Comparative net energy ratio analysis of pellet produced from steam pretreated biomass from agricultural residues and energy crops

Hassan Shahrukh[1], Adetoyese Olajire Oyedun[1], Amit Kumar[11], Bahman Ghiasi[2], Linoj Kumar[2], Shahab Sokhansanj[2,3]

[1] Department of Mechanical Engineering, 10-263 Donadeo Innovation Centre for Engineering, University of Alberta, Edmonton, Alberta T6G 1H9, Canada.

[2] Department of Chemical and Biological Engineering, 2360 East Mall, University of British Columbia, Vancouver, BC, V6T 1Z3 Canada.

[3] Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831

Abstract.

A process model was developed to determine the net energy ratio (NER) for the production of pellets from steam pretreated agricultural residue (wheat straw) and energy crops (i.e., switchgrass in this case). The NER is a ratio of the net energy output to the total net energy input from non-renewable energy sources into a system. Scenarios were developed to measure the effects of temperature and level of steam pretreatment on the NER of steam pretreated wheat straw and switchgrass pellets. The NERs for the base case at 6 kg h^{-1} are 1.76 and 1.37 for steam-pretreated wheat straw and switchgrass-based pellets, respectively. The reason behind the

---

[1] Corresponding author. Tel.: +1-780-492-7797.

E-mail: Amit.Kumar@ualberta.ca (A. Kumar).

difference is that more energy is required to dry switchgrass pellets than wheat straw pellets. The sensitivity analysis for the model shows that the optimum temperature for steam pretreatment is 160 ˚C with 50% pretreatment (half the feedstock is pretreated, while the rest undergoes regular pelletization). The uncertainty results for NER for steam pretreated wheat straw and switch grass pellets are 1.62±0.10 and 1.42±0.11, respectively.

Keywords: Agricultural residue; energy crop; pelletization; process model; steam pretreatment.

1. Introduction

One of the ways to reduce the growing concerns of greenhouse gas (GHG) emissions is to substitute fossil fuels with sustainable biomass feedstocks like agricultural residue (wheat straw) and forest residue. The economics of biomass-based power generation have been evaluated earlier by several authors [1-8]. One of the key barriers to large-scale biomass use is the supply of consistent quality feed to biomass-based facilities [3, 9, 10]. The low energy density and yield of biomass-based feedstock limit the use of biomass. The pelletization of biomass is a process through which the calorific value of biomass can be increased. Pelletization, 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 [11]. Pelletization reduces transportation costs by increasing volumetric density. In addition, this technology allows the free flow of fuels, which simplifies loading and unloading [11]. There have been a number of studies on pelletization and economics of conventional pellet production using lignocellulosic biomass (e.g., forest residues, wheat straw, sawdust) [3, 4, 12]. Also studies have assessed energy consumption in pellet production [13].

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^{-1}, while that of pelletized biomass is 16-18 MJ kg^{-1}. The higher heating value can be improved through biomass pretreatment before pelletization, as suggested by Tooyserkani and Lam [9, 10]. Typically, this process includes steam pretreatment, ammonia pretreatment, and acid catalyzed pretreatment [14]. The steam pretreatment process is an additional process added to the pelletization supply chain to improve the calorific value and bulk density of biomass, which in turn reduces transportation and handling costs [15, 16].

The effect of steam pretreatment, also known as Masonite technology [10], 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 [17, 18]. 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 [19].

While a number of authors have previously estimated process net energy ratio (NER) for different biomass pathways [13, 20-22], the NER for steam pretreated biomass-based pellet production has received minimal discussion in the literature. The net energy ratio (NER) is the ratio of net energy output to the total energy input from non-renewable sources. In an earlier study, the authors evaluated the NER for pellets produced from steam pretreated forest residues [19], but the process energy requirements and NERs of pellets produced from wheat straw and switchgrass have not been evaluated so far. There is a need to evaluate the NER from a life cycle point of view for these feedstocks; this evaluation could help in further development of the most efficient technology. In light of this gap in the literature, 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.

2. Methodology

This study employs process modeling of the pellet production processes from wheat straw and switchgrass. The pellet production process model is built based on experimental results. The model evaluates the NER of steam pretreated pellets from two feedstocks and compares it with the NER of regular pellet production. Regular pellet production refers to pellet production without steam pretreatment. The process model evaluates the energy requirement of two processes, the steam pretreatment of biomass for pellet production and regular pellet production.

The process simulation model tool, Aspen Plus [23] was used for this study. The focus was 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 wheat straw 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.

The unit operations of steam pretreated pellet production, in order of highest to lowest energy consumption, are the dryer, the steam pretreatment process, and the pelletization process. 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 above.

Fig. 1

The pelletization process starts with the harvesting and collection of wheat straw and switchgrass in bales form and transporting them to the pellet mill [24]. The mean water mass fraction of the wheat straw and switchgrass is around 10-14%. The biomass collected from the forest is first chopped in a grinder to reduce particle size. The feedstocks are ground in a hammer mill to a particle size of 3.2 mm or less [25]. The particle size can be changed in the hammer mill by varying the mesh screen size.

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 [26]. Once pellets are formed, they are air-cooled from a temperature of 95 to 100 ˚C to 25 ˚C.

Experimental work of steam pretreatment carried out in laboratory condition is described thus: wheat straw- and switchgrass-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 takes this scenario into account. The steam pretreatment experiments showed that at temperatures beyond 180 ˚C, the solid yield falls significantly due to the loss of volatiles [27]. The loss of volatile occurs due to exposure of the biomass to high temperature steam. This means that partial decomposition of biomass occurs beyond this temperature. The steam-pretreated biomass is dried in a convective dryer at 80°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 wheat straw and switchgrass steam pretreated pellets and forest residue pellets is in the grinding process. No grinding is required after steam pretreatment for either wheat straw or switchgrass for pellet production. The ground biomass is pelletized at 12 kg h^{-1} in a California pellet mill (CPM Laboratory Pellet Mill No. CL-397179). 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 batches of 2 kg to ensure that the roller and ring die are not clogged during the experiment [28]. The feed flow rate of material to the mill is controlled using a vibratory feeder. In this study, material flowability issues due to different feedstocks were neglected, as were the addition of additives [29]. The recycling of fines is also not considered in this study due to experimental limitations.

The developed model focuses on the effect pretreatment temperature has on NER and on the pretreatment itself. The increase in temperature improves calorific value, as suggested by author's previous work [19, 30], but this comes at the cost of pellet yield. Hence, this study focused on investigating the steam pretreatment temperature at which the calorific value is high without reducing pellet yield. Previous experiments by the authors found that steam pretreatment is energy intensive due to the high energy requirement during both steam pretreating and drying

[19, 30]. Hence, a trade-off was done by varying the levels of biomass pretreated, i.e. the amount of biomass 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. 2 and Tables 1 and 2.

Fig. 2

Table 1

Table 2

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 regular and steam pretreated pellet production. The validated results are presented in Table 3. Energy consumption for the experimental unit operations was calculated using the equations from our previous research [19]. 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

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 gives the net energy impact with respect to each process. The comparative results of steam pretreated pellet production from wheat straw and switchgrass indicate that wheat straw requires more energy for steam pretreatment. However, more drying energy is required for switchgrass biomass before its use for pellet production.

Fig. 3

A comparative analysis shows that more energy is required for wheat straw pellets than for switchgrass pellets (see Table 3). This difference can be attributed to the particle size difference of the two feedstocks. A particle size analysis was carried out on samples using a mesh analyzer.

The NER is a key decision-making metric and an important parameter to assess process efficiency. Table 4 presents the variation of NER with different steam pretreatment temperatures. The NER results for the steam treated pellets show that the wheat straw pelletization process has an 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 the switchgrass case is due to the greater energy requirement for drying since switchgrass feedstock has a higher water mass-fraction than wheat straw. Moreover, the NER results and the mass and energy balance at different temperatures proves that 100% biomass pretreatment level is not feasible based on the NER results of the steam pretreatment process (see Table 4 and Fig. 4). When all of the available biomass undergoes steam pretreatment, extra steam for pretreatment will be required. The extra steam condenses on the biomass after pretreatment and this condensed water is later burned off from the biomass. To exemplify the effects of the variations of the pretreatment levels on the NER of the entire energy chain, a scenario analysis was conducted.

Table 4

Fig. 4

The energy requirement for the entire chain for large-scale steam-pretreated pellet production from both switchgrass and wheat straw at a base case of 45 kt y^{-1} is shown in Fig. 5. This plant capacity was chosen based on the typical size of pellet plants in Western Canada [3, 9, 10]. 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 wheat straw pellets since energy crop pellets have a higher water mass retention fraction.

Fig. 5

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 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 Table 4. The results show that the NER of the steam pretreatment process drops with increasing temperatures. The increase in energy densification comes at the expense 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 wheat straw pellets and 2.20 to 1.37 for switchgrass 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 without causing significant loss in pellet mass.

The energy requirement for drying and steam pretreatment is the key driver 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 from 160 ˚C. The solid yield and calorific value are both optimum at a temperature of 160 ˚C, as shown in Table 5. This scenario is defined as ideal based on the increase in calorific with minimum reduction in pellet yield. 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, thereby reducing pellet yield, and more process steam condenses on the biomass with the increase in temperature, and therefore the steam pretreatment of biomass leads to the need for more evaporation energy for drying. This conclusion is based on the earlier experiment for steam explosion of biomass-based pellets [19] that found that below 140 ^{o}C the calorific value increase is minimal, while beyond 180 ^{o}C the loss of solids is high and leads to low pellet yield. Hence, the optimum range considered in this study is 140-180 ^{o}C.

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 pellet yield. Three 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 5 shows that partial treatment would lead to better calorific value of pellets without reducing process NER.

Table 5

A sensitivity analysis was conducted to understand the effects of fines generation on the process NER. Table 6 represents the results of this analysis. The results show that the NER of the process falls with an increase in fines generation. This can be attributed to the low pellet yield with the increased fines generation.

Table 6

5. Uncertainty Analysis

The lack of exact representative data and issues relating to uncertainty during the experiment are a major concern for the accuracy of the predicted NER. In these cases, available data sources and assumptions 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 [31]. 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 [32].

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 wheat straw pellets shows that the process NER is in the range of 1.62±0.10 at a confidence level of 95% [19], while for the steam pretreated switchgrass pellets the NER is in the range of 1.42±0.11. The authors have previously done uncertainty analyses of steam pretreated wood pellets [19]. The Monte-Carlo simulation results for the base case scenario of steam pretreated wood pellets show a process NER range of 1.35±0.09 at a confidence interval of 95%. The Monte-Carlo simulation shows that the uncertainty in the production of steam pretreated wheat straw and energy crop pellets is higher than wood pellets as reflected by the higher standard deviation of the process at a 95% confidence interval.

Fig. 6

6. Conclusions

In this study, a process model was developed to conduct a comparative energy analysis for steam-pretreated pellet production of agricultural residues (wheat straw) 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 an increase in the process energy requirement for drying and steam pretreatment. The drying energy requirement is higher for switchgrass pellets than for wheat straw 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 this study's results. The comparison between the NERs of the steam pretreated wood-, with the wheat straw- and energy crop-based pellets shows that the NER of steam pretreated wheat straw-based pellet production has the highest NER (1.62) followed by switchgrass and wood pellets. The low NER for the wood pellets can be attributed to the high energy requirement of both steam pretreatment and drying during wood pellet production. The motivation behind this research was to understand the overall energy input and output in the production of steam pretreated pellets from agricultural residues and switchgrass to make informed decisions.

7. Acknowledgments

The authors would like to acknowledge BioFuelNet Canada Inc. and the University of Alberta for funding this project. Technical support during the experimental stage from the departments of Chemical and Biological Engineering and Wood Sciences, University of British Columbia, is highly appreciated. The authors would especially like to mention Dr. Jack Saddler from the University of British Columbia for his support and cooperation in carrying out steam pretreatment experiment in his lab. Astrid Blodgett is acknowledged for editorial assistance.

Reference:

[1] Kumar A, Cameron JB, Flynn PC. Biomass power cost and optimum plant size in western Canada. Biomass Bioenerg 2003; 24(6): 445-64.

[2] Sokhansanj S, Fenton J. Cost benefit of biomass supply and pre-processing: BIOCAP Canada Foundation, Kingston (ON), Canada; 2006. Available from: http://www.cesarnet.ca/biocap-archive/rif/report/Sokhansanj_S.pdf

[3] Mani S, Sokhansanj S, Bi X, Turhollow A. Economics of producing fuel pellets from biomass. Appl Eng Agric 2006; 22(3): 421-26.

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

[5] Kumar A, Flynn P, Sokhansanj S. Biopower generation from mountain pine infested wood in Canada: An economical opportunity for greenhouse gas mitigation. Renew Energy. 2008; 33(6): 1354-63.

[6] Kumar A. A conceptual comparison of bioenergy options for using mountain pine beetle infested wood in Western Canada. Bioresource Technol 2009; 100(1): 387-99.

[7] Dassanayake GDM, Kumar A. Techno-economic assessment of triticale straw for power generation. Appl Energ 2012; 98: 236-45.

[8] Agbor E, Oyedun AO, Zhang X, Kumar A. Integrated techno-economic and environmental assessments of sixty scenarios for co-firing biomass with coal and natural gas. Appl Energ 2016; 169: 433-49.

[9] Tooyserkani Z. Hydrothermal pretreatment of softwood biomass and bark for pelletization. [dissertation]. Vancouver (BC): University of British Columbia; 2013.

[10] Lam PS. Steam explosion of biomass to produce durable wood pellets. [dissertation]. Vancouver (BC): University of British Columbia; 2011.

[11] Uslu A, Faaij AP, Bergman PC. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 2008; 33(8): 1206-23.

[12] Urbanowski E. Strategic analysis of a pellet fuel opportunity in Northwest British Columbia. [dissertation]. Vancouver (BC): Simor Fraser University; 2005.

[13] Sultana A, Kumar A. Development of energy and emission parameters for densified form of lignocellulosic biomass. Energy 2011; 36(5): 2716-32.

[14] Agbor VB, Cicek N, Sparling R, Berlin A, Levin DB. Biomass pretreatment: fundamentals toward application. Biotech Adv 2011; 29(6): 675-85.

[15] Lehtikangas P. Quality properties of pelletised sawdust, logging residues and bark. Biomass Bioenerg 2001; 20(5): 351-60.

[16] Lam PS, Sokhansanj S, Bi X, Lim CJ, Melin S. Energy input and quality of pellets made from steam-exploded Douglas fir (Pseudotsuga menziesii). Energ Fuel 2011; 25(4): 1521-8.

[17] Zhang Y, Chen H. Multiscale modeling of biomass pretreatment for optimization of steam explosion conditions. Chem Eng Sci 2012; 75: 177-82.

[18] Overend R, Chornet E, Gascoigne J. Fractionation of lignocellulosics by steam-aqueous pretreatments [and discussion]. Philos Trans R Soc Lond Ser A, 321 (1987), pp. 523–36.

[19] 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 Bioenerg 2015; 80(0): 286-97.

[20] Thakur A, Canter CE, Kumar A. Life-cycle energy and emission analysis of power generation from forest biomass. Appl Energ 2014; 128(0): 246-53.

[21] Kabir MR, Kumar A. Development of net energy ratio and emission factor for biohydrogen production pathways. Bioresour Technol 2011; 102(19): 8972-85.

[22] Kabir MR, Kumar A. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. Bioresour Technol 2012; 124: 394-405.

[23] Aspen P. User Guide. Version 84, Aspen Technology Inc., Burlington, MA, 2014.

[24] Kumar A, Sokhansanj S. Switchgrass (Panicum vigratum, L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. Bioresour Technol 2007; 98(5): 1033-44.

[25] Mani S, Tabil LG, Sokhansanj S. Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass Bioenerg 2006; 30(7): 648-54.

[26] Kuzel F. Wood Pelletization Sourcebook: A Sample Business Plan for the Potential Pellet Manufacturer. Prepared for the US Department of Energy, Great Lakes Regional Biomass Energy Program Prepared by NEOS Corporation. 1995.

[27] Campbell K. A feasibility study guide for an agricultural biomass pellet company. Minnesota, USA: Agricultural Utilization Research Institute (AURI); 2007. Available from: http://www.auri.org/wp-content/assets/legacy/research/FINAL%20FEASIBILITY%20STUDY%20GUIDE%2011-26-07.pdf.

[28] Brownell HH, Saddler JN. Steam pretreatment of lignocellulosic material for enhanced enzymatic hydrolysis. Biotechnol Bioeng 1987; 29(2): 228-35.

[29] Adapa PK, Tabil LG, Schoenau GJ. Factors affecting the quality of biomass pellet for biofuel and energy analysis of pelleting process. Int J Agric Bio Eng 2013; 6(2): 1-12.

[30] Shahrukh H, Oyedun AO, Kumar A, Ghiasi B, Kumar L, Sokhansanj S. Techno-economic assessment of pellets produced from steam pretreated biomass feedstock. Biomass Bioenerg 2016; 87: 131-43.

[31] Raynolds M, Checkel M, Fraser R. Application of Monte Carlo analysis to life cycle assessment. SAE Technical Paper No. 1999-01-0011; 1999.

[32] VoseSoftware [Internet]. Model Risk - Monte Carlo Simulation [Cited March 20 2015]. Available from: http://www.vosesoftware.com/index.php.

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

(a) **Wheat straw**

Treatment temperature	**^{o}C**	**Non treated**	**140**	**160**	**180**
Elemental analysis					
C	%	44.92	43.11	45.1	46.66
H	%	5.46	6.33	6.19	6.15
N	%	0.44	0.35	0.38	0.43
O	%	49.18	50.21	49.33	46.67
Proximate analysis					
Fixed carbon	%	17.98	18.1	18.5	18.78
Volatile matters	%	76.38	76.1	75.4	74.8
Ash content	%	5.64	5.8	6.1	6.4

(b) **Switchgrass**

Treatment temperature	**^{o}C**	**Non treated**	**140**	**160**	**180**
Elemental Analysis					
C	%	47	43.11	45.1	46.66
H	%	5.3	6.33	6.19	6.15
N	%	0.5	0.35	0.38	0.43
O	%	41.4	50.21	49.33	46.67
Ash content	%	5.7	6.1	6.5	6.8
Proximate analysis					
Fixed carbon	%	21.3	22.3	22.8	23
Volatile matters	%	72.9	71.6	70.7	70.2
Ash content	%	5.8	6.1	6.5	6.8

Table 2: Input data for the steam pretreated pellet simulation

	Unit operations	Model input conditions	Source
Boiler	Electric boiler	1.88 MPA and 180 ° C	[29]
Steam reactor	Capacity	2.5 L	[19]
		Wheat straw, Switchgrass	
	Reactor type	Yield reactor, based on elemental analysis	[19]
	Residence time	10 min	[28]
	Mean water fraction	10% (Wheat straw), 14% (Switchgrass)	[4, 24]
	Biomass and solid yield	82% (Wheat straw), 80% (Switchgrass)	[28]
Dryer	Inlet temperature	80 °C	[9]
	Target moisture level	15% wet basis	[9]
	Specification and model type	Thelco convection dryer operating at 80% efficiency	[9]

Hammer mill	Kick’s constant	100 kJ kg^{-1}	[9]
	Solid recovery	96%	[19]
Pellet mill	Operating temperature	80 ^{o}C	[19]
	solid recovery	95%	[19]

Table 3: Net Energy ratio for the base case

			Steam pretreated wheat straw pellet		**Steam pretreated switchgrass 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	
	Evaporation of water	kJ kg^{-1}	1446		1745.1	

	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

Table 4: Variation of net energy ratio with treatment temperature

(a). **Wheat straw**

	Treatment temperature								
	140 °C			**160 °C**			**180 °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 pretreatment	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 pretreatment	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[2] ratio			2.20			1.74			1.37

---

[2] The NER is the ratio of the total process output and the total non-renewable energy input (steam pre-treatment unit, dryer, and pellet mill)

For steam pretreatment, the energy input is steam. For the dryer, the energy input is flue gas from natural gas. For pellet mill, the energy input is from electricity. The output energy is measured using a bomb calorimeter to measure the pellet LHV.

Table 5: Variation of net energy ratio with level of pretreatment at 160 ^{0}C

(a). **Wheat 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 energ y kJ
Pretreatment level		0%			25%			50%	
Steam pretreatment	0	0	0	698	0.25	174	698	0.5	349
Drying	0	0	0	2068	0.54	1117	2068	1.1	2275
Grinding	323	1	323	324	0.75	243	324	0.5	162
Pelletization			766			649			446
Total			1089			2183			3231
Energy output			13967			13574			1310
Net energy ratio			12.8			6.2			4.1

(b). **Switchgrass**

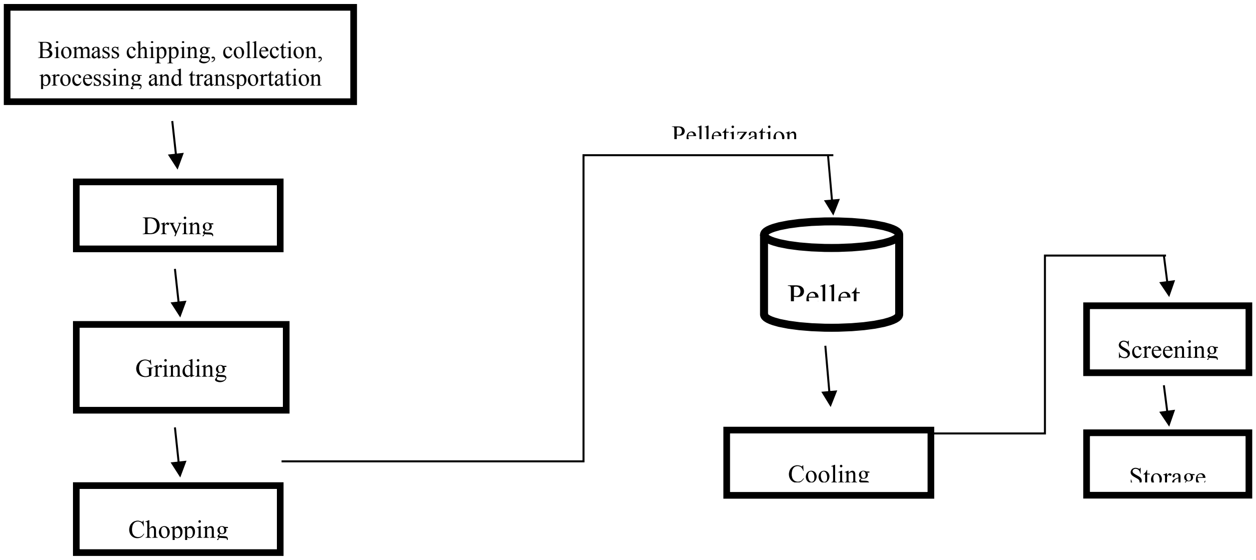
	Energy input (kJ kg^{-1})	Mass (kg)	Net energy (kJ)	Energy input (kJ kg^{-1})	Mass (kg)	Net energy (kJ)	Energy input (kJ kg^{-1})	Mass (kg)	Net energ y kJ
Pretreatment level		0%			25%			50%	
Steam pretreatment	0	0	0	593	0.25	148	593	0.5	296
Drying	0	0	0	2440	0.63	1537	2440	1.25	3050
Grinding	500	1	500	500	0.75	375	500	0.5	250
Pelletization			837			685			565
Total			1337			2745			4162
Energy output			14392			13448			13101
Net energy ratio			10.8			4.9			3.1

Table 6: Effect of fine generation on process model NER

	Wheat straw		Switchgrass	
Fines generation	**Regular**	**Steam pretreatment**	**Regular**	**Steam pretreatment**
0%	12.80	1.80	10.80	1.40
10%	12.40	1.29	10.10	1.25
20%	12.31	1.15	9.40	1.11

Figures

A. Regular pellet scheme



B. Steam-treated pellet scheme

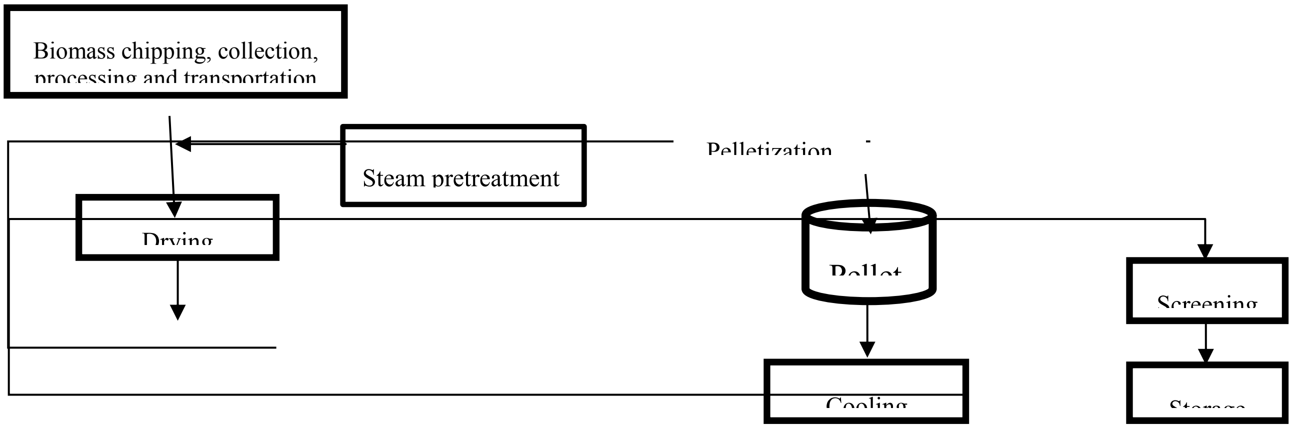
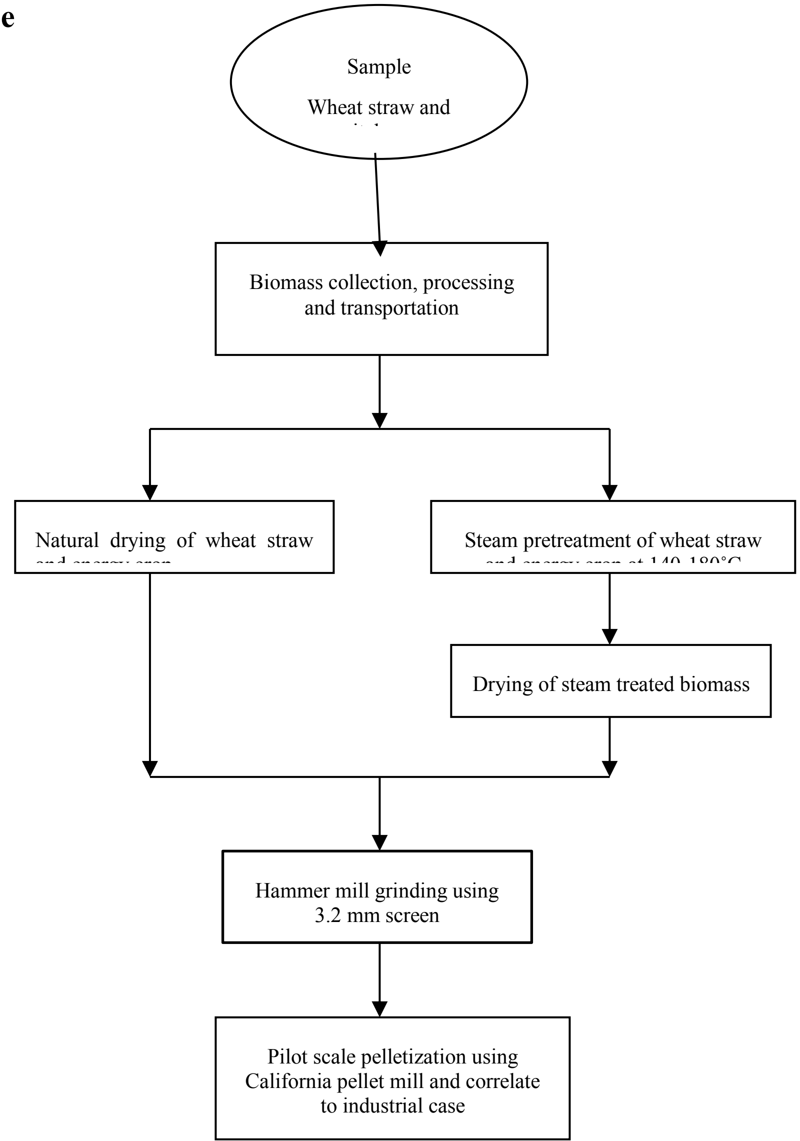
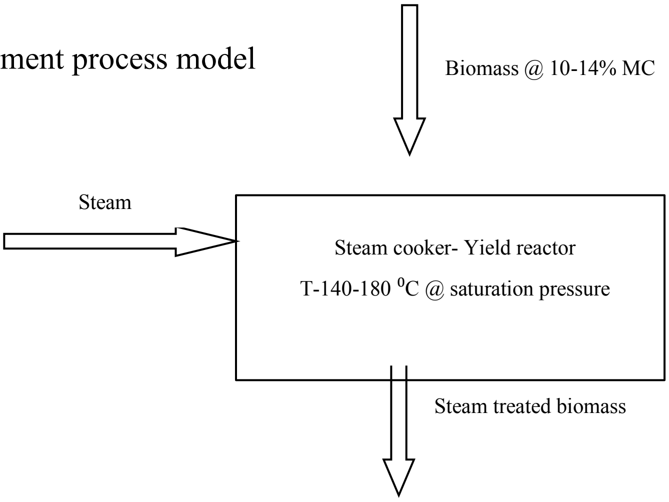


Fig. 1: Production chain of regular pellets and steam-treated pellets

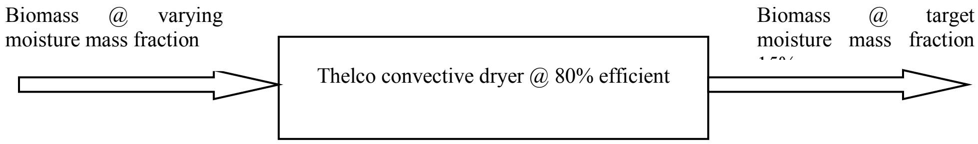
A. Process scheme



B. I. Steam pretreatment process model



II. Dryer process model



III. Pellet mill process model

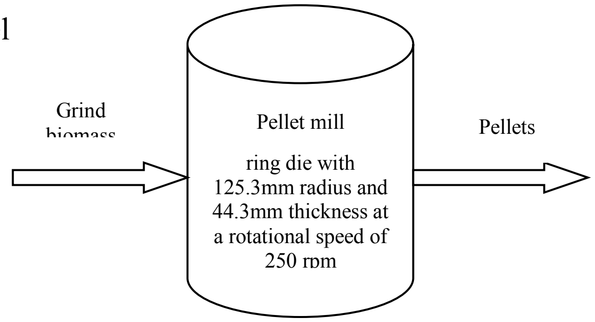
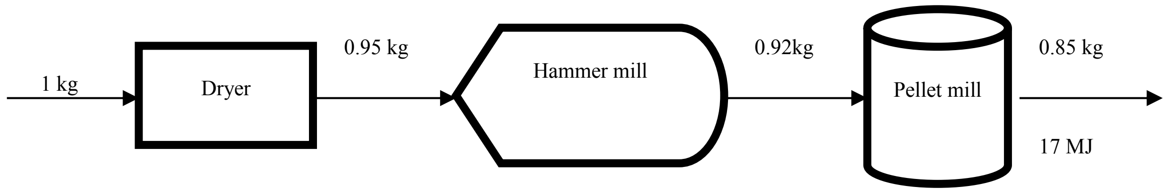


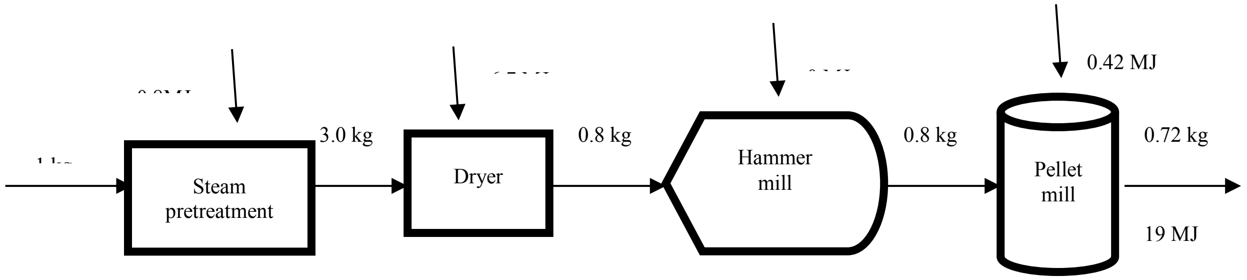
Fig. 2: Process scheme and model assumptions used in Aspen Plus for: (a) regular & steam pretreated pellet production; and (b) unit operation assumptions [29].

(a). Wheat straw

A. Mass and energy flow (regular pellet)

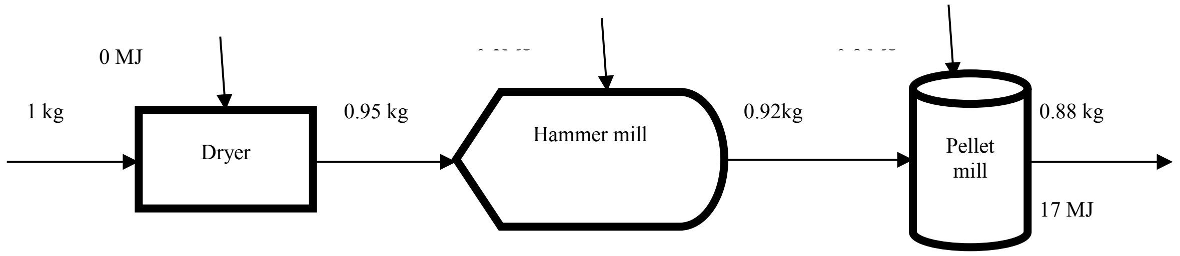


B. Mass and energy flow (steam treated pellet, base case)



(b). Switchgrass

A. Mass and energy flow (regular pellet)



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

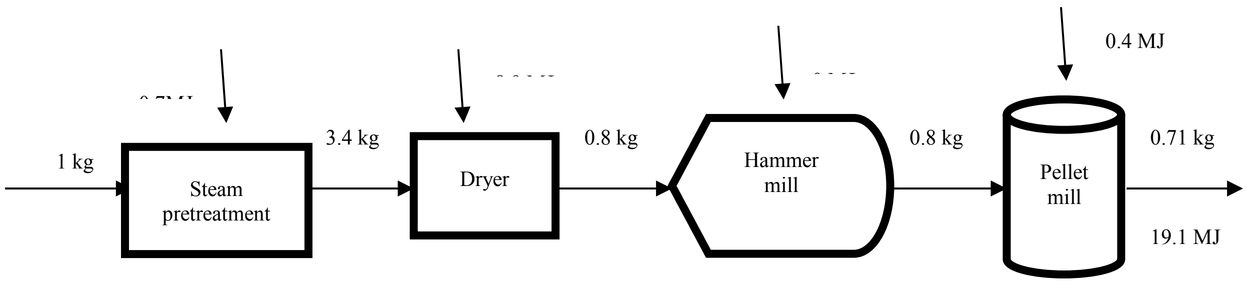
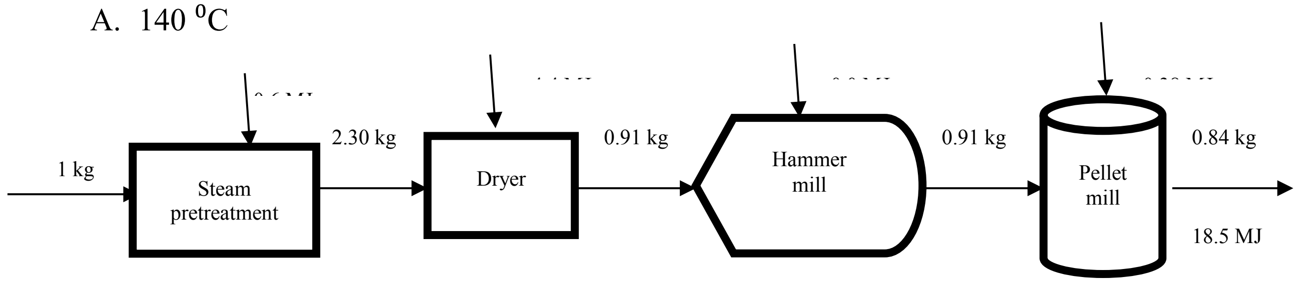


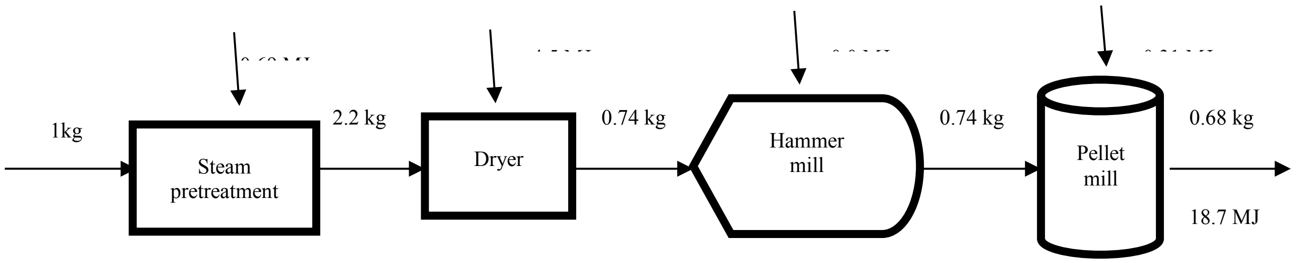
Fig. 3: Input and output energy and mass flow of regular and steam pretreated pellet production (base case of 180 ºC)

(a). **Wheat straw**

A. 140 ^{0}C

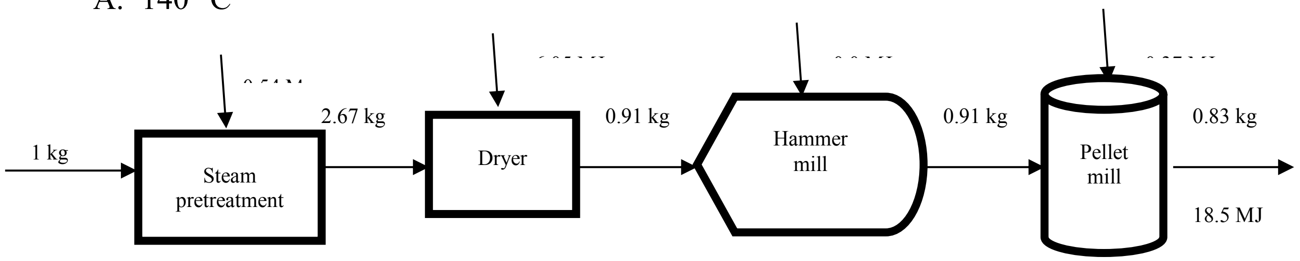


B. 160 ^{0}C



(b). **Switchgrass**

A. 140 ^{0}C



B. 160 ^{0}C

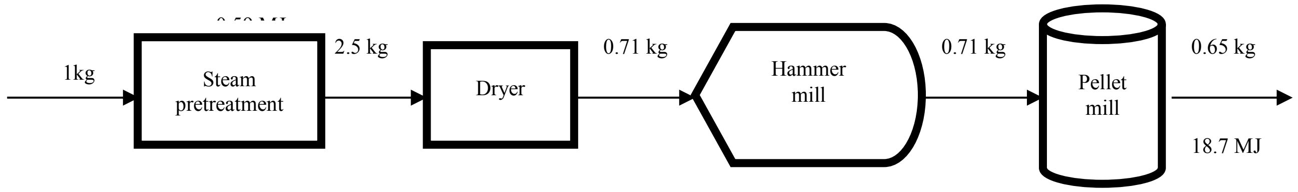
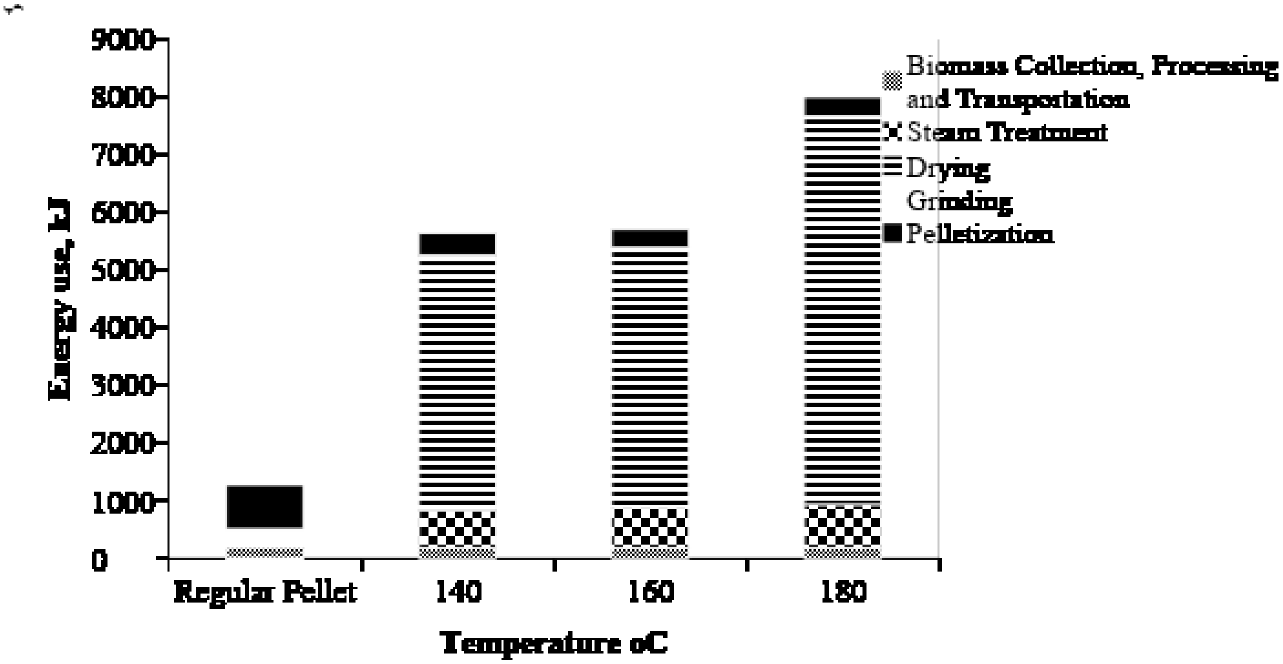


Fig. 4: Effect of change in temperature on energy and mass flow of steam pretreated pellet production

(a). Energy use for the entire chain at a large scale for switchgrass (45 kt y^{-1} plant)



(b). Energy use for the entire chain at a large scale for wheat straw (45 kt y^{-1} plant)

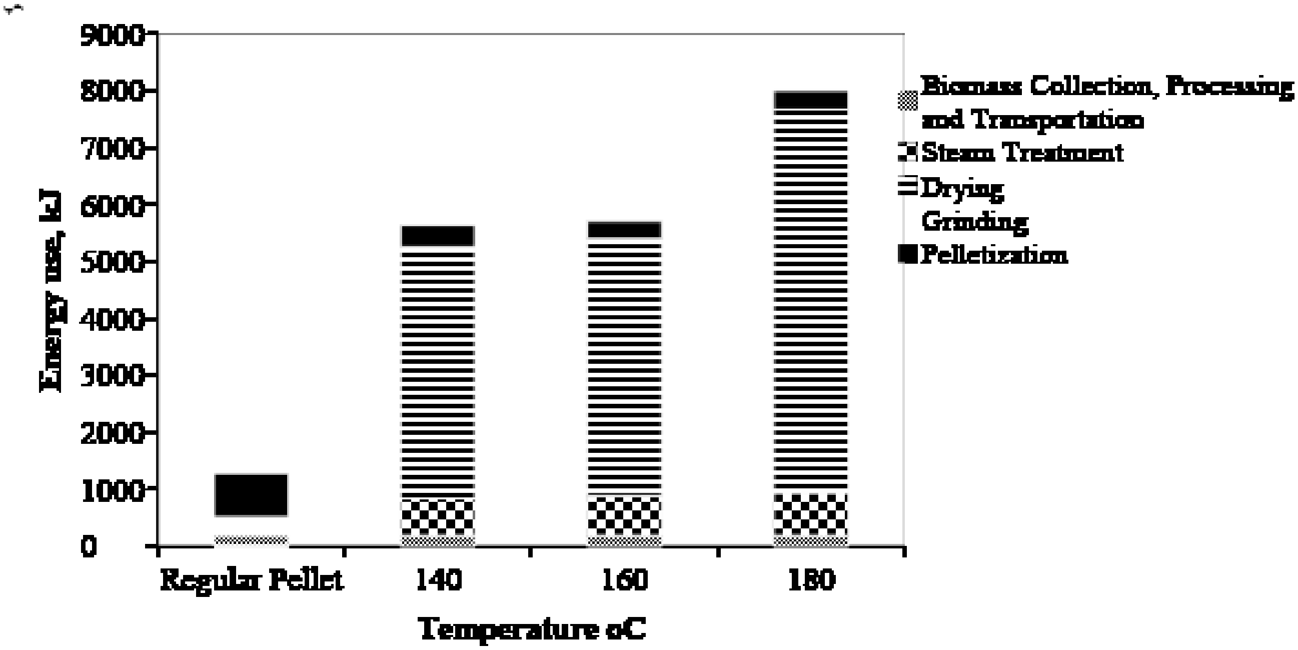
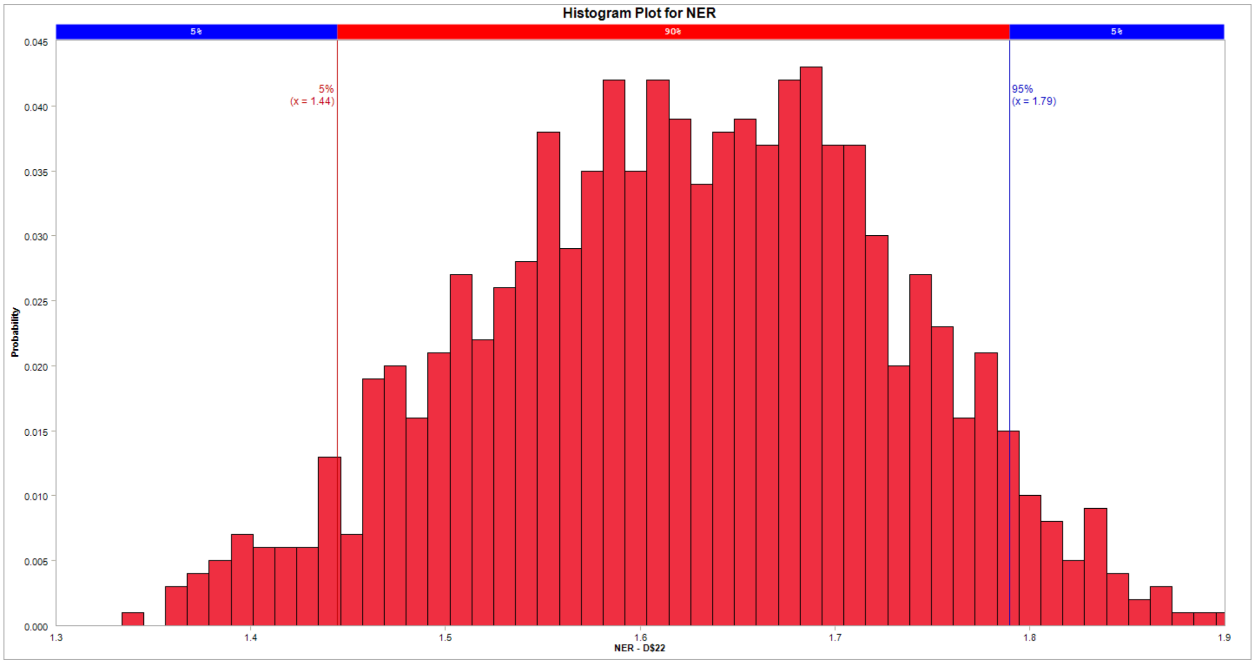


Fig. 5: Comparison of net energy ratios for (a) switchgrass (b) wheat straw at large scale case

(a). Wheat straw



(b). Switchgrass

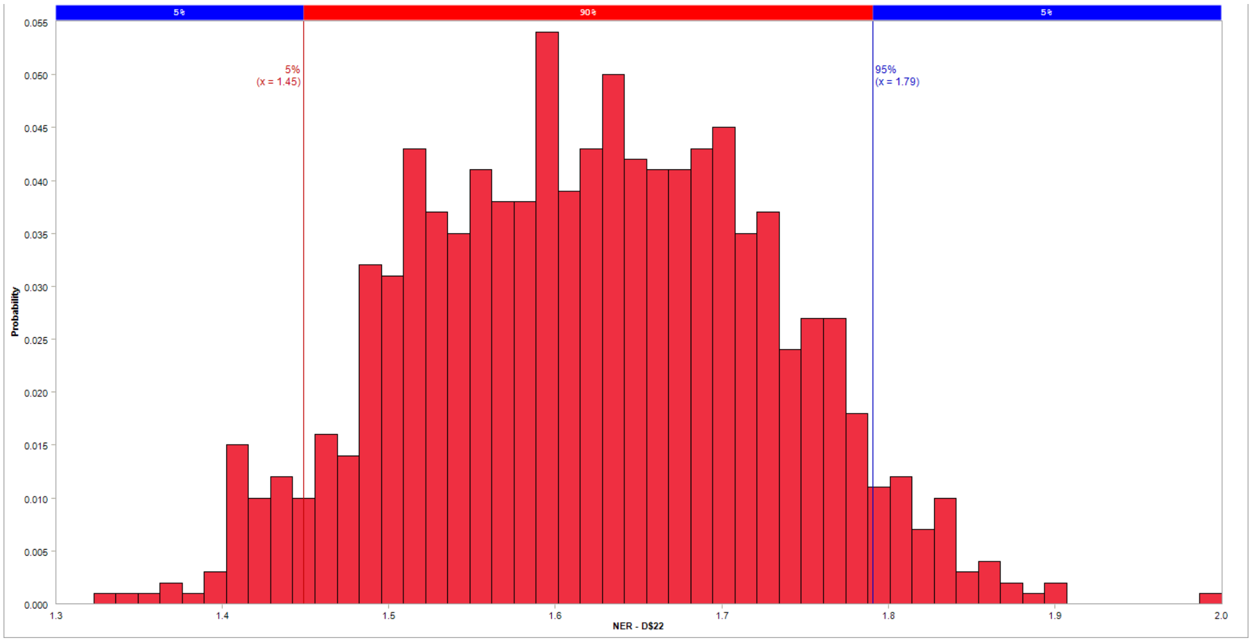


Fig. 6: Model uncertainty analysis of (a) steam pretreated wheat straw pellet NER and (b) steam pretreated switchgrass pellet NER