Biomass pre-treatment for bioenergy

Case study 4: The steam explosion process technology

The Thunder Bay power station where steam exploded pellets of Ontario Power Generation where steam exploded pellets are burned.

IEA Bioenergy

InterTask project on Fuel pretreatment of biomass residues in the supply chain for thermal conversion

Biomass pre-treatment for bioenergy

Case study 4: The steam explosion process technology

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Abstract

Biomass is a renewable source of carbon and energy that can substitute fossil fuels such as coal, petroleum and natural gas. As demand for biomass increases, it becomes important to diversify the resource base to lower grades of biomass, reducing costs and increasing fuel flexibility of various conversion technologies.

This case study is concerned with the upgrade of low-grade biomass feedstocks through steam explosion followed by densification to produce a fuel pellet. By comparing the current state of technology with conventional wood pellet production the economic potential is examined. Based on an actual user case, consultation with users and consultation with a producer, the properties and opportunities of steam explosion pellets are further explored.

From the case study, it can be concluded that the steam explosion technology:

- Is a technology that is known from other applications in the past
- Works in a batch-wise configuration, as per current state-of-the-art
- In a batch-wise configuration the reactor technology and process control are relatively simple
- Requires size reduction and drying before the biomass is fed in the steam explosion vessel
- At present has only few developers with operational producing plants
- Needs to be proven at scale for non-woody biomass types.

The steam exploded product:

- Can be stored outdoors for a longer duration with no significant impact on mechanical durability
- Requires measures for dust prevention
- Has a calorific value slightly higher than that of wood pellets but below that of torrefied pellets

The calculations presented in this report show that the production costs of steam explosion pellets are higher than those of wood pellets. This requires specific applications for the steam explosion pellets, such as peaking power plants where outdoor storage is permitted and the cost differentiation between wood pellets and steam explosion pellets can be balanced, e.g. by savings on handling equipment.

Table of contents

1 Introduction

Biomass is a renewable source of carbon and energy that can substitute fossil fuels such as coal, petroleum and natural gas. As demand for biomass increases, it becomes important to diversify the resource base to lower grades of biomass, reducing costs and increasing fuel flexibility of various conversion technologies.

Biomass materials are composed of three major components: cellulose, hemicellulose and lignin. These are tightly packed together and form fibre bundles which give biomass its strength and resist chemical and enzymatic degradation (Stelte, 2013). Biomass materials typically have high moisture content, low bulk density, low ash melting temperature, generate coarser particles after grinding steps and contain undesirable components such as nitrogen, alkali, chlorine or heavy metals. The low-grade biomass feedstocks when utilized as fuels may pose operational problems in feeding or converting the biomass to a useful energy carrier (heat, electricity, gaseous or liquid biofuel). Fuel pre-treatment through additives, leaching or thermal pre-treatment may provide an attractive approach to enable the use of these low-grade biomass feedstocks as a fuel.

This case study is concerned with the upgrade of low-grade biomass feedstocks through steam explosion followed by densification to produce a fuel pellet. Steam explosion has shown to be a valuable pre-treatment technology to open up the biomass fibers, improve the recovery of sugars, increase the calorific value and improve pelletizing properties of the biomass (Stelte, 2013). As a result, steam explosion can lead to expansion of biomass resources which is currently not utilized or under-utilized. Efficiency improvement in biomass utilization in terms of financial and carbon economics, can lead to new end-use applications which are currently excluded.

Numerous coal fired power plants worldwide have been converted to fire or co-fire sustainable biofuels such as wood pellets. Such conversions can be very costly due to the differences in the properties of pelletized wood and coal. Much of the conversion costs are related to new equipment for storage and handling, and modifications to the existing pulverisers and burners. Steam exploded pellets that have higher density and energy content (compared to conventional pellets) with enhanced storage and handling properties (less dust, mechanically durable) may prove to be a valuable part of the future global sustainable energy supply chain (Graham, et al., 2016).

Woody biomass has been and continues to be the major source of feedstock for pellet production. The steam explosion process may expand the resource base to other biomass residues, such as agricultural residues. Agricultural residues typically contain high ash and alkali metals, as well as high chlorine which present challenges in boiler operations. It has been shown in lab scale studies that steam explosion leads to reduction in ash content in biomass (Biswas, Yeang, & Blasiak, 2011).

2 The steam explosion process

2.1 DEFINITION

The steam explosion process is heating and pressurization of lignocellulosic material by direct contact with steam followed by a sudden decompression. Process conditions can be up to several minutes of residence time, typically under 1 to 3 MPa pressure and approximately 190 - 230 °C temperature range. Steam explosion causes biomass properties change from a tenacious flexible material towards a brittle rigid material, similar to coal (Stelte, 2013).

2.2 HISTORICAL DEVELOPMENTS

The steam explosion process has been used commercially in the 1950s as a means of preparing waste wood for hardboard manufacture (Baird & Schwartz, 1952). In 1980s and 1990s the process has also been employed as a means of pre-treating lignocellulosic materials to allow for their digestion by ruminant livestock (Schultz, Blermann, & McGlnnis, 1983) or to produce wood sugars by enzymatic hydrolysis. More recently, it has been investigated as an alternative to thermal mechanical pulping (Kokta & Ahmed, 1998). Currently, the viability of the steam explosion as a pre-treatment technology for producing advanced solid fuels is being investigated (Priyanto 2017; Tang 2018; Lam 2012), primarily as an alternative to wood pellets in thermal energy plants. For the various applications, different process conditions have been applied. A summary of process conditions employed in various applications is presented in Table 2-1.

Table 2-1 Summary of steam explosion process conditions employed in different applications

Process	**Pressure (Bar)**	**Temp (°C)**	**Time (min.)**	**Additives**	**Source**
Masonite Hardboard	Up to 68	Up to 290		None	(Baird & Schwartz, 1952)
Fibre board	9-28	191-226	1-3	H_2SO_4	(Angles, Ferrando, Farriol, & Salvado, (2001))
Pulping	10-18	180-210	3-4	None, $NaSO_4$, $NaSO_4$ + NaOH, NaS	(Kokta & Ahmed, 1998) (Zimbardi, Ricci, & Braccio, 2002)
Enzymatic Hydrolysis	10 to >60	160-280	0.05-10	None, H_2SO_4, SO_2	(United States of America Patent No. US 8017820 B2, 2011) (KAAR, GUTIERREZ, & KINOSHITA, 1998) (Zimbardi, et al., 2007) (SHEVCHENKO, BEATSON, & SADDLER, 1999) (Ruiz, Cara, Manzanares, Ballesteros, & Castro, 2008)
Advanced Solid Fuel	Up to 45	Up to 320	7.5	Air, Oxygen, or oxidants e.g. H_2O_2	(World Patent No. WO2014122163 A1, 2014)
Advanced Solid Fuel	Up to 60	180-275	1-12	Fatty acid, ester or triglyceride	(world Patent No. WO 2011156515 A3, 2012)
Advanced Solid	16, 24	200, 220	5,10	None	(Lam, Sokhansanj, Bi, Lim,

Fuel					& Melin, Energy Input and Quality of Pellets Made from Steam-Explode Douglas Fir (Pseudotsuga menziesii), 2011)

2.3 THE PROCESS FOR PRODUCING ENERGY PELLETS

The process for producing energy pellets depends on the raw feedstock type. For low-grade residues, first sand and rocky debris are removed. Then the biomass is shredded and (pre) drying may be required before it is fed into a steam explosion reactor. The biomass particles will need to be as uniform as possible.

The reactor is pressurized and the material resides in the reactor until the reactor is suddenly depressurized. For a batch-type installation, multiple reactors are applied in parallel. The steam explosion itself has been extensively tested on labscale using batch reactors.

A typical state-of-the-art layout for a number of batch-type reactors is shown in Figure 2-1.

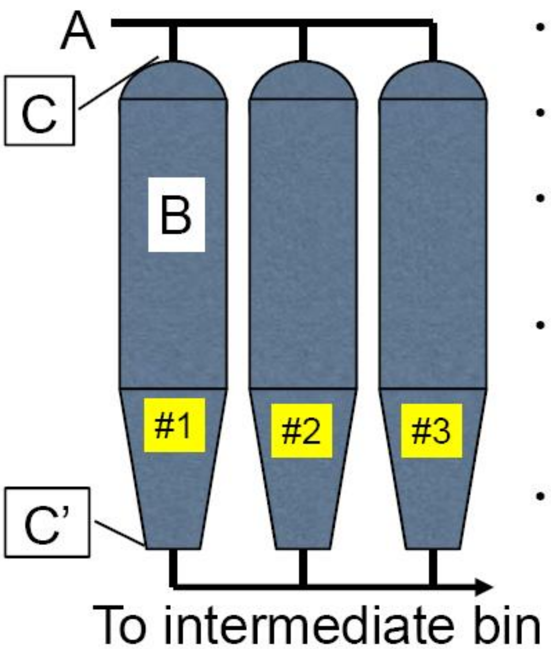

Figure 2-1 Configuration of steam explosion reactors that has been employed by Zilkha (A: feed for steam explosion, B active reactor; C, C' valves in order to put pressure on reactor) (Weick, 2011)

Once the biomass is discharged from the reactor, drying is typically required to reduce the moisture content to a level that meets densifying requirements. As wood pellets have a standardized geometry, it is currently the state-of-the-art that the steam explosion pellets have a similar geometry.

Figure 2-2 simplified steam explosion process by Zilkha.

2.4 PRODUCERS

Two well-known developers of the technology are Arbaflame and Zilkha. Below is a brief description of their commercial development.

2.4.1 Arbaflame

Arbaflame has been producing steam explosion pellets in Norway since 2003. The pellets are produced at the Grasmo plant in Norway. The plant has a capacity of 6 t/h. Biomass sawdust is pre-dried and then enters the steam explosion reactor in which it undergoes the steam explosion process. Hammermilling after the steam explosion process is not required. After it leaves the steam explosion reactor it is post-dried and then pelletized (Knappskog). Arbaflame has most experience with biomass from local suppliers (spruce and pine).

The total accumulated production amounts 130 000 tonnes. The pellets are sold under the name of Arbacore. Arbaflame also licences its technology to external partners as Arbakit and is planning to build a full scale 200 ktonnes per year plant. Several other projects in Europe, United States and the Pacific area are in different stages of development and amount to a total production capacity of 1 700 ktonne per year (Knappskog). Most of these projects are still in the early development stages. Arbaflame mentions that it can apply a co-funding business model as well as a licensing business model.

The Arbacore pellets have been tested in several large coal fired plants in Europe, and in total tested at 14 utilities (personal communications). The pellets have further been applied in a full conversion configuration in Ontario Power Generation's Thunder Bay Station in Ontario, Canada for the past three years.

2.4.2 Zilkha

Zilkha is located in the US and has developed the steam explosion process since 2004 (Zilkha). Zilkha has started operations of a production plant in Selma in 2015. It overhauled the existing Dixie Pellet plant and included three batch-type steam explosion reactors, providing the facility with a nameplate production capacity of 275 kton/year. Zilkha sells its pellets under the name of Zilkha Black® pellets. The process has used sawdust, chips, shavings, tree-tops, limbs and thinnings from sawmills and sustainably managed forests.

The Zilkha black pellets have been transported to Europe for co-firing in several plants. Zilkha also licences the technology.

2.5 PRODUCT SPECIFICATIONS

The steam explosion process changes the properties of biomass by opening up the fiber structure and releasing individual components of lignin, cellulose and hemicellulose. Degradation of hemicellulose leads to brittleness (better grindability) and rigidness. The removal of OH groups results in a more hydrophobic surface. Improved grindability and higher moisture resistance are put forward in support of steam explosion for the production of fuel pellets to substitute fossil fuels in heat and power plants (Stelte, 2013). Table 2-2 summarizes key fuel properties of steam exploded wood pellets (Shalini, Eastwick, Snape, & Quick, 2017).

Table 2-2 Average properties of steam exploded wood pellets

Property	Value
Lower Calorific value (LHV)	17 - 19 MJ/kg
Moisture Content	2 – 4 % wet basis
Volatile content	70 – 80 % dry basis
Bulk density	650 - 780 kg/m3

An overview of the most important advantages and disadvantages that relate to the mechanical and chemical properties of the steam explosion pellets are given in Table 2-3.

Table 2-3 Improvements and drawbacks of the biomass fuel product resulting from the steam explosion process

Aspect	Improvements	Drawbacks
Combustion properties	lower equilibrium of moisture with ambient air keeps lower moisture content of pellets prior to burning (Lam, Steam explosion of biomass to produce durable wood pellets, 2011)	less pores resulting in less surface area available for combustion (Biswas, Yeang, & Blasiak, 2011)
Milling properties	improved milling properties compared to wood pellets (Lam, Steam explosion of biomass to produce durable wood pellets, 2011).	-
Handling & Storage properties	enhanced hydrophobicity - making outside storage possible and reducing the risk on overheating and fire in the biomass pile (Arbaflame, 2015). Mechanically durable – retains shape, compactness and density.	High potential for microbial activity due to C5 sugars; more data / analysis needed on biological activity of steam exploded pellets

3 Supply chain analysis

Steam explosion as a pre-treatment process for fuel production is a relatively recent development and data from supply chain perspective is rather sparse. For the purpose of this report, a preliminary techno-economic model developed by CanmetENERGY was used to perform the supply chain assessment.

3.1 METHODOLOGY

In order to facilitate the analysis of a supply chain based on steam explosion, conventional wood pellet production is compared to pellet production integrated with steam explosion, schematic process diagrams used in the analysis are presented in Figure 3-1.

3.2 BOUNDARY DEFINITION

Conventional pellet plants should be quite similar to pellet plants producing steam explosion pellets. In both cases the plants must receive and store biomass at the front end of the plant and store and ship pellets at the back end of the plant. The plant operations which are most likely to be affected by the inclusion of steam explosion are biomass drying, grinding, pelletization and steam generation. These processes have been isolated and compared for the production of conventional and steam exploded wood pellets (Figure 3-1).

The scale of the steam explosion pellet plant is based on a steam explosion process utilizing three 11 m^3 steam explosion vessels processing 680 kg of biomass with a moisture content of 35 wt. % (d.b.) on a 10-minute cycle operating 24 h per day and 365 days per year.

The reactor vessel pressure was assumed to be 22 bar gauge this pressure was from the description in the arbaflame patent (World Patentnr. WO 2014122163 A1, 2014). 22 bar gauge is the saturation temperature of the steam used in the process, but the steam in the vessel is not saturated due to the presence of air and other non-condensable gases in the reaction mixture. These assumptions yield plants which convert 79 424 metric tonnes/annum of dry biomass to pellets. The steam exploded pellet plant was compared to a conventional pellets plant consuming the same quantity of biomass. The feed is assumed to be Norway Spruce with an average particle size of 40 mm and a moisture content of 35 wt. % d.b. and a higher heating value of 18.8 MJ/kg on a dry basis (Table 3-1).

Table 3-1 Fuel properties of biomass that are used in the preliminary TEA

Property	Value
Biomass Feedstock	Norway Spruce
Average particle size (mm)	40
Moisture content (wt.% d.b.)	35
HHV (MJ/kg dry)	18.8

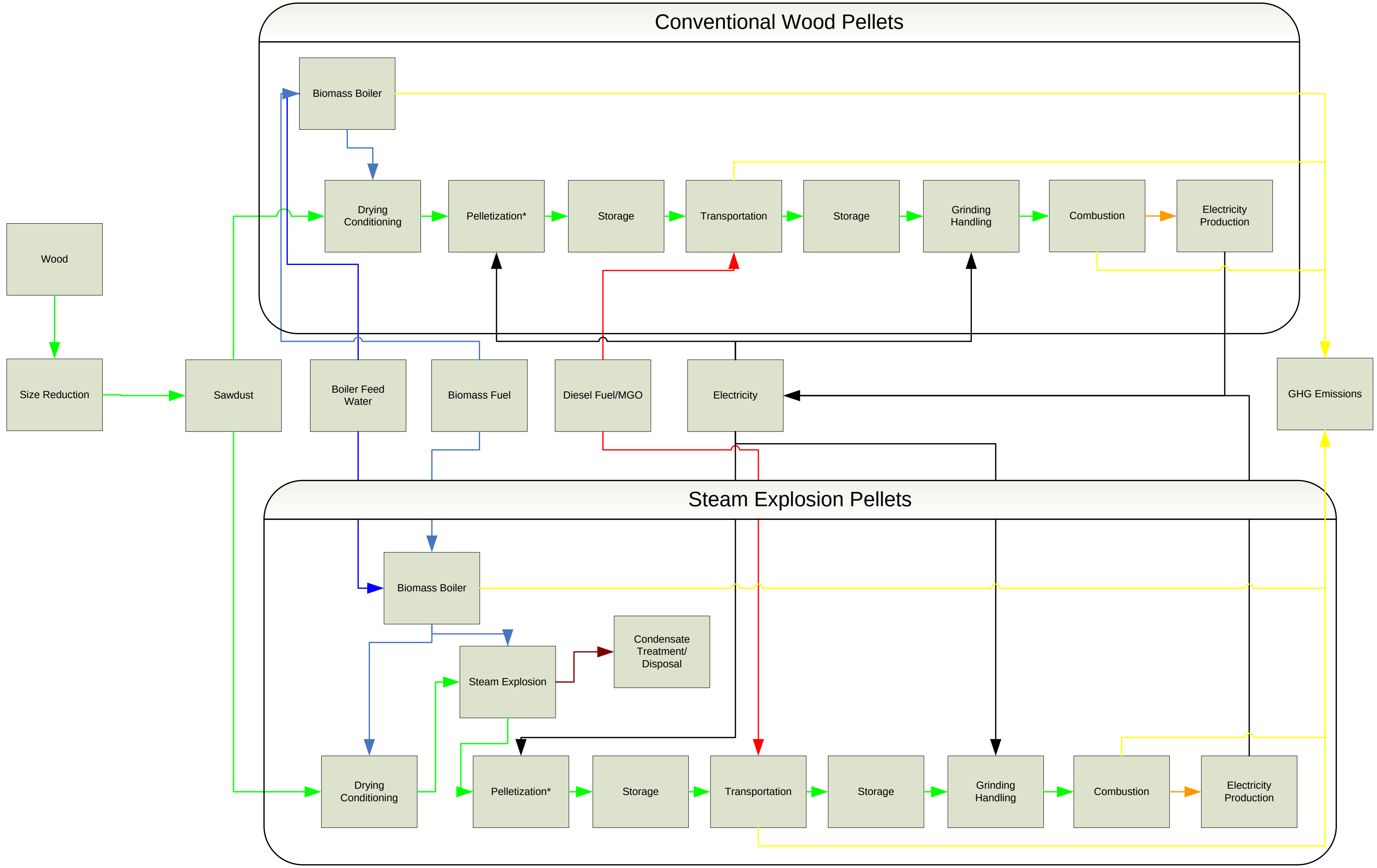

Figure 3-1 Schematic process diagram for conventional wood pellet production (reference case) and steam exploded pellet production

The process for making steam exploded pellets has been assumed to include the steam explosion vessels and cyclone separator, a direct fired rotary kiln dryer, a hammer mill and a pelletizer as well as a natural gas boiler for the production of steam (Figure 3-1). The conventional pellets plant is similar except that it lacks the steam explosion vessels and cyclone separator. A functioning pellet plant would have other equipment related to the storage and packaging of the pellets. These have been left aside since their cost is not likely to be influenced by the type of pellets produced. Although depending on the properties of the steam explosion pellets there may be opportunities to achieve savings in the storage of the pellets.

The yield from the steam explosion process is assumed to be 97 % of the dry biomass fed to the process. The assumed yield of 97 % may be quite generous, though it has been used in a previous study (Shahrukh, et al., 2015). Others have obtained yields as low as 79 % (Lam, Steam explosion of biomass to produce durable wood pellets, 2011). Given the high assumed yield from the steam explosion process, modest increase in higher heating value from 18.8 to 19.2 has been assumed. The yields from the drying, grinding and pelletization processes are assumed to be 100 %. Another simplification assumed that both the grinding and the pelletization steps do not reduce moisture content.

3.3 RESULTS

Mass and energy flows on a 1 kg dry feed basis are described in detail in Appendix X. The simplified yield assumptions result in a conventional pellets plant annual production capacity of 87 366 tonnes and a steam exploded pellet plant production capacity of 84 745 tonnes with a moisture content of 10 wt. % d.b. While there is a slight difference in the mass of pellets produced the slight gain in higher heating value of the steam exploded pellets offsets the loss of mass. The conventional plant produces 14.9 million and the steam exploded plant produces 14.8 million GJ/a of pellet higher heating value.

Table 3-2 Steam, Natural Gas, and Electricity requirements for the conventional and steam explosion processes (per kg dry biomass fuel)

	Steam (kg/s)		**Natural Gas (kW)**		**Electricity (kW)**	
	Conventional	Steam Exploded	Conventional	Steam Exploded	Conventional	Steam Exploded
Boiler	-	-	338	3 823	-	-
Steam Explosion	-	1.04	-	-	-	-
Drying	-	-	1 732	1 843	-	-
Grinding	-	-	-	-	266	60
Pelletization	0.11	0.11	-	-	138	269
Total	0.11	1.15	2 070	5 666	404	329

The only steam used in the conventional pelletization process is the steam used for conditioning the biomass prior to pelletization. Production of the conventional wood pellets utilizes 0.04 kg of steam per kg of material fed to the pelletizer (Thek & Obernberger, 2004) and the steam exploded pellets is assumed to consume the same amount of steam. The steam explosion reactors are assumed to consume 280 kg of steam per cycle. Both processes consume natural gas for the drying and for the generation of steam. For simplicity boilers and dryers were assumed to operate at 80 % thermal efficiency. Biomass could be used instead of natural gas. One study showed that the use of wet sawdust or coal for drying could reduce the cost of pellet production (Mani, Sokhansanj, Bi, & Turhollow, 2006). This already indicates that potential savings can be achieved, depending on regional prices of natural gas and biomass.

It should be noted that this TEA analysis do not include the costs of the emissions control equipment (Mani, Sokhansanj, Bi, & Turhollow, 2006) and assumed a natural gas price of US$ 10 per GJ. At the time of writing this report, natural gas prices, without adjusting for inflation, are, less than one third of this price. Both processes would consume some electricity to drive the rotary kilns. This has not been accounted for since it is not related to the nature of the materials being dried in the kilns. Steam exploded material has been found to be easier to grind and more difficult to pelletize than wood. Accordingly, larger quantity of electricity consumption is assigned to conventional pellet plant than the steam exploded pellet plant. In this case the particular assumptions was made where the energy required to grind the wood for conventional pellets more than compensates for the increased difficulty of pelletizing the steam exploded material. It should be noted that changes to these assumptions could result in reverse of the result.

The energy related to steam consumption is the greatest difference between the conventional and steam exploded pellet production processes: steam explosion process is assumed to consume nearly three times as much natural gas as conventional pellets. Given the variance and volatility in natural gas prices across the globe, this could have a significant impact on the annual operational cost of a plant.

Details on Capital Costs of major equipment for Steam Exploded and Conventional Pellets are presented in appendix Y. Table 3-3 compares installed capital costs of major equipment for both conventional and steam exploded pellet plants.

Table 3-3 Installed capital costs major equipment 1000s US$ (normalised to 2016)

Equipment	Conventional	Steam Exploded
Boiler	60	286
Steam explosion Vessels (3)	0	510
Cyclone	0	27
Dryer	429	463
Hammermill	437	202
Pelletizer	572	863
Total	1 498	2 351

The total installed capital costs associated with the drying, milling and pelletization, of the conventional pellets was found to be US$ 1 498 000 (2016). For the same unit operations, the capital costs of the steam exploded plant were calculated US$ 2 351 000 (2016) or 57 % greater than the conventional plant. It should be noted that when the entirety of a pellet plant is considered the relative cost difference fades.

Table 3-4 Conventional pellet plant capital cost estimates available in literature

Nameplate Plant capacity (tonnes/a)	Normalised Capital Cost for the Installed Plant (2016 US$)	2016 US$/ tonne/a	Estimated Capital Cost for a 79 kt/y (dry basis) pellet plant (US$)	Source
9 800	2 192 568	224	17 674 784	(Hunsberger & Mosey, 2014)
50 000	11 690 267	234	18 470 622	(FutureMetrics LLC, 2012)
52 560	2 930 399	56	4 404 518	(Dehkordi, 2015)
175 200	17 194 595	98	7 753 270	(Mobini, Sowlati, & Sokhansanj, 2013)
24 000	2 847 777	119	9 373 932	(Thek & Obernberger, 2004)
175 200	21 858 043	125	9 856 081	(Mobini, Sowlati, & Sokhansanj, 2013)
52 560	2 669 598	51	4 012 523	(Mani, Sokhansanj, Bi, & Turhollow, 2006)
75 000	13 794 363	184	14 530 063	(Piraglia, Gonzalez, & Saloni, 2010)
1	111	111	8 737 767	(Deloitte & Touche LLP and affiliated entities, 2008)
1	166	166	13 106 650	(Deloitte & Touche LLP and affiliated entities, 2008)
30 000	3 040 111	101	8 005 627	(BW McCloy & Associates Inc., 2009)
100 000	7 822 556	78	6 179 820	(Nunes, Matias, & Catalão, 2014)
100 000	4 582 144	46	3 619 894	(Hoque, et al., 2006)

A range of conventional pellet plant cost estimates were gathered. The capital costs in these estimates ranged from US$ 46-234 (normalised to 2016) per tonne of annual capacity. This would suggest that a conventional pellet plant producing 79,000 tonnes per year of pellets (dry basis) would have a capital cost between US$ 3 620 000 and 18 471 000 (2016). When the entire capital cost of a plant is considered the extra cost capital costs associated with steam explosion fall to between 5 and 24%.

Variations in the capital costs tend to be related to the nature of the material delivered to the plant, storage facilities, and product packaging facilities. A plant which processes whole trees will require large shredding units while a plant which processes sawdust may not require any grinding equipment. A plant which is intended to serve residential fuel market will require equipment for the packaging and palletization of pellets and even larger warehouse to store bagged pellets. Such equipment would not be required if the plant serves the bulk market. The lowest capital cost estimate is from a source which considers the pelletisation of sawdust.

Compared to conventional pellet plants the steam explosion process requires substantially more thermal energy and a plant with a higher capital cost than conventional pellet production. These costs would have to be justified by gains made in other parts of the value chain. Steam exploded pellets have a higher density than conventional wood pellets. This leads to reduced energy consumption and reduced costs in the transportation of steam exploded materials. Such gains are likely to be minor as are gains associated with the milling of pellets for use in pulverized coal burners. To justify the extra expense of producing steam exploded pellets it is probable that the steam exploded pellets would have to be capable of withstanding outdoor storage in a coal yard. Section 4.2 shows that there are positive experiences with outdoor storage.

4 Opportunities in the supply chain

4.1 GENERAL PERSPECTIVES

4.1.1 Cost perspectives

The TEA in the previous chapter shows that from a cost perspective, at the power plant gate, the steam explosion pellets are unlikely able to compete with wood pellets. This requires specific applications, such as peaking power plants where outdoor storage is permitted and the cost differentiation between wood pellets and steam explosion pellets can be balanced, e.g. by savings on handling equipment.

4.1.2 Logistics and trade

Currently ISO/Technical Standard 17225-8:2016 determines the fuel quality classes and specifications of graded densified solid biofuels produced from thermally treated biomass for non-industrial and industrial use. The technical standard covers pellets and briquettes, and includes materials produced by e.g. the torrefaction process or steam explosion process.

4.1.3 Feedstock flexibility

The current steam explosion feedstock is woody materials such as sawdust. The resulting product is of a consistent quality, suitable for combustion. This opens up possibilities to work with other industries to improve synergies in the industry by for instance using residual materials from a saw mill.

Several research organizations investigate the influence of steam explosion process (for example ENEA (Avella, 1998)) on the properties of treated biomass and on pellet production (Lam et al., 2011a; Biswas, 2011; Tumuluru, 2011; Lam, 2011b). The large variety in origin and composition of biomass is reflected in the different kind of trees and plants used in these studies. Lam has used Douglas fir, while Biswas investigated willow. Nevertheless these studies show important similarities with respect to the properties of treated biomass.

4.1.4 Ash

A potentially important benefit of the steam explosion process is the potential washing of the biomass, and the resulting content of alkalis in the ash (Biswas, Yeang, & Blasiak, 2011; Stelte, 2013). Although the ash content of biomass is generally much lower than for coal, the availability of alkalis (Na, K) in the ash, in combination with Cl results in KCl or NaCl and may induce increased slagging, fouling and corrosion.

4.2 AN EXAMPLE OF FIRING STEAM EXPLODED PELLETS

A typical case for the use of steam explosion pellets is presented below. This is referred to as the Ontario Power Generation (OPG) case.

4.2.1 Background

In April 2014, the province of Ontario stopped using coal in coal-fired thermal generating stations for electricity. As a result, Atikokan Generating Station was converted to wood pellets and the Thunder bay plant was converted to second generation biomass. The steam explosion wood pellets were considered for their main characteristics:

- Good pellet durability
- Increased heating value

- Water resistant
- Improved grindability

OPG evaluated the topics as safety, handling, storage and unit performance to ensure the proper operation of the Thunder Bay plant.

4.2.2 Safety

As biomass has a high volatile matter, and preferably a low moisture content, the risk of fire and explosion increases significantly. To ensure safe handling of the biomass, control of dust generation and ignitions is critical. For these reasons, the pellets were directly tested on:

- fire and explosivity
- Dust generation and control
- Electrostatic discharge

The explosion test results are noted in *Table 4-1 Explosion and fire testing results*Table 4-1. From this table, it can be concluded that the explosion and fire related characteristics are comparable to coal with the significant exception of the minimum ignition energy and ignition sensitivity. This highlights the need to control sources of ignition.

Table 4-1 Explosion and fire testing results

Parameter	Arbaflame Pellets	PRB Coal
Maximum Explosion pressure (P_{max}), Bar	7.6	7.5
Maximum Rate of Pressure Rise (- $(dP/dt)_{max}$	487	684
K_{st}, bar -m/s	132	186
Minimum Ignition Energy (MIE), MJ	12	79
Minimum Explosive Concentration (MEC), g/m^3	84	44
Minimum Ignition Temperature of a Dust Cloud (MIT), °C	400	420
Explosion Severity (ES)	0.98	1.3
Ignition Sensitivity (IS)	8.66	4.0

In order to evaluate the dust generation during handling, tumble tests were conducted for 48 hours. The amount of dust generated was comparable with that of PRB coal. The generated dust had a relative large particle size (1-3 mm). The suppression of dust was tested using the walker wetting test. The results show that the agents used for wetting coal show a similar performance with the steam exploded pellets, with wetting times up to 6 seconds.

The electrostatic discharge can be an ignition source and is therefore tested according to the standard method for DC resistance or Conductance of Insulating Materials. The results are noted in Table 4-2 and show that the pellets remain below the threshold resistivity of 10^{10} Ω-m.

Table 4-2 Electrostatic discharge test for steam exploded pellets

Parameter	15% RH	55% RH
Volume resistivity (Ω-m)	2.14×10^{13}	5.34×10^{9}
Measured decay time (s)	1453	1.45

4.2.3 Handling

To control the sources of ignition for the steam exploded pellets changes were made to the coal handling system: extra moisture application stations in combination with humidity control were installed, the fuel flow was throttled via a slide gate and additional grounding was applied on the dust collectors.

During a test period, the dust suppression system appeared very effective. The dust collectors had collected a minimal amount of dust; personal breathing zone samples were well below OEL and the airborne dust concentrations in the galleries were well below the coal numbers.

To create a proper combustion performance, the pellets need to be milled. OPG tested the steam exploded pellets on a pilot milling system. From this it could be concluded that the milling was possible in existing systems, but the power requirements was 2 times higher than for coal.

4.2.4 Storage

The pellets are stored outside for prolonged times as the plant is not operational all the time. This requires that the pellets are durable and retain their shape and sturdiness. For that, the weatherability test was executed by soaking the pellets for a prolonged time. The results are given in Figure 4-1. The results show that due to the hydrophobic character of the steam exploded pellets, the durability is maintained. This is also reflected on the comparison made between the steam exploded pellets and torrefied pellets in Figure 4-2.

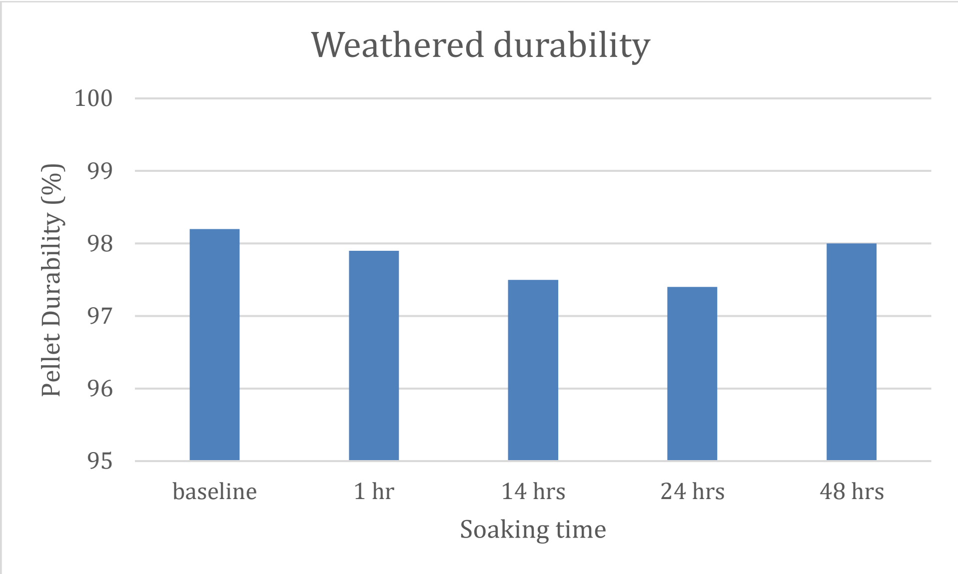

Figure 4-1 Weathered durability graph

Figure 4-2 Steam explosion pellets (l) and torrefied pellets (r) after weathering

4.2.5 Unit performance

To evaluate the performance of the plant, the plant was run on 100% steam explosion pellets. The previous results of the handling and storage tests were in agreement with the full-scale observations, maintaining low dust circumstances during handling and high durability of the pellets for storage.

In addition, the observations on combustion performance was that the generated steam temperatures were similar to coal performance, and the fire was stable. Emission rates of the steam exploded pellets were similar for NO_x and significantly lower for SO_2.

4.2.6 Investment costs

OPG evaluated all plant systems, from the fuel yard to the stack. Process/equipment modifications were made where necessary to improve safety and performance (Marshall, IEA 2016). The costs for these modifications were around CAN$ 5 million. This is typically a factor of 20-40 lower than for conversion of a coal generating station to wood pellets. For example, the conversion of

Atikokan power station to wood pellets was around CAN$ 170 million.

The Thunder Bay unit is still capable of firing 100% biomass through the normal operating range (40-160 MWe). This means that the specific cost is around 30 CAN$/kWe.

The total project duration was around 7 months and included the construction outage of less than 3 months (Marshall, IEA, 2016).

4.3 ONGOING RESEARCH AND FUTURE PROSPECTS

Research on the steam explosion process is wide, with around 1700 publications (Elsevier Science Direct) in the period 2014-2017 and 130 in 2018 (beginning of February). Around 430 of these publications relate to pretreatment, ethanol production, fermentation, and enzymatic hydrolysis.

Current research on pretreatment of biomass by the steam explosion process for producing a solid fuel has been covered in chapters 1 and 2. Recent research on the topic has been performed by various researchers (Dehkordi, 2015), (Graham, et al., 2016), (Lam, Steam explosion of biomass to produce durable wood pellets, 2011), (Shahrukh, et al., 2015), (Shalini, Eastwick, Snape, & Quick, 2017), (Stelte, 2013).

The steam explosion technology is also used to pretreat herbaceous feedstock, to obtain higher biogas yields in a fermentation process. Recent research was for example performed for coffee husks (Bruno Eduardo Lobo Baêta, 2017), corn stover (Javier Lizasoain, 2017), rice straw (Shukra Raj Paudel, 2017), (J. Zhou, 2016). For example, Lizasoain showed that mild pretreatment conditions are most effective and can result in an improved methane yield of 22% (Javier Lizasoain, 2017). Paudel mentions that larger amounts of lignocelluloses requires a harsher pretreatment such as alkali, thermal, and thermochemical methods. However, these methods can produce negative impacts on an aerobic digestion if not properly implemented (Shukra Raj Paudel, 2017). It needs to be taken into account, that inhibitors formation as by-product of steam explosion method is one major challenge that may disturb the microbial activity on the subsequent production stage (H.B. Aditiya, 2016).

Research is also performed on the effect of the steam explosion process on the coupled ethanol and methane generation (Franz Theuretzbacher, 2015), (Viktoria Leitner, 2016). Theuretzbacher shows that the steam explosion process is favorable for the total yield (biogas in combination with bioethanol) and that the share of ethanol at 220ºC is higher than that at 200ºC process temperature. Leitner found that the optimal process configuration consists of direct biogas production from steam explosion pretreated straw at 170ºC for 20 min combined with bioethanol production from straw pretreated at 200ºC for 20 min.

It can be concluded that the steam explosion process results generally in increased gas or ethanol yields for lignocellulosic biomass types. The temperature of the steam explosion pretreatment has a significant positive impact on ethanol yields.

5 Conclusions

The steam explosion process technology:

- Is a technology that is known from other applications in the past
- Has a relatively simple reactor technology and process control
- Works in a batch-wise configuration, as per current state-of-the-art
- Requires size reduction and drying before the biomass is fed in the steam explosion vessel
- At present has only few developers with operational producing plants
- Needs to be proven at scale for non-woody biomass types.

The steam exploded product:

- Can be stored outdoors for a longer duration with no significant impact on mechanical durability
- Requires measures for dust and odour prevention
- Has a calorific value slightly higher than that of wood pellets but below that of torrefied pellets

Per the calculations presented in this report, the production costs of steam explosion pellets are higher than those of wood pellets. This requires specific applications, such as peaking power plants where outdoor storage is permitted and the cost differentiation between wood pellets and steam explosion pellets can be balanced, e.g. by savings on handling equipment.

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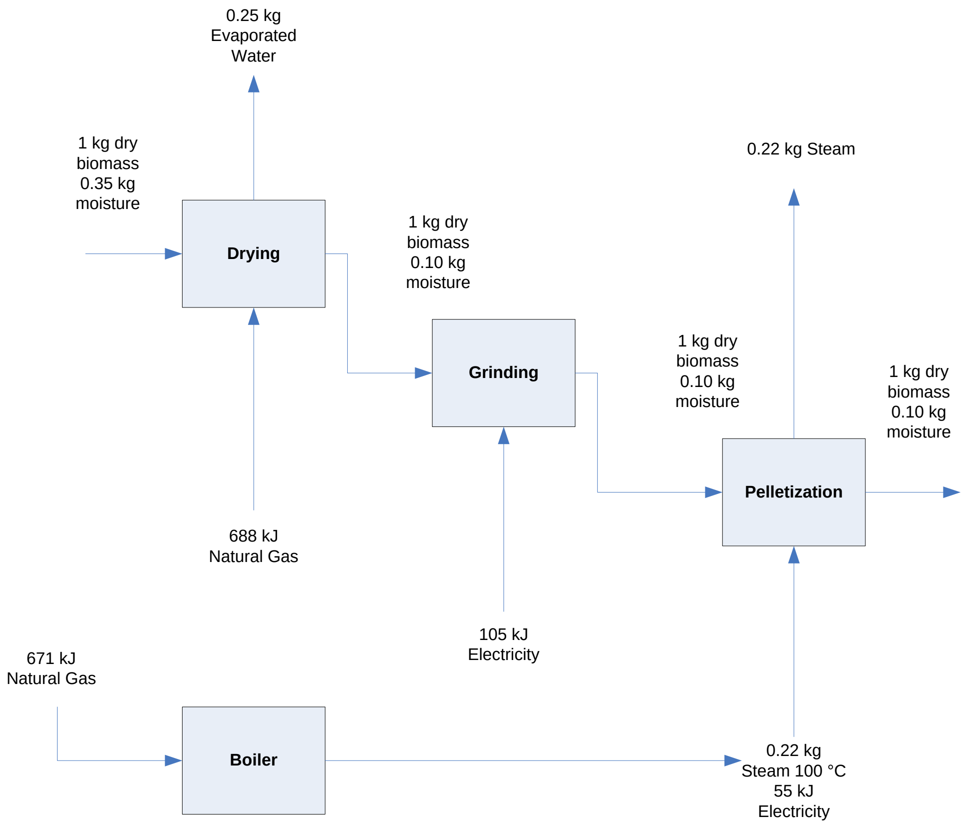
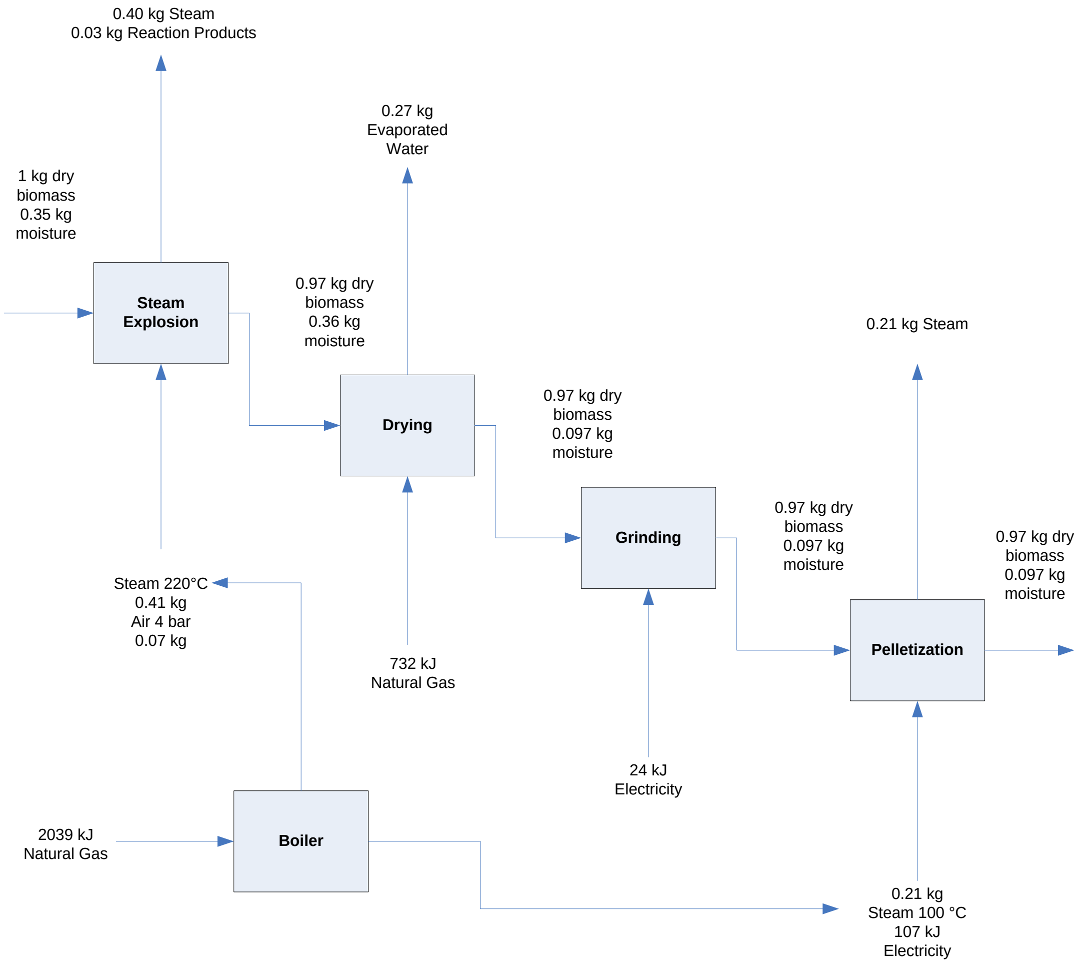
Appendices

X. MASS AND ENERGY BALANCES USED IN THE TECHNO-ECONOMIC ASSESSMENT





Y. CAPITAL COST ESTIMATES USED IN THE TECHNO-ECONOMIC ASSESSMENT

This appendix provides the capital costs of major equipment for steam exploded and conventional pellets.

Boiler

The boiler consumes natural gas and produces steam for the steam explosion reactors and for pellet conditioning. Information from a US DOE report was used to estimate the purchased capital costs of the boiler for the conventional and steam explosion pellet plants (Loh, Lyons, & White, 2002). The required capacities were less than the range of capacity covered by the DOE report. The capital cost of the steam explosion boiler was approximated using the rule of six-tenths. Boilers include forced draft fans, instruments, controls, burners, soot-blowers, deaerators, chemical injections systems, steam drums, mud drums and stacks (Loh, Lyons, & White, 2002). A factor of 2 was applied to the purchase costs of the boilers to account for the direct and indirect costs associated with their installation.

Steam explosion vessels and Cyclone

The steam explosions vessels are based on information from an ArbaFlame patent (World Patent No. WO 2014122163 A1, 2014). The cost module method originated by Guthrie, and modified by Ulrich, was used to estimate their installed costs of the steam explosion vessels and the cyclone (Turton, Bailie, Whiting, & Shaeiwitz, 2009). Vertical carbon steel vessels having a volume of 11 m3, and capable of withstanding operating at steam explosion pressure would have an installed cost of 170,000 (2016) USD. The plant would require 3 steam explosion vessels operating at 22 bar gauge. The same cost module method was used to estimate the installed costs of the cyclone required to separate the solid product from the steam explosion reactors. The cyclone was assumed to be a Lappel Conventional cyclone operating with an average inlet velocity of 25 m/s. This yielded a unit with a volume of 2.43 m3 and an installed cost of $27,000.

Dryer

For both cases the dryer is used to reduce the moisture content of the pelletizer feed to 10 wt.% d.b. The units are assumed to be rotary dryers directly fired with natural gas. The purchase costs for the dryers were estimated, from the amounts of water to be removed, using information contained in an NREL report (Amos, 1998). A factor of 1.25 was applied to the purchase cost of the dryers to account for direct and indirect costs associated with their installation.

Hammer mill

For both cases the hammermills are used to reduce the average particle size from 40 mm to 2mm. Kick's law was used to approximate the energy required for the hammer milling both materials (Shahrukh, et al., 2015). A Kick's law constant of 32 J/kg was assumed for grinding wood. It was assumed that milling of steam exploded biomass would require approximately one fifth the amount of energy as milling wood and a Kicks's law constant of 6.4 J/kg was assumed for estimating the energy required to mill steam exploded biomass. It is possible that an even smaller Kick's law constant could be used as one study found that the energy required to grind steam exploded forestry residue was only 8 % of the energy required to grind untreated forestry residue (Shahrukh, et al., 2015). The energy requirements were used to estimate its capital cost of the milling equipment for the two different cases. Information from California Pellet Mill (CPM) (California Pellet Mill, 2008) was used to estimate the purchased costs of the hammer mills including motors and air assists. A factor of 3.24 was applied to the purchase costs of the hammer mills to account for direct and indirect costs associated with their installation.

Pelletizer

In both cases experimental data from the literature was used to approximate the energy requirement of the pellet mills (Lam, Sokhansanj, Bi, Lim, & Melin, Energy Input and Quality of Pellets Made from Steam-Exploded Douglas Fir (Pseudotsuga menziesii), 2011). The energy requirements were used to approximate the purchased costs of the pellet mills using available cost data (Cambell). A factor of 3.24 was applied to the purchased costs of the pellets mills to account for direct and indirect costs associated with their installation including ancillary equipment like pellet coolers and storage bins.

i

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