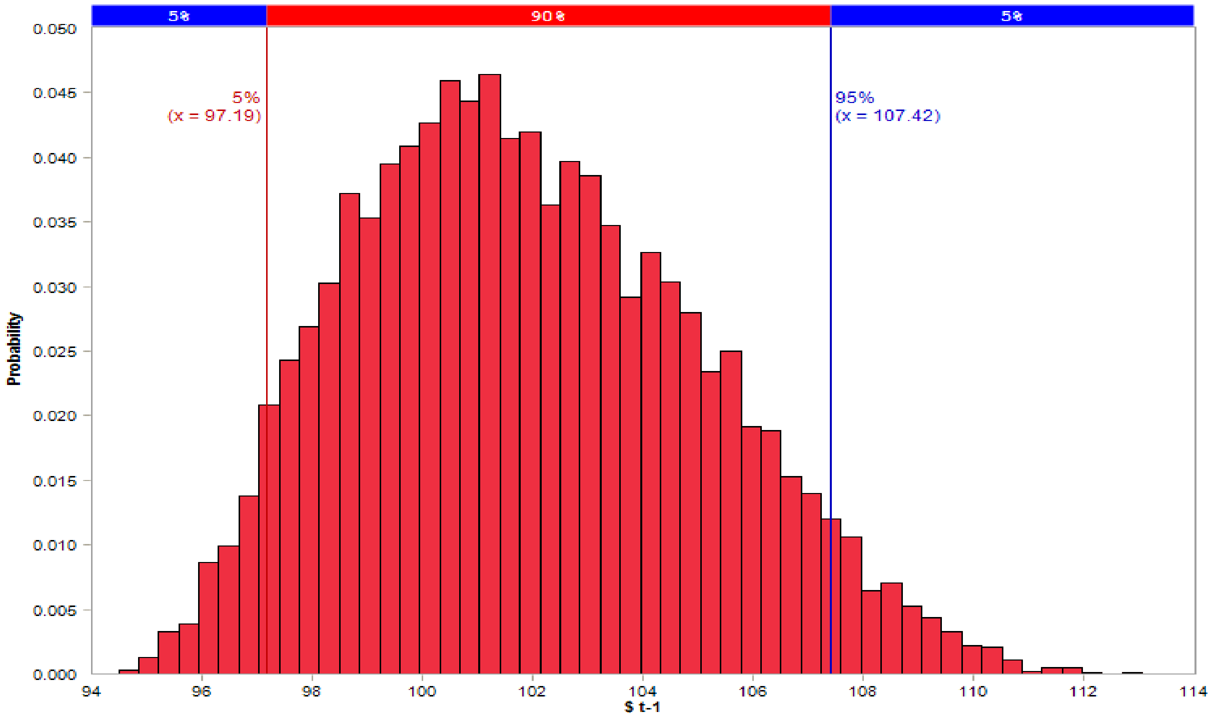


b. Steam Pretreated Pellets

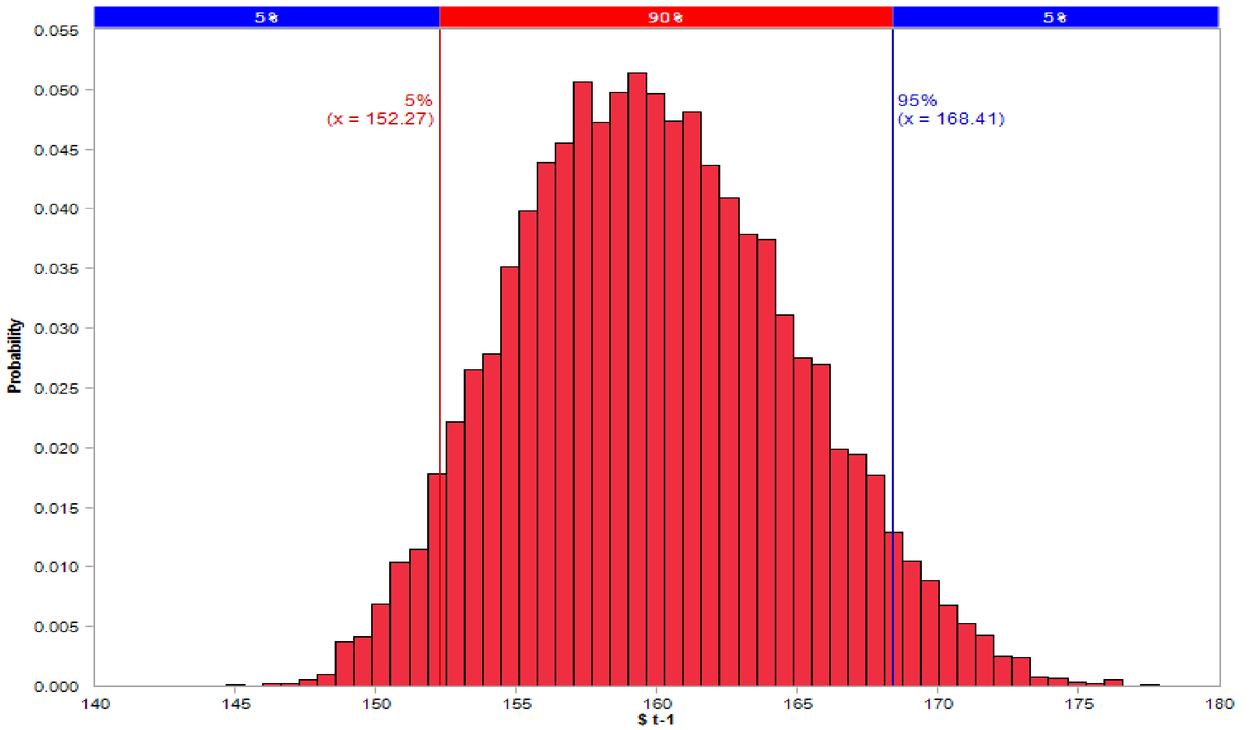


2. Wheat Straw

(a). Regular Pellets

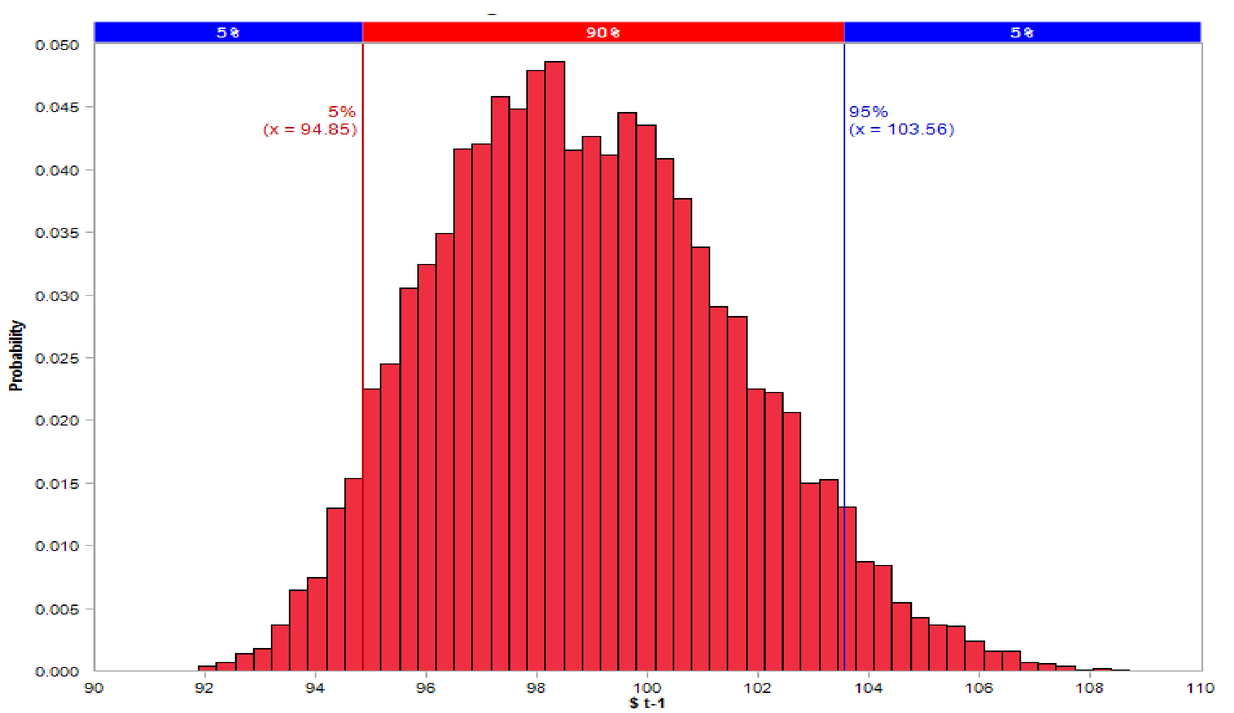


(b). Steam Pretreated Pellets



3. Switchgrass

(a). Regular Pellets



(b). Steam Pretreated Pellets

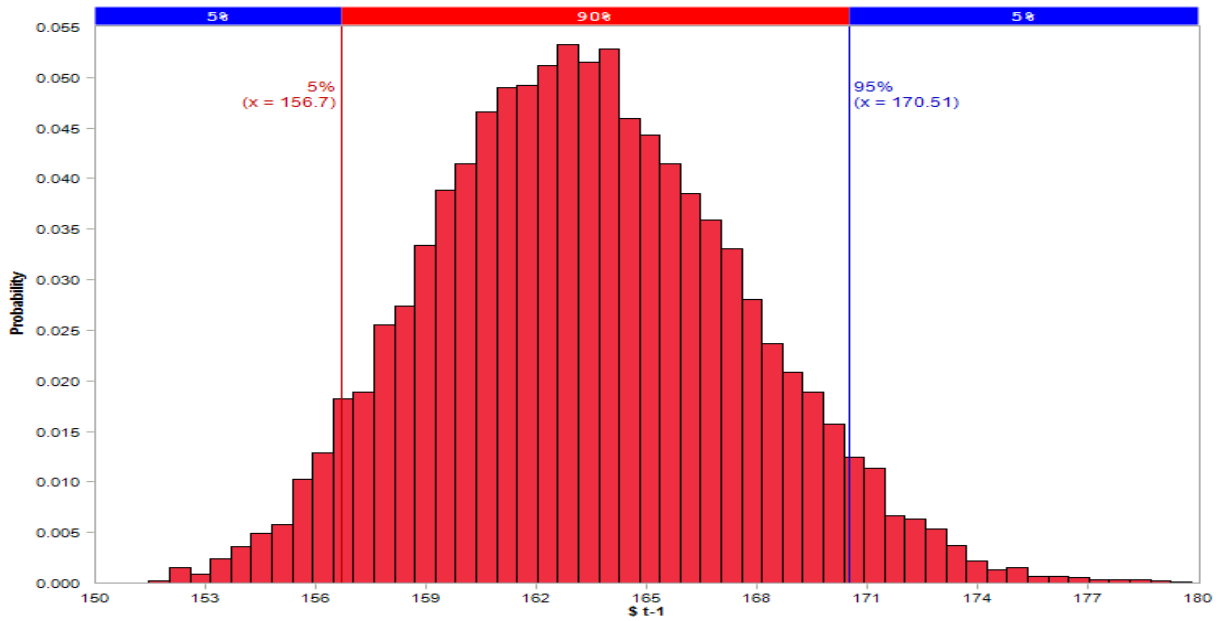


Fig. 8: Uncertainty analysis for the three feedstocks, forest residue, wheat straw and switchgrass: (a) Regular pellets, (b) Steam pretreated pellets