Energy Return on Investment and Techno-economics of Pellet Production from Steam Pretreated Biomass

by

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Abstract

Utilization of raw ligno-cellulosic biomass for energy use is limited because of its low heating value and low yield per unit area of biomass. Pellets are densified and compressed form of biomass which has less moisture and higher energy density compared to raw biomass. Pellets are typically produced by the forest industry from residues generated at the mills. This thesis aims are technical and economic assessment of the production of pre-treated biomass based pellets. Steam-pretreated biomass-based pellets have improved mechanical strength, hydro-phobicity, and energy density compared to wood pellets. A process model was developed for the production of pellets from stream-pretreated biomass. The process models were developed for three feedstocks, forest residues, agricultural residues, and switchgrass. These process models were developed to determine the net energy ratio (NER) for both regular and steam pretreated pellet processes and were validated through experimental work. NER is a ratio of the net energy output to the total net energy input from non-renewable energy source into the system. The results show that steam pretreated wood-based pellets has the lowest process NER at 1.29 followed by pellets from stream-pretreated switchgrass at 1.37. The highest NER is for the pellets from steam-pretreated straw at 1.76. The main reason for high NER of straw is that less energy is required for steam pretreatment and drying for straw than for the other two feedstocks. A techno-economic model was also developed for the three feedstocks to evaluate production cost of steam-pretreated biomass-based pellets. Minimum production cost and optimum plant size were determined for pellet plants for the same three biomass feedstocks. The life cycle cost, from harvesting to the delivery of the steam-pretreated biomass-based pellets to the co-firing facility, was evaluated and compared to the conventional pellets. The values vary from 116-122 \$ $tonne^{-1}$ for regular pellets and 180-190 \$ $tonne^{-1}$ 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 of the production plant at which the cost of production is minimum) is found to be 190,000 tonnes for regular pellet production and 250,000 tonnes for steam pretreated pellets. Model sensitivities and uncertainty analyses were carried out to identify sensitivity parameters and effects of error in the model error.

Preface

The research has been funded by BioFuelNet Canada Inc. (59_Kumar_West_SEES) and University of Alberta. Chapter 2 of this thesis has been published as Shahrukh H, Oyedun AO, Kumar A, Ghiasi B, Kumar L, Sokhansanj S. Net energy ratio for the production of steam pretreated biomass-based pellets. Journal of Biomass and Bioenergy 2015; 80:286. I was responsible for data collection, analysis as well as manuscript composition. Dr. A. O. Oyedun helped in editing and reviewing the data, models and manuscript. Dr. A. Kumar contributed to the development of the concept of this paper, helped in editing and reviewing the data and models and manuscript and overall supervision of the research work. This work was also done in collaboration with the researchers from the University of British Columbia including Drs. B Ghiasi, L Kumar and S. Sokhansanj. They assisted in data collection and experimental work involved in the research.

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Dedicated to my parents and wife

Hasina Akhter, S M Habibur Rahman & Nafisa Mahbub

List of Abbreviations

AR	Agricultural Residue
dt	dry tonne
GHG	Greenhouse gas
GJ	Gigajoule
GVW	Gross Vehicle Weight
ha	Hectare
hr	Hour
IEA	International Energy Agency
IHS	Information Handling System Inc.
ISO	International Organization for Standardization
km	Kilometer
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LHV	Lower heating value
MJ	Mega Joule
mm	Millimeter
Mt	Million tonne
MW	Mega Watt
NER	Net Energy Ratio
NG	Natural gas
NREL	National Renewable Energy Laboratory
OD	Origin-destination
PCCI	Power Plant Cost Index
UTC	Unit Transportation Cost
WPAC	Wood Pellet Association of Canada
wt%	Weight

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Chapter 1: Introduction

1.1. Background

The primary sources of renewable energy are wind, geothermal heat, sunlight, water, and biomass. Renewable energy constitutes 16.7% of global energy consumption. About 8.7% of the total renewable energy consumption is from biomass. A renewable (regrowable) fuel derived from a currently living organism or the by-product of a currently living organism. The main sources of lingo-cellulosic biomass are whole forest, forest residues, agricultural residues, purposely grown crops, animal manure, sewage sludge and other by-products. Lignocellulosic biomass is collected from the field and undergoes conversion to produce biofuels like bio-ethanol, pellets, and bio char. The use of lignocellulosic biomass (e.g., wood residues and agriculture residues) for bio-energy and biofuels in place of fossil fuels can help to address a number of global environmental problems [1].

Canada currently acquires 16% of its energy from renewable energy sources. Biomass from agricultural residues, forest residues, and switchgrass account for 6% of the total primary energy source [1]. However, fossil fuels still contribute a large portion of the total primary energy. High fossil fuel use leads to high greenhouse gas (GHG) emissions. One of the strategies for curbing GHG emissions is the replacement of fossil fuels with carbon neutral fuels. Evaluation of biomass-based fuels also leads to the requirement of appropriate forms of biomass-based fuels that can replace fossil fuels through co-firing. The requirement of appropriate forms of biomass-based fuels will reduce the production costs of biofuels since appropriate biomass fuels improve energy density and transportation cost.

Currently, lignocellulosic biomass (e.g., forest residues, agricultural residues such as straw, energy crops such as switchgrass) use is limited because of its low heating value and low yield per unit area of biomass. Raw lignocellulosic biomass feedstocks used for bio-energy and biofuels production have low bulk density (in the range of 75-200 kg m^{-3}) and have a high mean water mass fraction (in the range of 14-50%). However, regular wood pellets with high bulk density (600-800 kg m^{-3}), low mean water mass fraction (5-8%), and regular shape and size make a lucrative feedstock for bio-refineries. Pellets are a densified and compressed form of biomass that has less moisture and higher energy density compared to raw biomass. The pellet production supply chain currently consists of drying, grinding, pelleting, cooling, screening, and bagging [1]. However, there is potential of improvement of durability and bulk density of the regular pellets and the associated cost of production.

The steam pretreatment process includes pre-treatment of the material with saturated steam before its conversion to pellets. Even though pelletization leads to energy densification and bulk density improvement, pellet durability and energy density need to be improved further to ensure effective storage and handling [3, 4]. The real effect of steam pretreatment, also known as Masonite technology [5], at temperatures ranging from 180–240 ^{0}C, is decompression of the saturated steam from the Stake/Masonite gun environment to cause rapid expansion that ruptures the cellular structure (pressurized water in the lumen expands, flashes, and ruptures the cell walls when the external pressure is reduced) [6]. Steam pretreatment involves high-pressure saturated steam ranging from 150 to 500 psi (1.034-3.447 Mpa) that heats biomass and ruptures its rigid structure. A steam pretreatment unit can be operated in batch or continuous mode. A batch reactor is usually used in a laboratory to pretreat biomass while a continuous reactor is used by industry (SunOpta Bioprocess Inc. is one such company that uses a continuous reactor) [5]. The commercialized continuous system has been adapted for a variety of biomass feedstocks including forestry and agricultural residues like wheat straw, corn stover, switch grass, and wood chips.

Previous studies have speculated about different pretreatment methods like torrefaction, chemical pretreatment, and steam pretreatment for improvement in feedstock quality. According to these studies, steam pretreatment leads to improved mechanical strength, hydro-phobicity, and energy density of wood pellets [4, 7, and 8]. The previous studies also showed that the mean water mass fraction of the produced solid increased by up to two times after steam pretreatment [4,8].The additional moisture absorbed during steam pretreatment requires additional drying energy [9]. There are limited data available on the specific energy consumption of the steam pretreatment process and the effect of steam pretreatment at different temperatures on the net energy ratio (NER) of the entire process. The NER is a ratio of the net energy output to the total net energy input from a non-renewable energy source into the system. Similarly, there are no assessments on the varying scale of application of steam pretreatment in pellet production.

Previous studies have also evaluated the economics of biomass-based energy from the perspective of generic models [1]. The cost of producing pellets from sawdust has been reported by Mani et al. [9], who found that pellets can be produced from sawdust at a cost of \$51 t^{-1} at a plant capacity of 45,000 t. A European pellet production scenario has been reported by Thek and Obernberger [1] predicting the capital cost and production cost of saw dust based pellets in European setting. Urbonowski [1] used their study to evaluate the capital cost of regular pellet production plant. Other researchers evaluated the production cost of pellets in Europe and elsewhere [1]. However, none of this research evaluated the production costs of steam pretreated pellets, nor compared production costs of regular and steam pretreated pellets. In addition there is also very limited focus on the effects of the economic optimum size of the feedstocks like forest residue, straw and switch grass 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 not only to evaluate the life cycle emissions from bio-fuel based processes but also the economic viability of combining fossil fuels with biomass-based fuels. We have conducted a detailed techno-economic assessment of the steam pretreated pellet process.

1.2. The objective of this study

The overall objective of this thesis it to conduct the technical and economic assessment of the production of pre-treated biomass based pellets. This research also quantifies the energy density benefit from steam pretreatment of pellet production and the impact of steam pretreatment on the process NER. Several authors have previously estimated NER for various biomass pathways [2, 10]; however, none has looked at the NER for steam pretreated biomass-based pellet production. The thesis also aims at development of techno-economic models to determine the costs of steam pretreated pellet production from three feedstocks: forest residue, wheat straw, and switchgrass as there is very limited information available on the costs of these types of pellets. Based on this gap in the literature, the specific objectives of this research are to:

- Develop and validate a process model for stream pretreatment of ligno-cellulosic biomass for pellet production.

- Calculate the NER of the stream pretreated pellet production process.
- Develop a data-intensive techno-economic model to evaluate production costs (\$ $tonne^{-1}$ and \$ GJ^{-1}) of steam-pretreated biomass-based pellets for the three feedstocks.
- Determine the optimum pellet production size from the three feedstocks through two processes: steam pretreated and compare it with regular pellet production.
- Perform sensitivity analyses uncertainty analyses, and Monte Carlo analyses.

1.3. The scope and limitations of this study

This study is limited to pellet production using biomass residues. The residues are:

- Agricultural residues, i.e., straw.
- Forest residues, including limbs, tops, and branches from logging operations in the forest and residues from mills.
- Energy crop especially switchgrass.

The cost of pellet production has been estimated for the western Canadian setting. The results could be used elsewhere with the appropriate modification of local cost factors.

This study is based on current technology for biomass harvesting, collection, transportation, and processing.

1.4. The organization of this thesis

This thesis consists of five chapters and is in a paper format. It is a consolidation of papers, each of which is intended to be read independently. As a result, some concepts and data are repeated.

The current chapter introduces the research objective and a general introduction into the study.

The second chapter describes the process model and net energy ratio analysis for wood-based biomass pellet production with steam pretreatment.

The third chapter discusses the process model and NER analysis of steam pretreated agricultural residues and energy crop pellets.

The fourth chapter details the development of the techno-economic model used to estimate the cost to produce pellets from steam pretreatment using three feedstocks and comparative analysis of these costs with regular pellet production costs.

Finally, chapter five presents the conclusions and provides recommendations for future research.

Appendices are provided at the end of the thesis.

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Chapter 2: Net Energy Ratio for the Production of Steam Pretreated Biomass-based Pellets[1]

2.1. Introduction

The primary sources of renewable energy are wind, geothermal heat, sunlight, water and biomass. Renewable energy constitutes 16.7% of global energy consumption. About 8.7% of the total renewable energy consumption is from biomass. Biomass is a source of renewable energy collected from plant origin. The main sources of biomass are whole forest, forest residue, agricultural residues and purposely grown crops. The biomass is collected from the field and undergoes conversion to produce bio-fuels like bio-ethanol, pellets and bio char. The use of ligno-cellulosic biomass (e.g. wood residues and agriculture residues) for bio-energy and bio-fuels in place of fossil fuels can help to address a number of global problems, such as the dependence on fossil fuels and high GHG emissions from conventional fuel, and at the same time have a positive socio-economic effect by creating jobs [1].

The challenge for the use of ligno-cellulosic biomass is limited because of its low heating value and low yield per unit area of biomass [2]. Ligno-cellulosic biomass feed stocks used for

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[1] This chapter has been published in the Journal of Biomass and Bioenergy. Shahrukh H, Oyedun AO, Kumar A, Ghiasi B, Kumar L, Sokhansanj S. Net energy ratio for the production of steam pretreated biomass-based pellets. ***Biomass and Bioenergy*** 2015; 80:286-297.

bio-energy and bio-fuels production have low bulk density in the range of 75-200 kg m^{-3} and have a high mean water mass fraction (in the range of 14-50%) [3]. However, regular wood pellets with high bulk density (600-800 kg m^{-3}), low mean water mass fraction (5-8%) and regular shape and size make a lucrative feedstock for bio-refineries. Pellets are densified and compressed form of biomass which has less moisture and higher energy density. The pellet production supply chain currently consists of drying, grinding, pelleting, cooling, screening, and bagging. All of these processes are energy intensive and significantly impact specific energy consumption. Detailed unit operation reviews of the pelletization processes have been provided elsewhere in the literature [4-8].

The pelletization process starts with the collection of forest residues, which are sent to a shredder to be formed into wood chips. The wood chips that will be pelletized are transported to the pellet mill. The mean water mass fraction of these woods chips is around 50%. These chips require drying before being comminuted and pelletized. The size of the dryer can affect energy consumption significantly. The dryer unit used most often in pellet production plants is a rotary drum dryer [8, 9]. Once dry, chip mean water mass fraction is around 8-10% [9]. The dry chips are fed to a hammer mill for grinding and ground to a particle size of 3.2 mm or less [3]. The particle size can be changed in the hammer mill by varying the mesh screen size [10]. In summary, there are two steps in reducing forest residue particle size: chopping by shredder followed by grinding by hammer mill.

Pelletization of the feedstock is done by passing the feedstock through a pellet mill with a roller that extrudes the feedstock and pushes it though a die hole, compressing it into pellets. The feed rate of pellet mills are adjusted with their service life; this variation of feed rate is done purposely to ensure pellet quality since high feed rate impacts the compression provided by the die reducing pellet density [11]. A pellet mill's efficiency depends on a number of parameters like die temperature, die and roller configuration, and pressure [9]. Once pellets are formed, they are cooled from a temperature of 95 – 100 °C to 25 °C using air.

Recently, densified biomass has been receiving significant attention. Improving the physical and combustion characteristics of densified biomass could result in a superior quality product [1, 4]. Ligno-cellulosic biomass-based pellets are considered to be carbon neutral, which means that the emissions from their combustion are offset by the carbon absorbed by the plants during their re-growth [11]. Furthermore, regular pellet bulk density is 4-10 times higher than that of the ligno-cellulosic biomass received at the gate [11] and hence pellets are much easier to handle and transport. These above-mentioned factors make regular pellets a lucrative option for bio-energy and bio-fuels.

Biomass pellets have higher energy content, burning efficiency and leads to lower emission [12]. Current Canadian pellet production is 1.3 Mega tonnes per year with plants running at 65% capacity of the maximum capacity of plant. The produced pellets were exported mostly to Europe, the USA, and Japan for electricity production [1]. Compared to Canada, the USA has seen a much higher and more rapid growth in pellet production and export of wood pellets than Canada [13]. A breakdown of Canadian pellet production by province shows that 65% of the country's production capacity is from British Columbia (B.C.), followed by Alberta, Quebec, New Brunswick, Nova Scotia, and Newfoundland, which together contribute 35%. B.C. pellet plants are larger than those in Eastern Canada simply due to higher demand in B.C. The pellets produced in Canada are mainly used for export to Europe, the USA, and Japan [1].

The biomass feedstock supply logistic cost is around 30-50 % of the total bio-energy production cost [14]. It is essential to optimize the preprocessing of biomass into densified pellets for cost-effective bio-energy production. Regular pellet production leads to some improvement in bulk density and calorific value. But it fails to increase it significantly. Hence, the need for different pretreatment processes arises to improve the bulk density and calorific value. Further improvement can be achieved by increasing the yield and reducing the energy required for preprocessing. Two major technical problems during preprocessing need to be addressed. The focus of our research has been to improve the heating value and evaluate the specific energy consumption for both regular and steam-pretreated pellet production.

The steam pretreatment process pretreats the material by using saturated steam, thereby adding another process, but the entire supply chain remains the same as that of regular pelletization process. Even though pelletization leads to energy densification and bulk density improvement, pellet durability and energy density need to be improved further to ensure effective storage and handling [15, 16]. The real effect of steam pretreatment, also known as Masonite technology [17], at temperatures ranging from 180–240 ^{0}C is decompression of the saturated steam from the Stake/Masonite gun environment to cause rapid expansion which ruptures the cellular structure – as pressurized water in the lumen expands, flashes and ruptures the cell walls when the external pressure is reduced [18]. Steam pretreatment involves high pressure saturated steam ranging from 150 to 500 psi (1.034-3.447 Mpa) to heat biomass to rupture the rigid structure of the biomass. A steam pretreatment unit can be operated in batch or continuous mode. A batch reactor is usually used in a laboratory to pre-treat biomass while a continuous reactor is used by industry (Sun Opta Bioprocess Inc. is one such company that uses a continuous reactor). The commercialized continuous system has been adapted for a variety of biomass feed stocks including forestry and agricultural residues like wheat straw, corn stover, switch grass, and wood chips.

Previous studies have assessed different pretreatment methods like torrefaction, chemical pretreatment and steam pretreatment. Based on these studies, steam pretreatment leads to improved mechanical strength, hydro-phobicity, and energy density of wood pellets [16, 19, 20]. The previous studies also showed that the mean water mass fraction of the produced solid increased by up to two times after steam pretreatment [16, 20].The additional moisture absorbed during steam pretreatment requires additional drying energy [6]. There are limited data available on the specific energy consumption of the steam pretreatment process and the effect of steam pretreatment at different temperatures on the net energy ratio (NER) of the entire process. The net energy ratio (NER) is a ratio of the net energy output to the total net energy input from non-renewable energy source into the system. Similarly, there are no assessments on the varying scale of application of steam pretreatment in pellet production.

The purpose of our research is to develop a process model to evaluate the specific energy consumption of steam pretreated pellet production process and compare it to regular pellet production process at various scales. This research will also quantify the energy density benefit from steam pretreatment of pellet production and the impact of the steam pretreatment on the process NER. Several authors have previously estimated NER for various biomass pathways [21, 22], however none of these have looked at NER for steam pretreated biomass-based pellet production. Based on the gap in literature, the three main objectives of this research are to:

- Develop a process model for stream pretreatment of ligno-cellulosic biomass for pellet production
- Evaluate energy and mass balance of steam pretreated pellet production process
- Calculate the NER of the production process of stream pretreated pellet production process

2.2 Methodology and Model Details

The process simulation for the study was carried out through Aspen PLUS [23] with a focus on mass and energy balance. The entire steam pretreated pellet production process is broken down into several unit operations, which are then integrated by using mass and energy streams. The models are then validated with data collected through experimental work on steam pretreatment of ligno-cellulosic biomass. With the process model developed for this research, the specific energy consumption of each unit operation can be evaluated at the small scale. The model will be used to create a correlation between the energy consumption of the two process methods at the small scale and to use this correlation to predict the NER for the two processes at the large scale. The research work and the developed model will help to evaluate the NER of the steam pretreatment process and compare it with the NER of the regular pellets.

2.2.1 Feedstock

The feedstock chosen for the model is the forest residues from harvesting of softwoods. Normally, the dry mass fraction of tree is 3-8% bark, 3-8% needles (leaves), 7-15% branches, and 65-80% trunk. Conifers such as pine, spruce and fir are softwoods. Typically, dry mass fraction of pine consists of 40% cellulose, 28% hemicelluloses, 28% lignin and 4% extractives, and the outer bark can have up to 48% lignin [15]. A growing tree is approximately 50% water with variations from 35-65% between winter and summer. Wood extractives have the highest heating value in the wood, and lignin has a higher heating value than both cellulose and hemicelluloses. The mean water mass fraction assumed for the model is 45% [2].

2.2.2 Description of the experimental unit

For this study, the steam pretreated pelletization process is configured by integrating steam processing with a pellet making unit of the same size. The integrated system consists of a steam pretreatment unit, a convective dryer unit, a hammer mill unit, and a pellet making unit. Table 2-1 shows the fuel property improvement due to steam pretreatment earlier studied by Lam [17]. Other detailed inputs for the units are shown in Table 2-2.

Table 2-1: Fuel property improvement due to steam pretreatment

Condition	Unit	Untreated	1	2	3	4	Source
Treatment temperature	^0C	-	190	200	210	220	
Elemental analysis							
C mass fraction	% of dry solid	48.44	49.14	50.46	52.42	53.09	
H mass fraction	% of dry solid	6.23	6.08	6.1	5.95	5.91	
N mass fraction	% of dry solid	0.22	0.17	0	0.18	0.17	[16]
O mass fraction	% of dry solid	45.28	44.63	43.12	41.29	40.76	
Proximate analysis							
Fixed carbon	% of dry solid	14.4	16.9	17.7	20.9	22.5	
Volatile matters	% of dry solid	85.6	83.1	82.3	79.1	77.5	
Ash content	% of dry solid	3.1	3.2	2.2	2.5	2	

Table 2-2: Input data for the steam pretreated pellet simulation

	Unit operations	Model input conditions	Source
Boiler	Electric boiler	1.88 MPa and 210 ^{0} C	[18]
Steam reactor	Capacity	2.5 liter	(Based on previous experiment)
	Biomass feedstock	Douglas fir wood chip	
	Reactor type	Yield reactor, where yield defined by ultimate and proximate analysis	
	Residence time	10 min	[18]
	Water mas fraction of input biomass & solid yield	45%, 97%	(Calculated from Experimental result)
Dryer	Inlet temperature	80 ^{0}C	[2]
	Target moisture level	15%	Assumed
	Specification & model type	Thelco convection dryer operating at 80% efficiency drying at 6 kg h^{-1}	[2]
Hammer mill	Kicks constant	32 J kg^{-1}	
	Solid recovery	96%	(Based on previous experiment)
Pellet mill	Inlet Temperature	80 ^{0}C	(Based on previous experiment)
	Solid Recovery	95%	
	Mass Flow	12 kg h^{-1}	

The wood feedstock is pretreated using saturated steam at temperatures in the range of 190-230 ^{0}C. Pre-steaming is done at the beginning of the experiment to remove the air in the feed stream. The model created in Aspen PLUS also takes into account this scenario using excess steam to remove air in the feed stream. Based on the experiments done on steam pretreatment process, it was found that at temperatures beyond this, the solid yield falls significantly. The steam pretreatment is done with a Stake Tech steam gun with a 2.6 liter capacity and biomass flow rate of 6 kg h^{-1} and Douglas fir wood chips pretreated at 210 ^{0}C for 10 minutes. After steam pretreatment in a moisture analyzer, the pretreated biomass is tested for mean water mass fraction. The solid yield of the pretreated biomass is found to be 97% with a mean water mass fraction of 82%. Proximate and ultimate analyses of the biomass are then carried out to assess the change in heating value.

The steam-pretreated biomass is dried in a convective dryer at 80 ^{0}C for 1 hour to reach the target mean water mass fraction of 15%. The energy used for drying is calculated based on the amount of energy required to evaporate the water at a particular drying temperature. The dried biomass is then ground in hammer mill with a 3.3 mm screen. The energy consumed during grinding is measured. The solid yield after grinding is 96% and the mean water mass fraction is 11%. The ground biomass is then pelletized in a pellet mill of size 12 kg h^{-1}. At the start of each experiment, 2 kg of ground biomass are taken to the pellet mill. The feed flow rate of material to the mill is controlled using a vibratory feeder.

2.2.3 Process models and assumptions for the development of a process model

The unit operations of steam pretreated pellet production listed in order of highest to lowest energy consumption is the dryer, steam pretreatment, pellet making and grinder. The existing process models for these are shown in Fig. 2-1. The unit operations in the process model are chosen based on the operating conditions of the experimental units described. The assumptions made in choosing the unit operations and on operation conditions and materials are listed in Table 2-3.

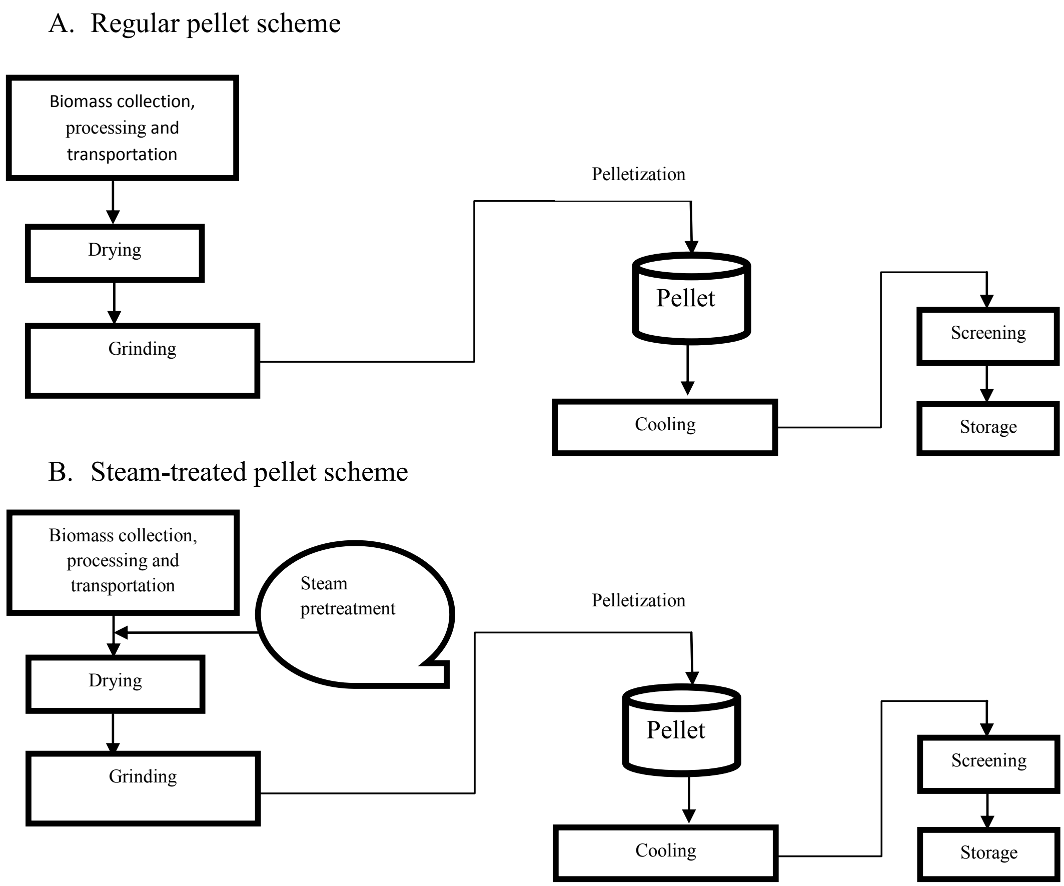


Fig. 2-1: Production chain of regular pellets and steam-treated pellets

2.2.3.1 Steam pretreatment unit

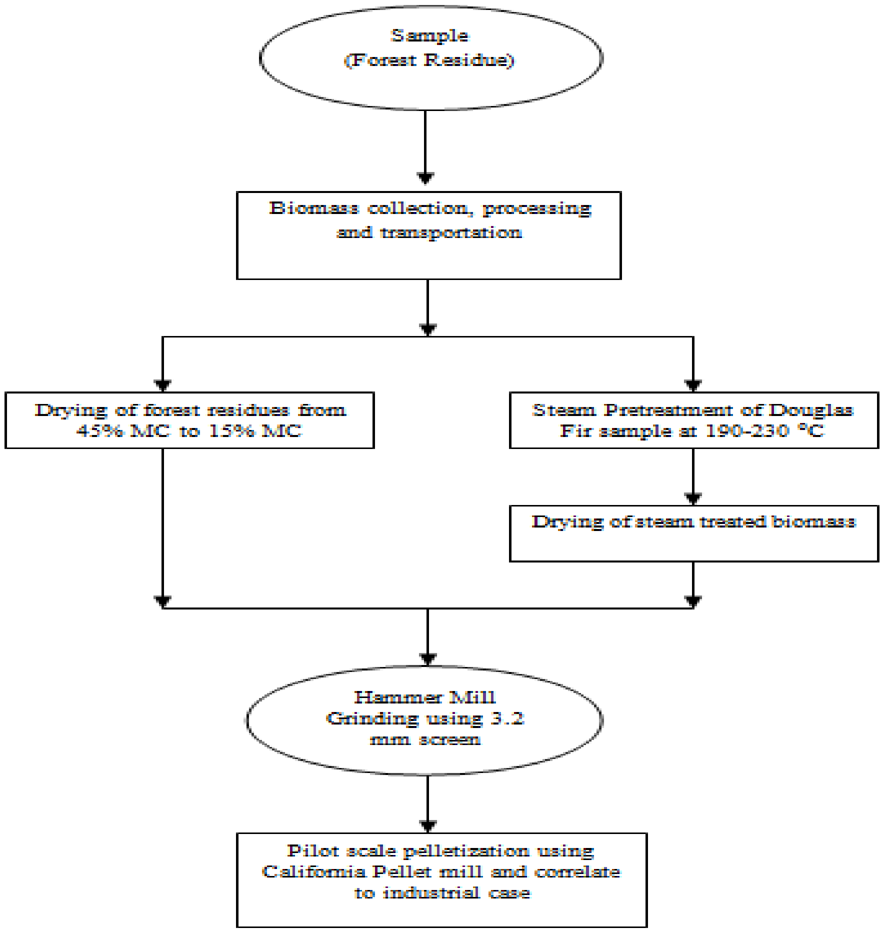
The modeled small scale steam pretreatment unit is a batch system, originally manufactured by Stake Technologies, Ontario, Canada [17]. The major operational parameters of steam explosion are biomass feedstock particle size (d_p), applied reaction pressure (P), reaction temperature (T), and residence time (t). Different combinations of reaction parameters cause distinct changes on biomass structure and chemical composition. A severity index (R_o) was developed by Overend et al. (1987). Steam pretreatment severity is described by Eq. (2-1) [24], which is widely used. The equation was developed based on the modeling of complex reaction systems by assuming each reaction is homogenous and the temperature function were linearized by a Taylor series [25, 26].

$$R_o = \int_0^t \exp\left[\frac{(t-100)}{14.75}\right] dt \tag{2-1}$$

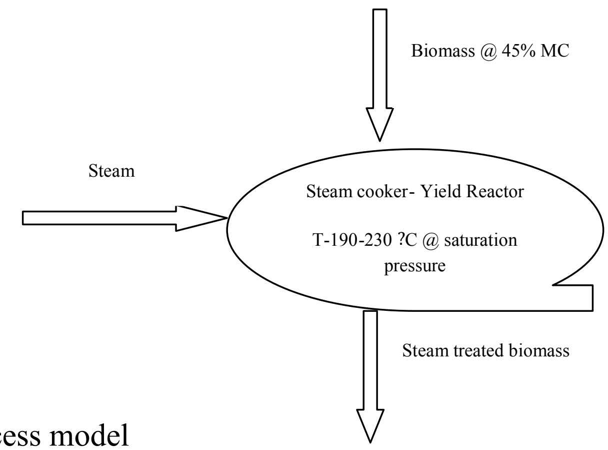
The equation above does not include the effects of mean water mass fraction and particle size, which also affect the kinetics of the physical and chemical changes of biomass structure by steam pretreatment. The range of R_o in Eq. (1) depends on the process conditions of end products. The goal of making steam pretreated pellets is to increase the energy density of the final pellet produced, which in turn will increase combustion efficiency. At low severity (R_o< 2), biomass restructuring begins. If the reaction is too drastic (R_o>4), then dehydration and condensation reactions of the hemicelluloses occur and more soluble sugar will be degraded to a side product during steaming [17]. With an increase in pretreatment severity, the solid yield reduces, which reduces the overall output energy of the produced pellets. Therefore, optimization of the steam explosion pretreatment within the range of R_o of 2–4 is the typical objective for preparing the fuel for biochemical conversions [17].

The assumption in the model is that the temperature of the saturated steam has an effect on the energy ratio and the specific energy requirement of the entire process. The effects of temperature were studied, at 10 ^{0}C intervals between 190 and 230 ^{0}C with a fixed mean water mass fraction of the received biomass of 45% and a fixed residence time of 10 minutes. The higher heating value is measured by ASTM Standard, D 2015-96, 1998 [17]. The increase in temperature increases the pellet's higher heating value. Based on previous experiments done, the temperature must be optimized to 230 ^{0}C; since beyond this point reduced solid yield makes the steam pretreatment process not feasible. The total biomass pretreated during the steam pretreatment process is 4 kg in a batch steam pretreatment reactor, which processed 400 gm of biomass at one time. The simplified block diagram used in the Aspen PLUS model is given in

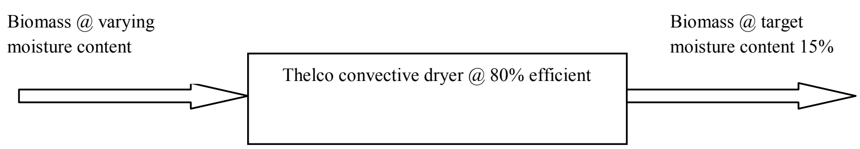
A. Process scheme



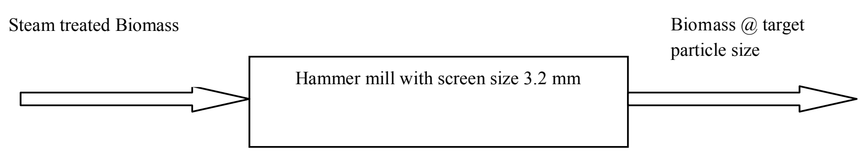
B. I. Steam Pretreatment Process model



II. Dryer process model



III. Hammer mill process model



IV. Pellet mill process model

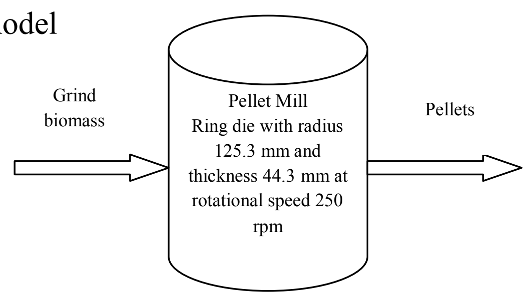


Fig. 2-2: Process scheme and model assumptions used in Aspen PLUS for: (a) Regular & Steam Pretreated Pellet Production; and (b) Unit Operation assumption [28]

Based on the experiments and data, we can assume a solid yield in the range of 95-98%. The composition of the steam pretreated yield is given in Table 1. A yield reactor is considered for the process as the information on the reaction kinetics and chemical changes are very limited and hence is difficult to model. The yield reactor takes into account the product composition at the end of steam pretreatment. The model predicts the amount of energy required to convert the initial biomass to steam pretreated biomass at the given saturated steam temperature condition and compares the amount of energy required in the experimental unit for the same pretreatment conditions [27]. The specific energy consumption for the process of steam pretreatment for the experiment is calculated using the equations included in the Appendix Section A1.

2.2.3.2 Dryer

Based on experiment, wet biomass is dried at about 80°C in a conventional dryer until the desired final mean water mass fraction is reached. In this calculation, we assume there are no extractives or volatile losses during the drying process and that only the moisture is exhausted from the system. Heat loss through drying is assumed in this research to be 20%, and the dryer efficiency is 80% [1].

Based on experiment, the dryer assumed in this study is a stoichiometric convective dryer, which is modeled to predict the energy required to dry the steam pretreated material from 78% and 45% to the desired mean water mass fraction of 15% as represented in Fig. 2 (a and b). The model is then validated against the energy consumption experimental unit. The equations used for the energy consumption of experimental unit are listed in supplementary section.

2.2.3.3 Grinder

The dried woodchips are ground through a 3.2 mm screen. It is assumed that 3% moisture is lost during grinding and exhausted as vapor [1]. The particles are then densified. Kick's law has been used to predict the net energy required for grinding based on the initial and final particle size [29, 30]. The Kick's constant used here is 32 J kg^{-1} as reported by [31]. Power consumption for the experimental unit is the average energy consumption per second divided by the feed flow rate [17], shown in Eq. (2-2):

$$\Delta E = K(k) ln \frac{L(f)}{L(p)} \tag{2-2}$$

where

ΔE is the energy consumption of the grinder unit, kJ kg^{-1}

K (k) is Kick's energy constant, kJ kg^{-1}

L (f) is the final size of the ground biomass, mm

L (p) is the initial size of ground biomass, mm

The grinder model in Aspen PLUS is a hammer mill unit that predicts the energy consumed to reduce biomass to 0.21 mm.

2.2.3.4 Pellet model

The steam pretreated grinds are converted to pellets using a laboratory-scale CPM CL-5 pellet mill (California Pellet Mill Co., Crawfordsville, IN) that has a corrugated roller and ring die assembly. The ring hole diameter and l/d ratio considered for the experiment are 6.1 mm and 7.31 mm. The roller's rotational speed is 4.17 Hz. 2 kg of steam pretreated wood grinds are fed to the pellet mill, and the feed is controlled using a vibratory feeder. The pelleting unit is operated for a mean duration of 10 minutes. The pellets produced are collected and weighed to calculate the pellet mill throughput in kg h^{-1}. The energy consumed is measured and is used to calculate the specific energy consumed by the pellet mill [28].The pellet mill modeled in Aspen PLUS is an agglomerator unit, which is modeled to produce solids at the desired particle size of 6.2 mm in diameter, 10-30 mm in length.

2.2.4 Assumptions

The modeled unit operations are given in Fig. 2-2. The developed Aspen PLUS model is provided in the supplementary section. Wood chips with a mean water mass fraction of 45% are used for the analysis. Steam pretreatment is assumed to be saturated steam at a certain temperature. The higher heating value for all cases in the analysis is expressed as shown in Eq. (2-3) [32]:

$$\mathrm{HHV} = 0.349\mathrm{X}_C + 1.1783\mathrm{X}_H + 0.1005\mathrm{X}_N - 0.0151\mathrm{X}_S - 0.1034\mathrm{X}_O - 0.0211\mathrm{X}_{Ash} \tag{2-3}$$

where X_i is mass fraction of each element.

A large scale analysis is created based on a literature review. The energy required to remove 1 kg of water from a typical biomass fuel is 2.6 MJ kg^{-1} of water removed, other references to rotary dryer performance in the literature indicate that the heat required to evaporate 1 kg of water from wood chips is 3.1 MJ [33]. The grinding energy for a large scale grinder is calculated using Eq. (2-4) [6]:

$$E = -203.06\log(S) + 206.11 \tag{2-4}$$

The grinding energy for a large scale grinder is calculated from this correlation. The typical energy consumption for a 224 kW pellet mill producing pellets at 4.5 t h^{-1} is 49.2 kWh t^{-1} [34]. The large scale case for steam pretreatment is created from the correlation of steam pretreated and regular pellet production at 190-230 ^{0}C. The key assumption is that the large scale case has the same yield as the small scale case, but unit operation efficiencies vary between the two scales. The large scale case also includes biomass collection, processing, and transportation energy; the amounts are calculated from equations in the literature [35]. The detailed model flow, plan, and inputs are listed in Fig. 2-1 and Table 2-2 for both regular and steam pretreated pellet production.

2.3. Results and Discussion

Table 2-3 shows the model validation based on energy consumed for each unit operation in regular and steam-pretreated pellet production. Energy consumption for experimental unit operations is calculated using the equation given in supplementary section. The process model developed in Aspen PLUS predicted the energy consumption for each unit operation given in the input scenarios for the experimental conditions described in supplementary section. The model predictions for energy consumption closely match the experimental results with an average error of 2%, which makes the model reliable for different scenario analyses for variations of NER at different temperatures.

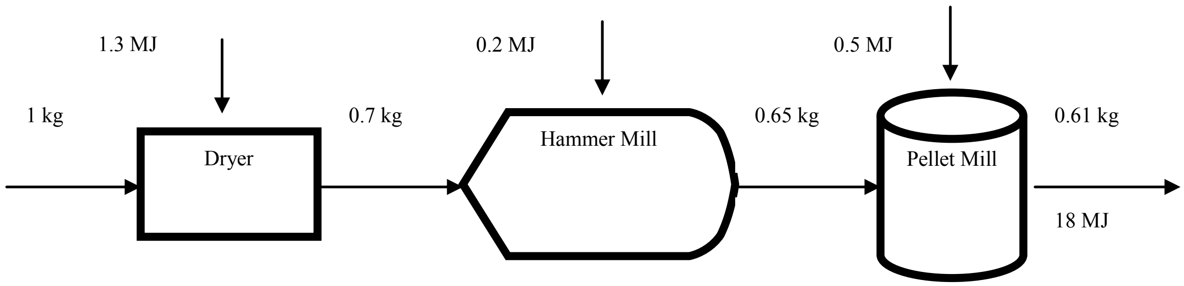
The base case scenario for the developed model and the experimental unit is created for 210 ^{0}C and a 10 minute residence period. The detailed energy analysis is shown in the energy and mass flow given in Fig. 2-3. The net energy impact with respect to each process is shown Table 2-3. The results indicate that steam pretreatment increases energy consumption significantly due to the additional steam required for the pretreatment and the additional energy required for drying, since the saturated steam condenses on the biomass when heat is released for pretreatment. The drying energy required for regular pellet production is 1.3 MJ, and for steam pretreatment this increases approximately fivefold to 6.2 MJ. The steam pretreatment also requires additional energy that is provided by burning natural gas, which is not required for regular pellet production.

Table 2-3 Validated Model and Net Energy ratio for base case

				Steam treated pellet		**Regular pellet**	
Number	**Unit operation**	**Energy Consumed**	**Unit**	**Experimental result**	**Model result**	**Experimental result**	**Validated**
1	Steam Pretreatment	Energy for biomass heating, E_b	$kJkg^{-1}$	821.33			
		Energy for steam generation, E_s	$kJkg^{-1}$	1276.65			
		Specific energy consumption	$kJkg^{-1}$	2097.99			
		Moisture content of feed stock	%	45			
		Initial mass	kg	1			
		Net Heat consumption	kJ	2097.99	2095		
2	Drying	Heating wood	$kJkg^{-1}$	34.85		87.12	
		Heating water	$kJkg^{-1}$	296.03		170.79	
		Heating air	$kJkg^{-1}$	92.41		92.41	
		Evaporation of water	$kJkg^{-1}$	1673.45		802.64	
		Heat loss	$kJkg^{-1}$	418.36		200.66	

Number	Unit operation	Energy Consumed	Unit	Experimental result	Model result	Experimental result	Validated
		Initial mass		2.45		1	
		Net Heat consumption	kJ	6162.02	6156	1353.61	1360
3	Grinding	Feed rate	kgh^{-1}	120		35	
		Average power consumption	Js^{-1}	838		2804.5	
		Specific energy consumption	$kJkg^{-1}$	25.15		291.9	
		Initial mass	kg	0.634		0.706	
		Net heat consumption	kJ	15.95	17	206.06	210
4	Pellet	Feed rate	Kgh^{-1}	5.4		5.4	
		Average power consumption	Js^{-1}	1154.83		1135	
		Specific energy consumption	$kJkg^{-1}$	774.18		756.98	
		Initial mass	kg	0.584		0.584	
		Net heat consumption	kJ	492.04	500	452	440
	Net energy ratio				5.0		1.29

A. Mass and energy flow (regular pellet)



B. Mass and energy flow (steam treated pellet, base case)

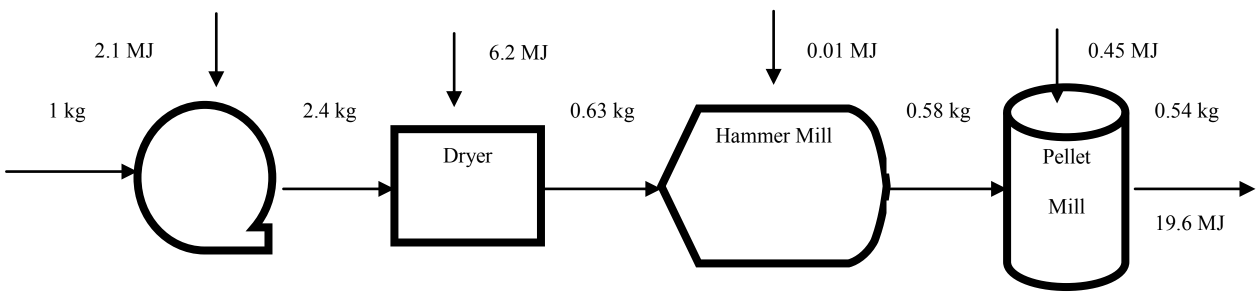


Fig. 2-3: Input and output energy and mass flow of regular pellet production and steam pretreated pellet production (base case)

The system process efficiency is low at the small scale since at the experimental stage an electric boiler with high heat loss and no means of recirculation the process steam is used. The drying energy required in the large scale case is lower than at the small scale, thereby improving the overall NER.

The NER (shown in Table 2-3) is an important parameter to assess the process efficiency and is a key decision-making metric. The NER of regular pellet making is 5.0 while for the pellets produced from steam pretreatment the NER is 1.29. The key reason driving the NER is the drying energy requirement difference between the two process plans. Thus, the efficiency of the dryer model assumed in the process model and the level of steam pretreatment and subsequent solid recovery for pelletization play key roles. The dryer efficiency assumed for this case is 80% [1], which is typical of most small scale-scale convective dryers drying biomass at 6 kg h^{-1}. The efficiency of an large scale dryer with a rotary drum and the flue gas recirculation is 85-90% [33]. Moreover, the NER as given in Table 4, makes clear that a 100% steam pretreatment situation is not feasible based on the NER of the steam pretreatment process. This is understandable, since pretreating 100% of the feedstock requires the addition of extra steam for pretreatment as well as the burning of this condensed water from the biomass after pretreatment. A scenario analysis has been done for this case to exemplify the effect of the percent of feedstock pretreatment on the NER of the entire energy chain. In this case pretreatment level has been varied. The pretreatment level is decided by the ratio of amount of biomass used for steam pretreatment and regular production.

Fig. 5-5 (b) shows the energy requirement for the entire chain for both regular and steam-pretreated pellet production at large scale. The key process differences are from increased drying energy and reduced grinding energy for steam pretreated pellet production. The reason for high drying energy is explained above. The reason for reduced grinding energy can be attributed to the disintegration of the biomass cell wall and structure due to high pressure steam pretreatment at high temperatures. Thus, it shows that the grinding process can be replaced completely through the amalgamation of steam pretreatment with other pretreatment processes that lead to biomass disintegration. This amalgamation will play key role in the economic analysis of the process since the grinder can be completely replaced and the overall process capital cost can be reduced.

Table 2-4: Variation of net energy ratio with treatment temperature

	Treatment Temperature								
	190 ^{0}C			200 ^{0}C			220 ^{0}C		
Unit operation	**Energy input (kJ kg^{-1})**	**Mass (kg)**	**Net energy (kJ)**	**Energy input (kJ kg^{-1})**	**Mass (kg)**	**Net energy (kJ)**	**Energy input (kJ kg^{-1})**	**Mass (kg)**	**Net energy (kJ)**
Steam Pretreated	1834	1	1834	1857	1	1857	1908	1	1908
Drying	2409	2.18	5248	2417	2.22	5373	2636	2.93	7734
Grinding	25	0.64	16	25	0.63	16	25	0.62	16
Pelleting	762	0.59	449	760	0.58	439	802	0.57	458
Total			7547			7685			10118
Energy output	19000	0.56	10640	19500	0.55	10725	19800	0.54	10692
Net Energy Ratio			1.41			1.39			1.10

The large scale scenario for regular and steam pretreated pellet production is created based on the data available in the literature. As mentioned above, the large scale case is based on the dryer model's high efficiency and the pellet mill's low specific energy. The large scale NER of the steam pretreatment process increases from approximately 1.3 in the small scale case to close to 2.0 in the large scale case because the efficiency of the rotary drum dryer is higher. The large scale case, moreover, is a realistic scenario to gauge the energy requirement of the entire chain since it starts with the energy requirement of biomass collection and ends with the energy requirement of pellet making.

2.4. Sensitivity analysis

A sensitivity analysis was carried out for both regular and steam pretreated pellet production both for effects of temperature and the level of pretreatment of the feedstock. Table 2-4 shows the results of the sensitivity analysis for varying temperature scenarios with respects to NER. Fig. 2-4 shows the variation of mass and energy balance with temperature change. The results of the model predicted that the NER falls with increasing temperatures. From experimental results in earlier study based on single pellet [17], it has been said that the higher heating value of steam pretreated pellets increases from 20.14 to 21.5 MJ kg^{-1} at higher steam pretreatment temperatures. However, experiments carried out with larger quantity, showed that the variation is between 19-19.5 MJ kg^{-1}. Consequently, higher energy densification comes at the trade-off of extra process energy and reduced solid yield for pellet making. Thus, increasing temperatures from 190 ^{0}C to 220 ^{0}C reduces the NER of the chain in the small scale case from approximately 1.5 to 1.29 and in the large scale case from approximately 2.25 to 1.9 as shown in Fig. 5-5(a). The change in the NER for both the large scale and the small scale scenarios between 190 – 200 ^{0}C which is the ideal temperature zone for steam pretreatment process is minimal. In this range, the pellet higher heating value increases while the process NER also remains high.

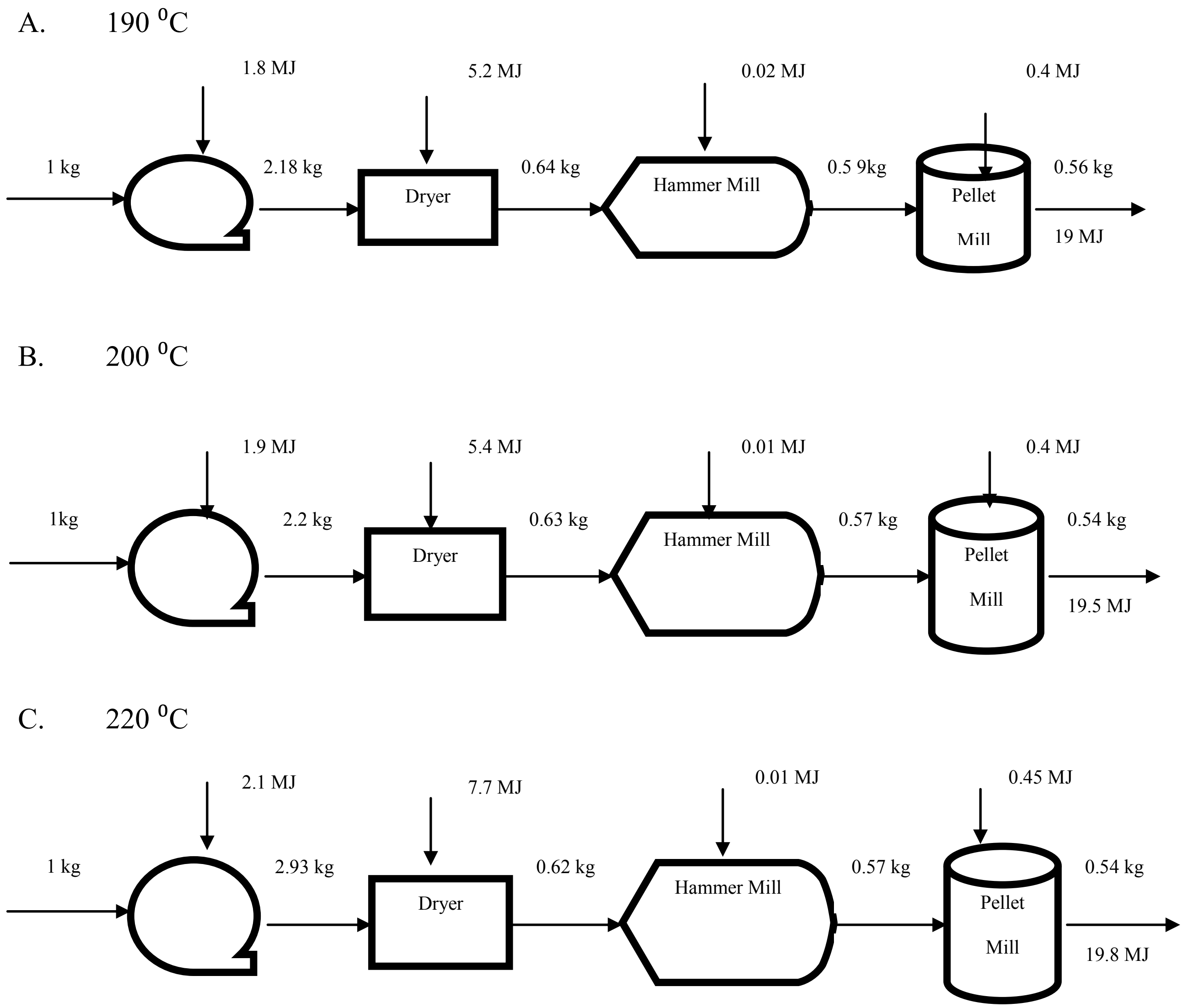
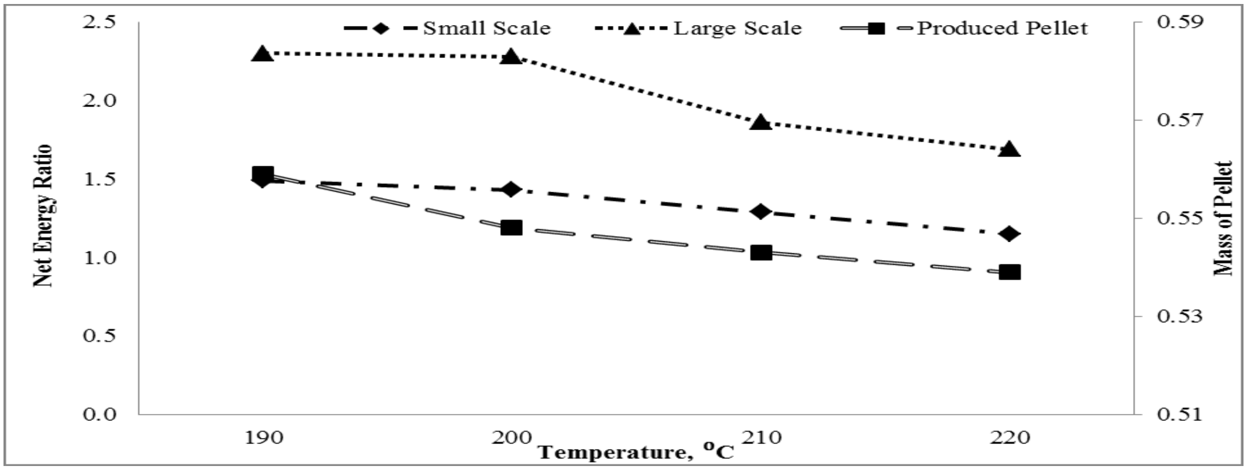


Fig. 2-4: Effect of change in temperature on energy and mass flow of steam pretreated pellet production

A. Variation of net energy ratio at different treatment temperatures for small and large scale cases



B. Energy use for the entire chain at large scale (45,000 tonne plant)

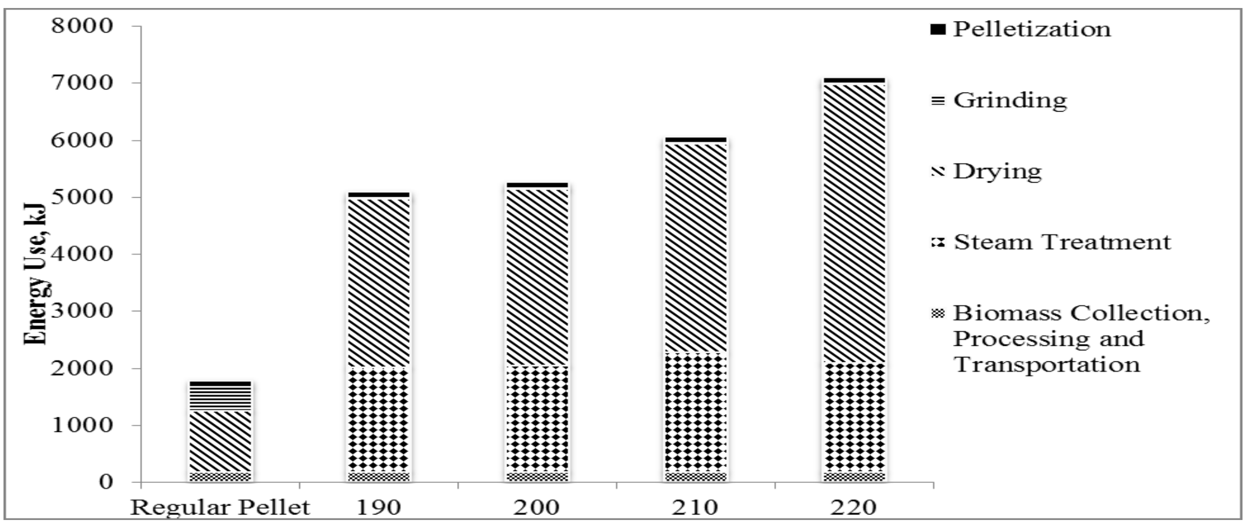


Fig. 2-5: Comparison of net energy ratios (a) and energy use (b) at different temperatures for small and large scale case

As mentioned in the results section, the key driver for the process NER is the energy required for drying and steam pretreatment. When the pretreatment temperature increases to 230 ^{0}C, drying energy increases by 48% and steam pretreatment energy by 16%. The temperature, however, at which the calorific value and the solid yield are both optimum is 200 ^{o}C as shown in Fig. 2-5(a). The factor responsible for this optimum is the higher energy required to raise the biomass temperature beyond 200 ^{o}C and maintain the steam pretreatment vessel temperature at the increased temperature level. With the increased temperature, more biomass disintegrates and more process steam condenses on the biomass. This increased pretreatment temperature thus leads to the need for more evaporation energy for drying. However, the energy required to grind and make pellets remains constant at a high pretreatment temperature and does not increase the NER.

The variation of the energy required for each unit operation with level of pretreatment has been analyzed and is shown in Table 5. We have chosen a pretreatment temperature of 200 ^{0}C since it gives an increased heating value with minimal reduction in the process NER. Four different scenarios are analyzed ranging from 0% (representing regular pellet production) to 100% pretreatment (representing complete steam pretreatment). The NER at a 25% pretreatment level increases by 107% from the case with a pretreatment level of 75%.

Table 2-6 shows the effect of pre-drying on the NER of the steam pretreated pellet process. NER of the process improves significantly from 1.49 in base case scenario to 2.18 with pre-drying of biomass prior to steam pretreatment. The reason for this is the lower energy requirement for steam pretreatment and the subsequent drying energy. However, the removal of pre-drying using natural convective drying increases NER significantly to 2.72 since natural convective drying requires no external energy.

Table 2-5 Variation of net energy ratio with level of treatment

	Energy input ($kJkg^{-1}$)	Mass (kg)	Net energy (kJ)	Energy input $kJkg^{-1}$	Mass (kg)	Net energy kJ	Energy input $kJkg^{-1}$	Mass (kg)	Net Energy kJ
Pretreatment Level		25%			50%			75%	
Steam Pretreated	1857.1	0.25	464.3	1857.1	0.5	928.6	1857.1	0.75	1392.8
Drying	2417.1	0.56	1343.3	2417.1	1.11	2686.5	2417.1	1.67	4029.8
Grinding	25.2	0.16	3.9	25.2	0.31	7.9	25.2	0.47	11.8
Pelletization	760	0.59	449.5	760	0.59	446.1	760.0	0.58	442.7
Total			2261			4069.1			5877.2
Energy output	18700	0.56	10475	19400	0.56	10785	20100.0	0.55	11089.9
Net Energy Ratio			4.6			2.7			1.9

Table 2-6: Effect of pre-drying on the NER of the steam pretreated pellet

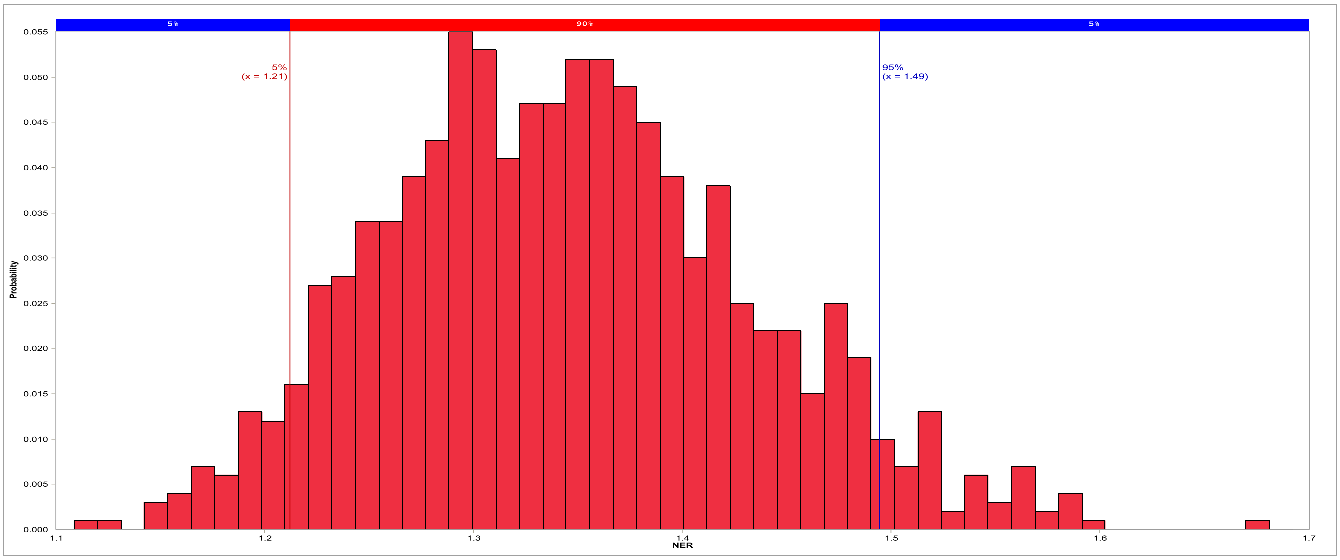
Pathway I- Pre-drying, Steam Pretreatment, Drying, Grinding, Pelletization			
Unit Operation	Unit energy required kJ kg^{-1}	Initial mass kg	Consumed energy kJ
Pre-drying	944.8	1.00	944.82
Steam Pretreatment	1091.9	0.79	857.95
Drying	1881.6	1.33	2509.54
Grinding	25.2	0.63	15.79
Pelletization	762.0	0.58	440.50
Total			**4768.59**
Energy output	19000	0.55	**10407.05**
Net Energy Ratio			**2.18**
Pathway II- Natural Convective Drying, Steam Pretreatment, Drying, Grinding, Pelletization			
Unit Operation	Unit energy required kJ kg^{-1}	Initial mass kg	Consumed energy kJ
Steam Pretreatment	1091.9	1.00	1091.93
Drying	1881.6	1.70	3193.96
Grinding	25.2	0.80	20.09
Pelletization	762.0	0.74	560.63
Total			4866.61
Energy output	19000	0.70	**13245.33**
Net Energy Ratio			**2.72**
Pathway III Base Case- Steam Pretreatment, Drying, Grinding, Pelletization			
Unit Operation	Unit energy required kJ kg^{-1}	Initial mass kg	Consumed energy kJ
Steam Pretreatment	1833.9	1.00	1833.93
Drying	2409.5	2.18	5247.93
Grinding	25.2	0.64	16.11
Pelletization	762.0	0.59	449.58
Total			7547.55
Energy output	20140	0.56	**11258.92**
Net Energy Ratio			**1.49**

2.5. Uncertainty Analysis

Unavailability of exact representative data and errors occurring during the experiment is a major concern for the accuracy of the model NER predicted. For such cases, researchers use assumptions for their model which leads to uncertainty. Monte-Carlo simulation has been carried out on the model considering maximum volatility in the values of drying and steam pretreatment energy required. Monte-Carlo analysis is well-known applications which deals with number of variability and quantify the uncertainty in the final output. The number of iterations used for the model is 10000. The simulation was carried out by using Model risk software found in public domain [36].

The results of Monte-Carlo simulation on the distribution of model generated NER is shown in Fig. 6. Monte-Carlo simulation result for the base case scenario of steam pretreated pellet shows process NER range is 1.35±0.09 at a confidence interval of 95%. While the Monte-Carlo simulation result for base case scenario of regular pellet is 4.52±0.34.

(A)



(B)

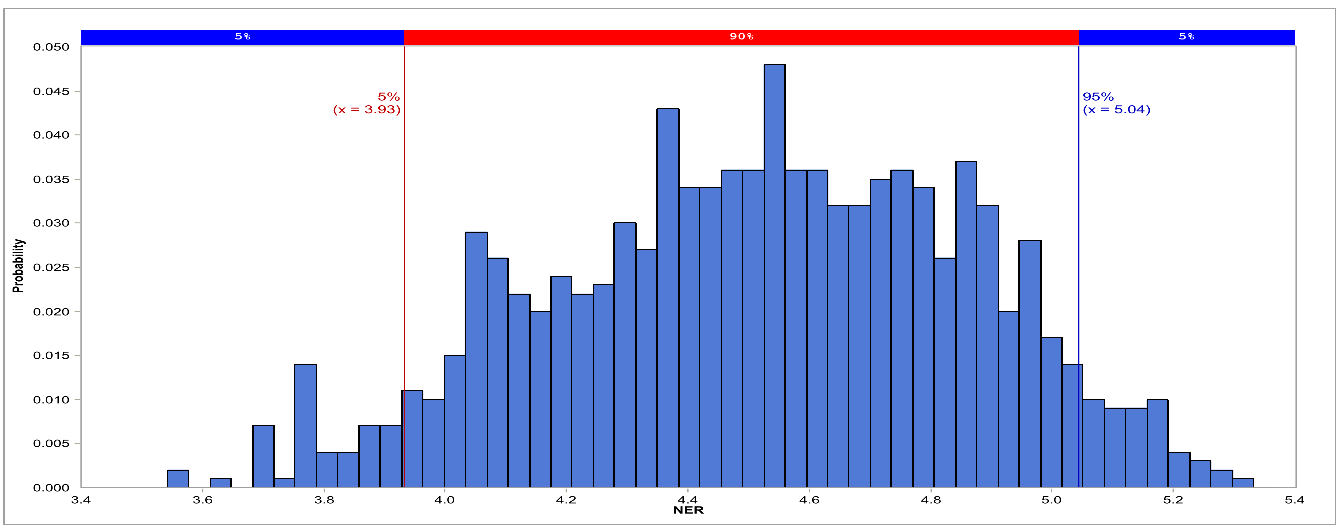


Figure 2-6: Model uncertainty analysis of (a) steam pretreated Pellet NER and (b) Regular pellet NER

2.6 Conclusions

This research work focused on creating a process model to give a comparative energy analysis for regular and steam-pretreated pellet production. From the analysis, it is concluded that the steam pretreatment process improves the heating value of the fuel. However, steam pretreatment increases the process energy requirement for drying and pretreatment. Thus, the process net energy is significantly reduced due to steam pretreatment. The process NER can be improved by increasing drying efficiency and reducing the pretreatment level and temperature. The results of this study also highlight that the grinding energy requirement is significantly reduced with steam pretreatment.

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Chapter 3: Comparative net energy ratio analysis of pellet produced from steam pretreated biomass from agricultural residues and energy crops[2]

3.1. Introduction

One of the ways to reduce the growing concerns of greenhouse gas (GHG) emissions is by substituting fossil fuels with sustainable biomass feedstocks like agricultural residue (AR) and forest residue (FR). The economics of biomass-based power generation have been evaluated earlier by several authors [1-7]. One of the key barriers to large scale biomass utilization is the supply of consistent quality feed to biomass-based facilities [3, 8, 9]. The low energy density and yield of biomass based feedstock limit the use of biomass. Densification of biomass in the form of pellets is one of the ways to convert the feedstock to a biomass-based facility to enhance the calorific value. Pelletization and densification, which can increase energy density, can be implemented to reduce transportation costs since the high energy density means that less feedstock needs to be transported [10]. Pelletization reduces transportation and transportation costs by increasing volumetric density. In addition, this technology allows the free flow of fuels,

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which makes loading and unloading simpler [10]. There have been a number of studies on technology for pelletization and associated economics of pellet production through a conventional process using lignocellulosic biomass (e.g., forest residues, straw, saw dust) [3, 4, 11] . Also studies have assessed energy consumption in production of pellets [12].

While regular pelletization improves the energy density of the biomass, significant improvement is required in biomass densification to make it lucrative to biomass-based facilities. The higher heating value of coal is 26 MJ/kg, while that of pelletized biomass 16-18 MJ/kg. The higher heating value can be improved through biomass pretreatment before pelletization, as suggested by Tooyserkani and Lam [8, 9]. Typically, the pretreatment process includes steam pretreatment, ammonia pretreatment, and acid catalyzed pretreatment [13]. The steam pretreatment process is an additional process added to the pelletization supply chain to improve the calorific value and bulk density of biomass. The improvement in fuel calorific value can be achieved through steam pretreatment, reduces transportation and handling costs [14, 15].

The effect of steam pretreatment, also known as Masonite technology [9], at temperatures ranging from 180 to 240 ˚C, is decompression of the saturated steam from the Stake/Masonite gun environment to cause rapid expansion, which ruptures the cellular structure [16, 17]. As discussed above, the steam pretreatment and pellet production processes involve energy for drying, grinding, pelleting, and steam pretreatment. The pelletization process, along with the steam pretreatment process, has been explained in detail in our previous work [18].

While a number of authors have previously estimated process NER for different biomass pathways [12, 19-21], the NER for steam pretreated biomass-based pellet production has received minimal discussion in the literature. In an earlier study, the authors evaluated the NER for pellets produced from steam pretreated forest residues [18], but the process energy requirements and NERs of pellets produced from AR and switchgrass have not been evaluated so far. There is need to evaluate the NER from a life cycle point of view for these feedstocks which could help in further development of the most efficient technology. In light of this gap, the main objectives of this study are to develop a process model for steam pretreatment of agricultural residues and energy crops for pellet production, evaluate the energy and mass balance of the steam pretreated pellet production process, and estimate the NER of the process.

3.2. Methodology

This study employs a process modeling of the pellet production processes from AR and switchgrass. The model of the pellet production process is built based on experimental results. The model evaluates the NER of steam pretreated pellets from two feedstocks and comparing them with NER of regular pellet production. The process model evaluates the energy requirement of two processes, the steam pretreatment of biomass for pellet production and regular pellet production.

The pelletization process starts with the harvesting and collection of AR and energy crops in bales form and transporting them to the pellet mill [22]. The mean water mass fraction of these AR and energy crops is around 10-14%. The chips require drying before being comminuted and pelletized. The feedstocks are ground in a hammer mill to a particle size of 3.2 mm or less [23]. The particle size can be changed in the hammer mill by varying the mesh screen size [24].

The feedstock is then passed through a pellet mill with a roller that extrudes the feedstock and pushes it though a die hole, compressing it into pellets. The pellet mill feed rate is adjusted with its service life and is done purposely to ensure pellet quality, since a high feed rate impacts the compression provided by the die and reduces pellet density [4]. A pellet mill's efficiency depends on a number of parameters like die temperature, die and roller configuration, and pressure [25]. Once pellets are formed, they are air-cooled from a temperature of 95 to 100 ˚C to 25 ˚C.

In this study, a process model was developed to evaluate the specific energy consumption of the steam pretreated pellet production process from AR and energy crops and compare it with regular pellet production process. The impact of steam pretreatment on the process NER and the energy density benefit are discussed.

Process simulation model, Aspen PLUS [26] was used for this study with a focus on mass and energy balance. The process model of steam pretreatment consists of a number of unit operations that are joined by the mass and energy streams. Experimental work on the steam pretreatment of AR and energy crops was used to validate the process model. The specific energy consumption of each unit operation was calculated using the developed process model. The model was also used to create a correlation between the energy consumption of small-scale steam pretreatment and regular pellet production processes for different feedstocks. The NER of the two processes was then evaluated and comparatively analyzed.

Experimental work of steam pretreatment carried out in laboratory condition is described below.AR and Energy crops based biomass is pretreated using saturated steam at temperatures in the range of 140 to 180 ˚C. Pre-steaming is done at the beginning of the experiment to remove the air in the feed stream. The developed process model also takes into account this scenario using excess steam to remove air in the feed stream. The steam pretreatment experiments showed that at temperatures beyond 180 ˚C, the solid yield falls significantly due to the loss of volatiles

[27] . The steam-pretreated biomass is dried in a convective dryer at 80 ^{o}C for 1 hour to reach the target mean water mass fraction of 15%. The energy used for drying is calculated based on the amount of energy required to evaporate the water at a particular drying temperature. The difference between AR and energy crop steam treated pellets and forest residue pellets is in the grinding process. No grinding is required after steam pretreatment for AR and energy crop for the production of pellets. The ground biomass is pelletized at 12 kg h^{-1} in a California pellet mill. This is the maximum capacity of the small scale pellet mill. At the start of each batch, 2 kg of ground biomass are fed to the pellet mill. The experiment is done in batch of 2 kg to ensure that the roller and ring die is not clogged during the experiment[28]. The feed flow rate of material to the mill is controlled using a vibratory feeder.

The unit operations of steam pretreated pellet production, in order of highest to lowest energy consumption, are the dryer, steam pretreatment process, and palletization process. The existing process models for these are shown in Fig. 3-1. The unit operations in the process model are chosen based on the operating conditions of the experimental units described above.

The developed model focuses on the effect pretreatment temperature on NER as well as the pretreatment. Increase in temperature lead to improvement of calorific value as suggested by author's previous work [18], however this comes at the cost mass yield of pellet. Hence, the study focused on investigating the steam pretreatment temperature at which calorific value will be high without reducing yield of pellet. Previous study by the author shows that the process of steam pretreatment is an energy intensive process due to high energy requirement during steam *pretreating and drying. Hence, a trade-off study has been done by varying the level of biomass pretreated. This is defined as pretreatment level i.e. the amount of biomass out of the total quantity of biomass that undergoes steam pretreatment.

The assumptions made in choosing the unit operations, operating conditions, and materials are listed in Fig. 3-2, Table 3-1 and 3-2.

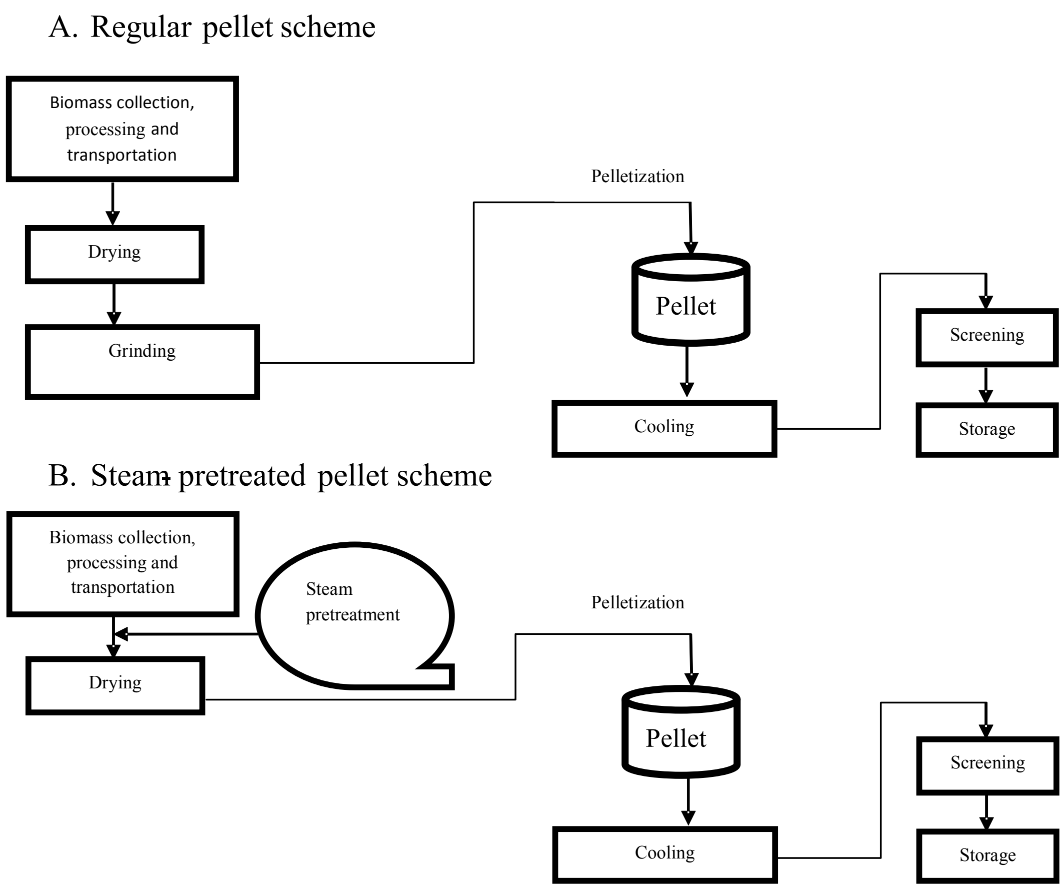
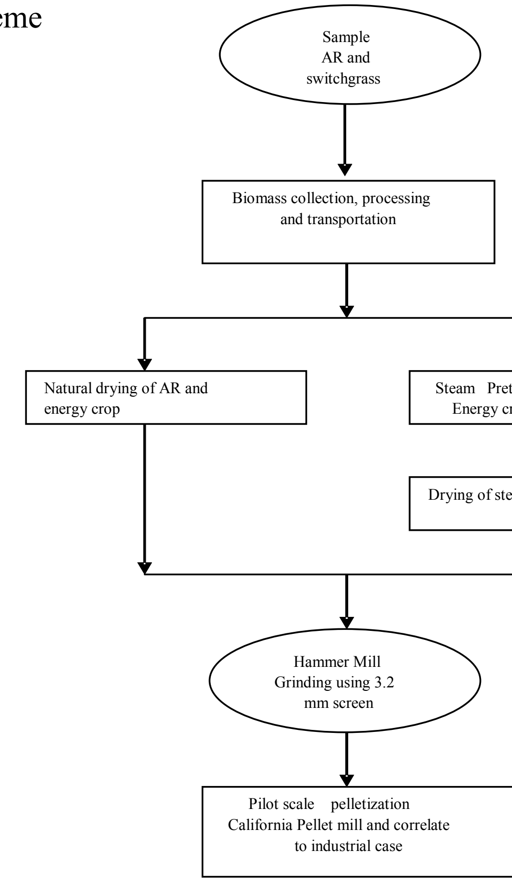
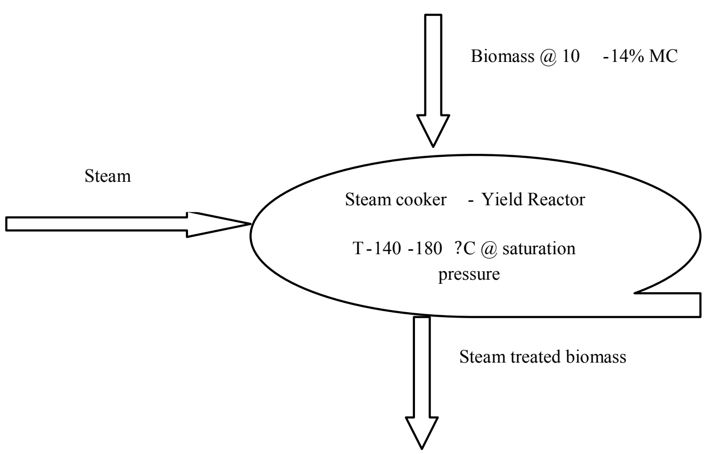


Fig. 3-1: Production chain of regular pellets and steam-treated pellets

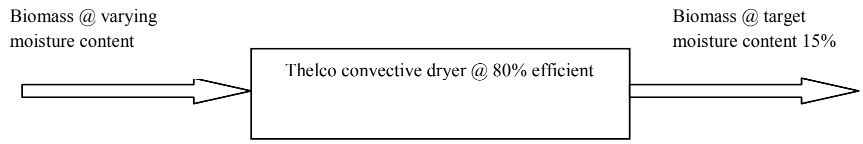
A. Process Scheme



B. I. Steam Pretreatment process model



II. Dryer process model



III . Pellet mill process model

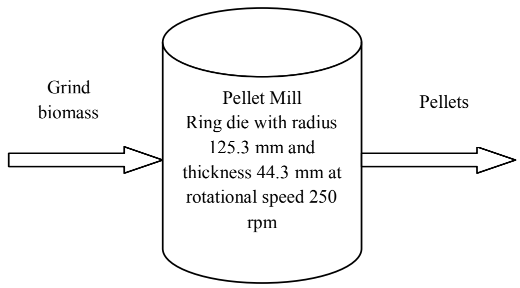


Fig. 3-2: Process scheme and model assumptions used in Aspen PLUS for: (a) Regular & Steam Pretreated Pellet Production; and (b) Unit Operation assumption [28]

Table 3-1: Fuel property based on ultimate and proximate analysis of sample

(a) Straw

TREATMENT TEMPERATURE	°C	FEEDSTOCK	140	160	180
ELEMNTAL ANALYSIS					
C	% dry solid	44.92	43.11	45.1	46.66
H	% dry solid	5.46	6.33	6.19	6.15
N	% dry solid	0.44	0.35	0.38	0.43
O	% dry solid	49.18	50.21	49.33	46.67
PROXIMATE ANALYSIS					
FIXED CARBON	% dry solid	17.98	18.1	18.5	18.78
VOLATILE MATTERS	% dry solid	76.38	76.1	75.4	74.8
ASH CONTENT	% dry solid	5.64	5.8	6.1	6.4

(b) Switchgrass

TREATMENT TEMPERATURE	°C	FEEDSTOCK	140	160	180
ELEMNTAL ANALYSIS					
C	% dry solid	47	43.11	45.1	46.66
H	% dry solid	5.3	6.33	6.19	6.15
N	% dry solid	0.5	0.35	0.38	0.43
O	% dry solid	41.4	50.21	49.33	46.67
ASH CONTENT	% dry solid	5.7	6.1	6.5	6.8
PROXIMATE ANALYSIS					
FIXED CARBON	% dry solid	21.3	22.3	22.8	23
VOLATILE MATTERS	% dry solid	72.9	71.6	70.7	70.2
ASH CONTENT	% dry solid	5.8	6.1	6.5	6.8

Table 3-2: Input data for the steam pretreated pellet simulation

	Unit operations	Model Input conditions	Source
Boiler	Electric Boiler	1.88 MPA and 180 °C	[28]
Steam Reactor	Capacity	2.5 L	[18]
		Straw, Switchgrass	
	Reactor type	Yield reactor, based on elemental analysis	[18]
	Residence time	10 min	[27]
	Mean water fraction	10% (Straw), 14% (Switchgrass)	[4, 22]
	Biomass and Solid Yield	82% (straw), 80% (Switchgrass)	[27]
Dryer	Inlet Temperature	80 °C	[8]
	Target moisture level	15%	[8]
	Specification and Model Type	Thelco convection dryer operating at 80% efficiency	[8]
Hammer mill	Kicks constant	100 kJ kg^{-1}	[8]
	Solid recovery	96%	[18]
Pellet Mill	Operating Temperature	80 °C	[18]
	Solid Recovery	95%	[18]

3.3. Results and Discussion

The process model results were validated based on the experimental results by calculating the energy consumed for each unit operation in the regular and steam pretreated pellet production. The validated results are presented in Table 3-3. Energy consumption for the experimental unit operations was calculated using the equations from our previous research study [18]. The results show that the model predictions for energy consumption closely match the experimental results with an average error of 2%. Thus, it can be concluded that the model is reliable for the different scenario analyses for variations of NER at different temperatures.

Table 3-3: Model Validation

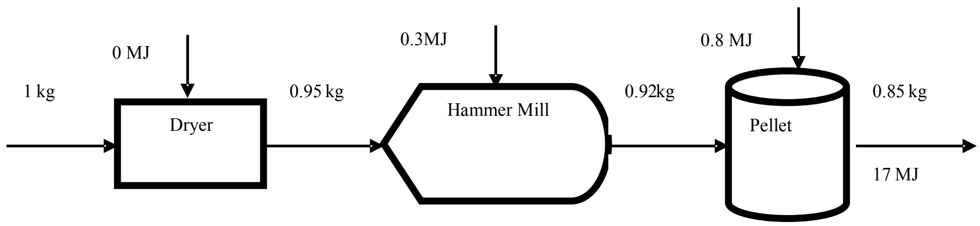
			STEAM TREATED STRAW PELLET		STEAM TREATED SWITCH GRASS PELLET	
Unit Operation	**Energy Consumed**	**Unit**	**Measured**	**Validated**	**Measured**	**Validated**
Steam Pretreatment	Energy for biomass heating, E_b	kJ kg^{-1}	300		270	
	Energy for steam generation, E_s	kJ kg^{-1}	449.6		408	
	Specific Energy Consumption	kJ kg^{-1}	749.6		678.2	
	Moisture content of feed stock	%	10		14	
	Initial mass	kg	1		1	
	Net Heat consumption	kJ	749.6	760	678.2	710
Drying	Heating wood	kJ kg^{-1}	36.68		32.94	
	Heating water	kJ kg^{-1}	284.65		303.6	
	Heating air	kJ kg^{-1}	92.41		92.41	
	Heat loss	kJ kg^{-1}	361.53		436.9	
	Specific Energy Consumption	kJ kg^{-1}	2221.38		2610.4	
	Initial mass		3.03		3.44	
	Net Heat consumption	kJ	6731/7	6951	8979.8	9045
Pellet	Feed rate	g s^{-1}	2.5		2.64	
	Average power consumption	J s^{-1}	1046.7		1080	
	Specific Energy Consumption	kJ kg^{-1}	418.6		409.5	
	Initial mass	kg	0.79		0.78	
	Net Heat consumption	kJ	330.4	352	318.9	325

The base case scenario for the experimental unit and the developed model is created for 180 ˚C and a 10-minute residence period. Fig. 3 shows the detailed energy analysis for the mass and energy flow and Table 3-3 gives the net energy impact with respect to each process. The comparative results of steam pretreated pellet production from AR and switchgrass indicate that AR require more energy for steam pretreatment since the temperature at which steam pretreatment is done for straw is higher than switchgrass. However, more drying energy is required for switchgrass biomass before its use for pellet production. This is because the water mass fraction of the switchgrass biomass is higher than straw biomass. Hence, more input energy is required to burn the extra moisture in the biomass before pelletization.

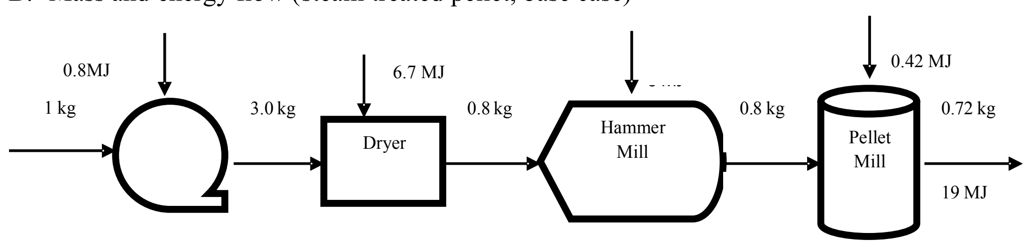
A comparative analysis shows that more energy is required for straw pellets than switchgrass pellets (see Table 3-3). This difference can be attributed to the particle size difference of AR and switchgrass. The NER is a key decision-making metric and an important parameter to assess process efficiency. Table 3-4 presents the variation of NER with different steam pretreatment temperatures. The results of the NER for the steam treated pellets show that the AR pelletization process has a NER of 1.76, higher than that of the switchgrass pelletization process, which is 1.37 for the base case scenario of 180 ˚C at 6 kg h^{-1}. The low NER value for switchgrass case is due to the greater energy requirement for drying. Moreover, the NER results and the mass and energy balance at different temperatures proves that all biomass undergoing steam pretreatment is not feasible based on the NER of the steam pretreatment process (see Table 3-4 and Fig. 3-4). When all biomass quantity undergoes steam pretreatment, extra steam for pretreatment will be required which then condenses on the biomass after steam pretreatment. This condensed water will be burned from the biomass after pretreatment. To exemplify the effects of the variation of the pretreatment levels on the NER of the entire energy chain, a scenario analysis was conducted.

(a). Straw

A. Mass and energy flow (regular pellet)

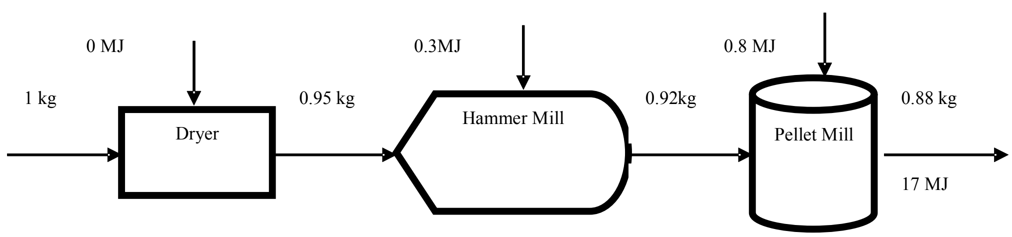


B. Mass and energy flow (steam treated pellet, base case)



(b). Switchgrass

A. Mass and energy flow (regular pellet)



B. Mass and energy flow (steam treated pellet, base case)

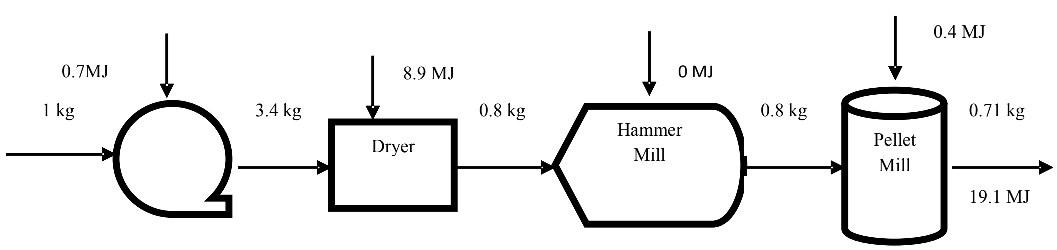


Fig. 3-3: Input and output energy and mass flow of regular pellet production and steam pretreated pellet production (base case)

Table 3-4: Variation of net energy ratio with treatment temperature

(a). Straw

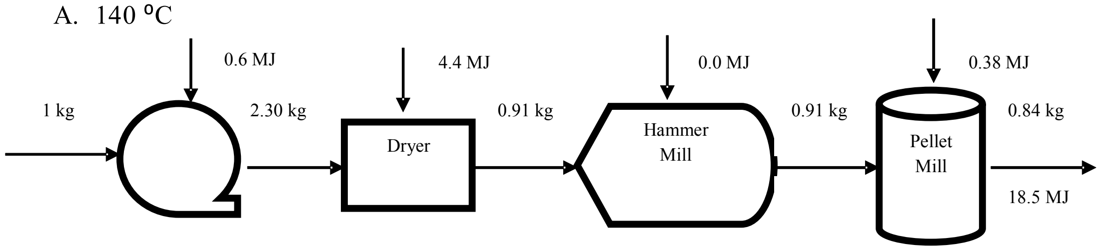
	Treatment Temperature								
	140 ^{0}C			160 ^{0}C			180 ^{0}C		
Unit operation	**Energy input (kJ kg^{-1})**	**Mass (kg)**	**Net energy (kJ)**	**Energy input (kJ kg^{-1})**	**Mass (kg)**	**Net energy (kJ)**	**Energy input (kJ kg^{-1})**	**Mass (kg)**	**Net energy (kJ)**
Steam Pretreated	650	1.00	650	698	1.00	698	750	1.00	750
Drying	1915	2.30	4416	2068	2.18	4511	2221	3.03	6731
Pelleting	419	0.90	383	419	0.74	310	419	0.79	330
Total			5449			5519			7811
Energy output	18500	0.84	15497	18700	0.68	12670	19000	0.72	13738
Net Energy Ratio			2.84			2.30			1.76

(b). Switchgrass

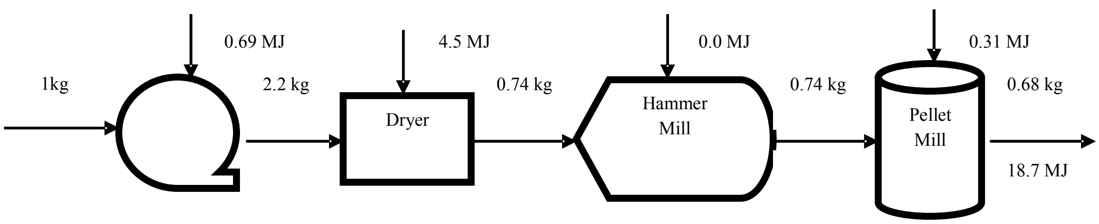
	Treatment Temperature								
	140 ^{0}C			160 ^{0}C			180 ^{0}C		
Unit operation	**Energy input (kJ kg^{-1})**	**Mass (kg)**	**Net energy (kJ)**	**Energy input (kJ kg^{-1})**	**Mass (kg)**	**Net energy (kJ)**	**Energy input (kJ kg^{-1})**	**Mass (kg)**	**Net energy (kJ)**
Steam Pretreated	547	1.00	547	593	1.00	593	678	1.00	678
Drying	2271	2.67	6054	2440	2.51	6129	2610	3.44	8979
Pelleting	410	0.91	371	409	0.71	291	409	0.78	319
Total			6972			7013			9977
Energy output	18500	0.83	15344	18700	0.65	12175	19100	0.71	13627
Net Energy Ratio			2.20			1.74			1.37

(a). Straw

A. 140 °C

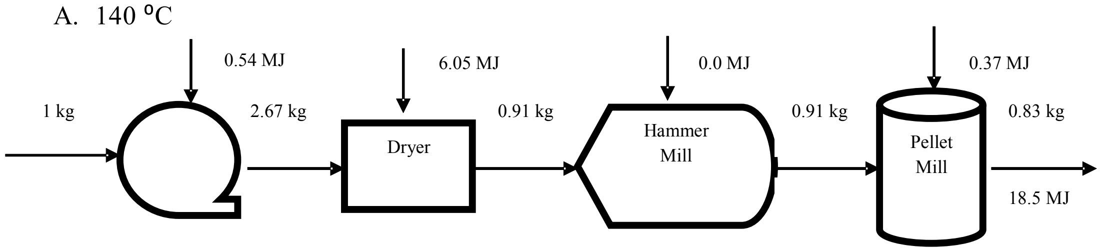


B. 160 °C



(b). Switchgrass

A. 140 °C



B. 160 °C

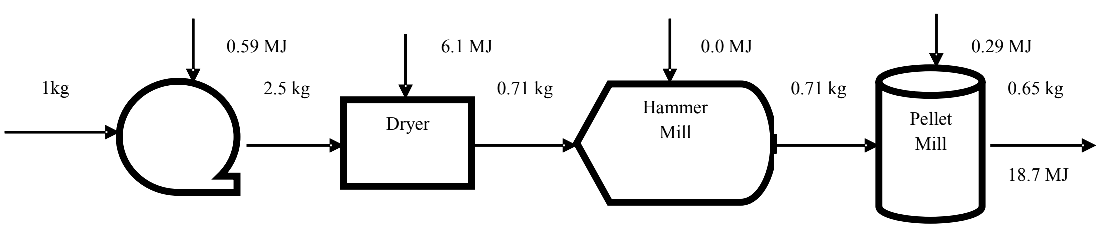
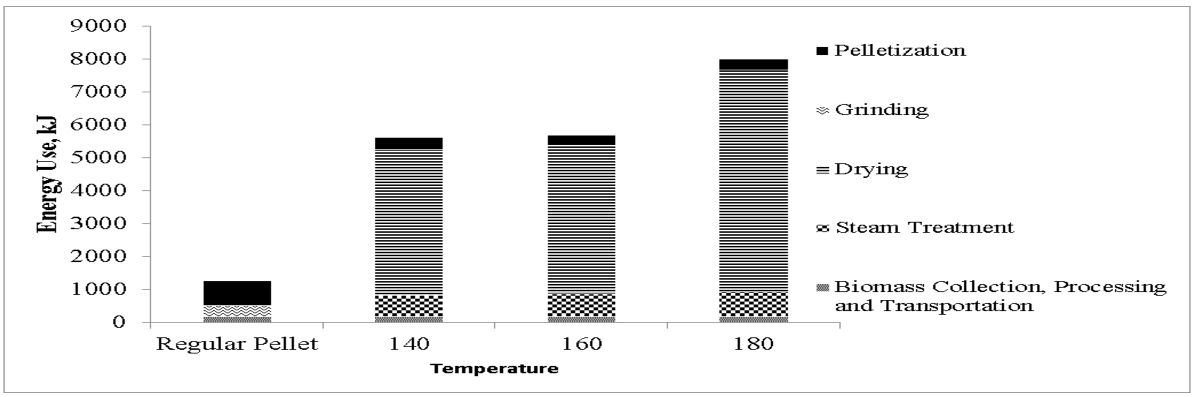


Fig. 3-4: Effect of change in temperature on energy and mass flow of steam pretreated pellet production

The energy requirement for the entire chain for large-scale steam-pretreated pellet production from both switchgrass and straw at a base case of 45,000 tonnes pellets per annum is shown in Fig. 3-5. This size has been chosen based on the typical size of pellet plants in Western Canada [3, 8, 9]. The key process differences are from increased drying energy with the increase in treatment temperature. The requirement for drying energy is greater for energy crop pellets than AR pellets since energy crop pellets have a higher water mass retention fraction.

(a). Energy use for the entire chain at large scale for switchgrass (45,000 tonne plant)



(b). Energy use for the entire chain at large scale for straw (45,000 tonne plant)

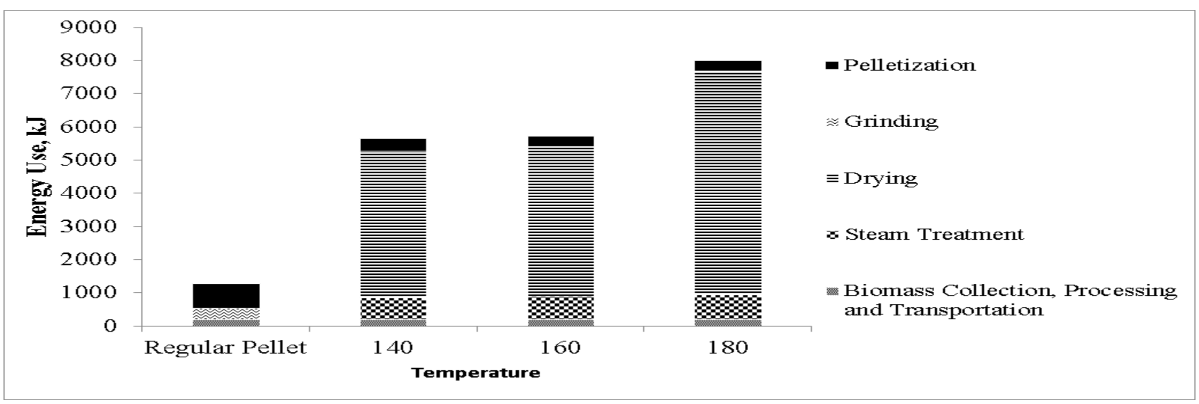


Fig. 3-5: Comparison of net energy ratios (a) switchgrass (b) straw at large scale case

3.4. Sensitivity Analysis

To determine the effects of temperature and steam pretreatment level on the calculated NER, a sensitivity analysis was conducted for the two biomass feedstocks. Table 3-4 shows the results of the analysis for varying temperature scenarios with respect to the NER pretreatment. The variation of mass and energy balance with temperature change is presented in Fig. 3-4. The results show that the NER of the steam pretreatment process drops with increasing temperatures. The increase in energy densification comes at the trade-off of extra process energy and reduced solid yield for pelletization. As a result, the NER of the process drops from approximately 2.84 to 1.76 for AR pellets and 2.20 to 1.37 for switchgrass case as the process temperature increases from 140 to 180 ˚C. The analysis also shows that 160 ˚C is the ideal temperature for the steam pretreatment process. At this temperature, the pellet's higher heating value increases and the process NER remains high.

The energy requirement for drying and steam pretreatment are the key drivers for the process NER, as earlier discussed. Drying and steam pretreatment energy increase by 47% and 18%, respectively, as the steam pretreatment temperature increases to 180 ˚C. The solid yield and calorific value are both optimum at a temperature of 160 ˚C, as shown in Table 3-4. This scenario is defined optimum based on the increase in calorific with minimum reduction of yield of pellet. Beyond this temperature, higher energy is required to raise the biomass temperature and maintain the steam pretreatment vessel temperature at the increased temperature level. More biomass disintegrates reducing pellet yield and more process steam condenses on the biomass with an increase in temperature and therefore steam pretreatment of biomass leads to the need for more evaporation energy for drying.

The results of the analysis of the variations in unit operation energy and changes in NER with pretreatment levels are shown in Table 5. In this study, the pretreatment temperature of 160 ˚C was chosen since it gives an increased heating value with minimal reduction in process NER and yield of pellet. Four different scenarios are analyzed ranging from 0% (representing regular pellet production) to 100% pretreatment (representing complete steam pretreatment). The NER at a 25% pretreatment level increases by 96% from the case with a pretreatment level of 75%.

Table 3-5: Variation of net energy ratio with level of pretreatment at 160°C

(a). Straw

	Energy input ($kJ\ kg^{-1}$)	**Mass (kg)**	**Net energy (kJ)**	**Energy input ($kJ\ kg^{-1}$)**	**Mass (kg)**	**Net energy kJ**	**Energy input ($kJ\ kg^{-1}$)**	**Mass (kg)**	**Net Energy (kJ)**
Pretreatment Level	25%			50%			75%		
Steam Pretreated	698	0.25	174	698	0.50	349	698	0.75	523
Drying	2068	0.54	1117	2068	1.10	2275	2068	1.67	4030
Grinding	324	0.75	243	324	0.50	162	324	0.25	12
Pelletization			649			446			442
Total			2183			3231			5007
Energy output			13574			13101			12815
Net Energy Ratio			6.2			4.1			2.6

(b). Switchgrass

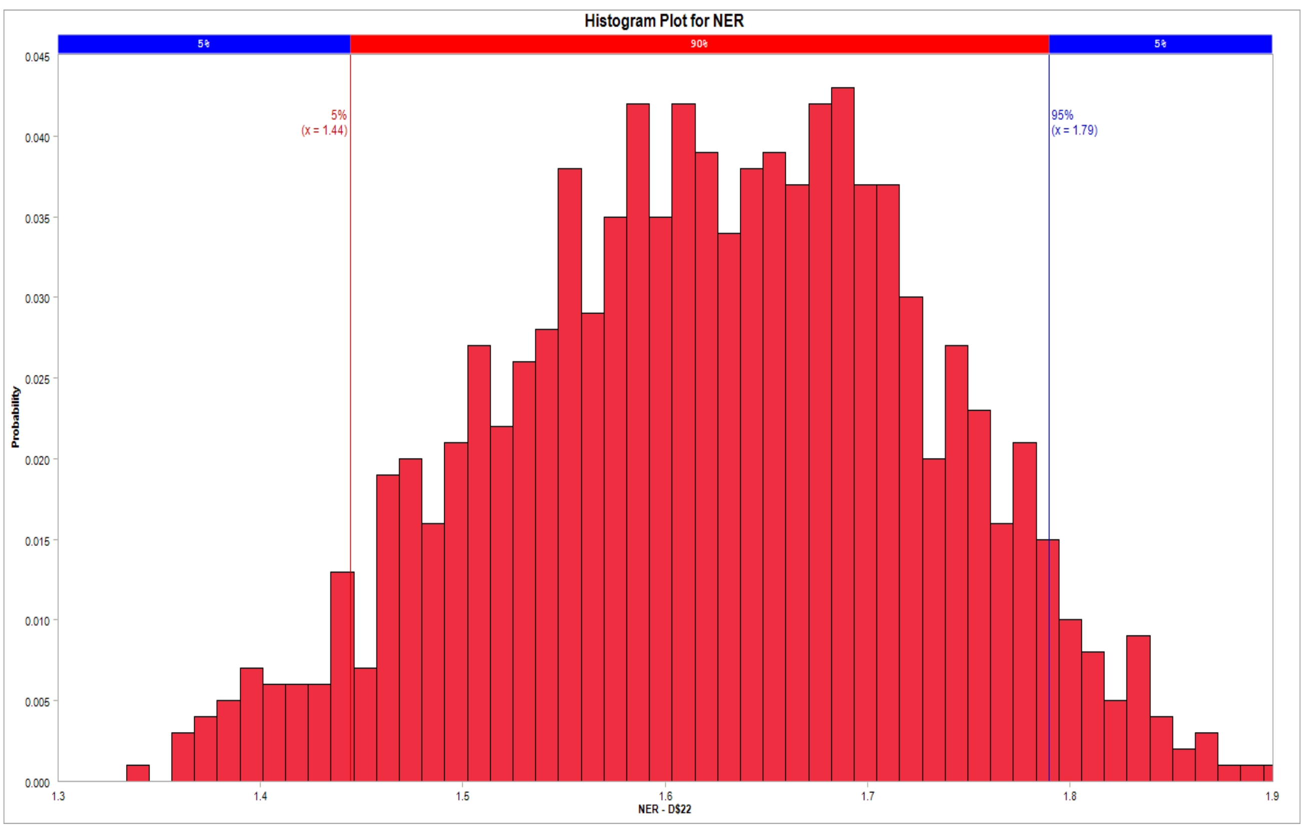
	Energy input (kJ kg^{-1})	Mass (kg)	Net energy (kJ)	Energy input (kJ kg^{-1})	Mass (kg)	Net energy kJ	Energy input (kJ kg^{-1})	Mass (kg)	Net Energy (kJ)
Pretreatment Level	25%			50%			75%		
Steam Pretreated	593	0.25	148	593	0.50	296	593	0.75	445
Drying	2440	0.63	1537	2440	1.25	3050	2440	1.67	4068
Grinding	500	0.75	375	500	0.50	250	500	0.25	125
Pelletization			685			565			394
Total			2745			4162			5032
Energy output			13448			13101			12606
Net Energy Ratio			4.9			3.1			2.5

3.5. Uncertainty Analysis

Lack of exact representative data and issues relating to uncertainty during experiment are a major concern for the accuracy of the predicted NER. In such cases, appropriate data sources and assumptions to complete the modelling studies are used, and this practice creates uncertainty in the modelling results. The Monte Carlo analysis is a well-known simulation application for uncertainty analysis that deals with a large number of variables to obtain accurate results without propagating errors [29]. In this study, a Monte Carlo simulation was conducted based on maximum volatility in the values of the required energy for drying and steam pretreatment. A sufficient number of iterations are required for the model to produce an accurate result, and 10000 iterations were used in our model. ModelRisk software was used for this simulation [30].

The Monte Carlo simulation results for the model NER are shown in Fig. 6. The Monte-Carlo results for the base case scenario of steam pretreated straw pellets shows that the process NER is in the range of 1.62±0.10 at a confidence level of 95%, while for the steam pretreated switchgrass pellet the NER is in the range of 1.42±0.11. Author has previously done uncertainty analysis of steam pretreated wood pellets [18]. Monte-Carlo simulation result for the base case scenario of steam pretreated wood pellet shows process NER range is 1.35±0.09 at a confidence interval of 95%. The Monte-Carlo simulation shows that the uncertainty in the production of steam pretreated AR and energy crop pellets is higher than wood pellets as reflected by the higher standard deviation of process at 95% confidence interval.

(a). Straw



(b). Switchgrass

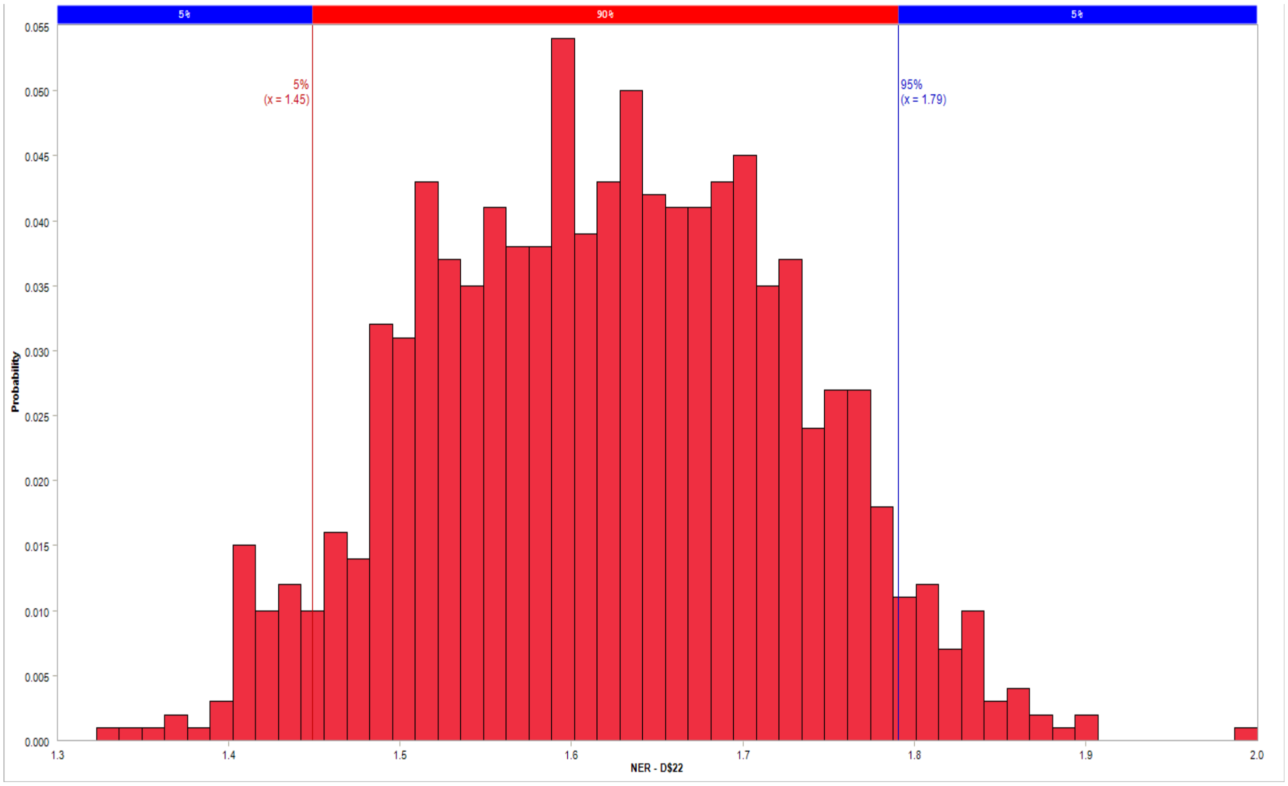


Fig. 3-6: Model uncertainty analysis of (a) steam pretreated Straw Pellet NER and (b) steam pretreated Switchgrass Pellet NER

3.6. Conclusions

In this study, a process model was developed to conduct a comparative energy analysis for steam-pretreated pellet production of agricultural residue (AR) and energy crops (switchgrass). The results of the analysis show that the heating value of the fuel can be improved by the steam pretreatment process. At the same time, the steam pretreatment process results in increase in the process energy requirement for drying and steam pretreatment. The drying energy requirement is higher for switchgrass pellets than AR pellets. Therefore, the process net energy is significantly reduced as a result of the drying energy required for energy crop pellets. The process NER can be improved by reducing the pretreatment level and temperature and increasing the drying efficiency. Earlier work by the authors on pre-treated wood based pellets was used for comparison with current results. Comparison between the NERs of the steam pretreated wood, AR and energy crop-based pellet shows that NER of the steam pretreated straw based pellet production has highest NER of 1.62 followed by switchgrass and wood pellet. This can be attributed to the high energy requirement of both steam pretreatment and drying process during wood pellet production.

Reference:

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Chapter 4: Techno-economic Assessment of Pellet Produced from Steam Pretreated Biomass Feedstocks[3]

4.1 Introduction

Fossil fuels have long been the source of energy production worldwide. However, fossil fuels are being used faster than they are generated as the world population is growing faster than the generation and extraction of fossil fuels [1]. In addition, fossil fuels have long been considered less environmentally friendly since burning these produces large amounts of greenhouse gases (GHGs) which contributes 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 recent focus on utilization 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 [1].

Biomass-based facilities are faced by a number of challenges that has limited their development so far. The quality and quantity of the biomass produced from various feedstocks (i.e., forest residue, wheat straw, and switchgrass) varies significantly. This characteristic of the feedstocks is one of the key factors affecting its large scale practical use in a biomass-based

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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 in reducing some of these barriers.

Pelletization is one of the biomass pre-processing methods. The pelletization process starts with the collection of biomass, which is sent to a shredder to be formed into chips and bales. The chipped biomass that is pelletized is transported to the pellet mill. Most of the pellets produced today are based on sawdust a residue from saw mills. The biomass requires drying before being comminuted and pelletized. Pelletization helps in improving the bulk density and calorific value of the fuel. However, significant improvement is required in bulk density and calorific value to make pellets feasible to be co-fired with coal [4, 5]. Steam pretreatment, as described by Lam [4] and Tooyserkani [5], is a non-chemical pretreatment that exposes biomass to high pressure and high temperature steam ranging from 1 to 3.5 MPa and 180-240^{0}C [4]. Steam pretreatment of biomass pellets, however, can help reduce some of the barriers of utilizing pellets for co-firing. Steam pretreatment is essential to ensure high energy output and improve thermal efficiency [4].

Steam pretreatment prior to the bioconversion of pellets has been proposed by Lam [4] and Tooyserkani [5] 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 improving the cost of fuel production from biomass.

Previous studies have evaluated the economics of biomass-based energy from the perspective of generic models [2, 6-11]. The cost of producing pellets from sawdust has been reported by Mani et al. [12], who found that pellets can be produced from sawdust at a cost of \$51 t^{-1} at a plant capacity of 45,000 t. A European pellet production scenario has been reported by Thek and Obernberger [13] predicting the capital cost and production cost of saw dust based pellets in

European setting. Urbonowski [14] used their study to evaluate the capital cost of regular pellet production plant. Other researchers evaluated the production cost of pellets in Europe and elsewhere [15-18]. However, none of this research evaluated the production costs of steam pretreated pellets, nor compared production costs of regular and steam pretreated pellets. In addition there is also very limited focus on the effects of the economic optimum size of the feedstocks like forest residue, straw and switch grass 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 pre-treated 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 with the cost of regular pellet production process. The key specific objectives for the study are:

- To develop of a data-intensive techno-economic model to evaluate the steam pretreated biomass-based pellet production costs.
- To estimate the steam pretreated biomass-based pellet production cost in terms of $ t^{-1}$ and $ GJ^{-1} for the three feedstocks including forest residue, wheat straw and switchgrass.
- To evaluate the economic optimum production plant size for the steam pretreated biomass-based pellet from the three feedstocks.
- To perform sensitivity analyses of various parameters on the cost of production of pellets.

4.2 Biomass sources, yields, and properties

4.2.1 Forest residues

Forest resources are valuable as fiber in pulp and lumber industry; hence forest residues are an alternative in bio-fuel industry. It is possible to collect limbs and tops. This study is based on the limbs and tops recovery from the side of the road. Cost for construction of logging roads and silviculture are not considered for the production cost [3].

4.2.2 Agricultural residues

Agricultural residues are the largest concentrate of field based residues in western Canada. It is possible to generate 2000 MW of power from the available quantity of uncollected straw; this shows the magnitude of available straw. However, significant cost of delivery is given in the form of nutrient replacement while removing straw from field for bio-fuel production. This study is based on full replacement of removed nutrients plus full recovery of cost from the farmers end [3]. A recent study estimated the amount of agricultural straw availability in Alberta to be more than 6 megat of dry biomass [8].

4.2.3 Energy crop

The energy crop considered in this study is switchgrass (*Panicum vigratum, L.*). Switchgrass is a hot weather perennial grass native to the United States. The grass can grow in dry weather and is suitable for marginal land. The above-ground biomass yield reported by Kumar et al. [11, 19] is from 3 to 30 t ha^{-1}. This yield is dependent upon soil fertility, location, variety, and number of harvests per season [11]. The yield considered for the purpose of this research is 3 tonne 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 are listed in Tables 4-1 and 4-2 respectively.

Table 4-1: Feedstock properties

Characteristic	Wheat Straw	Forest Residue	Switch grass	Source
Moisture content (%)	14	45	14	[3, 8, 11]
Regular pellet heat value ($MJ\ kg^{-1}$)	17.8	19.2	18.1	[23]
Steam Pretreated pellet heat value ($MJ\ kg^{-1}$)	19	19.5	19	[23]
Regular pellet bulk density ($kg\ m^{-3}$)	780	800	660	[20]
Steam pretreated pellet bulk density ($kg\ m^{-3}$)	1086	1112	834	[20]

Table 4-2: Calculation of net yield for wheat straw and switchgrass

Crop	Yield Grain/ straw (green tonne ha^{-1})	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 content (%)	Net yield (dry tonne ha^{-1})	Source
Wheat straw	2.66	1.1	2.93	0.75	70	0.66	15	0.73	14	0.63	[8]
Switch-grass	3.5	-	3.5	0.75	70	0.66	15	-	14	1.56	[8, 11]

4.3 Methodology

4.3.1 Techno-economic analysis and optimization

A data-intensive techno-economic model was developed for production of pellets from the three different steam pretreated feedstocks. The focus of this study is to apply a specific cost number methodology to western Canada. Region-specific data are available for the delivered cost of different feedstocks in western Canada. However, very 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 pellet production from the regular process and the process involving steam pretreatment added to regular production.

Cost parameters were developed based on detailed literature review, in consultation with experts and modeling and are specific to western Canada. These costs consist mainly of feedstock harvesting, transportation, and pellet production. Costs associated with processing within the plant consist of capital cost, energy cost, employee cost, and consumable cost. The model was created based on the yields of the three different feedstocks. Feedstock yield affects the delivered cost of the feedstock, specifically the transportation cost. The plant life considered in model is 30 years. Total pellet production cost is the sum of the delivered feedstock cost and the pellet plant's production costs.

The economic optimum pellet plant size is the capacity of the plant at which the cost of production of pellet is minimum. The 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.

Our research focused on the evaluation of a uniform end use of biomass: bio-pellet production from different biomass feedstocks. Keeping the end use fixed for the three considered feedstocks allows us to assess the relative value of the feedstocks and to evaluate an optimum pellet production size. 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, 7, 9, 10].

In our research we evaluated the economic feasibility of a steam pretreatment process that has got very limited attention so far. Thus, 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 compare the production costs of steam pretreated pellets with regular pellets. Details on the different cost parameters and the techno-economic model are given in the following sections.

4.3.2 Input data and assumptions for development of cost estimates

Note: All currency figures are taken in US$ in the base year 2015. An inflation rate of 2% has been assumed. The conversion rate between the US and Canadian dollar is considered at the rate of $1 US = C$1.27. In the base case, the pellet plant is assumed to run at 6 t h^{-1} with an annual production capacity of 44,000 tonnes. This size has been used based on earlier studies on the pellet plants and associated barriers in getting to a larger unit size [8]. The cost parameters considered for the model development are given listed in Tables 4-3 to 4-5.

Table 4-3: Reference input data for the techno-economic model

Items	Values/formulae	Comments/sources
Forest Residue		
Biomass yield (d t ha^{-1})	0.24	Assumed yield based on hardwood and spruce yield in Alberta [3, 6, 7, 24, 25].
Biomass chipping cost ($ d t^{-1})	9.42	The cost of chipping consists of forwarding and piling [3, 6, 7, 24, 25].
Chip loading, unloading, and transportation cost ($ m^{-3})	$0.7585\times(2.30+0.0257\,D)$	D is the round-trip transportation distance between in-bush chipping and a centralized bio-fuels production plant [3, 6, 7, 24, 25].
Tortuosity factor	1.27	Increases feedstock transportation distance for geographical conditions such as swamps, hills, and lakes in the biomass site [6].
Straw		
Yield (d t ha^{-1})	0.52	[3, 6, 7, 8]

Items	Values/formulae	Comments/sources
Straw harvesting cost ($\$$ d t^{-1})	44	The harvesting cost consists of shredding, raking, baling, collection, storage and nutrient replacement [8]
Straw loading and unloading cost ($\$$ g t^{-1})	6	Green tonne indicates the cost is calculated based on the moisture content of the feedstock [8]
Straw transport cost ($\$$ g t^{-1} km^{-1})	0.18	[8]
Switch grass		
Yield (d t ha^{-1})	3	[11, 19]
Field cost ($\$$ d t^{-1})	22.62	[11, 19]
Distance fixed cost ($\$$ d t^{-1})	12.38	[11, 19]
Distance variable cost ($\$$ d t^{-1} km^{-1})	0.11	[11, 19]

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

Plant equipment	Scale factor	Capital cost - base case ($)	Maximum size of equipment (t y^{-1})	Source
Primary grinder	0.99	650,000	105,000	[8]
Dryer	0.6	430,000	100,000	[8]
Steam pretreatment unit	0.75	29,302,000	660,000	[21]
Hammer mill	0.6	150,000	108,000	[8]
Feeder	0.57	44,700	50,000	[8]
Boiler	0.7	51,000		[8]
Pellet mill (with conditioner)	0.72	350,000	50,000	[8]
Pellet cooler	0.58	170,000	216,000	[8]
Screener/shaker	0.6	18,300	100,800	[8]
Bagging system	0.63	450,000	100,800	[8]

Table 4-5: General Assumptions

Factors	Value	Sources
Operating life (years)	30	Assumed based similar bio-fuels studies [4, 8]
Inflation	2.0%	Assumed 2% based on average inflation of the last 12 years [4, 8]
IRR	10%	Assumed
Pelletization mass loss	5%	Based on experiment [23]
Plant capacity factor		Account for the production profile of the plant [4, 8]
Year 1	0.7	
Year 2	0.8	
Year 3 and onward	0.85	
Capital cost spread		Taken from earlier studies [4, 8]
Year 1	20%	
Year 2	35%	
Year 3	45%	
Other costs such as tax, insurance, etc., are	0.50%	[4, 8]

Factors	Value	Sources
<u>Equipment power used for energy calculation :</u>	(kW)	[8]
Primary grinder	112	
Dryer	120	
Hammermill	75	
Boiler	75	
Pellet mill	300	
Cooling	5	
Bagging	40	
Light and heat	112	

Cost factors considered for the model are briefly explained as follows:

- *Biomass field cost*: The price estimate of biomass can vary from producer to producer and from plant to plant [8, 20]. Field costs in general for all feedstocks consist of harvesting and collection, chipping, nutrient replacement, and farmer's premium. It was assumed that farmers harvested, baled, and left the feedstock by the roadside to be transported to a pellet plant. The other field cost is storage cost. This model assumes that the biomass feedstock is typically stored without any fixed structure, and hence storage cost is low since there is no capital cost for a storage facility [8]. Nutrient replacement is in the form of payment to farmers to replenish it after biomass harvesting. Nutrient replacement is considered for straw and switchgrass, but not for forest biomass. Forest residues are currently burnt to prevent forest fires without any ash spreading [10] .

- *Transport of biomass to pellet plant*: For agricultural residues and energy crops, biomass is transported over existing roads. Forest harvest residues are transported on roads built for the pulp and lumber industry [3]. As noted above, biomass transportation costs vary directly with the capacity of the bio-fuel facility. 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. Thus, overall pellet production capacity is sensitive to changes in harvest area and transportation distance, and 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. 4-1.

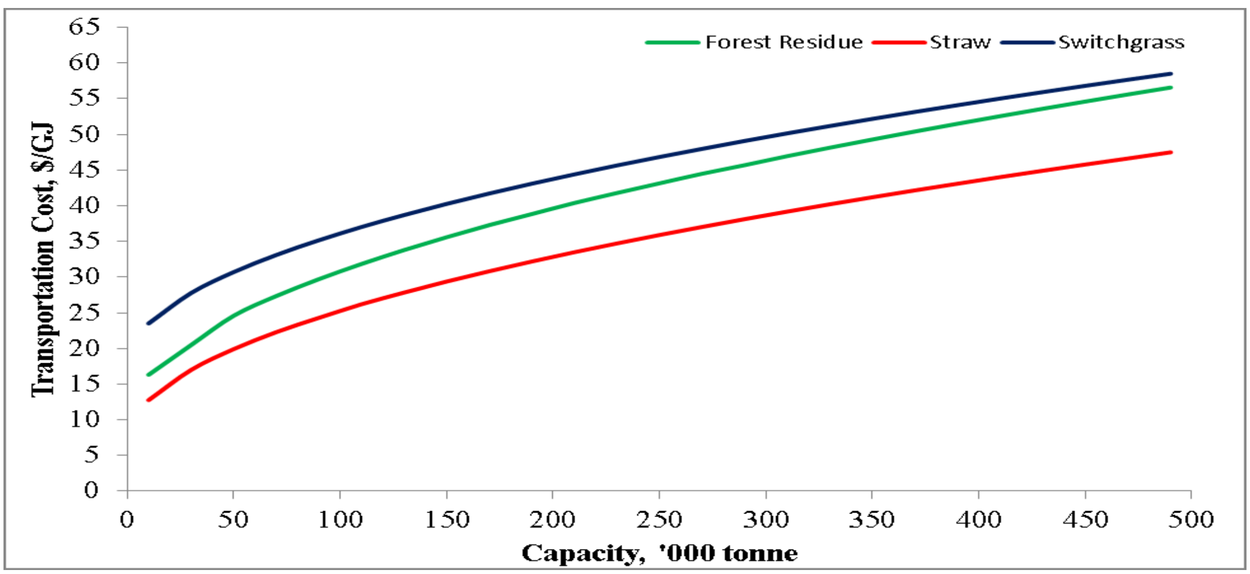


Fig. 4-1: Transportation cost of straw as a function of pellet plant capacity

- *Capital cost, power plant capital cost index, and scale factor*: The capital cost assumed for the model considers 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 [8] and the steam pretreatment capital cost is based on McAloon and Taylor [21]. The maintenance cost considered for the model is 2.5% of the equipment cost. All equipment prices are adjusted to 2015 $ using the power plant cost index (PCCI) factor [22]. The change in capital cost with capacity is shown in Fig. 4-2.

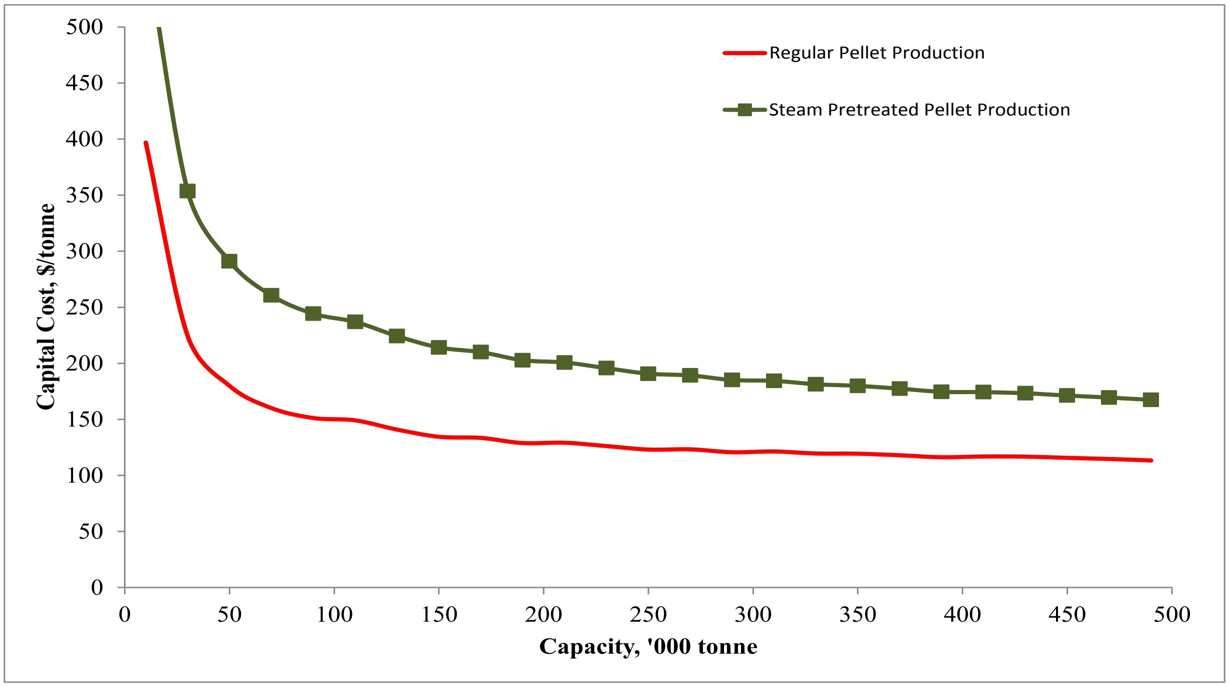


Fig. 4-2: Change of unit capital cost of pellet production plant with capacity

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. Hence, the PCCI is used to inflate the equipment capital cost from a base year to 2015 in the model developed in our research work. The numbers are maintained by Information Handling Systems Inc. (IHS) and date back to 2000 [22]. 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 (4-1) [3, 8], where

$$Cost_2 = Cost_1 * (Capacity_2/Capacity_1)^{\text{Scale factor}} \quad [4\text{-}1]$$

The scale factor considered for this model is based on work by Sultana et al. [8]. The number is less than 1. This means that capital cost increases at a rate lower than the production capacity of the plant. 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 as given in Table 4. The maximum capacity of the pellet plant limits the optimum size and economy of scale. The largest manufactured single unit pellet plant reported in the literature is 50,000 t yr^{-1} [8]. The capital cost per unit capacity decreases as the plant size increases up to 50,000 t yr^{-1} plant capacity. For capacity beyond 50,000 t yr^{-1}, the capital cost per unit production increases with the increase in the capacity. This has an impact on the economic optimum size of production plant.
- *Operating cost:* The operating cost considered for the model consists of employee cost, energy cost, and consumable cost.

1. Employee cost: Employee cost is a major cost component in the pellet production process. Two types of employees are considered for this study: permanent employees and hourly employees. In the production process, 7 hourly employees and 4 permanent employees are required for regular pellet production at a base case production of 44,000 t yr^{-1}. However, two

additional hourly employee operators are considered for the steam pretreatment unit for steam pretreated pellet production [8]. The employee cost has an important role in determination of 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 cost considered for the model consists of electricity and natural gas costs. The electricity cost is considered based on the equipment wattage information taken from an earlier study [15]. The equipment type and wattage vary with the quality and type of feedstock used. For example, straw pellets require less energy for production than softwood pellets and more energy for grinding [23]. However, the model assumes the electricity demand to be the same for the three feedstocks.

Natural gas is required for feedstock drying and steam pretreatment. The natural gas requirement is based on the energy requirement of the unit operations. This is calculated from the simulation process 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 [23]. The gas price considered is 5.94 \$ GJ^{-1} [8].

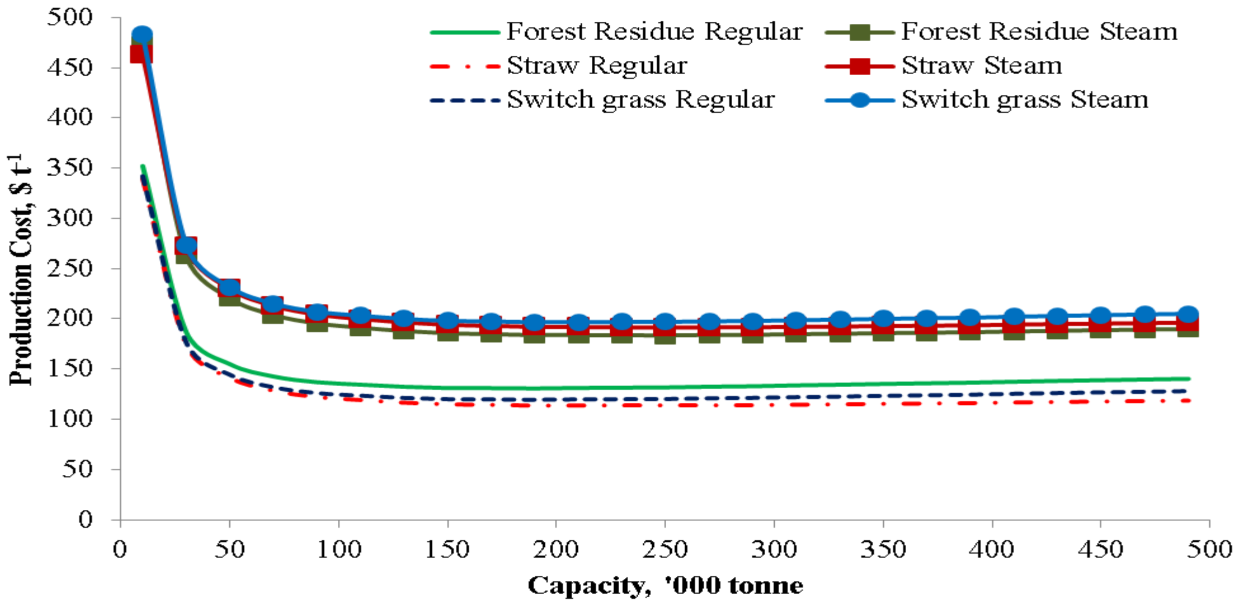
- *Plant reliability and start-up profile*: Biomass facilities have frequent plant outages due to solids blockages [3]. The plant reliability factor considered for this study is 0.85. The start-up of most biomass facilities is smooth, and facilities are considered to start at 70% of their rated production 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.

4.4 Results and Discussion:

For the three sources of biomass considered in this study, production costs and the economic optimum size of production are shown in Fig. 4-3. 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 power 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 transportation cost of the project increases with the square root of the capacity of the project. 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 production of energy will decrease 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 the biomass-based plants. This concept has been explored earlier for different biomass conversion pathways [3, 6, 7, 10, 12, 24, 25]. The optimum plant size for regular pellet production is 150,000-190,000 t yr^{-1}, while for steam pretreated pellet production it is 230,000-270,000 t yr^{-1}. The production costs vs. capacity profile in \$ t^{-1} and \$ GJ^{-1} is presented in Fig. 4-3.

(a)



(b)

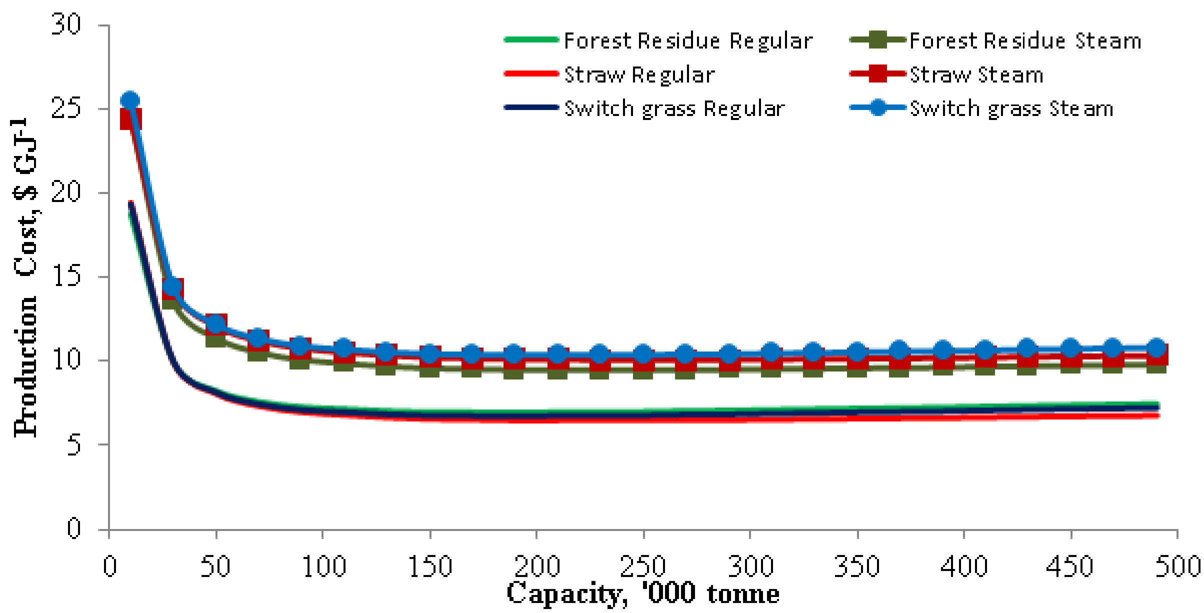


Fig. 4-3: Pellet production cost for the three feedstocks in (a) $ tonne^{-1} (b) $ GJ^{-1}

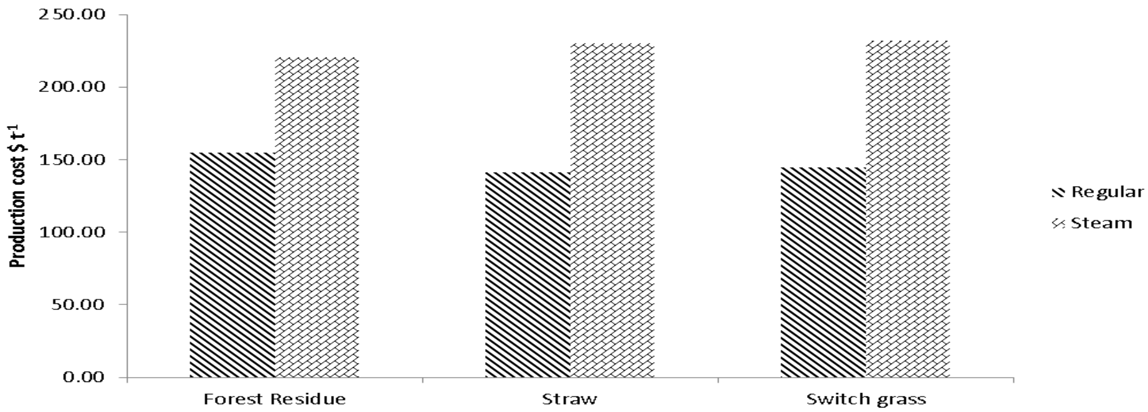
- *The assumption that maximum unit size will impact production cost*: The largest pellet plant size reported in the literature is 50,000 t yr^{-1}. The maximum unit size is a guiding factor in creating small pellet plants. It is observed from the model that at every interval of 50,000 t yr^{-1}, the cost of pellet production increases. Thus, a small increase in production capacity beyond every increment of 50,000 t yr^{-1} leads to an increase in production cost, up to 190,000 t yr^{-1} for regular pellets and 270,000t yr^{-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 cost increases beyond this capacity for regular and steam pretreated pellets, hence these are considered as optimum scale of production.
- *The composition of pellet production cost*: Table 6 shows the delivered cost 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 size. Improving transportation and field costs will help in increasing the size of the pellet. The effect of delivered cost is significant for 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 4-6: Economic optimum size and components of production cost of pellet production from three feedstocks

	Straw		Forest residue		Switchgrass	
	Regular	Steam pretreated	Regular	Steam pretreated	Regular	Steam pretreated
Optimum size (t y^{-1})	190,000	250,000	190,000	290,000	190,000	230,000
Pellet cost (\$ t^{-1})	122.04	188.34	116.01	183.14	116.20	192.41
-Capital recovery	9.56	15.31	10.83	20.34	13.74	21.53
- Maintenance cost	2.64	3.68	2.34	3.59	2.58	3.76
-Field cost	52.34	58.75	28.19	32.08	25.57	29.39
-Transportation cost	33.89	42.99	37.04	50.24	45.38	57.68
-Premium	0.00	0.00	6.39	5.50	5.34	6.13
-Employee cost	7.27	7.85	6.58	6.76	7.27	8.53
-Energy cost	5.41	48.91	14.74	53.79	5.41	54.50
-Consumable item cost	10.93	10.86	9.90	10.84	10.93	10.88
Pellet transportation	6.30	5.50	6.20	5.45	6.80	6.10
Total pellet cost	128.34	193.84	122.21	188.59	123.00	198.51

- *Effect of steam pretreatment on the cost of pellet production*: 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 large amount of natural gas, which significantly increases the energy requirement [23]. Table 4-6 shows that the difference between steam pretreated and regular pellet production cost 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 is varied due to the material losses happening during steam pretreatment. The material losses happen during steam pretreatment since the high pressure steam breaks the biomass and reduces the solid content of the biomass. High material losses have been predicted for switchgrass as compared to straw and forest residue in literature [4, 5].
- *Cost per unit mass ($ t^{-1}) vs. cost per unit energy ($ GJ^{-1}) cost variation*: As explained in the introduction, steam pretreatment increases the calorific value of the fuel (see Table 4-2) by 8-10%. This is the primary motivation for the steam pretreatment of biomass feedstock prior to pelletization. This parameter is quantified by the $ GJ^{-1} parameter. The change in $ GJ^{-1} cost capacity shows the same flat trend and the same economic optimum size (see Fig. 4-3). However, the striking difference is the reduced gap in the $ GJ^{-1} value for steam pretreated and regular pellets. Fig. 4-4 (a) and (b) show that the difference between the cost to produce regular and steam pretreated pellets in $ GJ^{-1} is within 2 - 3 $ GJ^{-1}. Hence pellet production costs in terms of the energy value of the fuel improve due to steam pretreatment.

(a)



(b)

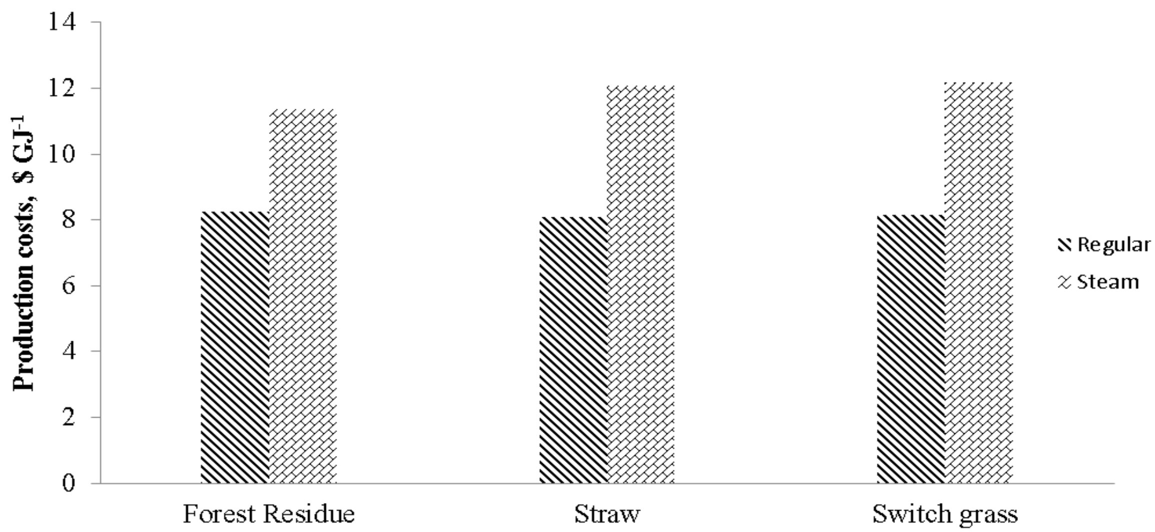


Fig. 4-4: Comparative analysis of production costs for the base case in (a) $ t^{-1} (b) $ GJ^{-1} for the three feedstocks

- *Effect of bulk density*: Bulk density is also improved through steam pretreatment as shown in Fig. 4-5. 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 actual load carried by the trucks and hence do not impact the variable cost of transporting pellets.

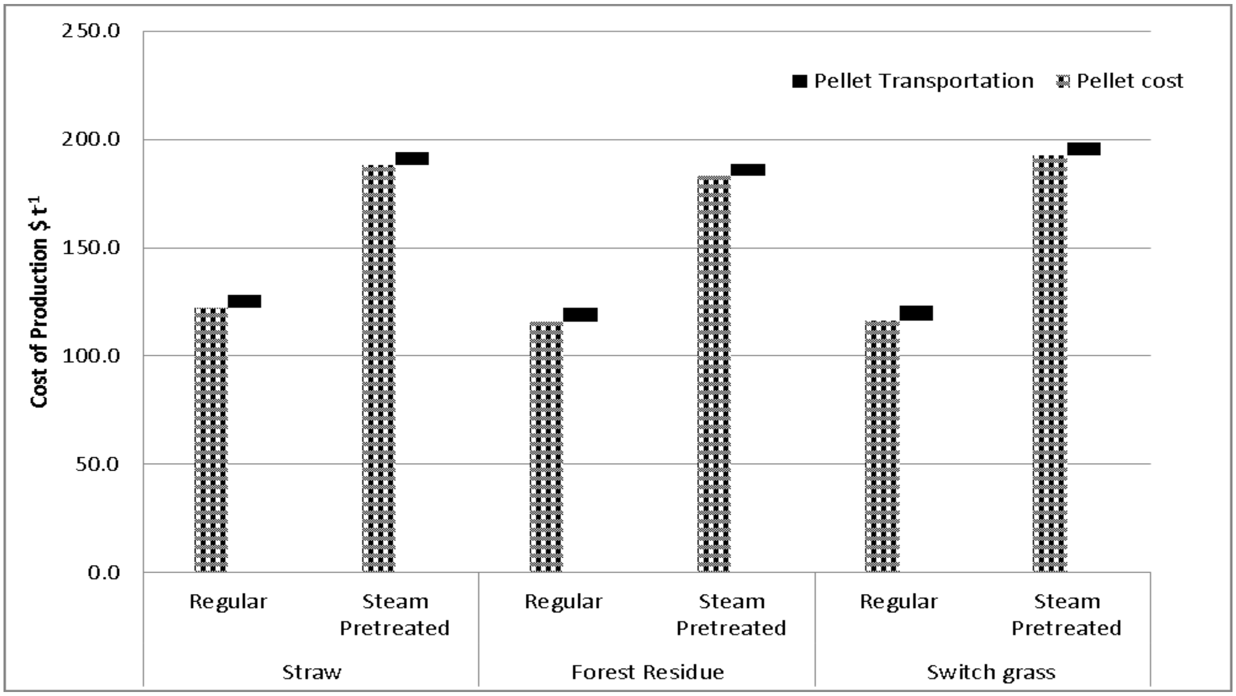


Fig. 4-5: Effect of bulk density on the delivered cost of pellet production

- *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 $ t^{-1} value of the cost of production: 116 $ t^{-1} for wood and 122 $ t^{-1} for 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 straw (see Table 4-6).

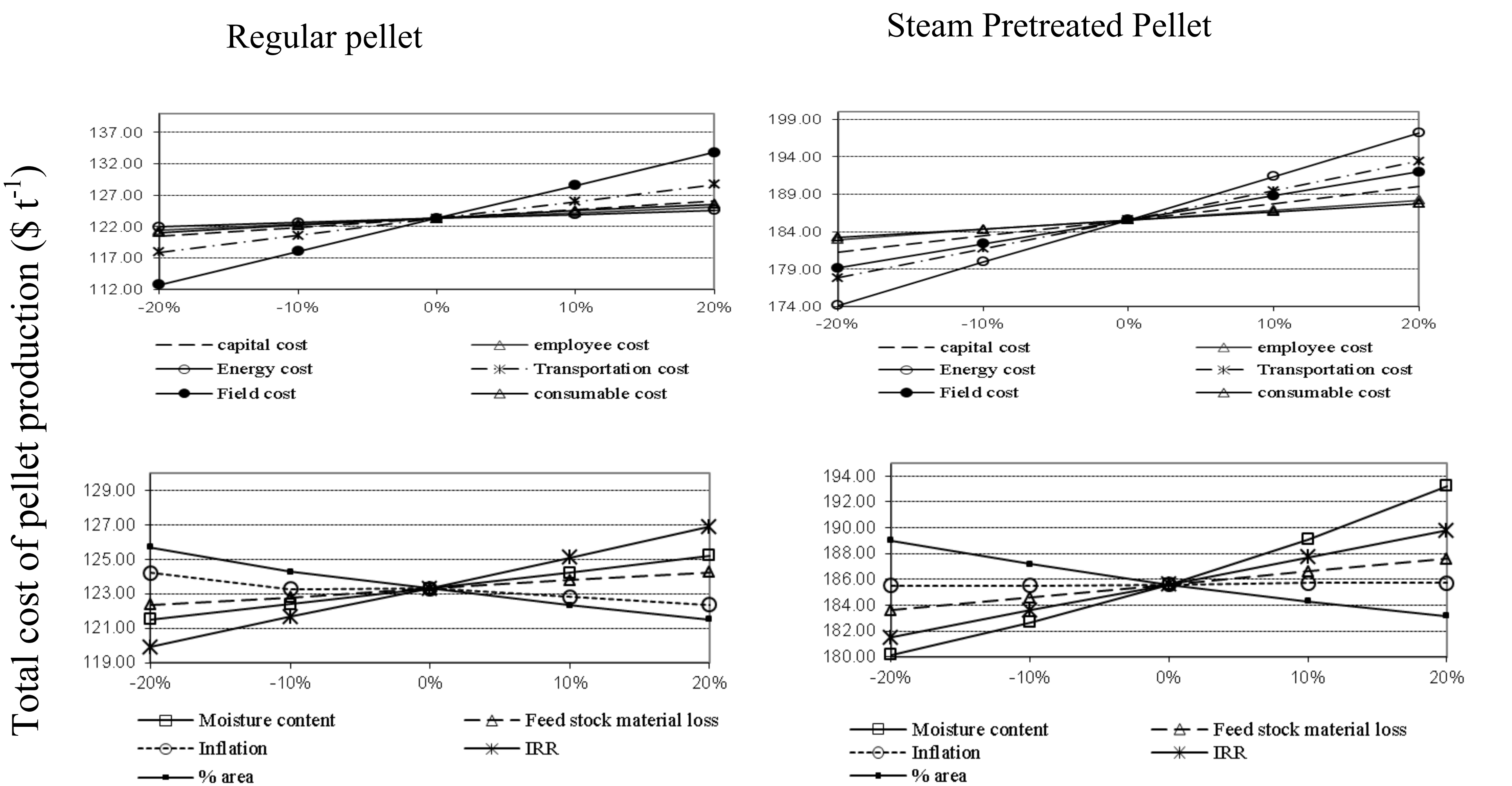
The steam pretreatment of pellets has a different effect on the $ t^{-1} value of the production cost for the three feedstocks. The $ t^{-1} is highest for switchgrass since steam pretreatment leads to material loss, and this loss is highest for switchgrass (see Table 4-2). The economic optimum plant size is lower for switchgrass than for the other feedstocks since higher material loss occurs in steam pretreated switchgrass pellet production than in other feedstock pretreatment. This can be accounted that both field cost and transportation cost are related to biomass harvested. As discussed above, switchgrass has the highest mass loss among the three feedstocks. This increases the field cost and transportation cost and cannot be offset by the reduction of capital cost. Hence it has a smaller optimum plant size compared to other feedstock.

4.5 Sensitivity Analysis

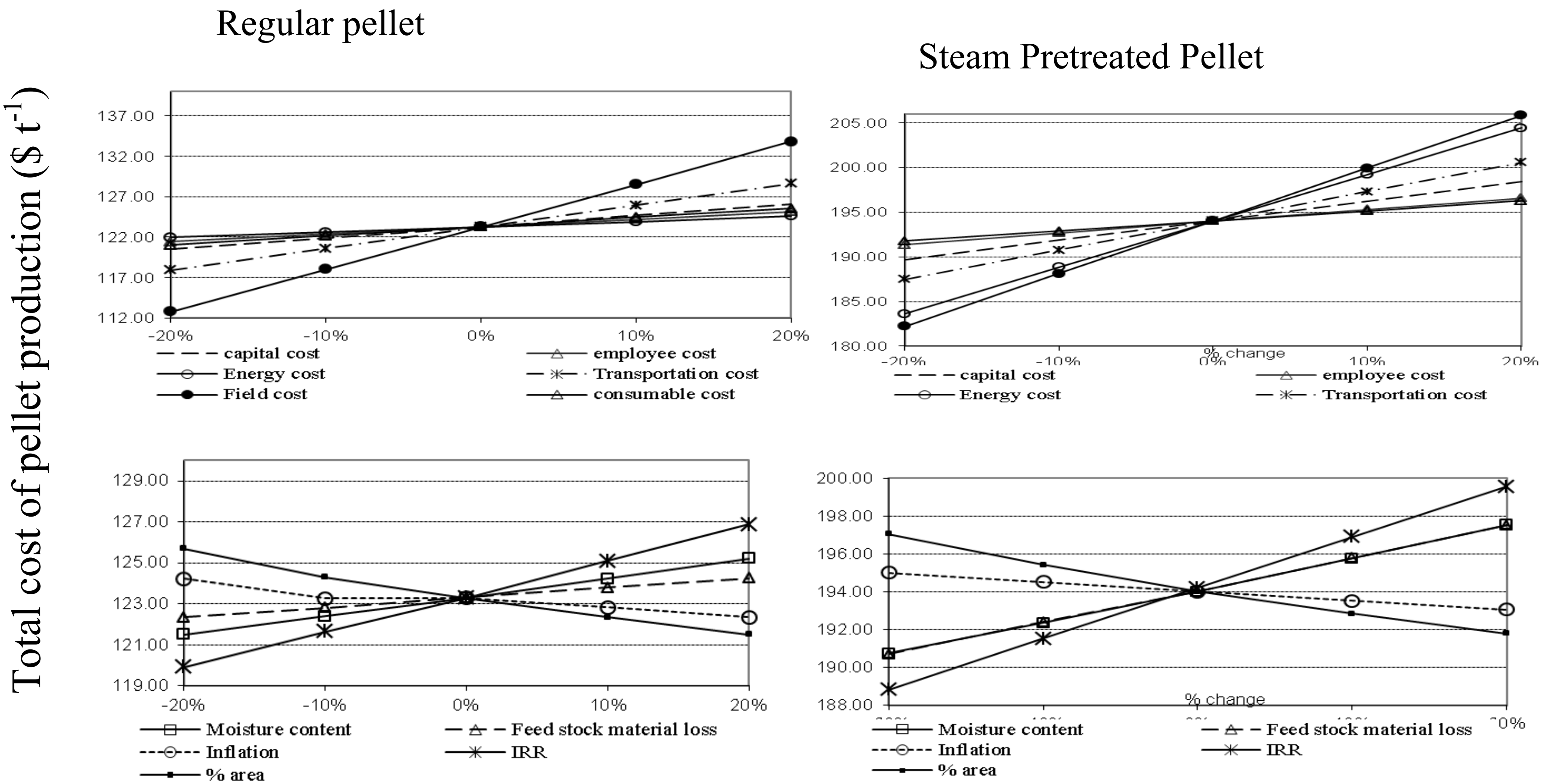
A sensitivity analysis for cost and technical factors was conducted for the base case scenario. The sensitivity analysis was carried out by varying cost and technical parameters by ±20%. The cost factors considered are field, transportation, capital, employee, energy, and consumable. The technical parameters include moisture content, material loss, inflation, return, and biomass harvesting area.

The results of the sensitivity analysis are shown in Fig. 4-6. Field and transportation costs are the most sensitive factors and range from 15-20 \$ 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 content, IRR, and biomass yield lead to production costs of 6-10 \$ t^{-1}. Hence, cost factors are more sensitive to variation than technical factors.

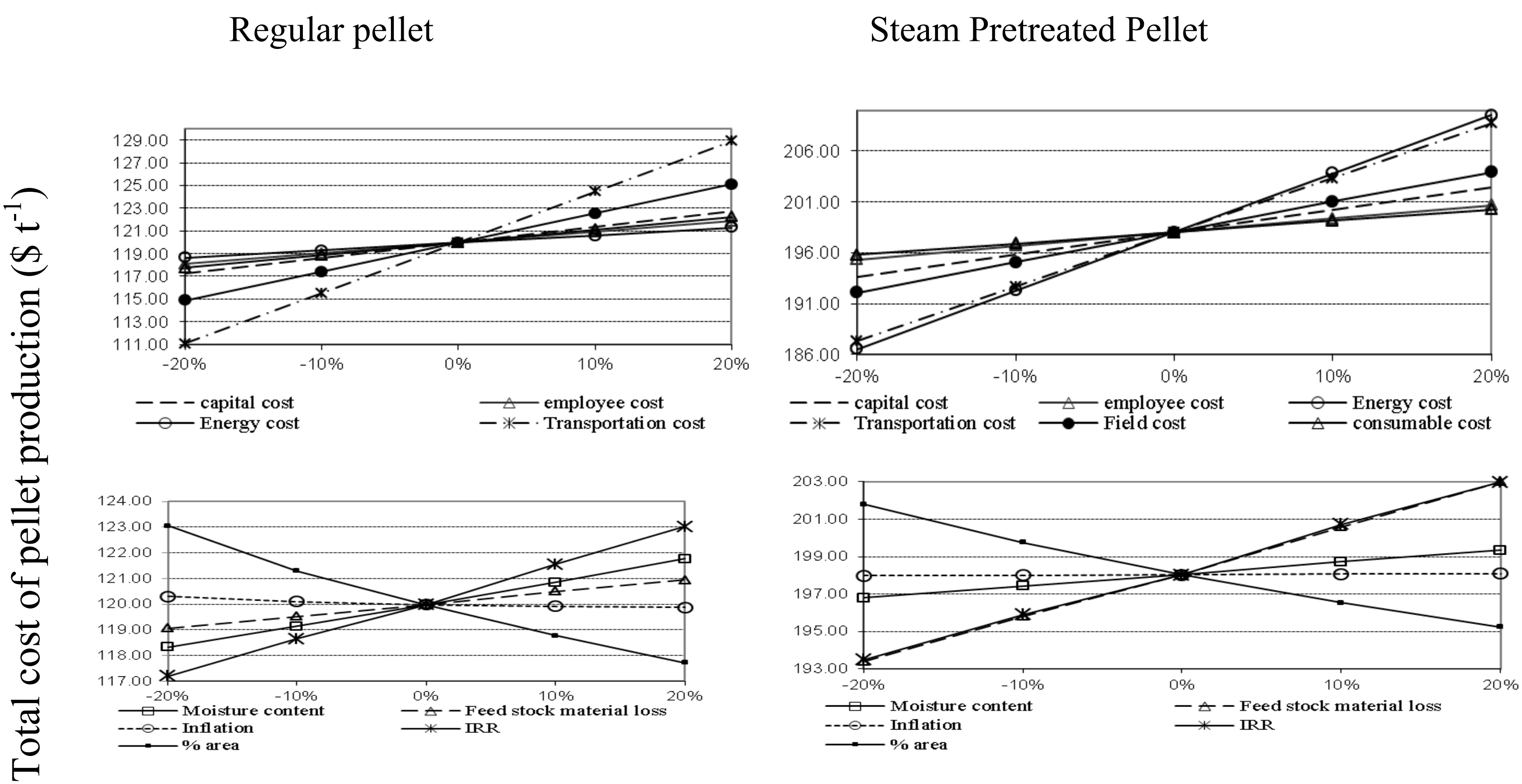
Steam pretreatment sensitivity models show that the model outputs are sensitive to the material loss parameter, which changes the requirement of biomass for producing the same quantity of pellet. Switchgrass shows more sensitivity since, of all the feedstocks studied here, it has the highest material 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). Forest Residue


Regular pellet
Steam Pretreated Pellet
Total cost of pellet production ($ t-1)
137.00
132.00
127.00
122.00
117.00
112.00
-20%
-10%
0%
10%
20%
capital cost
employee cost
Energy cost
Transportation cost
Field cost
consumable cost
205.00
200.00
195.00
190.00
185.00
180.00
% change
capital cost
employee cost
Energy cost
Transportation cost
129.00
127.00
125.00
123.00
121.00
119.00
Moisture content
Feed stock material loss
Inflation
IRR
% area
200.00
198.00
196.00
194.00
192.00
190.00
188.00
% change
Moisture content
Feed stock material loss
Inflation
IRR
% area

(b). Straw



(c). Switchgrass

Fig. 4-6: Sensitivity analysis of Regular and steam pretreated

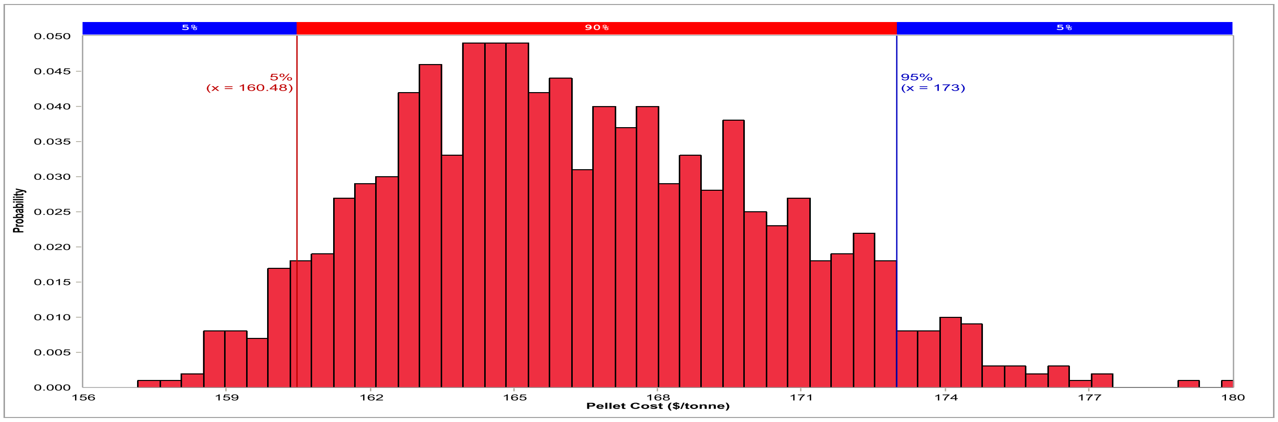
4.6 Uncertainty Analysis:

The lack of exact representative data for different cost parameters is a limitation of the modelled cost of production. When there is 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 10,000. The simulation was carried out using ModelRisk software [26]. Uncertainties are considered for transportation cost, field cost, material loss during steam pretreatment with a high variation of 40% based on the sensitivity analysis while it is considered 20% for capital cost.

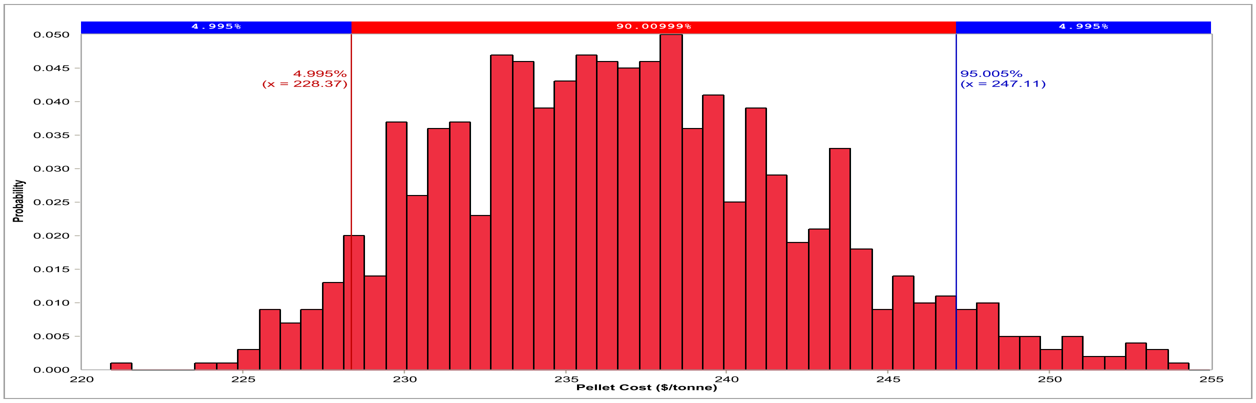
The production costs generated from a Monte Carlo simulation are shown in Fig. 4-7. The Monte Carlo simulation result for the base case scenario variation for different feedstocks for regular pellet production shows a production cost of 155-173 $ t^{-1} with a standard deviation of $5 at 95% confidence and 233-260 $ t^{-1} with a standard deviation of $10 at 95% confidence for the base case scenario for steam pretreated pellets.

1. Forest Residues

a. Regular Pellets

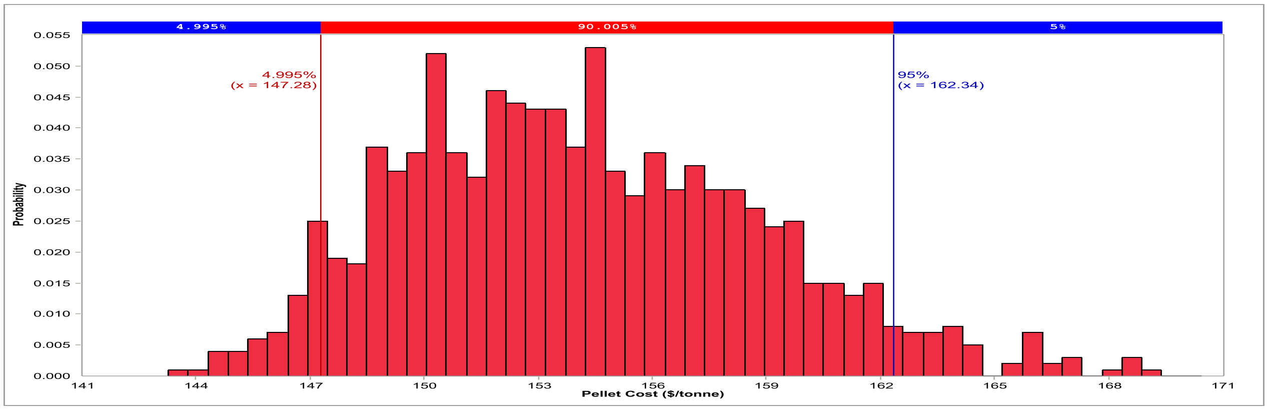


b. Steam Pretreated Pellets

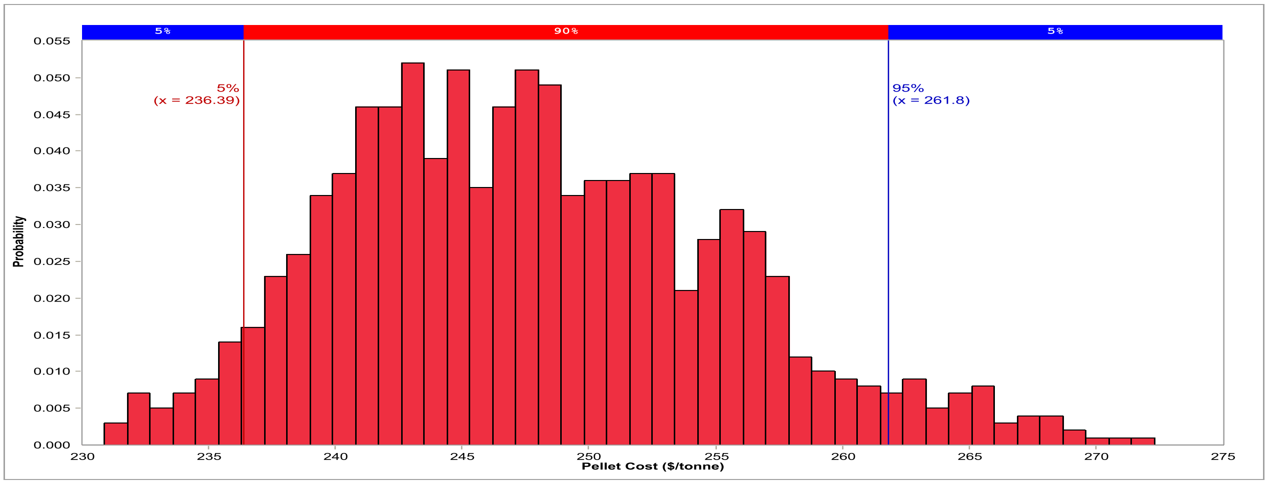


2. Straw

(a). Regular Pellets

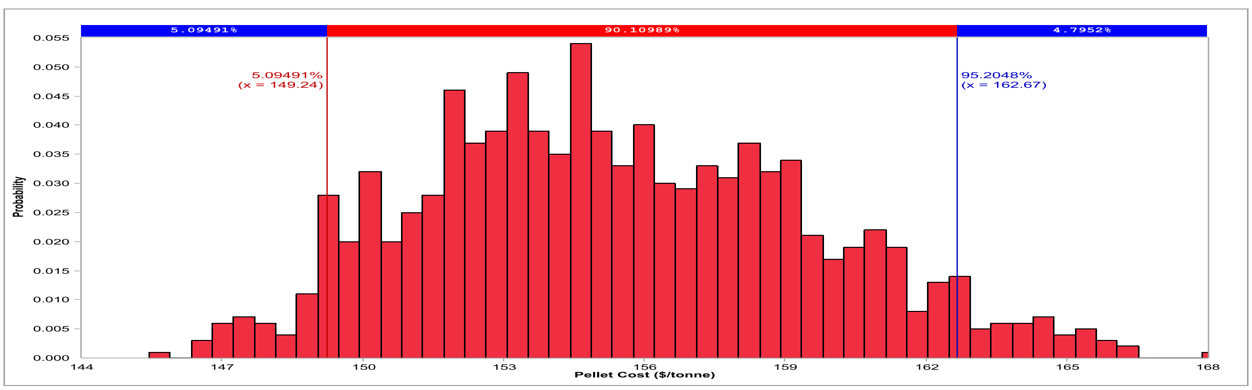


(b). Steam Pretreated Pellets



3. Switchgrass

(a). Regular Pellets



(b). Steam Pretreated Pellets

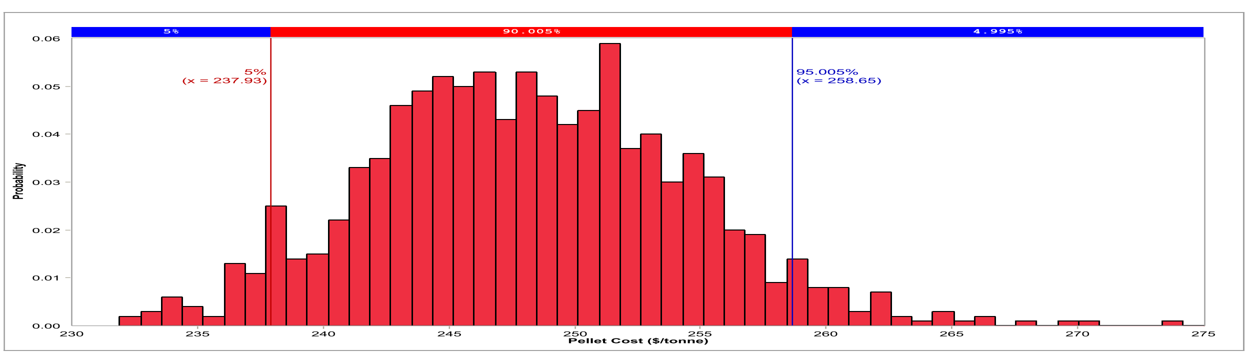


Fig. 4-7: Uncertainty analysis for the three feedstocks: (a) Regular Pellets, (b) Steam Pretreated Pellets

4.7 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 the harvesting of biomass 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 190,000 t for regular pellets and 250,000 t 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.

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Chapter 5: Conclusion and Recommendations for Future Work

5.1. Conclusions

This research work focused on study of pellet production process from steam-pretreated biomass in terms of its energy requirement and economics of production. This involved development of a process model to give a comparative energy analysis for regular and steam pretreated pellet production. From the analysis, it is concluded that the steam pretreatment process improves the heating value of the fuel. However, steam pretreatment increases the process energy requirement for drying and pretreatment. Thus, the process net energy ratio (NER) is significantly reduced due to steam pretreatment. The process NER can be improved by increasing drying efficiency and reducing the pretreatment level and temperature. The results of this study also highlight that the grinding energy requirement is significantly reduced with steam pretreatment.

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 switchgrass were considered for two pelletization processes, regular and steam pretreated. The total cost was calculated, from the harvesting of biomass 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 190,000 tonnes for regular pellets and 250,000 tonnes 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.

5.1.1. Net energy ratio for the production of steam pretreated biomass-based pellets

The results indicate that steam pretreatment increases energy consumption significantly due to the additional steam required for the pretreatment and the additional energy required for drying, since the saturated steam condenses on the biomass when heat is released for pretreatment. The drying energy required for regular pellet production is 1.3 MJ and for steam pretreatment is approximately five times greater (6.2 MJ). The steam pretreatment also requires additional energy, provided by natural gas, which is not required for regular pellet production.

The NER is an important parameter to assess process efficiency and is a key decision-making metric. The NER of regular pellet making is 5.0 and for pellets produced from steam pretreatment is 1.29. The key reason behind the difference in NER is the drying energy requirement difference between the two processes. Thus, the efficiency of the dryer model and the level of steam pretreatment and subsequent solid recovery for pelletization play key roles. The dryer efficiency assumed for this case is 80%, which is typical of most small-scale convective dryers drying biomass at 6 kg h^{-1}. The efficiency of a large-scale dryer with a rotary drum and flue gas recirculation is 85-90%. Moreover, the NER for steam pretreatment indicated above makes clear that a 100% steam pretreatment situation is not feasible based on the NER of the steam pretreatment process. This is understandable, since pretreating 100% of the feedstock requires the addition of extra steam for pretreatment as well as the burning of this condensed water from the biomass after pretreatment. A scenario analysis has been done for this case to exemplify the effect of the percent of feedstock pretreatment on the NER of the entire energy chain. In this case the pretreatment level has been varied. The pretreatment level is decided by the ratios of the amount of biomass used for steam pretreatment and for regular production.

The key process differences are from increased drying energy and reduced grinding energy for steam pretreated pellet production. The reason for high drying energy is explained above. The reason for reduced grinding energy can be attributed to the disintegration of the biomass cell wall and structure due to high pressure steam pretreatment at high temperatures. Thus, the grinding process can be replaced completely through the amalgamation of steam pretreatment with other pretreatment processes that lead to biomass disintegration. This amalgamation will play a key role in the economic analysis of the process since the grinder can be completely replaced and the overall process capital cost can be reduced.

5.1.2. Comparative NER analysis of the steam pretreated pellet process for agricultural residues and switchgrass

A comparative analysis of pelletization energy indicates that the pelletization energy required for straw pellets is higher than that of switchgrass pellets. This higher energy requirement can be attributed to the particle size difference of AR and switchgrass. Typically, the particle size of AR is higher than that of switchgrass.

The NER is a key decision-making metric and an important parameter to assess process efficiency. The comparative results of the NER for the steam treated pellets show that the AR pelletization process has an NER of 1.76, higher than that of the energy crop pelletization process, which is 1.37 for the base case scenario of 180˚C at 6 kg h^{-1}. The low NER value for the energy crop is due to the higher energy requirement for drying during the pelletization of switchgrass. At 100% pretreating, the addition of extra steam for pretreatment will be required as well as the burning of this condensed water from the biomass after pretreatment. To exemplify the effect of the variation of the pretreatment level on the NER of the entire energy chain, a scenario analysis was conducted for this situation. The pretreatment level is the ratio of the amount of biomass used for steam pretreatment and regular production.

5.1.3. Techno-economic model for steam pretreated pellet production from three feedstocks

The profile of power cost vs. capacity shows a flat trend. This can be explained in the following manner in terms of capital cost and transportation cost. Biomass projects depend on two cost parameters, transportation cost and capital cost. The transportation cost increases with the square root of the capacity of the project. 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 biofuel plant, the pellet production cost remains fairly unchanged with changes in capacity. Figure 4-3 represents the scale curve for the three feedstock under steam pretreatment and regular pellet production. The optimum unit size for regular pellet production is 150,000-190,000 t yr^{-1}, while for steam pretreated pellet production it is 230,000-270,000 t yr^{-1}.

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 size. Improving transportation and field costs will make plants larger than 150,000 tonnes feasible. The effect of delivered cost is significant for straw and switchgrass feedstocks since harvesting costs are high; for forest residue feedstocks, delivered costs are low. Thus, agricultural pellets cost more than forest residue pellets.

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 large amounts of natural gas, which significantly raises the energy requirement. The difference between steam pretreated and regular pellet production cost is $50-60. However, the optimum size for a steam pretreatment pellet plant is greater than a regular pellet plant due to the economy of scale of a steam pretreatment unit.

5.2. Recommendations for future research

This study focuses mainly on the net energy ratio and cost of pellet production from steam pretreatment and compares the results with the regular pellet production process.

- Life cycle greenhouse gas (GHG) analysis of the whole production chain of steam-pretreated biomass should be conducted.
- Assessment of the GHG abatement cost ($/tonne of CO_2) should be evaluated to Compare this with other options of GHG mitigation.
- The NER study for the three feedstocks is evaluated for standard small- and large-scale equipment. The study can be enriched by varying the type of equipment and their efficiency and calculating their impact on the NER.
- Biomass co-firing of steam-pretreated biomass based pellets could be explored as a pathway for GHG mitigation under the scenario of favorable government incentives.
- Study effect of reduction in cost of storage due to increased hydrophobicity as a result of steam pretreatment of biomass.
- Evaluate economics of ethanol production from steam pretreated pellet as a feedstock.

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Appendix

Appendix A1: Steam Pretreated Pelletization Experimental Calculation Equation

Steam Pretreatment

The specific energy consumption for the process of steam pretreatment for the experiment is calculated using the equations [1].

$$M(c) = \frac{C(b)(\Delta T)}{C(b)(\Delta T)+(\Delta h)m(w)} \quad (A.1)$$

$$E(b) = C(b)(\Delta T) + m(w)(\Delta h) \quad (A.2)$$

$$m(cs)E(evap) = E(b) \quad (A.3)$$

$$m(o) = \frac{V}{v} \quad (A.4)$$

$$m(s) = m(cs) + m(o) \quad (A.5)$$

$$E(s) = m(s)\Delta h \quad (A.6)$$

$$E(t) = E(s) + E(b) \quad (A.7)$$

where

M(c) is the mass of the moisture content of the biomass, kg

C (b) is the specific heat capacity of the biomass, kJ $kg^{-1}K^{-1}$

ΔT is the temperature difference between the operation temperature and the initial temperature, ^{0}C

Δh is the enthalpy difference of biomass water content with respect to ΔT, kJ kg^{-1}

E (b) is the amount of energy required to heat biomass to operating temperature, kJ kg^{-1}

E (even) is the evaporation heat at the operating temperature, kJ kg^{-1}

V is the volume of the steam pretreatment reactor, m^3

v is the specific volume of saturated steam under operating pressure and temperature, m^3 kg^{-1}

m(cs) is the mass of condensed saturated steam, kg

m(o) is the amount of steam necessary to maintain pressure, kg

m(t) is the total amount of steam generated, kg

E(s) is the total energy required to generate steam, kJ kg^{-1}

E(t) is the total amount of energy consumed in the steam pretreatment process, kJ kg^{-1}

Dryer

The equations used for the energy consumption of experimental dryer unit are listed below:

$$H\ (wood) = Mass(wood - dry) * C(wood) * \left(T(t) - T(o)\right) \quad (A.8)$$

$$H(water) = Mass(water) * C(water) * (T(t) - T(o) \quad (A.9)$$

$$H(air) = Mass(air) * C(air) * (T(t) - T(o)) \quad (A.10)$$

$$H(evap) = \left(Mass(initial) - Mass(threshold)\right) * q(latent) + \left(Mass(initial) - Mass(threshold)\right) * \left(q(latent) + q(bound)\right) \quad (A.11)$$

$$H(loss) = A(dryer) * h(loss) * time(drying) \quad (A.12)$$

where

H_{wood} is the heat energy required to heat dry wood, kJ

H_{water} is the heat energy required to heat water in biomass, kJ

H_{air} is the heat energy required to heat air, kJ

H_{evap} is the heat energy required to evaporate biomass moisture, kJ

H_{loss} is the heat lost from the system due to leakage in the dryer, kJ

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Appendix A2: Aspen PLUS flowsheets

Aspen PLUS model Steam Pretreated Pellet

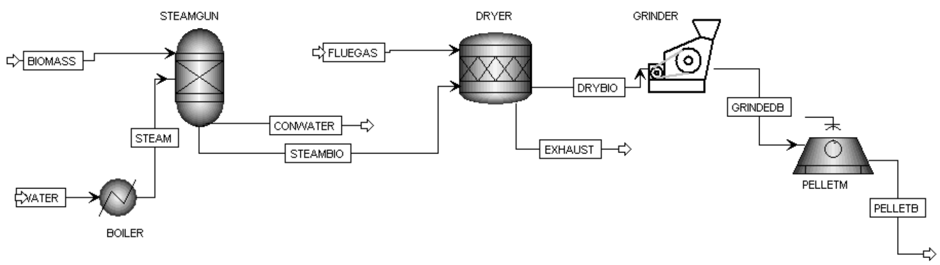

Fig. A.2-1: Representative Aspen PLUS model Flowsheet for Steam Pretreated wood Pellet Production

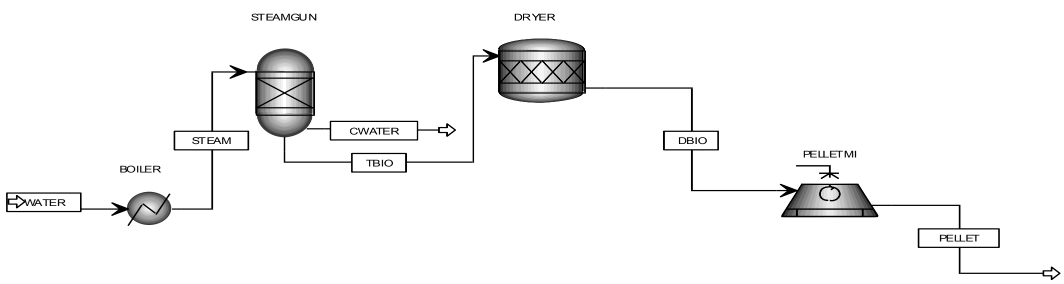

Fig. A.2-2: Representative Aspen PLUS model Flowsheet for Steam Pretreated AR and Energy crop Pellet Production

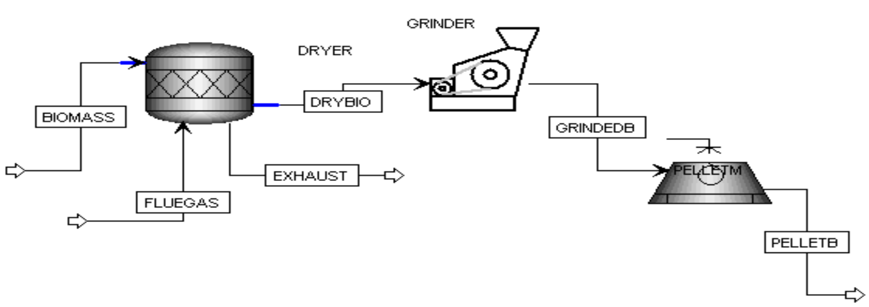

Fig. A. 2-3: Representative Aspen PLUS model Flowsheet for Regular Pellet Production

Appendix A3: Aspen PLUS Results

1. Steam Treated Wood Pellet

(a). Steam Treatment

(i). Stream Result

	RAWBIO	STEAM	TRBIO	WATER
TEMPERATURE (C)	25	210	30	25
PRESSURE (bar)	1.013	19.039	19	1.013
MASS VFRAC	0	1	0.842	0
MASS SFRAC	1	0	0.059	0
*** ALL PHASES ***				
MASS FLOW (kg/hr)	6	2.76	8.76	2.76
VOLUME FLOW (cum/hr)	0.005	0.323	0.711	0.003
ENTHALPY (gcal/hr)	-0.015	-0.009	-0.003	-0.01
DENSITY (kg/cum)	1255.633	8.538	12.315	993.957
MASS FLOW (kg/hr)				
WATER		2.76	0.876	2.76
H2			0.655	
O2			6.709	
N2			0.002	
CARBON			0.518	
WOOD	6			
*** SUBSTREAM NCPSD ***				
WOOD PROXANAL				
MOISTURE	45			
FC	14.4			
VM	82.5			
ASH	3.1			
WOOD ULTANAL				
ASH	0			
CARBON	48.44			
HYDROGEN	6.23			
NITROGEN	0.22			
CHLORINE	0			
SULFUR	0			
OXYGEN	45.11			

(ii). Block Result

BLOCK: BOILER MODEL: HEATER				

INLET STREAM: WATER				
OUTLET STREAM: STEAM				
*** MASS & ENERGY BALANCE				
	IN		OUT	RELATIVE DIFF.
CONV. COMP.(kmol/hr)	0.153203		0.153203	1.81E-16
(kg/hr)	2.76		2.76	0
NONCONV. COMP (kg/hr)	0		0	0
TOTAL BALANCE				
MASS (kg/hr)	2.76		2.76	0
ENTHALPY(gcal/hr)	-0.104580E	-1	-8.62E-03	-0.17604
***	INPUT DATA	***		
TWO PHASE TV FLASH				
SPECIFIED TEMPERATURE	(C)			210
VAPOR FRACTION				1
MAXIMUM NO. ITERATIONS				30
CONVERGENCE TOLERANCE				0.0001
***	RESULTS	***		
OUTLET TEMPERATURE (C)				210
OUTLET PRESSURE (bar)				19.039
HEAT DUTY (gcal/h)	R			1.84E-03
OUTLET VAPOR FRACTION				1
BLOCK: STEAMTR MODEL: RYIELD				

INLET STREAMS: STEAM	RAW	BIO		
OUTLET STREAM: TRBIO				
PROPERTY OPTION SET: IDEAL	IDEAL		IDEAL GAS	
*** MASS & ENERGY BALANCE				
	IN	OUT	GENERATIO	N RELATIVE DIFF.
CONV. COMP.(kmol/hr) 0.1532	03 0.	61221	7 0.459013	0
(kg/hr) 2.760	00 8	0.76	0	-0.684932

(b). DRYER

(i). Stream Result

	DRYBIO	EXHAUST	IN-DRIER	NITROGEN	WETBIO
TEMPERATURE (K)	299.6	299.6	299.6	353.1	298.1
PRESSURE (N/sqm)	101352.93	101352.93	101352.93	101325	101325
MASS VFRAC	0	1	0.959	1	0
MASS SFRAC	0.445	0	0.018	0	1
*** ALL PHASES ***					
MASS FLOW (kg/sec)	< 0.001	0.004	0.004	0.004	< 0.001
VOLUME FLOW (cum/sec)	< 0.001	0.004	0.004	0.004	< 0.001
ENTHALPY (watt)	-2206.348	-1260.699	-3467.047	238.4	-3705.447
DENSITY(lb/cuft)	68.482	0.07	0.073	0.06	78.886
MASS FLOW (kg/sec)					
H2O	< 0.001	< 0.001	< 0.001		
N2	TRACE	0.004	0.004	0.004	
O2	TRACE	TRACE	TRACE	TRACE	
WOOD	< 0.001		< 0.001		< 0.001
*** SUBSTREAM NCPSD ***					
WOOD PROXANAL					
MOISTURE	15		15		75
FC	16.9		16.9		16.9
VM	79.9		79.9		79.9
ASH	3.2		3.2		3.2
WOOD ULTANAL					
ASH	0		0		0
CARBON	49.14		49.14		49.14
HYDROGEN	6.08		6.08		6.08
NITROGEN	0.17		0.17		0.17
CHLORINE	0		0		0
SULFUR	0		0		0
OXYGEN	44.61		44.61		44.61
WOOD SULFANAL					
PYRITIC	0		0		0
SULFATE	0		0		0
ORGANIC	0		0		0

(ii). Block Result

BLOCK: DRY-FLSH MODEL: FLASH2
INLET STREAM: IN-DRIER
OUTLET VAPOR STREAM: EXHAUST
OUTLET LIQUID STREAM: DRYBIO
PROPERTY OPTION SET: IDEAL IDEAL LIQUID / IDEAL GAS
*** MASS AND ENERGY BALANCE ***
IN OUT RELATIVE DIFF.
CONV. COMP.(kmol/sec) 0.159601E-03 0.159601E-03 0.00000
(kg/sec) 0.436274E-02 0.436274E-02 0.198811E-15
NONCONV. COMP(kg/sec) 0.816993E-04 0.816993E-04 0.00000
TOTAL BALANCE
MASS (kg/sec) 0.444444E-02 0.444444E-02 0.195156E-15
ENTHALPY(watt) -3467.05 -3467.05 -0.561132E-07
*** INPUT DATA ***
TWO PHASE PQ FLASH
SPECIFIED PRESSURE (N/sqm) 101,353.
SPECIFIED HEAT DUTY (watt) 0.0
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.000100000
*** RESULTS ***
OUTLET TEMPERATURE (K) 299.59
OUTLET PRESSURE (N/sqm) 0.10135E+06
VAPOR FRACTION 0.96460

BLOCK: DRY-REAC MODEL: RSTOIC

INLET STREAMS: WETBIO NITROGEN
OUTLET STREAM: IN-DRIER
PROPERTY OPTION SET: IDEAL IDEAL LIQUID / IDEAL GAS
*** MASS AND ENERGY BALANCE ***
IN OUT GENERATION RELATIVE DIFF.
CONV. COMP.(kmol/sec) 0.148717E-03 0.159601E-03 0.108840E-04 0.00000
(kg/sec) 0.416667E-02 0.436274E-02 -0.449438E-01
NONCONV COMP(kg/sec) 0.277778E-03 0.816993E-04 0.705882
TOTAL BALANCE
MASS(kg/sec) 0.444444E-02 0.444444E-02 0.278668E-07
ENTHALPY(watt) -3467.05 -3467.05 -0.839798E-07

(c). Grinder

(i). Stream Result

	S1	S3
*** ALL PHASES ***		
MASS FLOW (kg/sec)		
WOOD	2	2
TOTAL FLOW (cum/sec)	0.001583	0.00158274
MASSVFRA	0	0
MASSSFRA	1	1
DENSITY (kg/cum)	1263.628	1263.628
TEMPERATURE (K)	298.15	298.15
PRESSURE (N/sqm)	101325	101325
SUBSTREAM: NCPSD		
MASS FLOW (kg/sec)		
WOOD	2	2
TOTAL FLOW (kg/sec)	2	2
TEMPERATURE (K)	298.15	298.15
PRESSURE (N/sqm)	101325	101325
VAPOR FRAC	0	0
LIQUID FRAC	0	0
SOLID FRAC	1	1
ENTHALPY (J/kg)	-7272800	-7272800
ENTHALPY (watt)	-1.5E+07	-14546000
ENTROPY		
DENSITY (kg/cum)	1263.628	1263.628
AVERAGE MW	1	1
WOOD PROXANAL		
MOISTURE	15	15
FC	16.9	16.9
VM	79.9	79.9
ASH	3.2	3.2
WOOD ULTANAL		
ASH	0	0
CARBON	49.14	49.14
HYDROGEN	6.08	6.08
NITROGEN	0.17	0.17
CHLORINE	0	0
SULFUR	0	0

(ii). Block Result

BLOCK:	JAW1	MODEL:	CRUSHER		
------------------------------ -					
INLET	STREAM:	S1			
OUTLET	STREAM:	S3			
***	MASS	AND	ENERGY	BALANCE	***
IN	OUT	RELATIVE	DIFF.		
CONV.	COMP.(kmol/sec)	0	0	0	
(kg/sec)		0	0	0	
NONCONV.	COMP (kg/sec)		2	2	0
TOTAL	BALANCE				
MASS(kg/sec)		2	2	0	
ENTHALPY(watt)		-1.45E+07	-1.45E+07	0	
***	CO2	EQUIVALEN T	SUMMARY	***	
FEED	STREAMS	CO2E	0	KG/SEC	
PRODUCT	STREAMS	CO2E	0	KG/SEC	
NET	STREAMS	CO2E	PRODUCTION	0	KG/SEC
UTILITIES	CO2E	PRODUCTIO N	0	KG/SEC	
TOTAL	CO2E	PRODUCTIO N	0	KG/SEC	
***	INPUT	DATA	***		
PSD	CALCULATION	METHOD:	DISTRIBUTIO N	FUNCTION	WITH
COMMINUTION	LAW:	KICK'S	LAW		
SPECIFIED	POWER		858		
HARDGROVE	GRINDABILITY	INDEX			
FOR	SUBSTREAM	NCPSD	77		
MAXIMUM	NO.	OF	FLASH	ITERATION S	30
FLASH	TOLERANCE	0.0001			
***	RESULTS	***			
PARTICLE	DIAMETER	WHICH	IS		
LARGER	THAN	80%	OF	INLET	MASS
PARTICLE	DIAMETER	WHICH	IS		
LARGER	THAN	80%	OF	OUTLET	MASS
D80	REDUCTION	RATIO	0.94923		
PARTICLE	DIAMETER	WHICH	IS		

(d). Pellet mill

(i) Stream Result

	GWOOD	PWOOD
TEMPERATURE(K)	298.1	624.4
PRESSURE (N/sqm)	101325	101325
MASS VFRAC	0	0
MASS SFRAC	1	1
*** ALL PHASES ***		
MASS FLOW (kg/sec)	0.001	0.001
VOLUME FLOW (cum/sec)	< 0.001	< 0.001
ENTHALPY (watt)	-10328.525	-9173.925
DENSITY (lb/cuft)	78.886	78.886
MASS FLOW (kg/sec)		
H2O		
WOOD	0.001	0.001
*** SUBSTREAM NCPSD ***		
WOOD PROXANAL		
MOISTURE	11.68	11.68
FC	16.9	16.9
VM	79.9	79.9
ASH	3.2	3.2
WOOD ULTANAL		
ASH	0	0
CARBON	49.14	49.14
HYDROGEN	6.08	6.08
NITROGEN	0.17	0.17
CHLORINE	0	0
SULFUR	0	0
OXYGEN	44.61	44.61
WOOD SULFANAL		
PYRITIC	0	0
SULFATE	0	0
ORGANIC	0	0

(ii). Block Result

BLOCK:	PELLETMI	MODEL:	GRANULATOR		

INLET	STREAM:	GWOOD			
OUTLET	STREAM:	PWOOD			
PROPERTY	OPTION	SET:	IDEAL	IDEAL	LIQUID
***	MASS	AND	ENERGY	BALANCE	***
IN	OUT	RELATIVE	DIFF.		
CONV.	COMP.(kmol/sec)	0	0	0	
(kg/sec)		0	0	0	
NONCONV.	COMP(kg/sec)		1.49E-03	1.49E-03	1.01E-07
TOTAL	BALANCE				
MASS (kg/sec)		1.49E-03	1.49E-03	1.01E-07	
ENTHALPY (watt)		-10328.5	-9173.92	-0.111788	
***	CO2	EQUIVALENT	SUMMARY	***	
FEED	STREAMS	CO2E	0	KG/SEC	
PRODUCT	STREAMS	CO2E	0	KG/SEC	
NET	STREAMS	CO2E	PRODUCTION	0	KG/SEC
UTILITIES	CO2E	PRODUCTION	0	KG/SEC	
TOTAL	CO2E	PRODUCTION	0	KG/SEC	
***	INPUT	DATA	***		
CALCULATION	OPTION	DISTRIBUTION	FUNCTION		
MAXIMUM	NO.	OF	FLASH	ITERATIONS	30
FLASH	TOLERANCE	0.0001			
***	RESULTS	***			
SEED	MEAN	DIAMETER	m	1.50E-03	
SEED	SAUTER	MEAN	DIAMETER	m	1.50E-03

2. Steam Pretreated Straw Pellet

(a) Steam Pretreatment

(i) Stream Result

	RAWBIO	STEAM	TRBIO	WATER
TEMPERATURE (C)	25	210	30	25
PRESSURE (bar)	1.013	19.039	19	1.013
MASS VFRAC	0	1	0.842	0
MASS SFRAC	1	0	0.059	0
*** ALL PHASES ***				
MASS FLOW (kg/hr)	6	2.76	8.76	2.76
VOLUME FLOW (cum/hr)	0.005	0.323	0.711	0.003
ENTHALPY (gcal/hr)	-0.015	-0.009	-0.003	-0.01
DENSITY (kg/cum)	1255.633	8.538	12.315	993.957
MASS FLOW (kg/hr)				
WATER		2.76	0.876	2.76
H2			0.655	
O2			6.709	
N2			0.002	
CARBON			0.518	
WOOD	6			
*** SUBSTREAM NCPSD ***				
WOOD PROXANAL				
MOISTURE	45			
FC	14.4			
VM	82.5			
ASH	3.1			
WOOD ULTANAL				
ASH	0			
CARBON	48.44			
HYDROGEN	6.23			
NITROGEN	0.22			
CHLORINE	0			
SULFUR	0			
OXYGEN	45.11			
WOOD SULFANAL				
PYRITIC	0			
SULFATE	0			

(ii) Block Result

BLOCK: BOILER MODEL: HEATER
INLET STREAM: WATER
OUTLET STREAM: STEAM
PROPERTY OPTION SET: IDEAL IDEAL LIQUID / IDEAL GAS
*** MASS AND ENERGY BALANCE ***
IN OUT RELATIVE DIFF.
CONV. COMP.(kmol/hr) 0.153203 0.153203 0.181168E-15
(kg/hr) 2.76000 2.76000 0.00000
NONCONV. COMP(kg/hr) 0.00000 0.00000 0.00000
TOTAL BALANCE
MASS(kg/hr) 2.76000 2.76000 0.00000
ENTHALPY(gcal/hr) -0.104580E-01 -0.861697E-02 -0.176040
*** CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E 0.00000 (kg/hr)
PRODUCT STREAMS CO2E 0.00000 (kg/hr)
NET STREAMS CO2E PRODUCTION 0.00000 (kg/hr)
UTILITIES CO2E PRODUCTION 0.00000 (kg/hr)
TOTAL CO2E PRODUCTION 0.00000 (kg/hr)
*** INPUT DATA ***
TWO PHASE TV FLASH
SPECIFIED TEMPERATURE (C) 210.000
VAPOR FRACTION 1.00000
MAXIMUM NO. ITERATIONS 30

CONVERGENCE TOLERANCE	0.000100000
*** RESULTS ***	
OUTLET TEMPERATURE (C)	210.00
OUTLET PRESSURE (bar)	19.039
HEAT DUTY (gcal/hr)	0.18410E-02
OUTLET VAPOR FRACTION	1.0000
V-L PHASE EQUILIBRIUM :	
COMP F(I) X(I) Y(I) K(I)	
WATER 1.0000 1.0000 1.0000 1.0000	
BLOCK: STEAMTR MODEL: RYIELD	

INLET STREAMS: STEAM RAWBIO	
OUTLET STREAM: TRBIO	
PROPERTY OPTION SET: IDEAL IDEAL LIQUID/IDEAL GAS	

(b) Dryer:

(i) Stream Result

	DRYBIO	EXHAUST	IN-DRIER	NITROGEN	WETBIO
TEMPERATURE (K)	299.6	299.6	299.6	353.1	298.1
PRESSURE (N/sqm)	101352.9	101352.9	101352.9	101325	101325
MASS VFRAC	0	1	0.959	1	0
MASS SFRAC	0.445	0	0.018	0	1
*** ALL PHASES ***					
MASS FLOW (kg/sec)	< 0.001	0.004	0.004	0.004	< 0.001
VOLUME FLOW (cum/sec)	< 0.001	0.004	0.004	0.004	< 0.001
ENTHALPY (watt)	-2226.07	-1260.71	-3486.78	238.4	-3725.18
DENSITY (lb/cuft)	68.413	0.07	0.073	0.06	78.682
MASS FLOW (kg/sec)					
H2O	< 0.001	< 0.001	< 0.001		
N2	TRACE	0.004	0.004	0.004	
O2	TRACE	TRACE	TRACE	TRACE	
WOOD	< 0.001		< 0.001		< 0.001
*** SUBSTREAM NCPSD ***					
WOOD PROXANAL					
MOISTURE	15		15		75
FC	17.38		17.38		17.38
VM	77.08		77.08		77.08
ASH	5.54		5.54		5.54
WOOD ULTANAL					
ASH	0		0		0
CARBON	46.66		46.66		46.66
HYDROGEN	6.15		6.15		6.15
NITROGEN	0.43		0.43		0.43
CHLORINE	0		0		0
SULFUR	0.08		0.08		0.08
OXYGEN	46.67		46.67		46.67
WOOD SULFANAL					
PYRITIC	0.08		0.08		0.08
SULFATE	0		0		0
ORGANIC	0		0		0

(ii) Block Result

BLOCK:	DRY-FLSH	MODEL:	FLASH2		

INLET	STREAM:	IN-DRIER			
OUTLET	VAPOR	STREAM:	EXHAUST		
OUTLET	LIQUID	STREAM:	DRYBIO		
PROPERTY	OPTION	SET:	IDEAL	IDEAL	LIQUID
***	MASS	AND	ENERGY	BALANCE	***
IN	OUT	RELATIVE	DIFF.		
CONV.	COMP.(kmol/sec)	1.60E-04	1.60E-04	-1.70E-16	
(kg/sec)		4.36E-03	4.36E-03	0	
NONCONV.	COMP(kg/sec)		8.17E-05	8.17E-05	0
TOTAL	BALANCE				
MASS (kg/sec)		4.44E-03	4.44E-03	0	
ENTHALPY(watt)		-3486.78	-3486.78	-5.58E-08	
***	INPUT	DATA	***		
TWO	PHASE	PQ	FLASH		
SPECIFIED	PRESSURE	(N/sqm)	101,353.00		
SPECIFIED	HEAT	DUTY	(watt)	0	
MAXIMUM	NO.	ITERATIONS	30		
CONVERGENCE	TOLERANCE	0.0001			
***	RESULTS	***			
OUTLET	TEMPERATURE	(K)	299.59		
OUTLET	PRESSURE	(N/sqm)	1.01E+05		
VAPOR	FRACTION	0.9646			
BLOCK:	DRY-REAC	MODEL:	RSTOIC		
***	MASS	AND	ENERGY	BALANCE	***
IN	OUT	GENERATION	RELATIVE	DIFF.	
CONV.	COMP.(kmol/sec)	1.49E-04	1.60E-04	1.09E-05	0
(kg/sec)		4.17E-03	4.36E-03	-4.49E-02	

(c). Pellet mill:

(i) Stream result

	GWOOD	PWOOD
TEMPERATURE (K)	298.1	628.8
PRESSURE (N/sqm)	101325	101325
MASS VFRAC	0	0
MASS SFRAC	1	1
*** ALL PHASES ***		
MASS FLOW (kg/sec)	0.001	0.001
VOLUME FLOW(cum/sec)	< 0.001	< 0.001
ENTHALPY (watt)	-10713.773	-9559.173
DENSITY (lb/cuft)	78.654	78.654
MASS FLOW (kg/sec)		
H2O		
WOOD	0.001	0.001
*** SUBSTREAM NCPSD ***		
WOOD PROXANAL		
MOISTURE	11.68	11.68
FC	17.38	17.38
VM	77.08	77.08
ASH	5.54	5.54
WOOD ULTANAL		
ASH	0	0
CARBON	46.66	46.66
HYDROGEN	6.15	6.15
NITROGEN	0.43	0.43
CHLORINE	0	0
SULFUR	0.08	0.08
OXYGEN	46.67	46.67
WOOD SULFANAL		
PYRITIC	0	0
SULFATE	0	0
ORGANIC	0	0
PSD		
1	0.0001229	0
2	0.999877	0
3	0	1

(ii) Block Result

BLOCK:	PELLETMI	MODEL:	GRANULAT OR		

INLET	STREAM:	GWOOD			
OUTLET	STREAM:	PWOOD			
PROPERTY	OPTION	SET:	IDEAL	IDEAL	LIQUI D
***	MASS	AND	ENERGY	BALANCE	***
IN	OUT	RELATIVE	DIFF.		
CONV.	COMP.(kmol/se c)	0	0	0	
(kg/sec)		0	0	0	
NONCONV.	COMP(kg/sec		1.49E-03	1.49E-03	1.01E-07
TOTAL	BALANCE				
MASS(kg/sec)		1.49E-03	1.49E-03	1.01E-07	
ENTHALPY(watt)		-10713.8	-9559.17	-0.10777	
***	CO2	EQUIVALEN T	SUMMARY	***	
FEED	STREAMS	CO2E	0	KG/SEC	
PRODUCT	STREAMS	CO2E	0	KG/SEC	
NET	STREAMS	CO2E	PRODUCTIO N	0	KG/SE C
UTILITIES	CO2E	PRODUCTIO N	0	KG/SEC	
TOTAL	CO2E	PRODUCTIO N	0	KG/SEC	
***	INPUT	DATA	***		
CALCULATION	OPTION	DISTRIBUTI ON	FUNCTION		
MAXIMUM	NO.	OF	FLASH	ITERATIO NS	30
FLASH	TOLERANCE	0.0001			
***	RESULTS	***			
SEED	MEAN	DIAMETER	m	1.50E-03	
SEED	SAUTER	MEAN	DIAMETER	m	1.50E-03
PRODUCT	MEAN	DIAMETER	m	6.00E-03	

3. Steam Pretreated Switchgrass

(a). Steam Pretreatment

(i). Stream Result

	RAWBIO	STEAM	TRBIO	WATER
TEMPERATURE (C)	25	180	30	25
PRESSURE (bar)	1.013	19.039	19	1.013
MASS VFRAC	0	1	0.842	0
MASS SFRAC	1	0	0.059	0
*** ALL PHASES ***				
MASS FLOW (kg/hr)	6	2.76	8.76	2.76
VOLUME FLOW (cum/hr)	0.005	0.323	0.711	0.003
ENTHALPY (gcal/hr)	-0.015	-0.009	-0.003	-0.01
DENSITY(kg/cum)	1255.633	8.538	12.315	993.957
MASS FLOW (kg/hr)				
WATER		2.76	0.876	2.76
H2			0.655	
O2			6.709	
N2			0.002	
CARBON			0.518	
WOOD	6			
*** SUBSTREAM NCPSD ***				
WOOD PROXANAL				
MOISTURE	14			
FC	21.3			
VM	72.9			
ASH	5.8			
WOOD ULTANAL				
ASH	5.7			
CARBON	47			
HYDROGEN	5.3			
NITROGEN	0.5			
CHLORINE	0			
SULFUR	0.1			
OXYGEN	41.4			

(ii). Block Result

BLOCK:	BOILER	MODEL:	HEATER		

INLET	STREAM:	WATER			
OUTLET	STREAM:	STEAM			
PROPERTY	OPTION	SET:	IDEAL	IDEAL	LIQUID
***	MASS	AND	ENERGY	BALANCE	***
IN	OUT	RELATIVE	DIFF.		
CONV.	COMP.(kmol/hr)		0.153203	0.153203	1.81E-16
(kg/hr)		2.76	2.76	0	
NONCONV.	COMP(kg/hr)		0	0	0
TOTAL	BALANCE				
MASS (kg/hr)		2.76	2.76	0	
ENTHALPY(gcal/hr)		-1.05E-02	-8.62E-03	-0.17604	
***	INPUT	DATA	***		
TWO	PHASE	TV	FLASH		
SPECIFIED	TEMPERATURE	(C)	180		
VAPOR	FRACTION	1			
MAXIMUM	NO.	ITERATIONS	30		
CONVERGENCE	TOLERANCE	0.0001			
***	RESULTS	***			
OUTLET	TEMPERATURE	(C)	180		
OUTLET	PRESSURE	(bar)	19.039		
HEAT	DUTY	(Gcal/hr)	1.84E-03		
OUTLET	VAPOR	FRACTION	1		
BLOCK:	STEAMTR	MODEL:	RYIELD		

INLET	STREAMS:	STEAM	RAWBIO		
OUTLET	STREAM:	TRBIO			
PROPERTY	OPTION	SET:	IDEAL	IDEAL	LIQUID
***	MASS	AND	ENERGY	BALANCE	***
IN	OUT	GENERATION	RELATIVE	DIFF.	
CONV.	COMP.(kmol/hr)		0.153203	0.612217	0.459013
(kg/hr)		2.76	8.76	-0.68493	
NONCONV	COMP(kg/hr)		6	0	1
TOTAL	BALANCE				

(b). Dryer:

(i) Stream Result

	DRYBIO	EXHAUST	IN-DRIER	NITROGEN	WETBIO
TEMPERATURE K	299.6	299.6	299.6	353.1	298.1
PRESSURE N/SQM	101352.93	101352.93	101352.93	101325	101325
MASS VFRAC	0	1	0.959	1	0
MASS SFRAC	0.445	0	0.018	0	1
*** ALL PHASES ***					
MASS FLOW kg/sec	< 0.001	0.004	0.004	0.004	< 0.001
VOLUME FLOW cum/sec	< 0.001	0.004	0.004	0.004	< 0.001
ENTHALPY WATT	-2156.83	-1260.711	-3417.541	238.4	-3655.942
DENSITY lb/cuft	69.163	0.07	0.073	0.06	80.949
MASS FLOW kg/sec					
H2O	< 0.001	< 0.001	< 0.001		
N2	TRACE	0.004	0.004	0.004	
O2	TRACE	TRACE	TRACE	TRACE	
WOOD	< 0.001		< 0.001		< 0.001
*** SUBSTREAM NCPSD ***					
WOOD PROXANAL					
MOISTURE	15		15		75
FC	17.38		17.38		17.38
VM	77.08		77.08		77.08
ASH	5.54		5.54		5.54
WOOD ULTANAL					
ASH	6		6		6
CARBON	49		49		49
HYDROGEN	6		6		6
NITROGEN	0.5		0.5		0.5
CHLORINE	0		0		0
SULFUR	0.1		0.1		0.1
OXYGEN	38.4		38.4		38.4
WOOD SULFANAL					
PYRITIC	0.1		0.1		0.1
SULFATE	0		0		0
ORGANIC	0		0		0

(ii). Block Result

BLOCK:	DRY-FLSH	MODEL:	FLASH2		

INLET	STREAM:	IN-DRIER			
OUTLET	VAPOR	STREAM:	EXHAUST		
OUTLET	LIQUID	STREAM:	DRYBIO		
PROPERTY	OPTION	SET:	IDEAL	IDEAL	LIQUID
***	MASS	AND	ENERGY	BALANCE	***
IN	OUT	RELATIVE	DIFF.		
CONV.	COMP.(kmol/sec)	1.60E-04	1.60E-04	1.70E-16	
(kg/sec)		4.36E-03	4.36E-03	1.99E-16	
NONCONV.	COMP (kg/sec)		8.17E-05	8.17E-05	0
TOTAL	BALANCE				
MASS (kg/sec)		4.44E-03	4.44E-03	1.95E-16	
ENTHALPY(watt)		-3417.54	-3417.54	-5.70E-08	
***	INPUT	DATA	***		
TWO	PHASE	PQ	FLASH		
SPECIFIED	PRESSURE	N/SQM	101,353.00		
SPECIFIED	HEAT	DUTY	(watt)	0	
MAXIMUM	NO.	ITERATIONS	30		
CONVERGENCE	TOLERANCE	0.0001			
OUTLET	TEMPERATURE	K	299.59		
OUTLET	PRESSURE	N/SQM	1.01E+05		
VAPOR	FRACTION	0.9646			
BLOCK:	DRY-REAC	MODEL:	RSTOIC		
INLET	STREAMS:	WETBIO	NITROGEN		
OUTLET	STREAM:	IN-DRIER			
PROPERTY	OPTION	SET:	IDEAL	IDEAL	LIQUID
***	MASS	AND	ENERGY	BALANCE	***
IN	OUT	GENERATION	RELATIVE	DIFF.	
CONV.	COMP.(kmol/sec)	1.49E-04	1.60E-04	1.09E-05	0
(kg/sec)		4.17E-03	4.36E-03	-4.49E-02	
NONCONV	COMP (kg/sec)		2.78E-04	8.17E-05	0.705882
TOTAL	BALANCE				
MASS (kg/sec)		4.44E-03	4.44E-03	2.79E-08	
ENTHALPY (watt)		-3417.54	-3417.54	-8.48E-08	

(c). Pellet mill:

(i) Stream Result

	GWOOD	PWOOD
TEMPERATURE (K)	298.1	628.8
PRESSURE (N/sqm)	101325	101325
MASS VFRAC	0	0
MASS SFRAC	1	1
*** ALL PHASES ***		
MASS FLOW (kg/sec)	0.001	0.001
VOLUME FLOW (cum/sec)	< 0.001	< 0.001
ENTHALPY (watt)	-9629.574	-8474.974
DENSITY (lb/cuft)	80.36	80.36
MASS FLOW (kg/sec)		
H2O		
WOOD	0.001	0.001
*** SUBSTREAM NCPSD ***		
WOOD PROXANAL		
MOISTURE	11.68	11.68
FC	17.38	17.38
VM	77.08	77.08
ASH	5.54	5.54
WOOD ULTANAL		
ASH	6	6
CARBON	48	48
HYDROGEN	6.15	6.15
NITROGEN	0.43	0.43
CHLORINE	0	0
SULFUR	0.1	0.1
OXYGEN	39.3	39.3
WOOD SULFANAL		
PYRITIC	0	0
SULFATE	0	0
ORGANIC	0	0
PSD		
1	0.0001229	0
2	0.999877	0
3	0	1

(ii) Block Result

BLOCK:	PELLETMI	MODEL:	GRANULATO R		

INLET	STREAM:	GWOOD			
OUTLET	STREAM:	PWOOD			
PROPERTY	OPTION	SET:	IDEAL	IDEAL	LIQUID
***	MASS	AND	ENERGY	BALANCE	***
IN	OUT	RELATIVE	DIFF.		
CONV.	COMP.(kmol/sec)	0	0	0	
(kg/sec)		0	0	0	
NONCONV.	COMP(kg/sec)		1.49E-03	1.49E-03	1.01E-07
TOTAL	BALANCE				
MASS (kg/sec)		1.49E-03	1.49E-03	1.01E-07	
ENTHALPY (watt)		-9629.57	-8474.97	-0.1199	
***	CO2	EQUIVALENT	SUMMARY	***	
FEED	STREAMS	CO2E	0	KG/SEC	
PRODUCT	STREAMS	CO2E	0	KG/SEC	
NET	STREAMS	CO2E	PRODUCTION	0	KG/SEC
UTILITIES	CO2E	PRODUCTION	0	KG/SEC	
TOTAL	CO2E	PRODUCTION	0	KG/SEC	
***	INPUT	DATA	***		
CALCULATION	OPTION	DISTRIBUTIO N	FUNCTION		
MAXIMUM	NO.	OF	FLASH	ITERATION S	30
FLASH	TOLERANCE	0.0001			
***	RESULTS	***			
SEED	MEAN	DIAMETER	m	1.50E-03	
SEED	SAUTER	MEAN	DIAMETER	m	1.50E-03
PRODUCT	MEAN	DIAMETER	m	6.00E-03	

Appendix A4: Techno-economic PV analysis of pellet production with different feedstock

1. Regular Wood

	Year	Capital cost	Maintenance cost	Harvesting cost	Transportation cost	Premium Paid	Employee cost	Energy cost	Consumables	other cost	Total cost
2014	-2	4898									4898
2015	-1	8571									8571
2016	0	11020									11020
2017	1	0	471	4869	5954	1104	1328	2973	1995	122	18815
2018	2	0	480	5565	7149	1261	1354	3032	2035	125	21002
2019	3	0	490	5913	7771	1340	1381	3093	2076	127	22191
2020	4	0	500	6031	7926	1367	1409	3155	2117	130	22634
2021	5	0	510	6151	8085	1394	1437	3218	2160	133	23087
2022	6	0	520	6274	8246	1422	1466	3282	2203	135	23549
2023	7	0	530	6400	8411	1450	1495	3348	2247	138	24020
2024	8	0	541	6528	8580	1479	1525	3415	2292	141	24500
2025	9	0	552	6658	8751	1509	1555	3483	2338	143	24990
2026	10	0	563	6792	8926	1539	1587	3553	2385	146	25490
2027	11	0	574	6928	9105	1570	1618	3624	2432	149	26000

2. Steam Pretreated Wood

	Year	Capital cost	Maintenance cost	Harvesting cost	Transportation cost	Premium Paid	Employee cost	Energy cost	Consumables	other cost	Total cost
2014	-2	10737									10737
2015	-1	18789									18789
2016	0	24158									24158
2017	1	0	1001	7662	11119	1314	1886	14993	3020	268	41262
2018	2	0	1021	8756	13388	1502	1923	15292	3081	274	45237
2019	3	0	1042	9304	14569	1596	1962	15598	3142	279	47492
2020	4	0	1062	9490	14861	1627	2001	15910	3205	285	48441
2021	5	0	1084	9679	15158	1660	2041	16228	3269	291	49410
2022	6	0	1105	9873	15461	1693	2082	16553	3335	296	50399
2023	7	0	1127	10070	15770	1727	2123	16884	3401	302	51406
2024	8	0	1150	10272	16086	1762	2166	17222	3469	308	52435
2025	9	0	1173	10477	16407	1797	2209	17566	3539	314	53483
2026	10	0	1196	10687	16736	1833	2253	17918	3610	321	54553
2027	11	0	1220	10901	17070	1869	2298	18276	3682	327	55644
2028	12	0	1245	11119	17412	1907	2344	18641	3755	334	56757
2029	13	0	1270	11341	17760	1945	2391	19014	3830	340	57892
2030	14	0	1295	11568	18115	1984	2439	19395	3907	347	59050
2031	15	0	1321	11799	18477	2024	2488	19782	3985	354	60231
2032	16	0	1347	12035	18847	2064	2538	20178	4065	361	61436
2033	17	0	1374	12276	19224	2105	2588	20582	4146	368	62664

3. Regular straw

	Year	Capital cost	Maintenance cost	Field cost	Transportation cost	Employee cost	Energy cost	Consumables	other cost	Total cost
2014	-2	4993								4993
2015	-1	8738								8738
2016	0	11234								11234
2017	1	0	482	8190	4919	1328	988	1995	125	17902
2018	2	0	492	9360	5919	1354	1008	2035	127	20168
2019	3	0	502	9946	6440	1381	1028	2076	130	21372
2020	4	0	512	10144	6440	1409	1049	2117	132	21670
2021	5	0	522	10347	6440	1437	1069	2160	135	21975
2022	6	0	532	10554	6440	1466	1091	2203	138	22286
2023	7	0	543	10765	6440	1495	1113	2247	141	22603
2024	8	0	554	10981	6440	1525	1135	2292	143	22926
2025	9	0	565	11200	6440	1555	1158	2338	146	23256
2026	10	0	576	11424	6440	1587	1181	2385	149	23592
2027	11	0	588	11653	6440	1618	1204	2432	152	23935
2028	12	0	599	11886	6440	1651	1228	2481	155	24285
2029	13	0	611	12124	6440	1684	1253	2531	158	24642
2030	14	0	624	12366	6440	1717	1278	2581	161	25006
2031	15	0	636	12613	6440	1752	1304	2633	165	25377
2032	16	0	649	12866	6440	1787	1330	2685	168	25756
2033	17	0	662	13123	6440	1822	1356	2739	171	26142

4. Steam Pretreated straw

	Year	Capital cost	Maintenance cost	Field cost	Transportation cost	Employee cost	Energy cost	Consumables	other cost	Total cost
2014	-2	9562								9562
2015	-1	16733								16733
2016	0	21514								21514
2017	1	0	884	12095	8184	1886	11752	2610	239	37411
2018	2	0	902	13823	9869	1923	11987	2662	244	41166
2019	3	0	920	14687	10747	1962	12227	2716	249	43258
2020	4	0	938	14981	10747	2001	12472	2770	254	43908
2021	5	0	957	15280	10747	2041	12721	2825	259	44571
2022	6	0	976	15586	10747	2082	12975	2882	264	45248
2023	7	0	995	15897	10747	2123	13235	2940	269	45938
2024	8	0	1015	16215	10747	2166	13500	2998	275	46641
2025	9	0	1036	16540	10747	2209	13770	3058	280	47359
2026	10	0	1056	16870	10747	2253	14045	3120	286	48092
2027	11	0	1078	17208	10747	2298	14326	3182	291	48838
2028	12	0	1099	17552	10747	2344	14612	3246	297	49600
2029	13	0	1121	17903	10747	2391	14905	3310	303	50377
2030	14	0	1143	18261	10747	2439	15203	3377	309	51170
2031	15	0	1166	18626	10747	2488	15507	3444	315	51978
2032	16	0	1190	18999	10747	2538	15817	3513	322	52803
2033	17	0	1213	19379	10747	2588	16133	3583	328	53644

5. Regular Switchgrass

	Year	Capital cost	Maintenance cost	Harvesting cost	Transportation cost	Premium Paid	Employee cost	Energy cost	Consumables	other cost	Total cost
2014	-2	4898									4898
2015	-1	8571									8571
2016	0	11020									11020
2017	1	0	471	4001	6713	835	1328	988	1995	122	16453
2018	2	0	480	4572	7972	954	1354	1008	2035	125	18501
2019	3	0	490	4858	8622	1014	1381	1028	2076	127	19596
2020	4	0	500	4955	8794	1034	1409	1049	2117	130	19988
2021	5	0	510	5054	8970	1055	1437	1069	2160	133	20388
2022	6	0	520	5155	9149	1076	1466	1091	2203	135	20796
2023	7	0	530	5258	9332	1098	1495	1113	2247	138	21212
2024	8	0	541	5364	9519	1120	1525	1135	2292	141	21636
2025	9	0	552	5471	9709	1142	1555	1158	2338	143	22069
2026	10	0	563	5580	9904	1165	1587	1181	2385	146	22510
2027	11	0	574	5692	10102	1188	1618	1204	2432	149	22960

6. Steam Pretreated Switchgrass

	Year	Capital cost	Maintenance cost	Harvesting cost	Transportation cost	Premium Paid	Employee cost	Energy cost	Consumables	other cost	Total cost
2014	-2	9005									9005
2015	-1	15759									15759
2016	0	20261									20261
2017	1	0	831	5567	10290	1162	1886	12048	2405	225	34413
2018	2	0	848	6362	12252	1328	1923	12289	2453	230	37685
2019	3	0	865	6759	13267	1411	1962	12534	2502	234	39535
2020	4	0	882	6895	13533	1439	2001	12785	2553	239	40326
2021	5	0	900	7032	13803	1468	2041	13041	2604	244	41132
2022	6	0	918	7173	14080	1497	2082	13302	2656	249	41955
2023	7	0	936	7317	14361	1527	2123	13568	2709	254	42794
2024	8	0	955	7463	14648	1558	2166	13839	2763	259	43650
2025	9	0	974	7612	14941	1589	2209	14116	2818	264	44523
2026	10	0	993	7764	15240	1621	2253	14398	2875	269	45414
2027	11	0	1013	7920	15545	1653	2298	14686	2932	274	46322
2028	12	0	1034	8078	15856	1686	2344	14980	2991	280	47248
2029	13	0	1054	8240	16173	1720	2391	15279	3050	286	48193
2030	14	0	1075	8404	16496	1754	2439	15585	3111	291	49157
2031	15	0	1097	8573	16826	1789	2488	15897	3174	297	50140
2032	16	0	1119	8744	17163	1825	2538	16214	3237	303	51143
2033	17	0	1141	8919	17506	1862	2588	16539	3302	309	52166