Net Energy Ratio for the Production of Steam Pretreated Biomass-based Pellets

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Abstract. A process model was developed to determine the net energy ratio (NER) for both regular and steam-pretreated pellet production from ligno-cellulosic biomass. NER is a ratio of the net energy output to the total net energy input from non-renewable energy source into the system. Scenarios were developed to measure the effect of temperature and level of steam pretreatment on the NER of both production processes. The NER for the base case at 6 kg h^{-1} is 1.29 and 5.0 for steam-pretreated and regular pellet production respectively. However, at the large scale NER would improve. The major factor for NER is energy for steam and drying unit. The sensitivity analysis for the model shows that the optimum temperature for steam pretreatment is 200 ^{o}C with 50% pretreatment (Steam pretreating 50% feed stock,

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while the rest is undergoing regular pelletization). Uncertainty result for steam pretreated and regular pellet is 1.35±0.09 and 4.52±0.34 respectively.

Keywords: Biomass; pellets; process model; energy balance; steam pretreatment; NER

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 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. 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.

2.1 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 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 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.

Table 1

Table 2

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.

2.3 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. 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 3.

Fig. 1

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. (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].

$$R_o = \int_0^t \exp[\frac{(t-100)}{14.75}]\, dtR_o = \int_0^t \exp[\frac{(t-100)}{14.75}]\, dt \qquad (1)$$

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 Fig. 2. The steam pretreatment reactor is modeled based on experiments carried out in the steam pretreatment unit at 210 ^{0}C with a residence time of 10 minutes.

Fig. 2

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 Supplementary Section [28].

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.

2.3.3 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):

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

(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.

2.3.4 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.

2.4 Assumptions

The modeled unit operations are given in Fig. 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. (3) [32]:

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

where X_i 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. (4) [6]:

$$E = -203.06\log(S) + 206.11$$
$$E = -203.06\log(S) + 206.11$$

(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. 1 and Table 2 for both regular and steam pretreated pellet production.

3. Results and Discussion

Table 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.

Table 3

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. 3. The net energy impact with respect to each process is shown Table 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.

Fig. 3

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 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.

Table 4

Fig. 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.

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.

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 4 shows the results of the sensitivity analysis for varying temperature scenarios with respects to NER. Fig. 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(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. 4

Fig. 5

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. 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. The change of NER with level of pretreatment is shown in Fig. 5(a). 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 5

Table 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 6

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.

Fig. 6

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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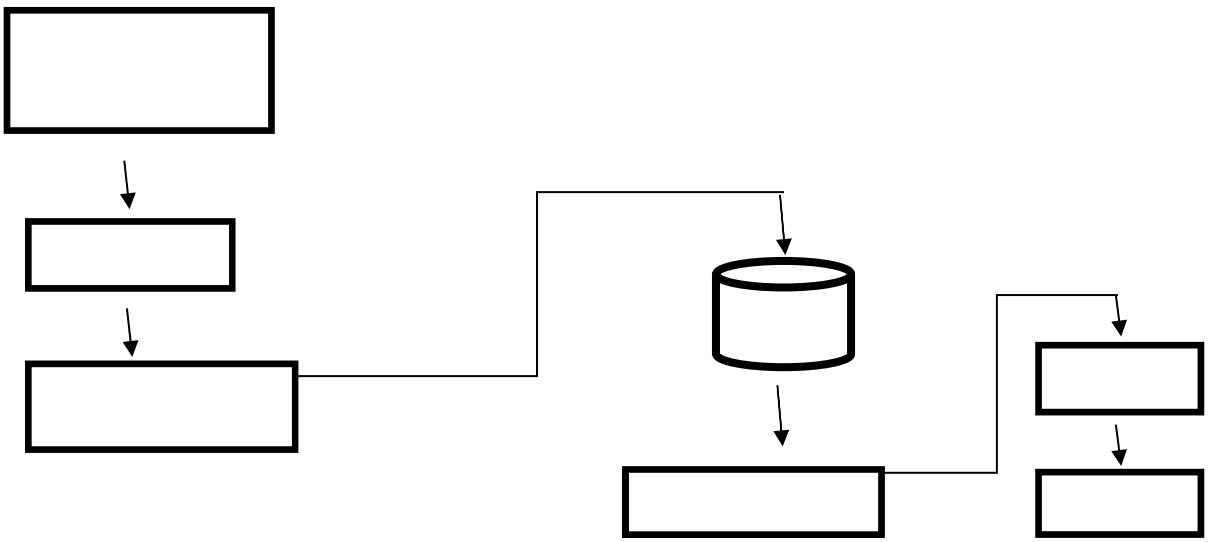
A. Regular pellet scheme



B. Steam-treated pellet scheme

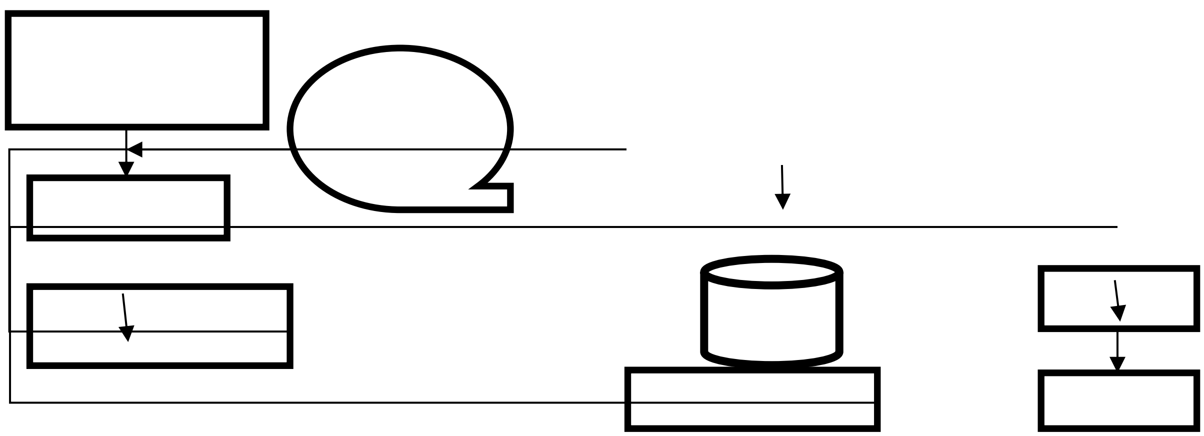
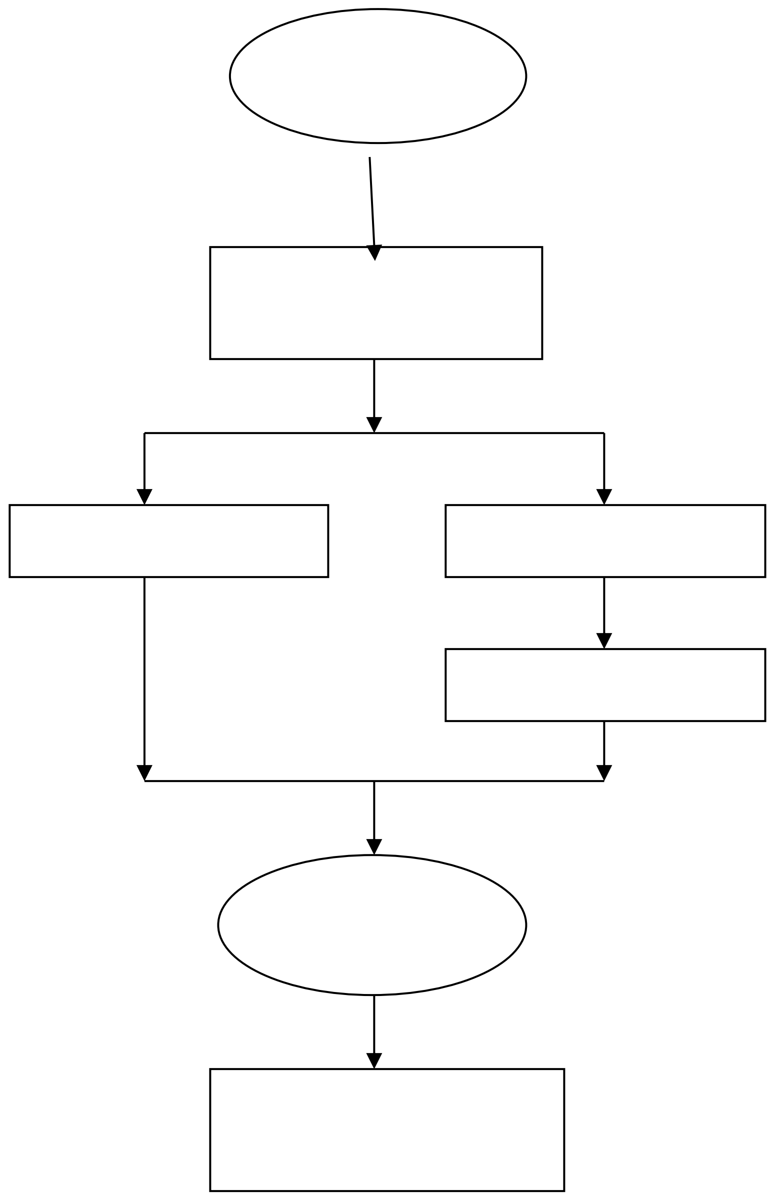
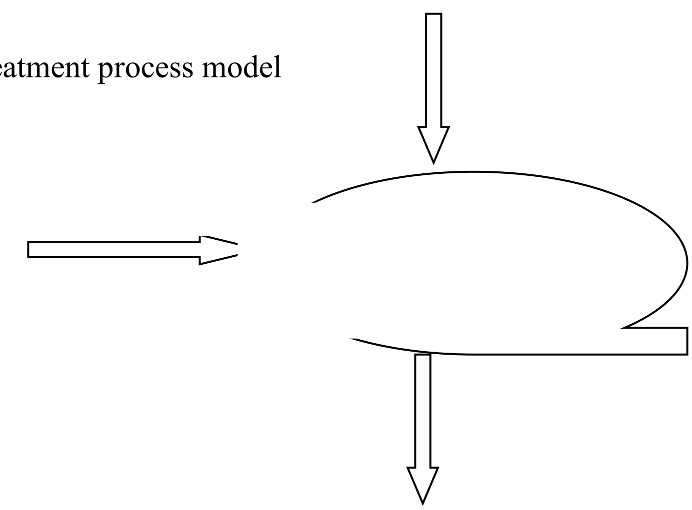


Fig. 1: Production chain of regular pellets and steam-treated pellets

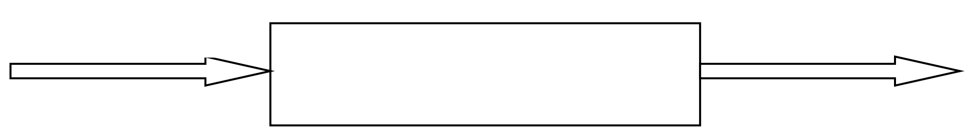
A. Process scheme



B. I. Steam Pretreatment process model



II. Dryer process model



III. Hammer mill process model

IV. Pellet mill process model

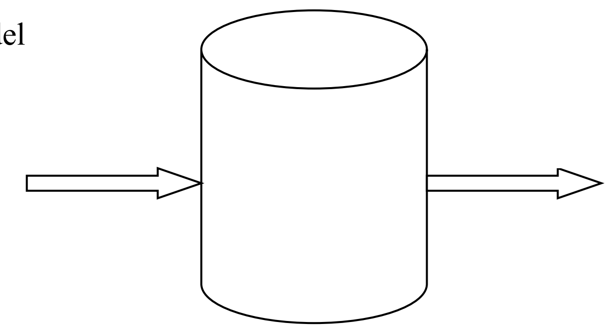
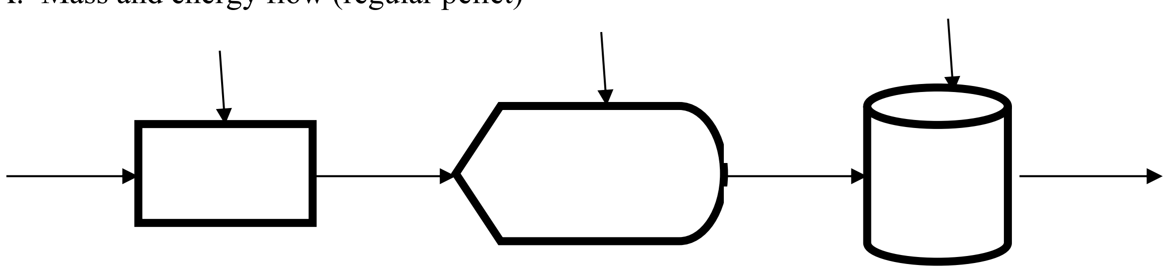
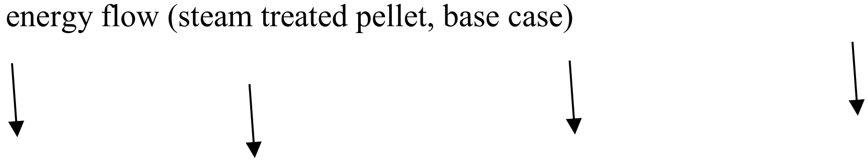


Fig. 2: Process scheme and model assumptions used in Aspen PLUS for: (a) Regular & Steam Pretreated Pellet Production; and (b) Unit Operation assumption [28]

A. Mass and energy flow (regular pellet)



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



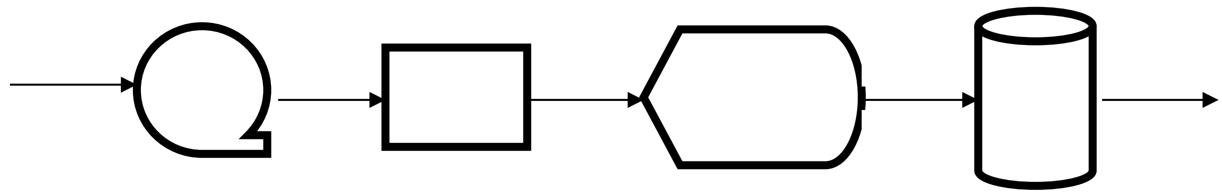
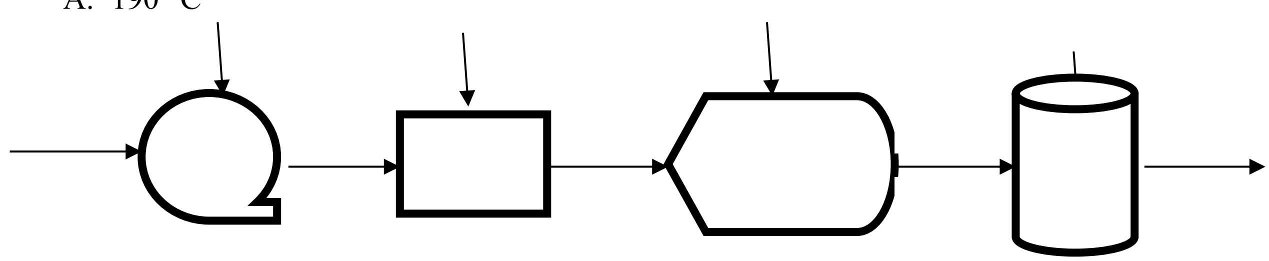
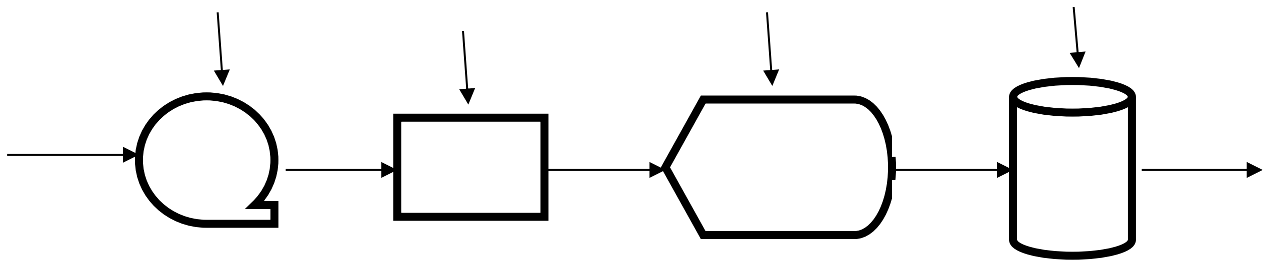


Fig. 3: Input and output energy and mass flow of regular pellet production and steam pretreated pellet production (base case)

A. 190 ^{0}C



B. 200 ^{0}C



C. 220 ^{0}C

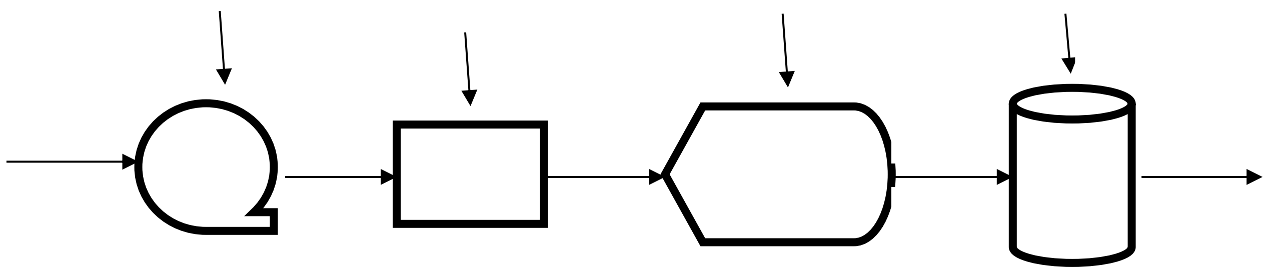


Fig. 4: Effect of change in temperature on energy and mass flow of steam pretreated pellet production

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 (45000 tonne plant)

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

(A)

(B)

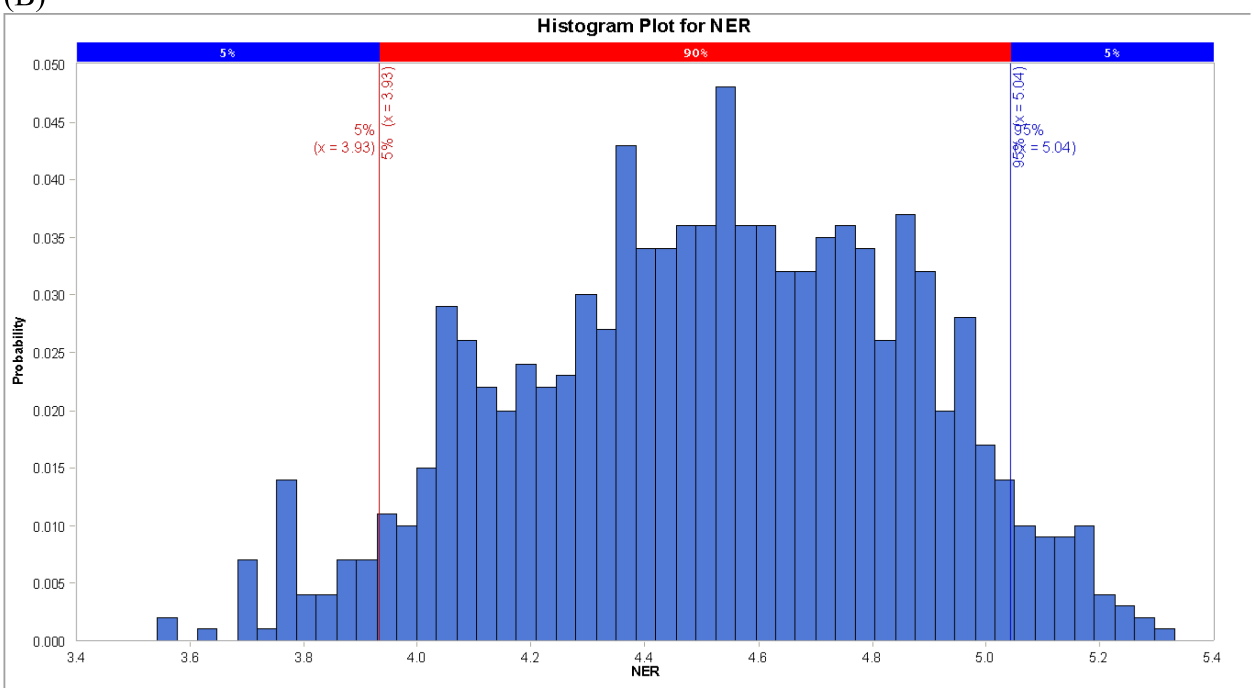


Fig. 6: Model uncertainty analysis of (a) steam pretreated Pellet NER and (b) Regular pellet NER

Table 1: Fuel property improvement due to steam pretreatment

Condition	Unit	Untreated	1	2	3	4	Source
Treatment temperature	^{0}C	-	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	
O mass fraction	% of dry solid	45.28	44.63	43.12	41.29	40.76	
							[16]
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: 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	Kicks constant	32 J kg^{-1}	

mill	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}	

Table 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	kJ kg^{-1}	821.33			
		Energy for steam generation, E_s	kJ kg^{-1}	1276.65			
		Specific energy consumption	kJ kg^{-1}	2097.99			
		Moisture content of feed stock	%	45			
		Initial mass	kg	1			
		Net Heat consumption	kJ	2097.99	2095		
2	Drying	Heating wood	kJ kg^{-1}	34.85		87.12	
		Heating water	kJ kg^{-1}	296.03		170.79	
		Heating air	kJ kg^{-1}	92.41		92.41	
		Evaporation of water	kJ kg^{-1}	1673.45		802.64	
		Heat loss	kJ kg^{-1}	418.36		200.66	

		Specific energy consumption	kJ kg^{-1}	2515.11		1353.61	
		Initial mass		2.45		1	
		Net Heat consumption	kJ	6162.02	6156	1353.61	1360
3	Grinding	Feed rate	kg h^{-1}	120		35	
		Average power consumption	J s^{-1}	838		2804.5	
		Specific energy consumption	kJ kg^{-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	kg h^{-1}	5.4		5.4	
		Average power consumption	J s^{-1}	1154.83		1135	
		Specific energy consumption	kJ kg^{-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

Table 4: Variation of net energy ratio with treatment temperature

	Treatment Temperature								
	190 ^{o}C			**200 ^{o}C**			**220 ^{o}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

Table 5: Variation of net energy ratio with level of treatment

	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	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 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**