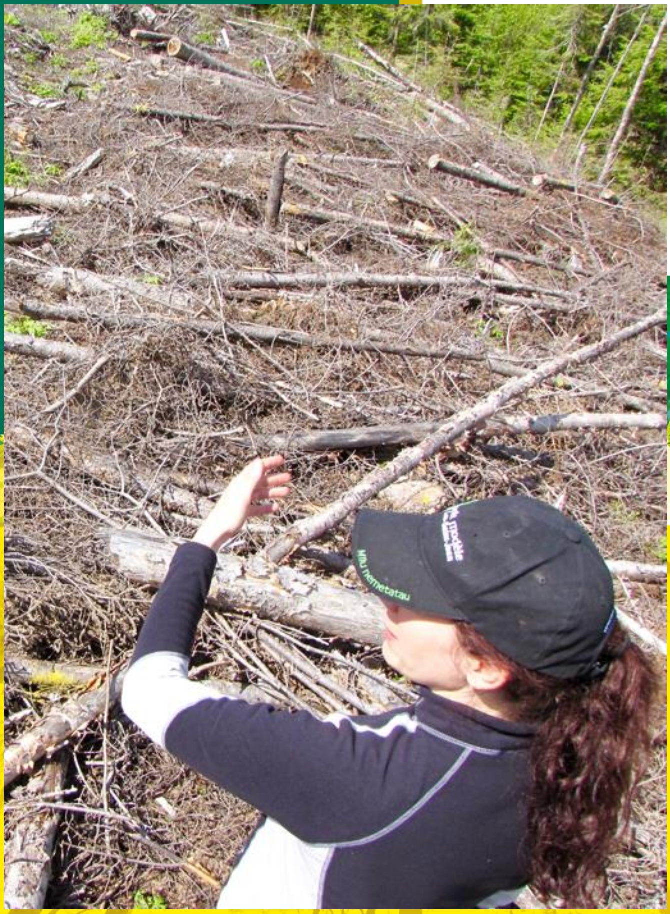
Biomass pre-treatment for bioenergy

Case study 2: Moisture, physical property, ash and density management as pre-treatment practices in Canadian forest biomass supply chains



IEA Bioenergy

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

Biomass pre-treatment for bioenergy

Case study 2: Moisture, physical property, ash and density management as pre-treatment practices in Canadian forest biomass supply chains

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Abstract

Based on the definitions of the Intergovernmental Panel on Climate Change (IPCC), forest biomass includes the following sources:

- surplus roundwood consisting of non-commercial or un-merchantable trees;
- primary residues i.e. by-products of harvesting and silvicultural operations;
- secondary residues, i.e. by-products of the industrial processing of wood;
- tertiary residues, i.e. post-consumer material such as demolition wood and scrap pallets.

In Canada, the annual production of bioenergy from forest biomass has been estimated to 0.48 exajoules (EJ) year^{-1}. The potential from currently unused primary, secondary and tertiary residues available amounts to an additional 0.17 EJ year^{-1}. More ambitious scenarios of increased mobilisation of forest biomass suggest that the potential of forest residues in Canada could vary from 0.68 to 4.43 EJ year^{-1}. Projected production for similar scenarios applied to selected North American, European and Oceanian countries that are part of the boreal and temperate biomes could reach 4.94 to 28.01 EJ year^{-1}.

Compared to fossil fuels, forest biomass is low in energy and bulk densities; is heterogeneous in physical, chemical and thermal properties; high in moisture, mineral and oxygen content; highly hygroscopic and difficult to handle. These features of forest biomass represent significant barriers for using biomass as a ready-to-use feedstock.

Pre-treatment processes are meant to upgrade the physical and chemical properties of biomass feedstock in order to facilitate and/or avoid stoppage of downstream processes. The usability and value of forest biomass for various end-uses can thus be increased by appropriate pre-treatments: they can significantly improve the quality, storability and transportability of biomass and enable more versatile end-uses, as well as cleaner combustion and energy production especially for small users.

Opportunities for pre-treatment include:

- moisture management by passive and active drying, covering, blending, and monitoring and modelling of moisture content;
- physical property management by chipping, grinding, sieving and machine visualization;
- ash content management by washing;
- density management by pelletizing.

In Canada, relative to e.g. European countries, the price of energy for industry and household is generally considered low, with the average retail price for residential electricity in 2015 was 23.30 and 17.52 United States Dollars (USD) per gigajoule (GJ) in British Columbia and Quebec, respectively, whereas the large industrial electricity prices were 13.85 and 11.92 USD GJ^{-1}. The energy mix for electricity generation is mostly dominated by fossil fuels, nuclear and hydro. In 2013, forest biomass covered 17 and 2% of residential space and water heating needs, respectively. In the industrial sector, about 10% of energy demands are provided by some form of forest-based residues and waste. Natural gas and electricity remain the main sources of energy for all those needs. The upstream average price of natural gas in Canada between 2005-2013 was 4.18 USD GJ^{-1}; however, it dropped considerably in the following years, and the average for the first four months of 2016 was 1.03 USD GJ^{-1}. There are also relatively few district heating systems in Canada. The generally low price of energy for households and industries and the absence of ambitious widespread policies for renewable energies often means that profit margins for forest bioenergy projects, relative to their fossil fuel reference cases, are very tight and often do not make room for large investments in the logistics of supply chains. Inclusion of pre-processing

operations in biomass supply chains will usually add to the cost of biomass delivered to the bio-conversation facility. However, they can provide cost savings in upstream and downstream storage, transportation, handling and conversion operations. The cost of pre-processing operations and the potential cost savings relative to the cost structure of the whole supply chain dictates the decision on whether to invest in the pre-processing operations.

Supply costs of biomass from primary forest residues, which do not include any significant pre-processing technologies, were estimated at 1.70-3.18 USD GJ^{-1} for heat plants, 7.21-41.39 USD GJ^{-1} for power plants, and 13.39-29.45 USD GJ^{-1} for combined heat-and-power plants. Case studies in British Columbia and Quebec suggest that the cost of pre-processing operations for pellet production amounts to 1.78 to 2.96 USD GJ^{-1}. Assuming that end-users could use pellets, the pre-processing operations leading to pellet production would add a proportionally high cost for heat plants, but a more reasonable cost to combined heat-and-power plants.

Another case study for a gasification plant in British Columbia estimated at 23 371 USD, as the total annual capitalized costs of simple pre-processing technologies for moisture and physical property, significant improvement in both transportation and conversion efficiencies can be achieved. Reduction in the moisture content of delivered wood chips at the gasification plant can bring cost savings for the supplier and increased benefits for the end user. Reduction in moisture content from 50% to 20% can result in a minimum cost saving of over 50 000 USD annually for the supplier. This cost saving is considerable for a small-sized wood recycling facility. This could be the minimum saving as the supplier can also use the same truck fleet more efficiently to deliver biomass to other customers. On the other hand, a reduction in moisture content from 50% to 20% can result in an increased daily profit of 642 USD, equivalent to an increase of 16%, for the gasification plant by generating more steam.

Several pre-treatment processes can be implemented at the beginning of the forest value chain (passive drying of residues on the forest cutblock and/or by roadside; covering to prevent re-moistening; monitoring and modelling of moisture content; chipping). This can be made easier by close integration of biomass operations with planning of stemwood procurement for conventional wood products, which can ensure that the utilization of available machinery is optimized, and that biomass feedstocks are handled and piled in a way that facilitate downstream processes. Proper implementation of pre-treatment at this early stage in the chain can considerably increase the energy density of the material and therefore significantly reduce transportation costs per unit of energy, a key aspect of bioenergy profitability.

Equipment for pre-treatment processes can be grouped within a biomass depot. The role of such depots for the mobilisation of profitable forest biomass supply chains is increasingly being demonstrated. They make it possible to access low-grade and diffuse forest biomass feedstock resources across a region and offer a buffer against variation in feedstock supply and quality. Research results suggest that a biomass depot within a supply chain can lead to cost reductions of 11-31% relative to a reference value chain without a depot, notably because it increases the capacity for moisture management of feedstock, with consequent benefits for transportation and energy conversion. Larger biomass volumes make it easier to justify the investments needed for the implementation of biomass pre-treatment equipment with which biomass characteristics and quality can be actively addressed and improved.

The energy efficiency (ratio of recovered energy in the end-use and energy content of green biomass) is a crucial component of economic sustainability and should be an important indicator for overall efficiency of pre-treatment methods. The costs associated with pre-treatments should be connected to the energy efficiency evaluations. These costs should be based on the monetary value per MJ or kWh delivered, and not on the monetary value per tonne of forest biomass delivered to the plant. These costs should include implicit costs like breakdowns, repairs, and stoppages due to feedstock characteristics.

In addition to the value of final product, the return on pre-treatment investment should be carefully investigated. It should be pointed out that it is not difficult to achieve good energy yield, but it is rather difficult to achieve good yields at low energy input and investments. More generally, a clear understanding of the effects of properties of raw or pre-treated feedstocks on efficiency of downstream processes and bio-conversion is needed. It is important to critically evaluate the need for pre-treatment along the supply chain both in thermal and economic terms. It requires fine-tuning of the entire forest value chain to ensure the profitability of bioenergy production in a context where generally low fossil fuel and energy prices call for high levels of agility and ingenuity.

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1 Introduction

This report details information about forest biomass supply chains for bioenergy, especially in the context of Canada, and is one out of six separate case study reports that illustrate the added value of pre-treatment technologies in specific fuel supply chains. **Pre-treatment is defined as all intermediate process steps, through which physical or chemical characteristics of a biomass resource are modified on purpose, before it is used for final conversion into a useful energy carrier** (heat, electricity, gaseous or liquid biofuel).

A supply chain is a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances and information from a source to a customer. Unlike other manufacturing supply chains, which has a convergent product structure, a typical forest product supply chain has a divergent co-production structure; trees are broken down into several product streams such as sawnwood of various qualities, chips and sawdust for pulp and bioenergy etc. at all levels of the production processes. Moreover, wood fibre has a highly heterogeneous nature, which makes planning and control a difficult task with regard to the production output control [1, 2]. Forest biomass supply chains for bioenergy therefore share the inherent complexity of forest product supply chains in general, and are intricately linked to those other products [3].

Based on the definitions of the Intergovernmental Panel on Climate Change (IPCC), forest biomass for bioenergy includes the following sources:

- surplus roundwood consisting of non-commercial or unmerchantable trees;
- primary residues i.e. by-products of harvesting and silvicultural operations;
- secondary residues, i.e. by-products of the industrial processing of wood;
- tertiary residues, i.e. post-consumer material such as demolition wood and scrap pallets.

Canada is the steward to vast forest resources and is expected to play an important role in the international mobilisation of forest bioenergy [4]. However, the country's current rates of bioenergy production for domestic and international markets are well below its theoretical potential[4]. While roundwood and secondary residues are used across Canada as feedstock for conventional wood product industries (sawntimber, pulp, panel), large quantities of forest biomass sit unutilized in forest fibre supply streams. These biomass resources are either left on forest sites or in yards, are landfilled, or are burned up in boilers with low efficiency for heat and power generation.

Several difficulties cause investors to be sceptical about a successful and sustainable business model for Canadian forest bioenergy. Notably, capital investment typically requires reasonable certainty of feedstock supplies and prices over at least a 20-year period. Among the main factors determining the price of forest biomass are the costs charged to purchase the material, and the costs of harvesting/collecting and transportation to the plant or terminal. In supply chains of forest biomass, it is difficult to achieve the same economies of scale as are possible with fossil fuel extraction. Therefore, any additional cost efficiency can have considerable value for ensuring a competitively priced end-product; on the other hand, poor efficiency in one or several steps can dramatically affect profitability and competitiveness of forest bioenergy. Research has shown that the cost structure of forest biomass supply chains is greatly dependent on biomass characteristics all through the chain. Cost efficiencies can therefore be achieved by improving the quality of biomass by using proper pre-treatment, which can decrease transport costs, improve the scale of operations, make new volumes of resources available, and improve conversion efficiency [5, 6].

In Canada, the generally low price of energy for households and industries and the absence of ambitious widespread policies for renewable energies often means that profit margins for bioenergy projects, relative to their fossil fuel reference cases, are very tight and often do not make room for large investments in the logistics of supply chains. However, simple and relatively low-cost pre-treatment technologies, when properly applied, can lead to improvement of biomass characteristics: careful of management of moisture content, physical properties (particle size, shape and flowability), ash content and fuel density can yield to cost savings and increase the profitability and competitiveness of bioenergy business cases.

These processes will be presented and discussed by first describing a typical reference value chain of forest biomass that does not include the use of pre-treatment methods and the economic and energy environment within which they lie. Then, this report will detail opportunities within the reference value chain for improving forest biomass characteristics by presenting results and insights from experimental and operational trials and case studies.

2 Reference Value Chain

2.1 STRUCTURE OF SUPPLY CHAIN

Forest biomass feedstocks for bioenergy are mainly comprised of by-products and waste from other activities within the forest value chain. In Canada, a generic forest product value chain is illustrated in Figure 1: this value chain is mainly dedicated to the production of solid wood products, i.e. sawntimber, panels and pulp, which creates various residue streams. Evaluations from British Columbia (one of the main forestry provinces in Canada, along with Ontario and Quebec) estimate at about one-third the amount of harvested wood that ends up as residues [7]. Since the bioenergy sector is still nascent across the country, in such a reference case, these residue flows may end up being not utilized/directed to bioenergy production; they stay on forest site or are stranded in yards or landfills.

2.1.1 Forest harvesting

When forest stands are managed and harvested for roundwood for conventional wood products, residues consisting of branches, tree tops and bucking and trimming materials are generated (primary residues). The methods used to collect primary residues depend on the harvesting method and the degree to which the supply chain of residue removals (if it exists) is integrated with roundwood removals. The forest harvesting operations and related residue supply chains described in studies are mostly based on the following two systems:

- Stem-only (also called cut-to-length) harvesting, in which trees are cut, delimbed, topped, and bucked in the harvested block, and the stem forwarded to the roadside and then directed toward sawmills and/or pulpmills. If a bioenergy market exists, a portion of the remaining residues (mainly tree tops, branches, and bucking and trimming material) may then be picked up from the forest floor as loose slash or as bundles, and brought to the roadside or central landing, usually with the same forwarder used for the merchantable stem wood.

- Whole-tree harvesting, in which trees are cut and skidded in one piece to the roadside or central landing, where they are delimbed and/or bucked to specifications for sawntimber and pulp products. Most of the residues are therefore produced directly at the roadside or landing, and can be picked up for bioenergy production

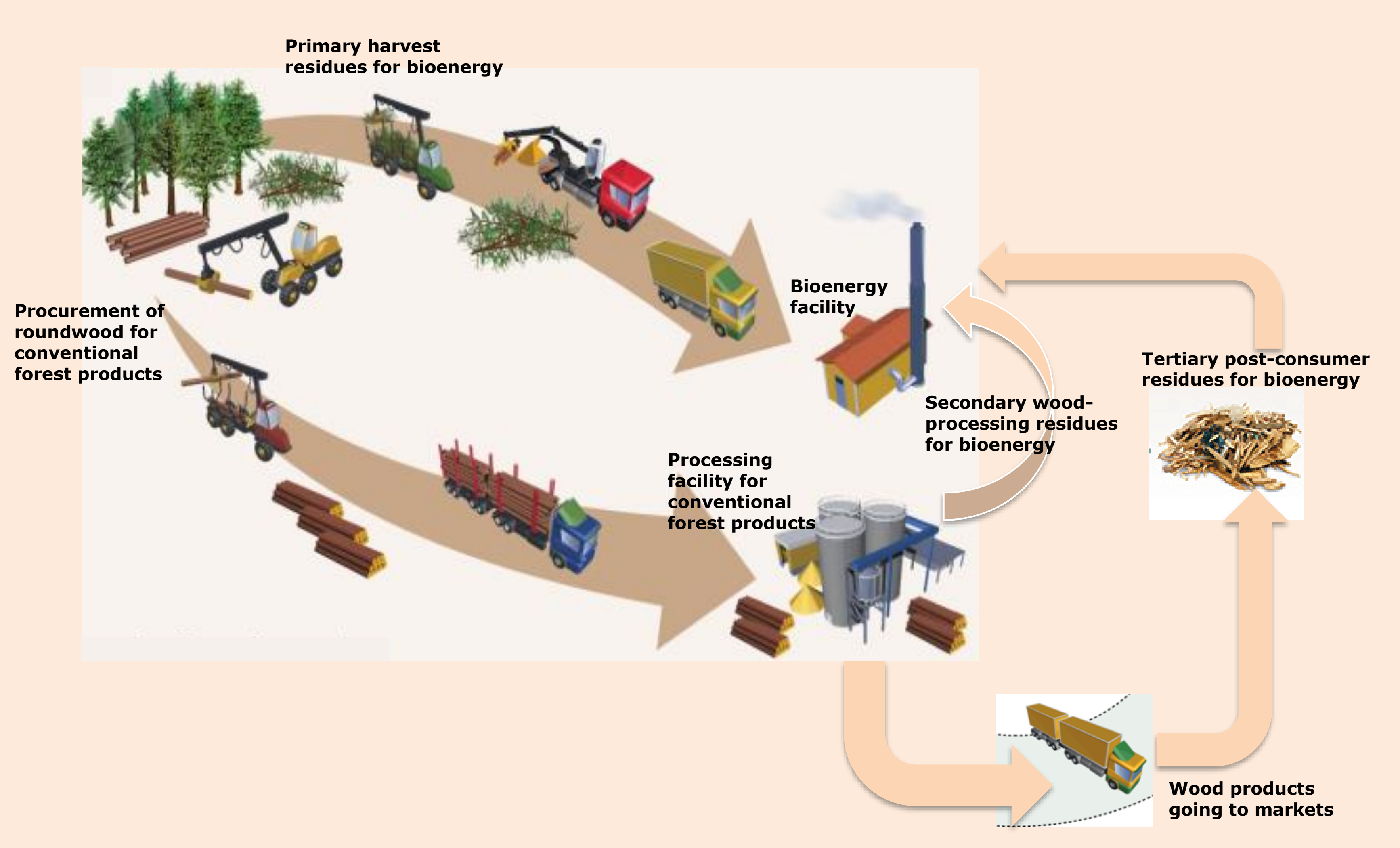

Figure 1: Generic forest value chain.

2.1.2 Primary residues

The amount of primary residues for bioenergy production that is theoretically available and technically recovered in typical harvesting operations varies depending on the forest and site conditions, type of machinery used and training of the workforce. For example, for typical forest stands of the eastern Canadian forests, the theoretical potential from residues vary from 36 to 53% of the total stand biomass [8]. Across Canada, this potential would amount to 14±2 millions of oven-dry metric tonnes (odmt) per year. This resource is however scattered over a very large area, and has an average density of 24±1.2 odmt per hectare [9]. The fraction of potential biomass that can be recovered for bioenergy given technical constraints is on average 52% in Canadian conditions; the technical potential of primary residues from Canadian forests would therefore be 14 M odmt X 52% = 7.3 M odmt. Assuming a calorific value of 19.2 GJ odmt^{-1}, the energy potential from primary residues would be 0.14 EJ per year. As a reference, the technical potential of primary residues on a given harvest cutblock observed in Nordic countries is 72%; the homogeneity of forest stand conditions, the availability of highly trained workforce and well-adapted machinery provide close-to-ideal operational conditions for residue recovery for bioenergy production in those countries, which is not the case in Canada [10].

As a bioenergy feedstock, primary residues are difficult to manage for several reasons. First, this source is highly heterogeneous in terms of shape and bulkiness, since it is comprised of branches, tree tops and trimming material. Second, as mentioned above, its distribution across the landscape is scattered and diffuse. Furthermore, it is often contaminated with soil and stones, which increase the ash content at combustion and cause equipment wear and tear [11]. On the other hand, their usage for bioenergy does not compete with any other industry.

2.1.3 Secondary residues

Harvested roundwood enters processing facilities for production of conventional wood products and produce secondary residues. Ghafghazi et al. [7] estimated that from 51.8 Mt of wood entering Canadian sawmills in 2013, about its 43.2% became lumber, and 29.8% was transformed into wood chips for the pulp and paper sector; 5.5 Mt of whitewood residues (11% of the original amount of wood) and 4.1 Mt of hog fuel (bark-containing and/or coarse and low-quality wood refuse; 8% of the original amount of wood) were produced. About 68% of secondary residues were then used for manufacturing of other wood products (particle/fibre boards, wood pellets). The material balance for a given Canadian sawmill that uses coniferous species has on average 43% of the roundwood volume becoming sawn wood, 35% wood chips and slabs and 13% sawdust and shavings; there is also 7% of processing waste that is used for internal energy production, and 2% of (unutilized) hog fuel [7]. As a comparison, material balance in Finland has 45-50% of the log volume becoming sawn wood, 28-32% wood chips, 10-15% sawdust, and 10-12% bark; 62% of secondary residues would then go to pulp, 8% to board manufacturing 2% to other solid product uses and 30% to energy production [12].

However, many mills in Canada create enough residues to exceed their own energy requirements. For example, Dymond and Kamp [13] identified that a portion of thermal energy produced within mills in British Columbia was vented, so that boilers were operated mostly as a way to get rid of residues and not strictly as energy production. Moreover, characteristics of the residues (such as moisture content) often do not allow for very efficient burning. Secondary residues of very poor quality (including hog fuel) might sit unused and become stranded.

Although clear estimates are hard to obtain and values vary widely among different provinces, availability of unused secondary residues across Canada was estimated at about 1.4 million odmt in 2013, i.e. 9.7% of the total amount of residues from wood processing [7]. Assuming a calorific value of 19.2 GJ odmt^{-1}, the calorific potential from secondary residues in Canada is therefore estimated at 0.027 EJ $year^{-1}$.

2.1.4 Tertiary residues

Tertiary, i.e. post-consumer, wood products sit at the end of the forest value chain. Although a portion of wood products is recycled, Canada has a poor record on waste management in general according to a recent international ranking of countries from the Organisation for Economic Cooperation and Development (OECD). Nationally, the amount of non-hazardous total waste (residential and non-residential) sent to disposal in 2010 was 25 million metric tonnes. Some jurisdictions (municipal or provincial) have put in place (or are planning to) ban landfilling of post-consumer wood products, such as wood generated by construction, renovation and demolition activities. Statistics for specific types of waste do not exist, but the overall disposal (i.e. landfilling) rate of waste in Canada (including all sources and types of waste) is close to 75%. Non-recycled wood waste should therefore represent a significant source of biomass that can be explored. As an example, statistics from 2002 estimate at around 1 700 000 odmt the amount of disposed wood waste for that year in Canada [14]. On the total amount of disposed wood waste, about 80% can be assumed to be either highly or mildly contaminated (based on contamination estimates of solid waste from construction, renovation and demolition in Quebec) and therefore 20% (340 000 odmt) could be diverted further valorised for bioenergy production; assuming a calorific value of 16.72 GJ $odmt^{-1}$, this gives a calorific potential for Canada of 5.6 M GJ $year^{-1}$ (0.005 EJ $year^{-1}$).

2.1.5 Global potential from forest residues

In Canada, the annual production of bioenergy from forest biomass, using the average from years 2002-2013, has been estimated to 0.48 EJ $year^{-1}$ [4]. Estimations made in the previous sections about additional forest biomass feedstocks that can be provided by primary, secondary and tertiary residues available across the country amount to an additional 0.17 EJ $year^{-1}$. However, scenarios of increased mobilisation of forest biomass with ambitious policies promoting technological and institutional learning, compiled in Thiffault et al. [15], suggest that the potential of forest residues in Canada could vary from 0.68 to 4.43 EJ $year^{-1}$. Projected production for similar scenarios applied to selected North American, European and Oceanian countries that are part of the boreal and temperate biomes could reach 4.94 to 28.01 EJ $year^{-1}$.

Table 1: Projections of forest biomass production for selected countries of the boreal and temperate biomes. All data are in EJ year^{-1}*. See Thiffault et al.* [15] *for detailed description of scenarios.*

	Average 2002-2013	**Projected Production: Scenarios with increasing mobilisation of forest biomass ----->**				
Australia	0.19	0.19	0.21	5.63	5.63	6.37
Belgium	0.03	0.03	0.03	0.03	0.03	0.03
Canada	0.48	0.68	1.12	1.91	2.66	4.43
Croatia	0.02	0.02	0.03	0.02	0.02	0.03
Denmark	0.04	0.04	0.04	0.04	0.04	0.04
Finland	0.31	0.31	0.35	0.31	0.31	0.35
Germany	0.38	0.38	0.38	0.38	0.38	0.38
Ireland	0.01	0.01	0.02	0.01	0.01	0.02
New Zealand	0.05	0.09	0.15	0.11	0.22	0.36
Norway	0.05	0.05	0.07	0.10	0.10	0.14
Sweden	0.35	0.35	0.49	0.35	0.35	0.49
US	2.06	2.06	2.69	3.74	3.74	4.88
Russia	0.14	0.74	1.23	1.19	6.31	10.48
Total	**4.09**	**4.94**	**6.82**	**13.80**	**19.79**	**28.01**

2.1.6 Characteristics of residues

All potential sources of forest biomass feedstocks for bioenergy production along the forest value chain in Canada (primary, secondary and tertiary residues) share common features. They are abundant; they mostly remain unutilized (although this varies regionally); their characteristics and variability are poorly documented, although it is generally recognized that they are highly heterogeneous in composition, shape, granulometry (distribution of particle size), moisture content, density, and chemical composition. As an example, Table 2 and Table 3 summarize characteristics of typical currently unused or stranded biomass feedstocks from Canada: Table 1 reports characteristics of wood chips from ground primary residues produced during logging, land clearing and fire protection/fuel reduction activities in coniferous forests of the Williams Lake region of British Columbia (BC); Table 2 reports characteristics of secondary and tertiary residues from the Metro Vancouver area consisting of woody scraps from construction and demolition, tree trimmings collected from curb sides and landfills, and clean waste wood from pallet manufacturing operations, scrap lumber from sawmills, and scrap pallets that were previously used to handle packaged goods from various local companies.

Table 2: Example of variability of properties of wood chips from ground primary residues.

Parameter		Case 1	Case 2	Case 3	Case 4
Moisture content (wet basis, %)	Average	31.5	39.05	29.8	30.8
	Standard dev.	4.5	7.4	4.8	11.7
	% Coef. Var.	14.3	19.0	16.1	38.0
Loose density (kg m^{-3})	Average	210.4	257.8	215.4	239.7
	Standard dev.	11	33.7	15.4	53.7
	% Coef. Var.	5.2	13.1	7.1	22.4
Dense filled density (kg m^{-3})	Average	210.4	257.8	215.4	239.7
	Standard dev.	11	33.7	15.4	53.7
	% Coef. Var.	5.2	13.1	7.1	22.4
Ash content	Average	1.63	1.03	1.29	1.03

Parameter		Case 1	Case 2	Case 3	Case 4
(%)	Standard dev.	1.15	0.58	0.91	0.68
	% Coef. Var.	70.6	56.3	70.5	66.0
High heating value (MJ kg^{-1})	Average	18.6	18.9	19.5	18.96
	Standard dev.	0.4	0.7	0.4	0.2
	% Coef. Var.	2.2	3.7	2.1	1.1

Note: Standard dev. = Standard deviation. % Coef. Var.= Coefficient of variation in %. The material used for this study was ground biomass from forests in and around Williams Lake in the interior region of British Columbia. Case 1 is comprised of debris from a grassland restoration project that is mostly small-diameter Douglas fir with branches and needles still on. Cases 2 and 4 are comprised of the same pile of debris from a fuel reduction treatment at the regional airport; samples from case 2 were collected in October 2008, and samples from Case 4 were collected in February 2009. Case 3 are comprised of roadside logging debris from a Mountain Pine infested cut block for lumber production.

Table 3: Example of variability of properties for secondary and tertiary residues from the Metro Vancouver area

Parameter	Moisture content (wet basis, %)	Bulk density (Kg m^{-3})	High heating value (MJ kg^{-1})	Ash content (%)
Average	31.0	187.4	19.4	0.8
Standard deviation	9.6	37.8	0.5	0.2
Coef. variation (%)	31	20	3	25
Minimum value	10.0	92.0	18.1	0.2
Maximum value	57.4	327.7	20.9	1.5

Note: The material used for this study came from the Metro Vancouver area, and consisted of a mix of woody scraps from construction and demolition), tree trimmings, and clean waste wood from pallet manufacturing operations, scrap lumber from sawmills, and scrap pallets.

For the U.S., Leinonen [16] categorized the operational quality criteria of logging residue chips. Values for moisture content ranged from 39 to 53% (wet mass basis), for effective heat value from 16.0 to 17.2 MJ kg^{-1}, for ash content from 0.1 to 2.0%, and for wood dry density from 368 to 575 kg m^{-3}. Mitchell and Gallagher [17] reported the results of a series of trials on several whole-tree chipped species, with moisture content ranging from 41 to 52% and bulk density ranging from 245 to 360 kg m^{-3}.

On the other hand, since most bioenergy facilities installed in Canada are small, their requirements in terms of feedstock characteristics are very strict. Small biomass boilers, such as the ones being installed in institutional building, require very consistent feedstock in order to perform well. Kofman [18] specified the desired woodchip moisture content to be a function of boiler size. For example, boilers with a capacity of less than 250 kW (house size) requires wood with less than 30% moisture content, whereas larger boilers with a capacity of 1 MW or more (institutional and small industries) can handle feedstock with a moisture content of up to 55%. For these larger boilers, consistency in moisture content is more important than the moisture content itself. The size of chips is also related to the size of boiler: as the size of a boiler increases the size of chips and the number of long pieces increase [18].

Gasification plants are another type of facility for thermal production with different feedstock specifications than boilers. For example, the gasification plant installed at the University of British Columbia (UBC) requires particle size in the range of 6-76 mm, moisture content in a range of 10-55%, and up to 10% in ash content. This gasification produces 2 MWe electricity, 4600 lb hr^{-1} steam and 1 MWt hot water in the cogeneration mode and 20000 lb hr^{-1} steam in the thermal mode.

2.2 ECONOMIC BREAKDOWN

2.2.1 Energy prices

In Canada, relative to e.g. European countries, the price of energy for industry and household is generally considered low (Figure 2). For example, the average retail price for residential electricity in 2015 was 23.30 and 17.52 USD[1] GJ^{-1} in British Columbia and Quebec, respectively, whereas the large industrial electricity prices were 13.85 and 11.92 USD GJ^{-1} [19]. The energy mix for electricity generation is mostly dominated by fossil fuels, nuclear and hydro [20]. In 2013, forest biomass covered 17 and 2% of residential space and water heating needs, respectively. In the industrial sector, about 10% of energy demands are provided by some form of forest-based residues and waste. Natural gas and electricity remain the main sources of energy for all those needs [19]. The upstream average price of natural gas in Canada between 2005 to 2013 was 4.18 USD GJ^{-1}; however, it dropped considerably in the following years, and the average for the first four months of 2016 was 1.03 USD GJ^{-1}. There are also relatively few district heating systems in Canada [21].

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[1] All monetary values in the report are expressed as United States Dollars (USD); they were converted from Canadian Dollars (CAD) and other currencies using exchange rates and adjusted to the reference year of 2016 when possible using inflation rates and currency exchange rates provided by the Bank of Canada.

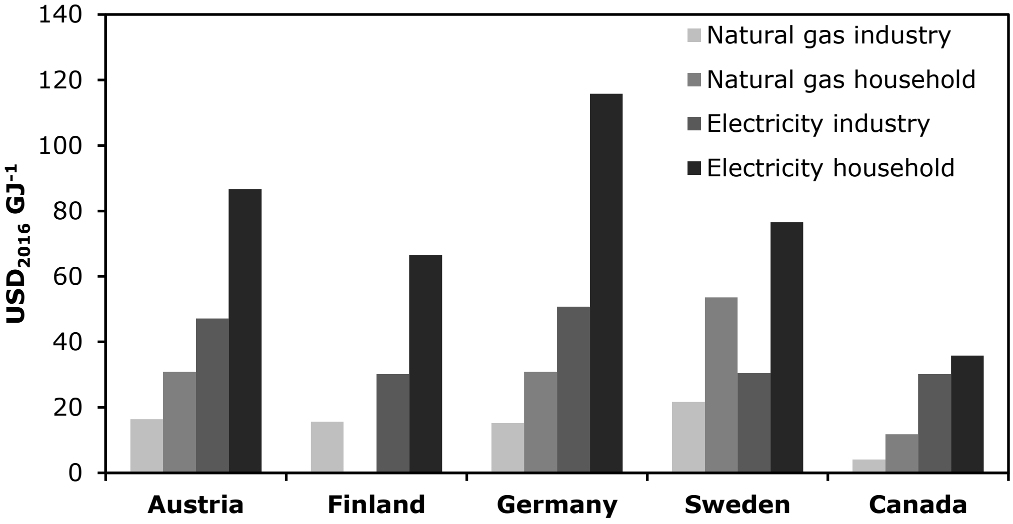

Figure 2: Gas and electricity prices in 2012 for a suite of countries. (source: [22]).

The market pull for forest biomass for thermal production in the country is therefore not very strong. There is also no nationally coordinated bioenergy strategy in Canada, nor are there specific national targets for biomass development. In 2013, the Canadian National Energy Board released forecasts of energy sector demand and composition to 2035, and the proportion of stationary energy derived from biomass is not forecast to change significantly during this period [23].

Nevertheless, policies at the national, provincial and local levels are evolving. Initiatives at the provincial level have facilitated the deployment of several bioenergy projects, including the conversion of coal power plants to biomass in the province of Ontario and the installation of community district heating systems, using biomass to replace heavy oil, in the provinces of Quebec and British Columbia. Policy support for forest bioenergy development is often embedded in larger government efforts to revitalize the forest sector, which has been struggling with the fall in demand for paper and the economic downturn in the United States. Nevertheless, thermal production from forest biomass therefore remains extremely cost sensitive in the absence of large-scale, ambitious plans and policies for renewable energy/bioenergy.

2.2.2 Forest biomass supply costs

A recent paper by Xu et al. [24] provides a breakdown of prices and costs for forest harvesting and products from softwoods for British Columbia (BC). Supply costs (in USD_{2016}) for forest primary residues in three regions of the province (

Table 4) include collecting, processing and transporting residues. The assumption was that residues were collected directly at roadside, and not on the forest cutblock, as the main harvesting method in the regions is whole-tree harvesting. For projected facilities that use primary residues as feedstock, the total production costs vary between 1.70-3.18 USD GJ^{-1} for heat plants, 7.21-41.39 USD GJ^{-1} for power plants, and 13.39-29.45 USD GJ^{-1} for combined heat-and-power (i.e. CHP) plants. Given the current prices for energy in Canada, it shows the tight margin that potential bioenergy producers must work with in order to compete with other energy players, mostly fossil fuel and hydro.

Table 4: Example of supply costs for primary residues for three regions of British Columbia. (source: [25]).

Region	**Supply**		**Transport**		
	Processing	**Other costs**	**Fixed cost**	**<50 km**	**>50 km**
	USD tonne^{-1}	**USD tonne^{-1}**	**USD tonne^{-1}**	**USD tonne^{-1} km^{-1}**	**USD tonne^{-1} km^{-1}**
Northern interior	18.08	6.89	6.89	0.27	0.14
Southern interior	18.08	6.89	6.89	0.27	0.14
Coast	16.36	6.89	6.89	0.31	0.17

3 Opportunities in the Reference Value Chain

Experience from countries with a well-established forest bioenergy sector such as Finland shows that as biomass supply volumes increase, the economic losses associated with poor management of feedstock characteristics become more obvious. Energy yields per unit of delivered biomass can be maximized through careful establishment of storage, prediction and measurement of changing moisture content, and the ability to match supply with demand in terms of feedstock properties.

Given the forestry and energy/bioenergy context in Canada, opportunities to increase the mobilization of biomass for thermal production mainly lie in logistical and technical solutions that do not necessitate important investments and that can improve the quality of currently untapped primary, secondary and tertiary residues. Such solutions can take the form of low-cost, basic feedstock pre-treatment methods that are proven to reduce the cost of transportation and improve efficiency of thermal conversion by reducing variability of feedstock properties: 1) moisture management by drying and blending; 2) physical property management by grinding and sieving; 3) ash management by washing; and 4) densification by pelletization.

3.1 MOISTURE MANAGEMENT

Moisture management of forest biomass feedstock for thermal production is a key element to improve conversion efficiency and reduce losses in biomass supply chains. Biomass quality is often defined by its calorific value. When moisture content of forest biomass is low, caloric value and energy density are improved, thereby reducing transport costs and maximizing profits [26].

In the absence of artificial drying, the moisture content of solid forest biomass can vary between 50-60% (fresh wood) and 20% [27, 28]. The energy content per unit mass and volume increases as moisture content of forest biomass decreases (Figure 3). With proper drying and storage techniques, it is possible to significantly improve the energy density of forest biomass, which directly improves transportation efficiency and the sustainability of the entire supply chain.

Biomass moisture content also influences the efficiency of thermal production. For example, high moisture content shifts the ignition point to higher temperatures [29], and inhibits the rise of temperature inside particles [30, 31]. In pyrolysis reactors, reduced particle and reactor temperatures lower the liquid yield at the expense of a larger fraction of biochar and non-condensable gases [30-34]. Water has a catalytic effect on volatile cracking. For thermal conversion applications, biomass should therefore be dried down to less than 10% moisture content to improve the quality of produced fuel [35].

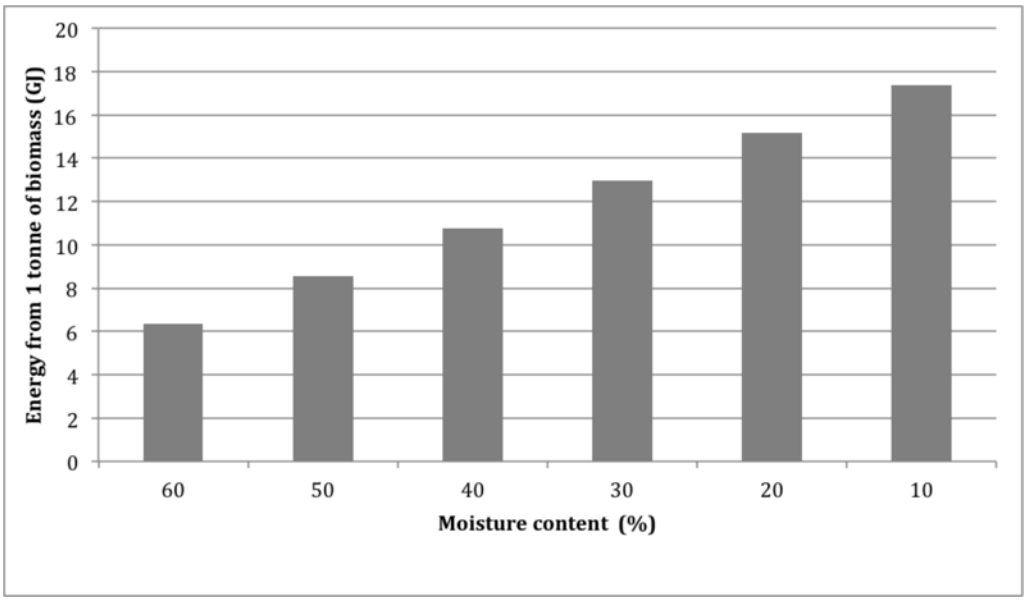

Figure 3: Relationship between moisture content and energy content of forest biomass (source: Asikainen et al. [6]).

3.1.1 Passive drying

Passive (or natural) drying reduces the moisture content of primary forest residues on site and during storage. The timing of the operations in relation to seasons is crucial in order to maximize the quality and monetary value of the forest biomass, notably through reduction of dry matter losses. Dry matter losses can be caused either by microbial activity, most commonly fungal attacks, or spillage of material during handling and storage [36]. After tree cutting, wood starts to react with the surrounding microclimate. In boreal conditions of the northern hemisphere, the moisture content of wood drops rapidly in the spring. In late August and September, evaporation usually decreases and the moisture content of the wood increases, in some cases even above the ”green” moisture found right after cutting. Maximizing natural drying and minimizing re-moistening are therefore key elements in the quality assessment of forest biomass feedstocks[11].

It is usually not profitable to forward fresh logging residues from the forest to roadside [11]. The dry matter losses can be lowered by leaving logging residues in piles on the cut block to dry for several weeks, and then forward them to roadside. The moisture content usually stays in an acceptable range when roadside storage is used for dry material and re-moistening is prevented. In the study of Routa et al. [37], dry matter losses within piles of fresh logging residues varied from 0.9% to up to 2.9% per month; whereas no matter loss occurred within piles of residues that had been previously dried on the cut block. Dry matter losses with small diameter stem wood varied from 0.5 - 1.2 % per month [38]. Dry matter losses cause huge economical losses to forest energy procurement. Economical losses can be hundreds of thousands of euros per year depending the procurement amounts, storage times and dry matter loss rates. The economic loss with high dry matter loss rates (1% with stem wood and 3 % with logging residues) was estimated to be between 4-17% of energy wood purchasing costs depending of the storage time (3-18 months) (Routa et al. 2017).

In suitable circumstances, covering of residue piles at roadside prevents re-moistening in autumn and winter. On the other hand, covering also could prevent ventilation, which consequently raises the pile temperature, increases microbiological activity and cause dry matter losses [37] The combination of tree species, moisture content, temperature, size and shape of the feedstock pile, nutrient and oxygen contents of the pile all influence the microbial activity and degradation of biomass [36], [39], [40]. Needles, leaves, and bark contain a large amount of living matter, water and nutrients, which accelerate mold and fungal growth. A combination of drying on the cut block prior to forwarding of residues to roadside, allowing needles/leaves to fall off from residues, and of covering of residue piles during roadside storage (prior to transportation to biomass centre or conversion plant) to prevent re-moistening is likely optimal to ensure proper moisture management.

Since the energy content per unit mass and volume increases as forest biomass dries, moisture content has a direct impact on transportation efficiency, notably when residues are so moist that the maximum weight of the load is reached before a truck has reached its full volumetric capacity. If a chip truck has a net volume of 130 m^3 and a maximum payload of 60 000 kg, then the average net payload of forest biomass is around 36 400 kg [41]. If the moisture content of wood chips is over 45%, however, the net payload can be exceeded before the truck has reached its full volume (Figure 4). With moisture management, the cost efficiency of transport could therefore increase remarkably.

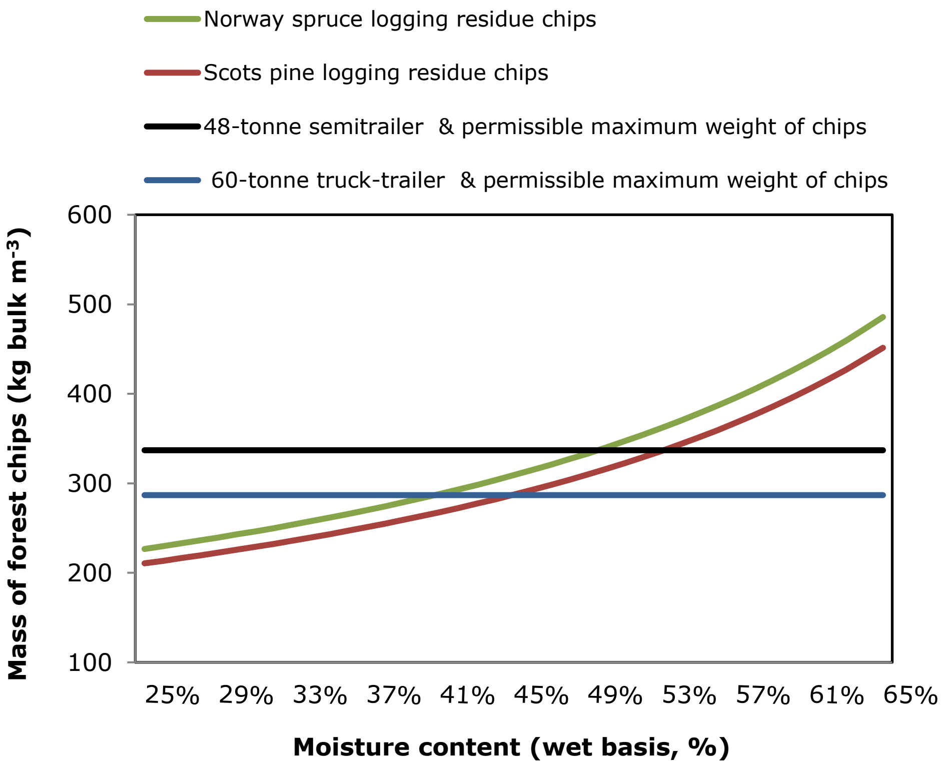

Figure 4: Mass of forest chips (kg bulk m^{-3}) as a function of moisture content, raw material and tree species, relative to truck payload (source: Laitila et al. [42]).

3.1.2 Monitoring and prediction of moisture content during passive drying

The latest research methodology for monitoring moisture change in forest biomass feedstocks has been the constant weighing of piles in racks built on load cells [43, 44]. This methodology allows moisture changes to be monitored in much more detail than previous sampling methods, and provides information about the moisture of the whole pile, which was not possible with other sampling methods [28]. Measurements can be taken automatically and as often as needed. This also enables an exact investigation of the effect of weather on biomass characteristics.

Models to forecast the biomass moisture content have also been developed [37, 43, 44]. They are an easy option for estimating the moisture content of energy wood piles compared to sampling and measuring the moisture of samples. For example, the model developed by Routa et al. [45] , applicable in Finland, is based on gridded weather data provided by Finnish meteorological networks: weather measurements (e.g. temperature, humidity, precipitation) are interpolated to a 10 km x 10 km grid by the kriging interpolation method. Based on the grid, the model serves to estimate moisture content of biomass piles for storage locations where recorded weather data are not directly available. The practitioners in the forest energy business have stated that their requirement for accuracy of moisture for planning purposes would be ±5% of the moisture content. Validation results indicate that moisture estimates provided by models fall within this limit for around 80% of the cases [37, 45].

3.1.3 Active (artificial) drying

In boreal and temperate biomes of the northern hemisphere, natural drying is most efficient during the spring and summer, but might not always be suitable for ensuring a year-long provision of forest biomass feedstocks. Active or artificial drying ensures a fast supply of fuel chips with the desired moisture content. However, it introduces additional processes and costs to the supply chain [46]. Utilization of waste heat from industrial processes might be a solution to significantly reduce energy consumption and profitability of active drying [47, 48]. The cost saving potential due to artificial drying depends of the supply chain, moisture content and procurement volume. Cost savings ranged between 1.2-3.2 € MWh^{-1} (1.33-3.54 USD MWh^{-1}) in supply chains of Finland in the study of Laitila et al. [49].

The aim of active drying is to dehydrate biomass rapidly down to the desired moisture content. The most common dryer types are rotary dryers, flash dryers, fluidized-bed dryers and belt dryers. Li et al. [47] provided typical range of properties and performance for these various dryers (Table 5).

Another mechanism of drying in power generation stations is through transporting of particles. In the power plants, biomass particles flow pneumatically using the re-circulated hot gases coming from the combustion chamber. The moisture content of the biomass evaporates down to below 10% while passing through pipelines towards the combustion chamber. The rest of the moisture is evaporated during the initial phase of pyrolytic reactions in the combustion chamber [50-54]. For these specific types of drying, the size of material should be small enough to be conveyed pneumatically.

Optimization of a drying process depends on various operating and feedstock conditions. Size of particles [55], initial moisture content [56], drying temperature [55, 57, 58], relative humidity of drying gas [59-61] and particle heating rate [62, 63] influence the rate of moisture loss. Moreover, the density of a single particle also influences the rate of heat and mass transfer [56, 58, 62, 64-68].: for example, ground pellet particles are denser and consequently dry slower than unprocessed ground chip particles [69].

Table 5: Typical range of parameters for various dryers (source: Li et al. [47]).

Parameter	**Dryer type**		
	Rotary	**Flash**	**Belt**
Evaporation rate (tonnes hour^{-1})	3-23	4.8-17	0.5-40
Drying temperature (°C)	200-600	150-280	30-200
Capacity (t h^{-1})	3-45	4.4-16	-
Moisture at inlet (%)	45-65	45-65	45-72
Moisture discharge (%)	10-45	10-45	15-25
Moisture at outlet (%)	-	12	25
Optimal particle size (mm)	19-50	-	-
Maximum particle size (mm)	25-125	0.5-50	-
Thermal requirement (GJ tonne-evaporation^{-1})	3.0-4.0	2.7-2.8	1.26-2.5

3.1.4 Case study: Drying of industrial hog fuels in BC Coastal region

An experimental and numerical analysis conducted by the researchers in Biomass and Bioenergy Research Group (BBRG) at the University of British Columbia (UBC) on drying of hog fuel (i.e. low-quality, bark-contaminated processing residues) from BC Coastal region is presented as an example of the effects of various parameters on drying rate of woody biomass streams.

On the day of sampling, there were three piles of hog fuel materials at the site of a biomass pre-processing facility (Figure 5). Three sub-samples from each pile were obtained for characterization of particle size distribution, bulk density and ash content, and for drying tests.

Figure 5: Three piles of hog fuels in the open area of a biomass pre-processing facility in BC Costal region.

Generally, the samples contained three groups of particles. The first group were particles in the range of up to 2-3 mm, representing the main portion of all samples. The next category is large pieces of wood, with a width of 5-10 mm and length of 5-15 mm; this portion is minor and represents about 5% of samples. The third category is the thin and very long pieces of wood; due to their very small thickness, they mostly bend and cause the samples to be bulkier and significantly decrease the bulk density.

Figure 6 shows the sieving particle size distribution of all three samples. As observed visually, the particles smaller than 3 mm is the major portion of each sample. The peak fraction of particles is in the range of 1-2 mm. Sample 1 had about 65% particles of smaller than 3 mm. Samples 2 and 3 have about 80% particles of smaller than 3 mm. Figure 7 shows the fraction of material retained on top of the largest sieve, which has an opening size of 6.3 mm: large pieces and a fraction of long and thin pieces are retained on top sieve.

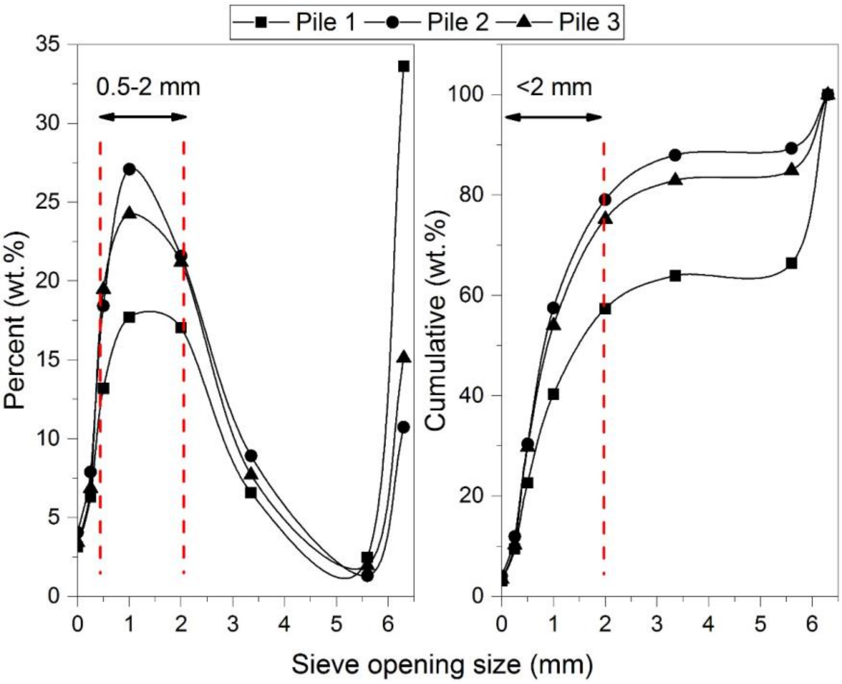

Figure 6: Particle size distribution of dried samples.

Pile 1 **Pile 2** **Pile 3**

Figure 7: Size and shape of wood pieces on top sieve (6.3 mm).

Drying temperature has the largest effect on the rate of drying. Table 6 lists the drying times from an initial moisture content of 71% to 30 and 15% (wet basis). The drying time needed to reach 30% drops from 22 minutes at 60°C to 8 minutes at 120°C. For a lower moisture content of 15%, the drying time decreases from 45 minutes a 60ºC to 10 minutes at 120ºC.

The drying process shows three distinct periods: a rising rate period, a very short constant rate period, and a falling rate period (Figure 8 and Figure 9). During the rising rate, the particles warm up and the drying rate increase to a maximum value. Higher drying temperature increases the rate of drying. In the constant rate period, the surface water evaporates. Part of the free water is expected to evaporate in the warm-up period and results in a short constant rate period.

Table 6: Drying times (in minutes) at various temperatures

Drying Temperature (ºC)	Drying time to 15% (minutes)	Drying time to 30% (minutes
60	45	22
80	26	17
100	20	12
120	10	8

In the falling rate period, the drying rate drops down until the moisture approaches zero. As shown on Figure 9, the falling rate period in drying curves of 60 and 80 °C consists of one stage, whereas the falling rate of the 100 and 120 °C drying curves is divided into two distinct periods. Migration of internal moisture to the particle surface during the first falling rate period occurs through moisture diffusion, capillary flow and internal pressure set up by shrinkage during kinetic. In the second falling rate period, the capillary flow of moisture ceases and internal moisture diffusion controls the rate of drying.

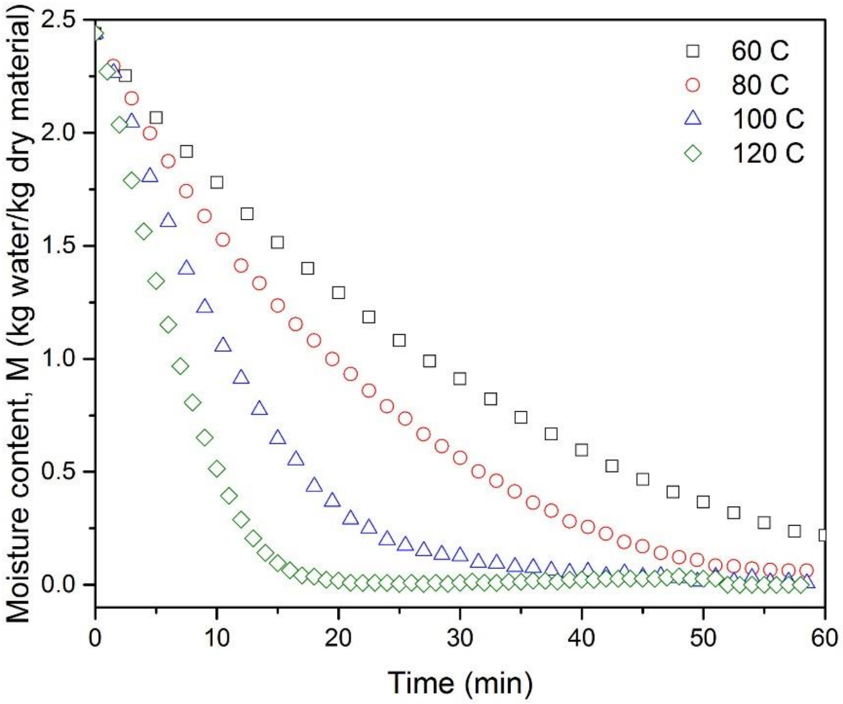

Figure 8: Moisture loss of hog fuels with initial moisture content of 2.5 (dry mass basis) at various drying temperatures.

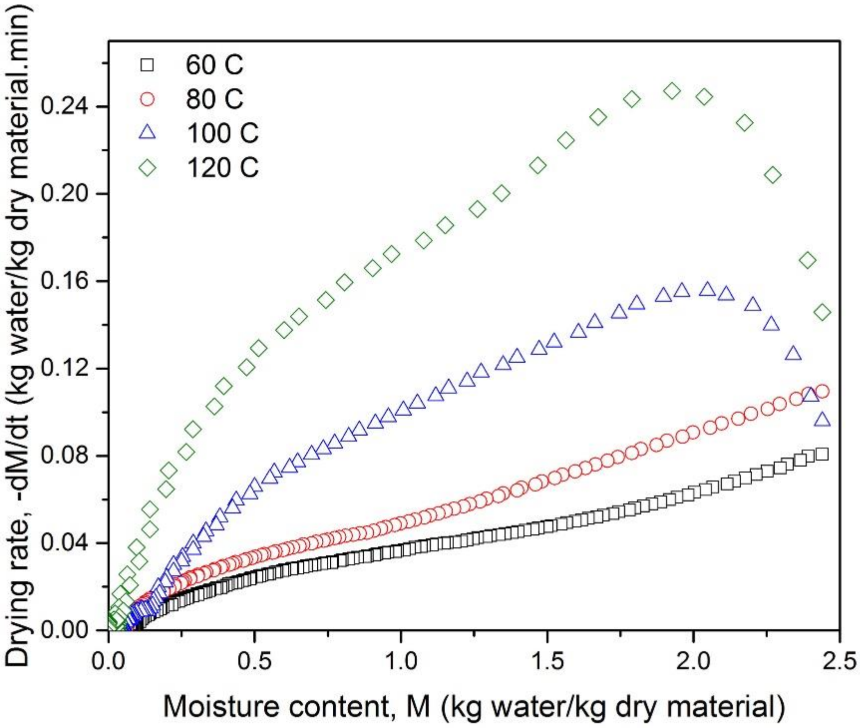

Figure 9: Drying characteristic curve, expressing the rate of drying as a function of dry basis moisture content at various drying temperatures.

The drying rate experimental data were used to model the process with a first-order moisture loss system with the equation:

$$MR = \exp(-k.t)$$

where:

MR = moisture ratio (instantaneous moisture content over initial moisture content, M/M_0),

k= drying rate constant (min^{-1}),

t = drying time (min).

The constant k represents the drying rate and can be related to drying temperature using

$k=k_o \exp(-E/RT)$.

T is in Kelvin. R = 9.8 kJ $mole^{-1}$.

As seen in Table 7, the drying rate constant k changes significantly with temperature. The value of activation energy is E=30.717 kJ mol^{-1} and pre-exponential factor is k_0=401.902 min^{-1}. These two drying kinetic parameters may be used to determine the drying rate and predict the instantaneous moisture content of material during a drying process. Figure 10 shows the agreement of experimental drying data and the developed model in the drying temperature range of 60-120 °C.

Table 7: Drying kinetic parameters of hog fuel samples with initial moisture content of ~70%.

Drying temperature (°C)	Drying rate constant, k (min^{-1})	Activation energy, E (kJ mol^{-1})	Pre-exponential factor, k_0 (min^{-1})
60	0.03534	30.717	401.902
80	0.05025		
100	0.08662		
120	0.14636		

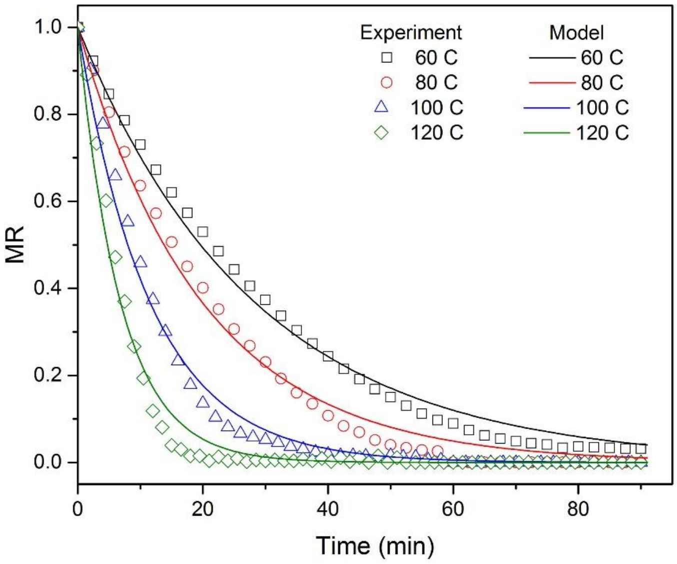

Figure 10: Comparison of experimental drying data with modelled data.

3.2 PHYSICAL PROPERTIES MANAGEMENT

3.2.1 Particle size

Grinding reduces the dimensions of a particle, increasing the particle's specific surface area (i.e. the ratio of its surface area relative to its mass). The same relationship holds for a bulk of particles that are grinded: the surface area of the solids increases in a given volume of bulk particles. Therefore, the rate of heat and mass transfer between the particles and the surrounding gas enhances with a reduction in particle size. Due to the increase in surface area for an enhanced heat and mass transfer, grinding is an essential pre-treatment in all thermal conversion processes. A significant number of published studies shows that a decrease in particle size in pyrolysis process reduces the char yield in improves liquid yield [33-35, 52, 70-74]. For fast thermal conversion processes, such as fast pyrolysis, the role of particle size is even more crucial. Most of the published data recommend a range of particle size of 1-2 mm for fast pyrolysis [53, 72, 73, 75-78].

Furthermore, size reduction is an essential operation for preparing biomass for the production of pellets. However, grinding to smaller particles requires more energy input. For example, size reduction ranks second in terms of energy consumption after drying in a pelleting operation. The major challenge in sizing and operating a grinder is the difficulty in predicting the performance of a grinder and the quality of product due to the variability in structure and composition of the biomass feedstock. As a result, grinders are often over-designed to handle a wide range of biomass species, leading to disproportionate equipment size and operating costs.

3.2.2 Particle shape

The American Society of Agricultural and Biological Engineers (ASABE) specifies mechanical sieving (S424.1, 2007) as a standard method to determine the particle size distribution of biomass particles. Particles pass through the sieves based on their width. The length of particles does not influence the reported mean and distribution of particle size. Similarly, mechanical sieving may not differentiate among irregular-shaped biomass particles, and therefore misses many particles' information such as the particles' length, shape etc.[68]. Machine vision is a practical alternative to mechanical sieving that determines the actual dimensions and shape of single particles [79]. Machine vision is not subjective and is repeatable over the same image [80, 81]. However, since image analysis is two-dimensional, it omits the thickness of the particles [80, 82].

Literature established a series of shape factors to describe and evaluate the shape, form and structure of particles. Riley [83] introduced the notion of projected shape factor, based on width, length, and diameter of an inscribed circle or of a circumscribed circle. In a comprehensive review of shape factors, Trottier and Dhodapkar [84] defined various shape factors: they defined the shape factors using two or three dimensions of an individual particle and categorized the shape factors using four parameters: (1) dimensional ratios, (2) sphericity that indicates the deviation of a particle from a sphere or circle, (3) roundness and circularity that show angularity and sharpness of corners, and (4) roughness that shows surface structure. Figure 11 illustrates the concept of various shape factors associated with a single wood particle.

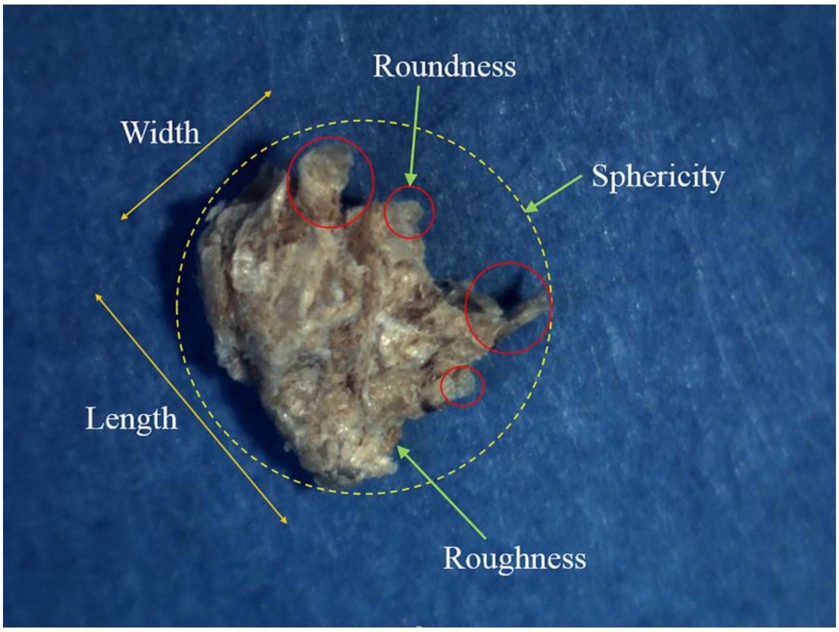

Figure 11: Particle shape characterization in terms of dimensional ratios, sphericity, roundness and surface roughness (source: Rezaei et al. [85]).

3.2.3 Case study: Upgrading wood residue for gasification

As part of GHG emission reduction efforts, the University of British Columbia (UBC) installed an updraft biomass gasification system at the Point Grey Campus in Vancouver in 2012. The gasifier was designed to provide up to 10% of 40 MW campus electricity and heat. UBC has a limited term contract with a waste wood recycling yard (depot) to deliver woodchip fuels to the gasification plant.

Table 8: List of feedstock specifications for the biomass gasification plant.

Parameter	Value
Length (> 76 mm or 3”)	none
Fines (6 mm or 1/4”)	< 25%
Moisture content	10-55%
Volatiles content	70-85%
Fixed carbon content	15-25%
Ash content	<10%
Calorific value	>19.1 MJ kg^{-1}
Carbon	48-52%
Hydrogen	5-6%
Oxygen	36-44%
Nitrogen	< 0.5%
Sulphur and chlorine	< 0.025%
Greens	trace amount
Metals, chemicals, glue, paint	none

The depot is located in Langley, a township 50 km from the gasification plant. The sources of feedstock are urban wood waste generally obtained from within a 100 km radius of depot. The urban wood waste consists of two classes of materials: woody scraps from construction and demolition (C&D), and tree trimmings collected from Metro Vancouver's curb sides and landfills. In Metro Vancouver 54% of the C&D materials (595 000 tonnes) are comprised of woody waste.

The UBC gasification plant consists of a fuel chip receiving area, feeding system, silo for temporary storage, gasifier, thermal oxidizer, boilers for steam production and an internal combustion engine (GE/Jenbacher). The fixed bed updraft gasifier "Nexterra" (4.9 meters diameter, 4.9 meters tall) was designed to produce about 7 MW thermal energy in the form of steam with the use of boiler. Table 8 lists the Nexterra's initial specifications for the physical and compositional make-up of the biomass fuel. A preliminary analysis showed that the feedstock from recycled clean wood in Metro Vancouver meets these properties. The estimated annual fuel chip for the Nexterra gasification is estimated at about 13 000 dry tonnes.

The objective of this case analysis was to quantify seasonal variations in quality characteristics of feedstock, plausible causes of the variations in feedstock quality, and the impact of feedstock quality on systems reliability and steam output. The UBC gasifier with its fuel supply system provides a real case study and an example of ways to improve the design and reliability of future biomass supply systems. This study was conducted by Biomass and Bioenergy Research Group (BBRG) at UBC.

Overview of fuel supply and gasification system

Figure 12 show a schematic diagram of fuel supply and pre-processing operations at the Clover Fuel Limited (depot). The depot is a privately owned commercial operation that handles more 200 000 tonnes of recycled wood annually.

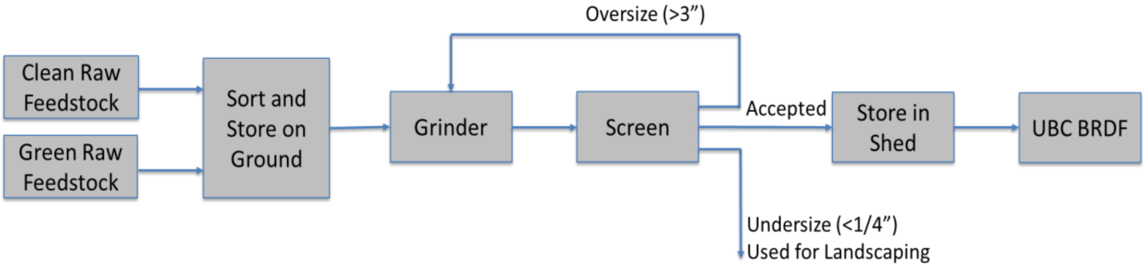

Figure 12: Processes inside the depot.

The wood supply to UBC is less than 7% of the depot's total volumes of wood handled annually. The depot collects the urban biomass from 114 sites using collection bins placed at each site. When these bins are full, the depot dispatches a truck to pick up the full bin and replace it with an empty bin. The City of Vancouver also sends green tree trimmings to the depot. Roughly 35% of suppliers (on a total of 114 suppliers of clean wood material) to the depot are located less than 20 km away from the depot; 40% of the suppliers are located at a distance between 20 to 40 km, and a few of the suppliers are further than 40 km. About 20 suppliers provide 80% of the clean wood, and about 90 suppliers provide the remaining 20% clean wood. Clean waste wood come from pallets from manufacturing and handling operations and scrap lumber from sawmills. Most of the clean wood originated from lumber grade wood and therefore had low variability in their properties. Table 9 lists typical data taken from clean dry wood and city trimmings as these materials were unloaded at the depot yard. For clean wood, the average moisture content was 16.7%, ash content was 0.85% and calorific value was 19.1 MJ kg^{-1}. For green biomass, the moisture content was measured at 40.2% while ash content and calorific value were 0.91 % and 18.9 MJ kg^{-1}, respectively. For clean wood, the coefficient of variation (CV) was 23% for moisture content (wet mass basis), 35% for ash content and 3% for calorific value. For green wood, the corresponding CV values were 9%, 29%, and 3%, respectively.

Table 9: *Feedstock properties (moisture content, ash content and calorific value) of raw clean and raw green materials measured at the depot. Number of samples n, standard deviation and coefficient of variation (CV) are listed under the mean values in the form of (CV, STD).*

Category	Moisture Content (% wet basis)	Ash Content (% dry basis)	Calorific value (MJ kg^{-1})
Clean wood (n=10)	16.7 (%23, 3.8)	0.85 (%35, 0.30)	19.1 (%3, 0.6)
Green wood (n=8)	40.2 (%9, 3.6)	0.91 (%29, 0.27)	18.9 (%3, 0.6)
Blend of material at the plant n=10)	31.0 (%23, 7.2)	0.83 (%20, 0.17)	19.2 (%2, 0.32)

Size reduction at depot

A commercial tub grinder for wood, Hogzilla Model WC-1354P (CW Mill Equipment Co., Inc. Asbetha, KS - www.hogzilla.com) comminuted the biomass to small pieces. The grinder was equipped with a rotating wheel on which a set of swinging hammers (9.4 mm x 16.5 mm) was installed. The curved housing around the rotor consisted of two removable rates. The square openings on one of the grates were 76 mm and on the other were 127 mm. The ground chips that passed through the grates were conveyed onto a set of three 3.5 mm thick oscillating screens (1.8 m x 3.5 m). The top screen had rectangular holes 38 mm x 54 mm; the bottom screen had round 7 mm holes. The bottom tray was a solid steel plate to separate fines from the mixture. The large pieces were overs coming off from the top screen. The material left over the middle screen were the mid-size destined for the gasification plant.

Grinding tests with three screening configurations were performed. For each grate configuration, samples at 4 different sampling points were collected. One sample was taken from the ground materials immediately after the grinder (S11) but before the screeners. The other three samples (S12, S13, S14) were taken as undersize, midsize and oversize streams after screening. The sampling was repeated for grate configuration 2 (S21, S22, S23, S24) and for grate configuration 3 (S31, S32, S33, S34). Altogether 12 unique operating conditions were evaluated. Three replicated samples were collected during each sampling event. Each batch of screened samples was further analysed in the lab using a stack of sieves.

Table 10: *Measurements of feedstock properties from the grinder and after the industrial screens. The properties measured include ash content, calorific value and moisture content.*

Screening configuration and sampling points		Moisture content (%)	Ash (%)	Calorific value (MJ kg^{-1})
Two 76 mm grates	Ground not screened	44.5	0.9	19.1
	Screened undersize	61.3	6.6	19.0
	Screened midsize	43.5	0.6	18.6
	Screened oversize	39.9	0.8	18.6
Two 127 mm grates	Ground not screened	42.2	0.9	18.8
	Screened undersize	61.3	10.6	17.7
	Screened midsize	41.9	0.9	18.2
	Screened oversize	35.9	0.8	18.5
76 mm grate + 127 mm grates	Ground not screened	49.9	0.8	18.8
	Screened undersize	51.4	4.7	18.5
	Screened midsize	41.9	0.4	18.8
	Screened oversize	39.7	0.8	18.4

Measurements at the depot

The data in Table 10 indicate the ash content of the undersize feedstock fraction was several times higher than the ash content in mid- and oversize fractions. The very high ash content in the smaller feedstock fraction (from 4.7% to 10.6%) must have originated from soil contamination. The ash content of the midsize and oversize was less than 1%. This reinforces the fact that the source of ash is from contamination with soil.

Moisture content of particles varied for various grinder configurations and screening streams. The result shows that the undersize fraction had biomass particles with the highest moisture content (55-60%), compared to the other output streams with moisture content ranging from 35-45%. This could be attributed to the greater surface area of the smaller particles that favour water absorption. This implies that if the undersize biomass fraction is removed, then the average moisture content of the resulting biomass will be lower.

Figure 13 shows the size analysis for the unscreened and mid-size particles after the screeners. The specifications for the Nexterra equipment ask for the percentage of particles smaller than 6.7 mm to be less than 25% (Table 8). Data from sieve analysis showed that screening ground biomass to three fractions improved the size distribution in each fraction. The unscreened stream had 21-26% of mass fraction smaller than 6.7 mm. The midsize stream fraction improved from 62% to 75% fraction of the biomass. The percentage of large size (>25 mm) also decreased in the screened fraction. Within the undersize stream, about 15% of the materials were smaller than 0.5 mm (data not shown).

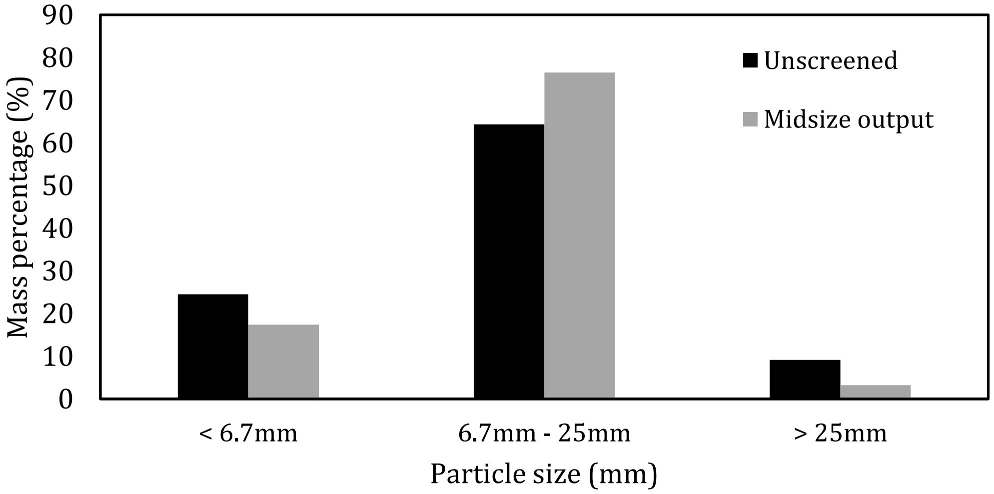

Figure 13: Distribution of particle size in ground unscreened feedstock and in the midsize fraction after screen.

Measurements at the gasification plant

The feedstock was sampled daily at UBC over two years (2012 to 2014). The measured properties included moisture content, ash content, wet bulk density, calorific value, and percentages of undersize and oversize materials. Roughly 870 loads of feedstock were tested, and methods of characterizing wood feedstock characteristics and quality were based on CEN standards.

The average and variation of daily measurements at the delivery point showed that moisture content had the largest variation among the measured feedstock properties. The average moisture content of the green materials was high at about 40.2%, and the average moisture content of clean dry material (Table 9) was 16.7%. The average delivered feedstock had a moisture content of 31% with a standard deviation of 9% resulting in a wide coefficient of variation (cv= 30%). The moisture content of the blended feedstock had the highest variability.

Steam production

The UBC gasification plant records operational parameters (biomass feeding rate to the gasifier, bed temperature, operating hours, and the amount of steam produced over time. Fortunately we were given access to the plant's database. The correlation between the biomass feeding rate (kg h^{-1}) and steam production rate (kg h^{-1}) was about 0.79. The operating gasifier temperature seemed to show some effect on steam flow but moisture content had a definite negative correlation with steam flow. Figure 14 shows the spread of data with a negative relation between the normalized steam (kg steam per tonne of dry biomass) and moisture content, with a correlation coefficient of -0.73. This trend was evident for moisture contents higher than 20%. For every tonne of fuel, the steam generated decreased from 5000 kg to 3600 kg per tonne of dry biomass when the moisture content of biomass increased from 20% to 50%. However the spread of data shows that the moisture content is not the only factor driving the heat output of the gasifier.

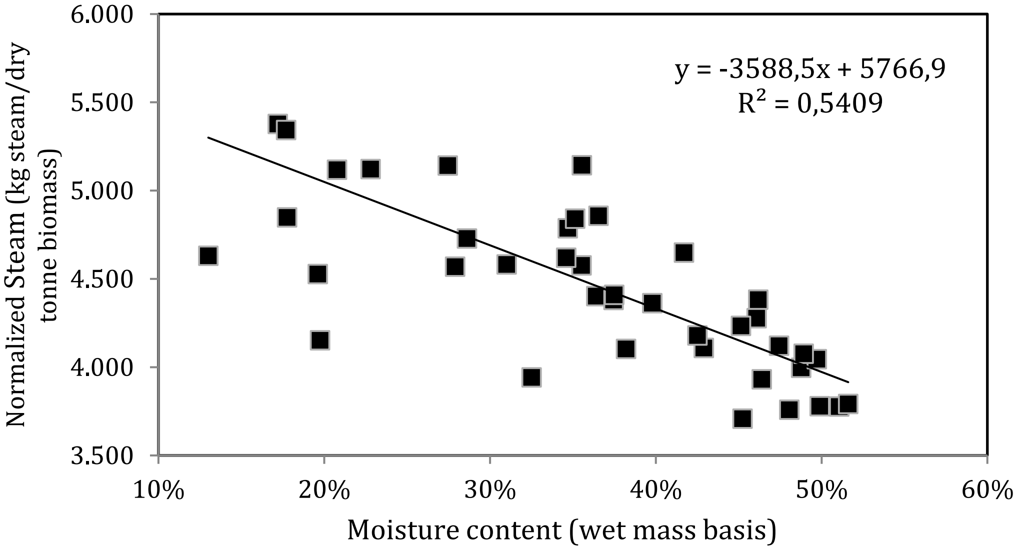

Figure 14: Relationship between normalized steam and moisture content.

Figure 15 is a line plot of monthly feedstock supply to the gasifier and steam produced in the boiler. Both biomass supply and steam production varied over time, with steam production following closely the ups and down in biomass feeding to the gasifier. Initially the amount of steam produced was less than the expected output from the quantities of biomass fed. But the system's performance improved gradually. The sharp reductions in the biomass supply and steam production were due to the shutdown of the plant. The overall percent of operating hours increased from 60% to 96% from July 2012 to December 2014.

The major quantitative factors in improving the performance of the gasifier as related to feedstock were particle size and moisture content. Off-spec feedstock size caused frequent stoppage in the in-flow of feedstock to the gasifier. Oversize particles greater than 76 mm led to bridging in storage tank and blockage of the screw conveyor feeding the gasifier. Moisture content has been considered as the major parameter effecting the steam generation. Other operational parameters suggested by the plant operators included volumes of combustion air oxygen fed to the gasifier, bed temperature, syngas temperature, oxidizer temperature, feed water temperature, stack O_2, pile height, ambient air, firing rate, bin speed and ID fan speed.

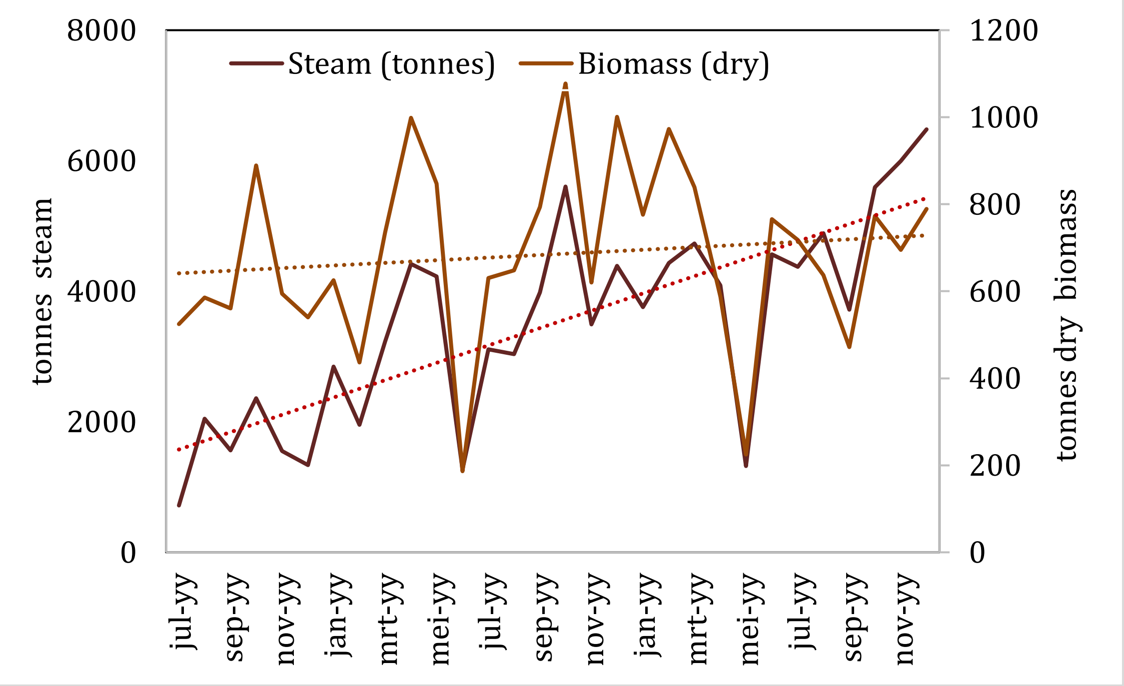

Figure 15: Average rate of steam production from April 2012 to March 2015.

Conclusions

Our analysis of feedstock properties and operating conditions of the commercial gasifier showed that blending of feedstock of differing moisture contents would increase the variability in the feedstock delivered in the absence of a dryer. Also, soil contamination during handling in depot increases the ash content in the fuel. Size reduction and fractionating fuel using three screens is effective in having a larger fraction of uniform feedstock size. Grates hole sizes and their combinations around the hammer mill housing did not have major effect on fractionation. Large variations in steam production are due to variations in feeding and probably due to change in moisture content of the feedstock. A cost/benefit analysis for the UBC gasification plant is provided in the financial analysis section of the report.

3.2.4 Biomass Handling and Flowability

Predicting the pressure drop across a bed of particles [86], hoppers, screws, pneumatic transportation in pipe lines and feeding systems in thermochemical conversion processes are industrial examples that show the importance of flowability of the biomass particles. In a flowing stream, biomass particles are cohesive, stick together and cause a variety of flow issues. Bridging of biomass particles in the feeding system of a gasifier is a common industrial problem [87, 88]. The studies show that physical properties such as particle size, particle shape, density and surface roughness affect the flow properties of particles [68, 89-93].

The analysis methods applied to characterizing the flowability of minerals can be applied to characterize biomass particles as well [68, 91, 92, 94-101]. Comparing the loose and tapped bulk densities gives a quick estimation of bulk compressibility [96, 97]. A larger difference before and after the tapping process implies the higher tendency of the particles to make a compact bulk. Particle size, particle shape, particle density, the way that particles are arranged in the bulk and friction among the particles influence the bulk density [96, 97, 102]. The dimensionless numbers of "Hausner ratio (HR)" and "Carr-compressibility index (CCI)" quantify the bulk compressibility [68]. Although these numbers represent similar concepts that compare the bulk density before and after tapping, both are used in the literature to evaluate the relative flowability of materials.

Hausner ratio is the ratio of bulk density after tapping to bulk density before tapping [68, 83]:

$$HR = \rho_{tb}/\rho_{lb}$$

where ρ_{lb} (kg m^{-3}) and ρ_{tb} (kg m^{-3}) are loose and tapped bulk density, respectively, of ground biomass particles. The Carr-compressibility index is expressed as follows [68, 83]:

$$CCI = (1 - \rho_{lb}/\rho_{tb}) \times 100$$

In a comprehensive fluidization review, Geldart [103] showed that the particles with HR less than 1.25 are free-flowing and easy to fluidize whereas particles with HR greater than 1.4 are cohesive and difficult to fluidize. The CCI values between 5-15, 12-16, 18-21, and 23-28% indicated excellent, good, fair, and poor flowability, respectively. Tannous et al. [68] showed that HR and CCI values of ground Douglas-fir particles decreased with increasing particle size; smaller particles also packed more with tapping and had poor flow properties compared with the larger particles.

Angle of repose (AOR) is another index to evaluate the flowability of particles. AOR is the angle of piled particles with respect to the horizontal surface. AOR indicates the failure properties of free flowing bulk under gravity [93]. AOR depends on the particle size, particle shape, cohesiveness and stickiness of particles. An increase in particle size is accompanied by a decrease in the cohesiveness [68, 94]. It is suggested that an AOR below 30° shows good flowability, 30-45° some cohesiveness, 45-55° true cohesiveness and above 55° very high cohesiveness [94]. In some other studies [95, 99, 104], AOR of 40° was identified as the criteria for free flowability. Wu et al. [89] analysed the angle of repose for wood chips (lengths of 20, 40 and 100 mm) and wood pellets (diameters of 6, 8 and 12 mm), and showed that wood pellets with AOR values of 35-38° were more flowable than wood chips with AOR values of 44-46°. Although AOR is an inexpensive and quick method to compare the flow properties of particulate materials, it is sensitive to the measurement procedure [105] and scale of the experiment [94].

In an experimental study at Biomass and Bioenergy Research Group, UBC, Rezaei et al. [85] investigated the effects that particle size, particle shape and particle density have on flowability of bulk. Figure 16 depicts that HR and CCI values decreased with particle size. Larger particles had less tendency to make a compact bulk. Smaller particles could fill small pores in the bulk and increase the bulk density. The same trend was also observed for the pellet particles, though the variation in the compressibility of pellet particles was less than chip particles.

In addition to the particle size, the level of bulk compression seems to be highly dependent on the shape of the particles. Greater length promoted the bulk compressibility. Chip and pellet particles subject to the 3.2 mm grinder screen had similar particle size distribution. Yet, the chip particles compacted by 50%, which is significantly more than the pellet particles, which compacted by 26%. Upon comparing the compressibility results, particle shape was confirmed to be more important than particle size in tapping compressibility.

Figure 17 shows the angle of repose (AOR) values of both chip and pellet particles. The AOR of chip particles was seen to decrease from 61.0° to 45.9° when grinder screen increased from 3.2 to 25.4 mm. It agrees with the literature that reported an increase in particle size is accompanied by a decrease in cohesiveness and hence AOR [68, 94]. Small particles have a higher specific surface area that boosts the contact and cohesiveness among the particles. Due to the similar particle size distribution of pellet particles, the AOR values of pellet particles were practically independent of grinder screen size. Similar to the results pertinent to compressibility, the effect of particle shape was more significant than particle size. Chip and pellet particles ground with 3.2 mm grinder screen had AOR values of 61.0° and 48.0°, respectively. Their different particle shapes could explain the difference between AOR of chip and pellet particles that have similar particle size distribution. More spherical pellet particles tend to roll over on each other and flow easier than longer and thinner chip particles that show a high level of interlock and poor flowability (Table 11).

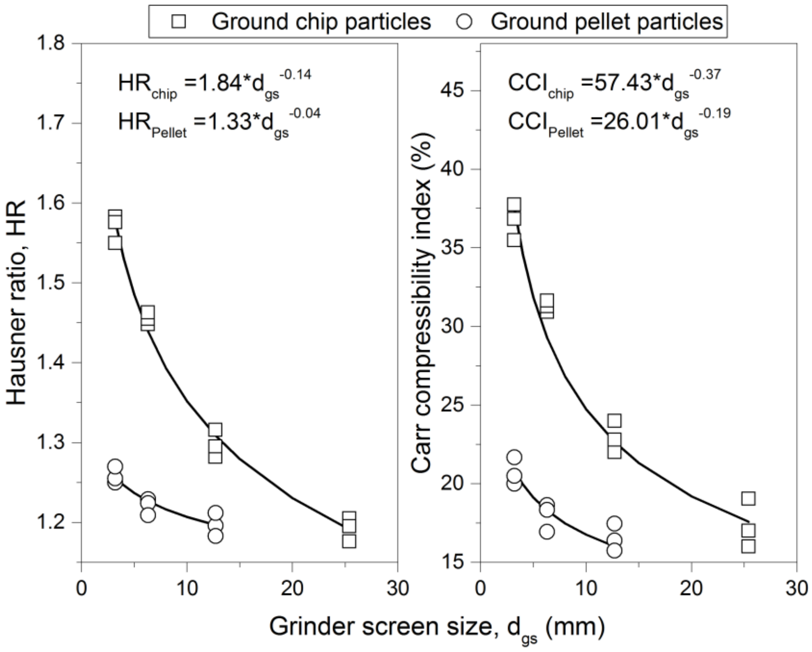

Figure 16: Hausner ratio (HR) and Carr-compressibility index (CCI) of ground chip and pellet particles.

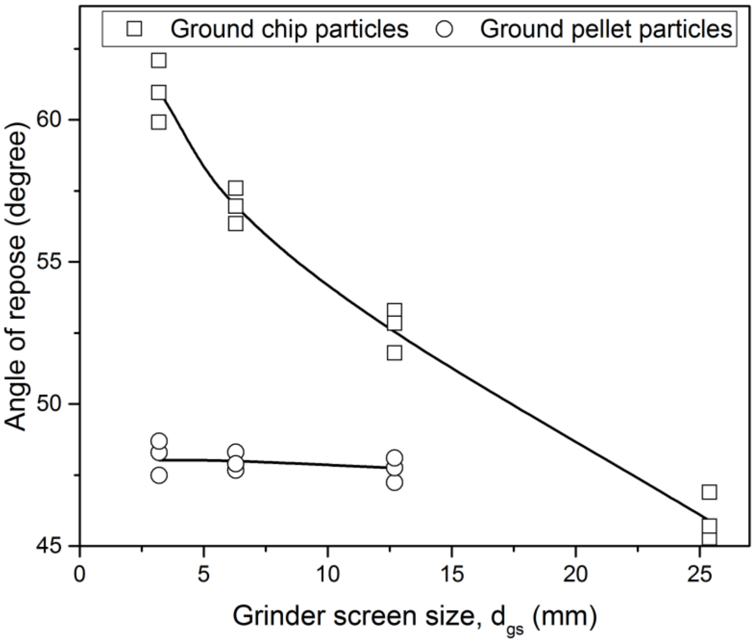

Figure 17: Angle of repose (AOR) of ground chip and ground pellet particles.

Table 11: Flow properties of ground chip and ground pellet particles (mean±standard error).

Material	d_{gs} (mm)	Density (g cm^{-3})			Bed porosity (%)	Flow class (HR/CCI)	Angle of repose (degree)
		Pycnometer	Loose bulk	Tapped bulk			
Ground chip particles	3.2	1.33±0.01	0.13±0.00	0.22±0.01	89.6±2.1	Poor/Poor	61.0±1.1
	6.3	1.32±0.01	0.14±0.01	0.21±0.01	89.1±1.9	Poor/Poor	57.0±0.6
	12.7	1.26±0.01	0.14±0.01	0.19±0.01	88.5±1.1	Good/Fair	52.5±0.7
	25.4	1.05±0.01	0.16±0.01	0.19±0.01	85.0±1.0	Excellent/Good	45.9±1.4
Ground pellet particles	3.2	1.43±0.01	0.39±0.00	0.49±0.01	72.7±0.9	Good/Fair	48.0±0.7
	6.3	1.42±0.01	0.40±0.00	0.49±0.01	71.6±1.1	Excellent/Fair	48.0±0.3
	12.7	1.40±0.01	0.42±0.00	0.50±0.01	69.9±0.7	Excellent/Good	47.6±0.3

3.3 ASH CONTENT MANAGEMENT

Minerals are present in all biomass species, in a much lower amount than carbon, hydrogen and oxygen elements. Minerals exist on the biomass surface, or within the material as biogenic characteristics. Surface minerals come from contacts with soil during harvest and/or transportation. Agricultural biomass has much more mineral contents than woody biomass. Mineral content results in a higher ash production after the thermal conversion processes. The biochar typically contains up to 90% of the biomass minerals [106]. Biomass-fired boilers experience serious fouling and corrosion problems due to elements such as potassium, chlorine, sulphur, silicon, calcium and magnesium [107]. Ash shifts the size distribution of the char to smaller sizes, which makes recovery from the gas stream challenging. In a pyrolysis process, incomplete separation of char and volatiles causes continuous secondary reactions in the liquid phase [52, 108, 109] that accelerate the aging phenomenon and contribute to its instability [110, 111]. Aging phenomena is defined as a slow increase in viscosity bio-oil resulting from secondary reactions [52]. Minerals also have a catalytic effect on the rate of secondary reactions [112, 113]. Secondary reactions reduce the desired part of volatiles (levoglucosan) and boosts the yield of non-desirable volatile components (hydroxyacetaldehyde) [114]. In the presence of minerals, levoglucosan breaks into unwanted compounds like acetic acid [115]. For example, an addition of 0.05 wt.% of NaCl to ash-free cellulose decreases the levoglucosan formation yield by a factor of 6 [116, 117].

One efficient pre-treatment to reduce the mineral content is washing the biomass with water, acidic and/or alkaline solutions. Washing biomass prior to pyrolysis may take away huge amounts of minerals from the biomass, up to 70% of the initial minerals [72, 118, 119]. However, washing with dilute acid and hot water results in a slight decomposition of hemicellulose [120], while washing with dilute alkali will disrupt lignin structure and solubilize the hemicellulose [121]. Figure 18 shows the effect of washing on demineralization process and the yields of gas, bio-oil, total liquid and char in pyrolysis of sugarcane bagasse. Das et al. [122] showed that the ash content could decrease from an initial value of 1.83% down to 0.03%. Washing with 5M HCl showed a negative effect on ash content and reduced the liquid yield drastically. The important point is the effect of washing on yield of total liquid compared to bio-oil. Total liquid contains bio-oil and aqueous solutions. All washing solutions declined the total liquid yield but the yield of bio-oil was boosted.

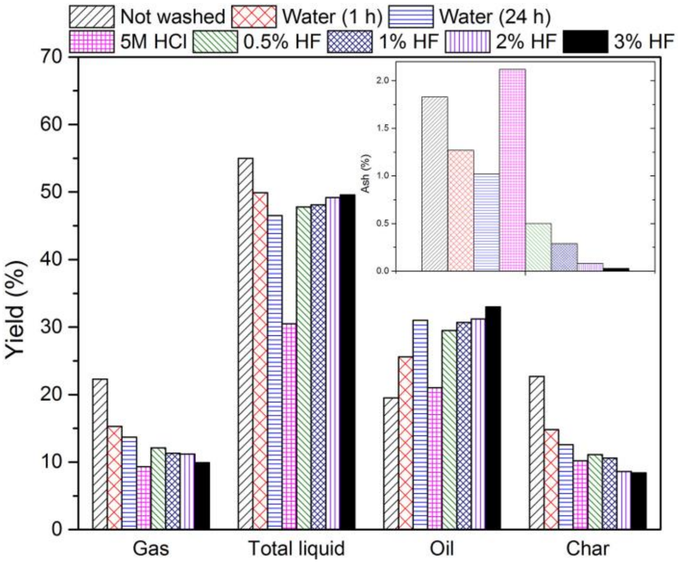

Figure 18: Effect of de-mineralization pre-treatment on ash content and pyrolysis products of

sugarcane bagasse pyrolysis (source: Das et al. [122]).

Table 12 shows an example of how different washing solutions can change the ash content, char and liquid yield and maximum biomass decomposition rate [123]. Washing increases the levoglucosan production 2-10 times, demineralize the biomass up to 98%, enhance liquid yield, lowered the char yield, shift up the decomposition rate and reduce the low molecular weight compounds in pyrolysis products. It is established that the washing solution's temperature is important. Deng et al. [124] showed that ash removal efficiency of candlenut wood rose from 8% at 303 K to 35% to 363 K. Mineral removal increased the higher heating value slightly, 16.53 kJ g^{-1} to 17.82 kJ g^{-1}; and the rate of devolatilization increased.

Natural rain and season of raining can also change the composition of minerals in biomass [125]. Rain water extracts potassium, chlorine and total ash. However, rain makes for a difficult working situation for machines, which can increase the total cost of process up to 30%. In addition, due to unpredictable rainfall, water washing is a more controllable process than natural rain-washing.

Table 12: Effects of various washing solutions on demineralization yield and further pyrolysis properties (source: Eom et al. [123]).

Washing solution	Demineralization yield (%)	Pyrolysis char yield (wt.%)	Volatile yield (wt.%)	T_p* (°C)
No washing	-	14.9	85.1	362
Hydrochloric acid (HCl)	69.3	11.8	88.2	366
Hydrofluoric acid (HF)	97.3	10.2	89.8	368
Deionized water	97.7	11.0	89.0	372
Tap water	98.2	11.4	88.6	376

**temperature at which the maximum decomposition rate happens*

3.4 PELLETIZATION

A whole wood chip is produced from chipping a tree parts, whereas pellets are produced from compacting sawdust (Figure 19). Table 13 lists the typical dimensions and density of wood chips and wood pellets.

Pelletized biomass is denser, has higher bulk and energy densities and has more homogenous physical properties than an unprocessed wood chip [126, 127]. The heating value of biomass improves from 10-11 MJ kg^{-1} for wood chips with moisture content of ~45% to 16-18 MJ kg^{-1} for wood pellet with moisture content less than 10%. Wood pellets provide a convenient form of biomass for its handling, storage and feeding to pyrolysis reactors [128, 129], and is compatible with existing facilities in the combustion plants [130, 131]. Although wood pellets are currently used mainly for oxidative combustion applications in boilers and pellet stoves, they may also become a potential feedstock for the pyrolysis operation to produce bio-oil.

Figure 19: Pine wood chips (left) and white wood pellets (right).

Table 13: Dimensions and density of wood chips and wood pellets (source: [77] and [6165])

Property	Wood chip	Wood pellet
Dimensions	Width=30-50 mm Length=50-100 mm Thickness=5-10 mm	Diameter=6.4 mm Length=3-30 mm
Density (g cm^{-3})	0.4-0.6	1.2-1.4
Bulk density (g cm^{-3})	0.2-0.3	0.6-0.7

3.4.1 Standards

Wood pellets can be used both in home and commercial applications, for example in small-scale stoves e.g. in private houses but also in large-scale electrical power plants to substitute coal. For these applications, it is important to have quality standards e.g. for dimensions, density, hardness and energy content. These standards enable fuel consumers to select the fuel grade best suited to their particular stove or furnace.

Table 14: Key specifications of graded wood pellets based on the CAN/CSA-ISO 17225 part 2 standards (source: www.nrcan.gc.ca).

Quality Parameter	Unit	Grade A1*	Grade A2*	Grade B*
Diameter	mm	6 or 8	6 or 8	6 or 8
Length	mm	3.15 - 40	3.15 - 40	3.15 – 40
Moisture	wt.%	≤ 10	≤ 10	≤ 10
Ash	wt.%	≤ 0.7	≤ 1.2	≤ 2.0
Mechanical durability	wt.%	≥ 97.5	≥ 97.5	≥ 96.5
Fine content	wt. %	≤ 1	≤ 1	≤ 1
High calorific value	MJ kg^{-1}	≥ 18.6	≥ 18.6	≥ 18.6
Bulk density	kg m^{-3}	600 - 750	600 - 750	600 - 750

Natural Resources Canada released the series of CAN/CSA-ISO solid biofuel standards in 2015 to standardize the following: terminology; specifications and classes; and test methods for raw and processed biofuel materials originating from forestry, arboriculture, agriculture, horticulture and aquaculture. The CAN/CSA-ISO 17225 Part 2 Standard classifies several grades of wood pellets based on the origins and source of raw materials (Table 14). Raw biomass used in the production of high-grade wood pellets, i.e. Grades A1 and A2 (residential or commercial applications), primarily comes from mill residues (including sawdust shavings and cut-offs) and stem wood. In addition to the above sources, Grade A2 allows for the use of logging residues and whole trees without roots.

The origin of the raw biomass impacts fuel specifications. For example, A1 grade wood pellets contain low ash and nitrogen contents, while Grade A2 wood pellets have slightly higher ash and nitrogen content. Grade B wood pellets are manufactured from more diverse sources, over and above those used for Grade A wood pellets, and can include bark, residues from thinning, pruning, and arboriculture operations in city parks, and chemically untreated used wood.

Table 15: Key specifications of graded wood pellets based on the ENplus standards (source: www.enplus-pellets.eu).

Property	**Unit**	**ENplus A1**	**ENplus A2**	**ENplus B**
Chlorine	wt.%	≤ 0.02	≤ 0.03	≤ 0.03
Sulphur	wt.%	≤ 0.05	≤ 0.05	≤ 0.05
Nitrogen	wt.%	≤ 0.3	≤ 0.5	≤ 1.0
Copper	mg kg^{-1}	≤ 10	≤ 10	≤ 10
Chromium	mg kg^{-1}	≤ 10	≤ 10	≤ 10
Arsenic	mg kg^{-1}	≤ 1	≤ 1	≤ 1
Cadmium	mg kg^{-1}	≤ 0.5	≤ 0.5	≤ 0.5
Mercury	mg kg^{-1}	≤ 0.1	≤ 0.1	≤ 0.1
Lead	mg kg^{-1}	≤ 10	≤ 10	≤ 10
Nickel	mg kg^{-1}	≤ 10	≤ 10	≤ 10
Zinc	mg kg^{-1}	≤ 100	≤ 100	≤ 100

The production of pellets starts with size reduction of the raw biomass source followed by drying. The material is then extruded under high pressure in pellet machines coming out as small cylinders typically with a 6 or 8 mm diameter, and a length of up to 40 mm. Small amounts of additives and binders can be blended with biomass material to improve the quality of wood pellets, though this is not common in Canada. A buyer or user of graded wood pellets should consider several quality characteristics; graded wood pellets conform to specific feedstock sources as well as the quality requirements as stipulated in the CAN/CSA-ISO 17225 Part 2 Standard. (Table 14).

The European certification ENplus (www.pelletcouncil.eu) for wood pellets was adopted in Canada in 2013 under the acronym CANplus (www.pellet.org). The ENplus and CANplus seals account for the whole wood pellet supply chain, from production to delivery to the final customer, to ensure high quality. Both ENplus and CANplus schemes define wood pellet quality classes following the ISO 17225 Part 2 Standard: A1, A2 and B. ENplus released the elemental standards of the graded wood pellets (Table 15).

Biomass pelletization process

Grinding biomass and applying a mechanical force to compact the material and create inter-particle bonding are the main steps for the densification. To produce biomass pellets, the biomass has to be processed depending on the feedstock quality.

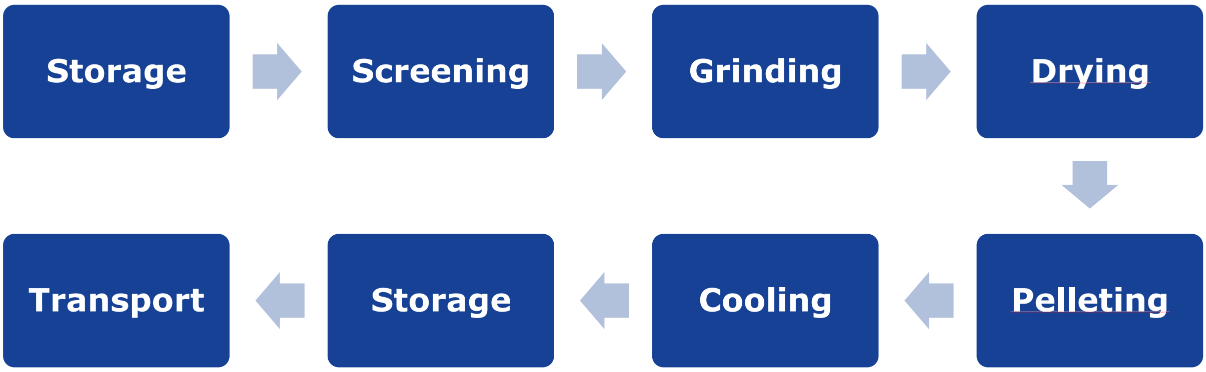

Figure 20: Flow chart of a typical pellet production process.

The flow chart of a pellet mill is shown in Figure 20. The delivered biomass e.g. sawdust, is stored open air or in a storage hall until it is used in the pellet plant. The first step in processing the feedstock is screening: pieces that are too big for the following steps are sorted out but also particles that are already small enough for pellet pressing are taken aside. This is usually done with screen sizes of 1/4" as maximum size for the big particles and 1/8" as minimum size for particles that have to be ground. The material on the 1/8" screen is passed through a hammer mill. After this step, the ground and the particles that passed the 1/8" screen are dried to 9% to 12% moisture content. The ground and dried material is brought to the pellet mill where the densification takes place. Finally, there is a further screening to separate fines from pellets. The produced pellets are stored in silos until it is transported to the customer.

3.4.2 Effect of process parameters on pelletization

Several process parameters have an influence on pelletization and pellet quality. These parameters are moisture content and particle size of the raw material, and temperature and pressure during pelletization.

Temperature

Gilbert et al. [132] showed the relation between temperature and pellet strength, Young's modulus and density applying a constant pressure, moisture content and particle size using switch grass as raw material.

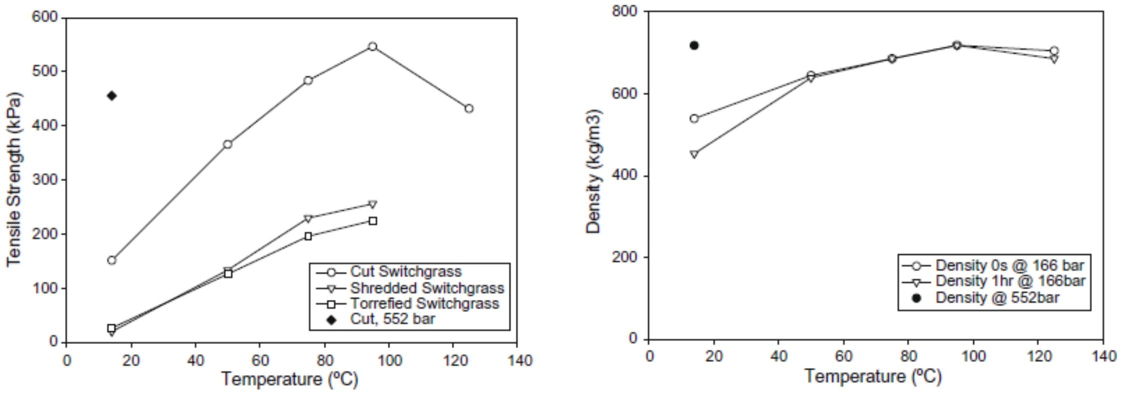

Figure 21: Relationship between Temperature and Tensile Strength and Temperature and pellet density (source: [132]).

Figure 21 shows for temperatures around 100 °C a maximum tensile strength and density applying the same pressure at each temperature. The temperature vs. density graph shows a lower density after 1h for temperatures below 50 °C and above 100 °C. The density does not change from 50 °C to 100 °C. An increasing density with increasing temperature from 50°C to 100°C is also seen on the results of Tumuluru et al. [133]. The tests were done using a single pellet press. The raw material was wheat distiller's dried grains. Stelte et al. [134] found a correlation between temperature and pressure required to reach a compression ratio of 2.5 for beech, spruce and straw. With increasing temperature between 20 °C and 180 °C, required pressure decreased significantly.

Investigations at the bonding mechanisms published by Stelte et al. [135] show that pellets made at 100°C have a greater mechanical strength compared to pellets made at 20°C, when other parameters are held constant. Filbakk et al. [136] considered that temperatures of 110 °C to 130 °C are needed to bind wood particles into a pellet due to the lignin softening at these temperatures.

Pressure

The pressure applied to the raw material to press a pellet is an important parameter for pelletizing as well. The pressure in the die of commercial pellet mills is caused by friction between wall and pellet. In a single pellet press this pressure has to be applied.

For example, Gilbert et al. [132] used a single pellet-making unit and applied pressure from 55.2 bar to 552 bar in steps of 55.2 bar: with increasing pressure, density as well as tensile strength increased (Figure 22).

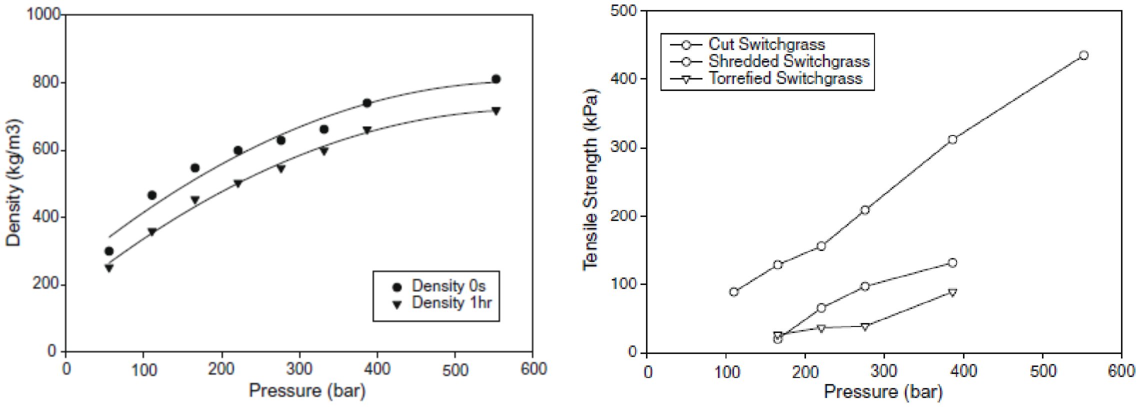

Figure 22: Relationship between pressure and density as well as pressure and tensile strength (source: Gilbert et al. [132]).

Stelte et al. [134] showed the dependence of pellet density on pressure applied during the pelletizing process at 20 °C in an 8 mm die. It appeared that the greatest decrease in volume is at pressures below 50 MPa. Pressures above 250 MPa resulted only in small changes in pellet density. Stelte et al. [135] set a maximum pressure of 200 MPa with a holding time of 5 seconds for his tests on bonding mechanisms at 20 °C and 100 °C.

3.4.3 Case study: Pelletization of forest residues from hemlock trees

The objective of this case study was to investigate pelletization of biomass from Hemlock trees from coastal forests of British Columbia. This study was conducted by Biomass and Bioenergy Research Group (BBRG) at UBC.

Various types of feedstocks for pelletization were tested (Figure 23):

- Chips from clean white stem wood without insipient rot;
- Chips from logs with a mix of clean outer shell white stem wood and incipient rot;
- Bark;
- Chips from clean white stem wood and from incipient rotted wood in a 85:15 mix.

Pellet measurements consisted of: pellet density, compressive strength and/or durability, ash content, heat value.

Figure 23: Samples for pelletization. From left to right: Hemlock clean white stemwood; Mix of clean white stemwood (85%)+ Rot (15%); Hemlock Bark

Pelletization

Batches of the dried sample at 12% moisture content were ground using a hammer mill (GlenMills Hammer Mill Type 1200, www.Glenmills.com). The mill had 6" wide feed opening and equipped with a 3 HP blower and a cyclone for dust collection. Two sizes screen 4 and 2 mm were available. All materials were easily ground on the grinder, though bark samples were the easiest to grind.

For making pellets from stemwood, several configurations were tried: moisture contents of ground sample from 8% to 19%, the grinder screen size from 2 to 4 mm, and feed temperature from 20-80°C. Pelletizing hemlock wood proved not to be as easy as pelletizing wood from other species such as pine and Douglas Fir. In a first try out we found it was easy to make pellets from ground Bark at moisture contents of 10-12%. But we had difficulty making pellets from Stemwood and Stemwood + Rot samples at moisture contents of 10-12%. Roughly 45 pelleting runs were made with a combination of these conditions. Only at high moisture content of 16-19% was it possible to make reasonable pellets from Stemwood and Stemwood + Rot. To make pellets from Stemwood + Rot, we followed a combination of factors similar to those used for Stemwood. It was much easier to make pellets from bark samples even at low moisture contents in the range of 10-14%. However, bark pellets were of lower durability than pellets made from Stemwood and the mix of Stemwood + Rot. Figure 24 shows resulting pellets.

As shown in Table 16, the average diameter of Bark pellet samples were slightly larger than the Stemwood and that of the mix Stemwood + Rot. This may indicate the Bark pellets expanded upon exit from the pelletizer. The range of individual pellet density was similar to the density of commercial pellets. Coefficient of variations indicated a large variability among length and mass of individual pellets.

Table 16: Dimensions, mass, volume, and density of individual pellets from 6 pellets make from each of the samples Stemwood, Stemwood+Rot, Bark. D= diameter in mm, L=length in mm, m=mass in g, b=specific density in g cm^{-3}

	Stemwood				**Mix Stemwood + Rot**				**Bark**			
	D	**L**	**m**	**b**	**D**	**L**	**m**	**b**	**D**	**L**	**m**	**b**
Avg	6.33	39.0	1.5	1.2	6.24	37.4	1.4	1.3	6.49	26.2	1.0	1.2
Min	6.32	31.0	1.2	1.2	6.13	22.1	0.8	1.2	6.38	22.1	0.8	1.0
Max	6.33	45.0	1.6	1.3	6.34	45.9	1.8	1.3	6.63	30.9	1.2	1.3
Stdev	0.01	7.0	0.3	0.0	0.08	8.6	0.3	0.0	0.10	4.1	0.2	0.1
CV%	0.1	17.8	19.5	1.8	1.3	22.9	23.5	3.1	1.6	15.7	16.2	8.5

Table 17: Loose bulk density of pellets.

	Stemwood		Mix Stemwood + Rot		Bark	
	Mass (g)	Density (kg m^{-3})	Mass (g)	Density	Mass (g)	Density (kg m^{-3})
Avg	242	719	232	689	237	704
Min	230	684	214	635	213	635
Max	247	734	257	765	271	806
Stdev	7	20	18	53	24	72
CV%	3	3	8	8	10	10

Durability of pellets

The durability of pellets is measured by the DURAL tester developed at the University of Saskatchewan for testing alfalfa pellets and cubes [137]. The device consists of a sharp blade rotating inside a canister. A sample of pellets weigh 50-100 g are cleaned using a sieve with mesh number 3.35 mm, weighted and placed in the machine canister. The impeller speed is set to 1615 rpm and run for 30 s. The treated sample is passed through the 3.35 mm screen. The sample left on the mesh is weighed (W_1) and loaded into the Dural tester for durability test. After the completion of the machine run, the contents of the canister are emptied on sieve 3.23 mm to remove any small particles. The samples remained on top of the mesh are weighed (W_2).

Durability is defined as following equation:

$$Durability = \frac{W_2}{W_1} \times 100$$

where W_1 is the initial weight of the pellets (g) and W_2 is the final weight of the sample after the machine run.

Table 18 shows the moisture contents of the ground feed at the time pelleting and the moisture content of the pellets at the time of durability measurements. Durability of pellets measured using DURAL can be converted to durability of pellets for the ASABE and ISO 14225 tumbler using the following equation $D_{tumb}=0.089\ (D_{dural}) + 91.97$

Table 18: Durability (DURAL Scale) of pellets.

	Stemwood			**Mix Stemwood + Rot**			**Bark**		
	Feed mc (%)	**Pellet mc (%)**	**Durability (%)**	**Feed mc (%)**	**Pellet mc (%)**	**Durability (%)**	**Feed mc (%)**	**Pellet mc (%)**	**Durability (%)**
Avg	16.1	6.2	85.5	17.2	6.6	82.6	13.8	6.8	56.3
Min	16.1	6.2	82.9	16.0	6.4	72.9	12.1	6.6	38.8
Max	16.1	6.2	87.3	18.5	6.8	92.3	15.5	7.0	74.1
Stdev	0.0	0.0	1.3	1.3	0.2	8.2	1.7	0.2	16.1
CV%	0.0	0.0	1.6	7.4	3.2	9.9	12.4	2.8	28.6

Calorific value of pellets

Table 19 lists the measured heat value of pellets. Bark had the largest heat value at 20 MJ kg^{-1} followed by the heat value of the Mix Stemwood + Rot at 19.6 MJ kg^{-1} and that of the Stemwood at 19.1 MJ kg^{-1}.

Table 19: Calorific value of pellets in MJ kg^{-1}.

	Stemwood	Mix Stemwood + Rot	Bark
Avg	19.1	19.6	20.0
Min	19.5	19.4	19.9
Max	18.8	19.9	20.3
Stdev	0.3	0.2	0.1
CV%	1.8	0.9	0.7

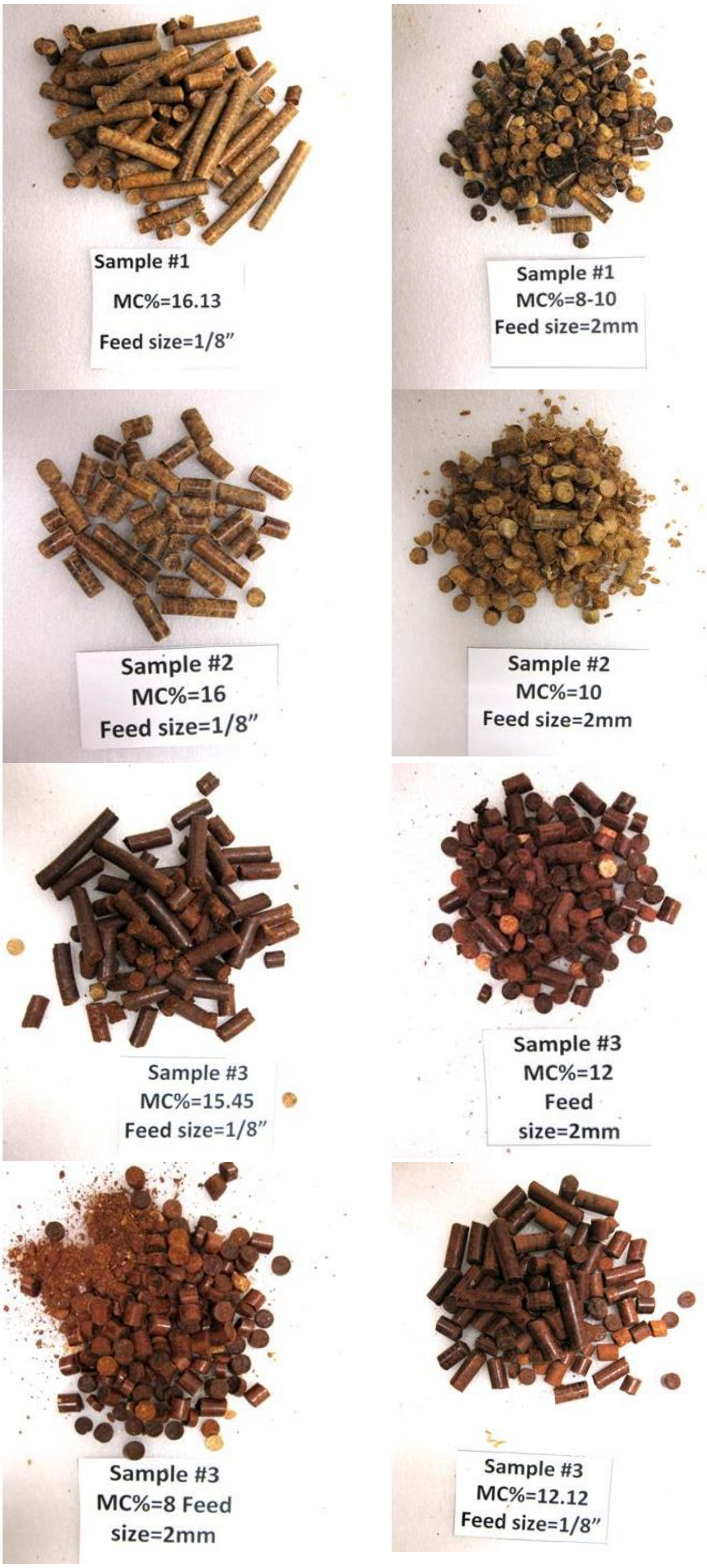

Figure 24: Pellets made from Hemloc samples: Sample 1 (Stemwood), Sample 2 (Stemwood+Rot), Sample 3 (Bark).

3.5 FINANCIAL ASPECTS AND COST SAVINGS OF PRE-TREATMENT PRACTICES

Pre-processing of biomass usually takes place between the upstream biomass production processes (e.g. harvest, collection and transportation) and the final conversion processes (e.g. combustion). Inclusion of pre-processing operations in biomass supply chains will usually add to the cost of biomass delivered to the bio-conversion facility. However, pre-processing operations can also provide cost savings in upstream and downstream storage, transportation, handling and conversion operations. On the one hand, a dense feedstock with good flowability characteristic can reduce handling and transportation costs; on the other hand, a feedstock with low moisture content, low ash content, and consistent particle size distribution can increase the yield of the final production at the conversion process.

The cost of pre-processing operations and the potential savings in the supply chain dictates the decision on whether to invest in these operations. The type and size of the pre-processing operations mainly depend on the fuel specifications of the end users (e.g. small boilers, large bio-conversion facilities).

In this section, financial aspects and cost/benefit analysis of pre-processing operations are discussed, notably using case studies of a commercial-scale wood pellet plant and the UBC gasification plant discussed earlier.

3.5.1 Case study: Financial aspects of pre-processing operations at a commercial-scale wood pellet plant

A typical wood pellet plant is a collection of pre-processing operations that manufacture a drop-in feedstock that is ready to use for downstream bio-conversion processes. To estimate the operating costs of the pre-processing operations, a commercial-scale wood pellet plant from British Columbia is studies here. A cost analysis is provided for a commercial wood pellet plant that covers the cost of drying, grinding, pelletization, cooling, screening, bagging and conveyors, based on the work of Mobini et al. [138]. The pellet plant operates seven days a week and 24 h a day (365 days per year) with 20 tonne hr^{-1} of nominal capacity. Sawdust is processed in a drum dryer and is fed into the hammer mill while shavings bypass the dryer and are directly fed to the hammer mill. The required heat for the drying process is generated in a 16 Mbtu furnace that burns wet sawdust. Ground materials are processed with four pelletizers and are fed into the coolers. After separating the fines in the shaker screens, the wood pellets are stored in the storage bins or packaged and then transported to the customers by railcars or trucks.

The general input data and assumptions regarding the pellet mill are given in Table 20, and *Table 21* shows the capital costs and annualized costs of the pre-processing operations in the wood pellet plant. Specifications of the equipment are shown in *Table 22*.

Table 20: The pellet plant input data and assumptions [138]

Parameters	Values
Nominal throughput	20 tonne hr^{-1}
Working hours/days	24 h 365 days a year
Electricity cost	79 USD MW hr^{-1}
Annual interest rate	8%
Cost of spare parts, lubricants, and other consumables	6 USD $tonne^{-1}$
Personnel needs and salary	14 full-time personnel, with the annual cost of 48 k USD per person, operating the plant in three shifts. Also, two foremen and a supervisor are employed that cost 59 k USD and 71k USD per person, respectively

Table 21: Capital cost estimation for the pellet plant (Mobini et al. [138]). All values were converted from Canadian Dollars for the reference year 2013 (CAD_{2013}) to USD_{2016} .

Pre-processing operation	Amortization period	Capital cost for 6 tonne hr^{-1} plant	Capital cost for 20 tonnes hr^{-1} plant	Nb equipment pieces	Annualized cost (USD yr^{-1})
Dryer	15	340 931	1 418 371	1	165 708
Hammer mill	15	118 929	775 868	2	90 644
Pellet mill	15	277 502	2 282 345	4	266 645
Cooler	15	134 787	870 379	2	101 686
Screener	15	14 509	71 736	1	8 381
Bagging system	15	356 788	1 828 872	1	213 666
Conveyers, tanks, etc.	15	882 456	5 226 507	1	610 610
Land, infrastructure, construction	25		3 409 308	-	319 380

Table 22: Specifications of the pre-processing equipment [138]

Equipment	**Heat demand (kWh per tonne $_{\text{ev. w.}}$)**	**Feed rate (tonne hr^{-1})**	**Power (kWh)**	**Feedstock**
Drum dryer	1300	25	270	Wet sawdust
Equipment	**Number of pieces**	**Capacity (tonne hr^{-1})**	**Power (kW)**	
Hammer mill	2	10	370	
Pellet mill	4	5	300	
Cooler	2	10	25	

Table 23 breaks down the operating costs of the pre-processing operations. It can be seen that the cost for pellet production amounts to 33 USD tonne^{-1}, which corresponds to 1.78 USD GJ^{-1} (assuming a calorific value of 18.6 GJ tonne^{-1}). In Quebec, the cost of these operations in pellet plants, which are fewer and smaller than those of British Columbia, are estimated to be closer to 55 USD tonne^{-1} [139], equivalent to 2.96 USD GJ^{-1}.

As mentioned in the section Economic breakdown of the reference value chain, current supply costs of biomass from primary forest residues, which do not include any significant pre-processing technologies, were estimated at 1.70-3.18 USD GJ^{-1} for heat plants, 7.21-41.39 USD GJ^{-1} for power plants, and 13.39-29.45 USD GJ^{-1} for combined heat-and-power plants [25]. Assuming that each of these end-users could use pellets, the pre-processing operations leading to pellet production would add a proportionally high cost for heat plants, but a more reasonable cost to combined heat-and-power plants. Depending on the impact of off-spec feedstock on the performance of the biomass plant (and their consequent costs for the value chain), the added costs from pre-processing operations therefore may not necessarily be worth it, especially for small heating facilities.

Table 23: Operating costs [138]*. All values were converted from CAD*$_{2013}$ *to USD*$_{2016}$*.*

Pre-processing operation	**Annual cost (USD)**	**Unit cost (USD tonne^{-1})**
Drying	86 842	0.62
Size reduction	390 041	2.78
Pelletization	632 355	4.50
Cooling	28 131	0.20
Annualized capital investment	1 776 717	12.64
Personnel	856 291	6.09
Spare parts and other consumables	891 708	6.34

3.5.2 Case study: Cost/benefit analysis for the UBC gasification plant

One of the main decisions to be made in a biomass supply chain is whether to dry biomass before its feeding into the conversion process. The decision of using a dryer depends on the historical moisture content of biomass throughout the year, the feedstock specification of the conversion technology (i.e. acceptable moisture content range) and the impact of off-spec moisture content on the performance of the conversion process and the final product.

For the UBC gasification project described before, the acceptable range of moisture content based on the gasification's feedstock specification was 5-40% (wet basis). The main economic question is whether the gain in performance of the gasifier due to a lower moisture fuel offsets the drying costs. The manufacturer did not specify the desired moisture content that would produce the most steam and thus the highest revenue per unit mass of wood fuel. Figure 25 shows the monthly steam generation for the UBC gasification plant from the start-up date in April 2012 to July 2015. The overall monthly steam production increased substantially from roughly 1500 metric tonnes per month to almost 6000 metric tonnes per month. As Figure 26 shows during this period the performance of the gasifier in terms of utilization rate improved gradually. The number of breakdowns decreased. The three low points in 2012, 2013, and 2014 are for the annual shutdown service during the month of June.

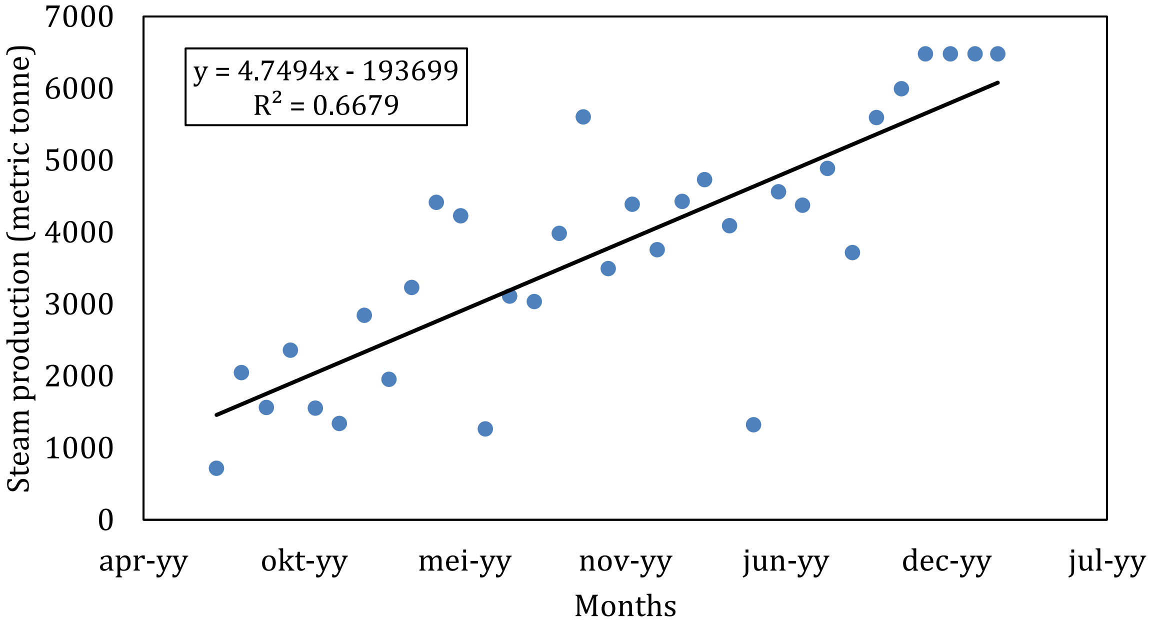

Figure 25: The plot of monthly steam generation for the UBC gasification plant from April 2012 to July 2015.

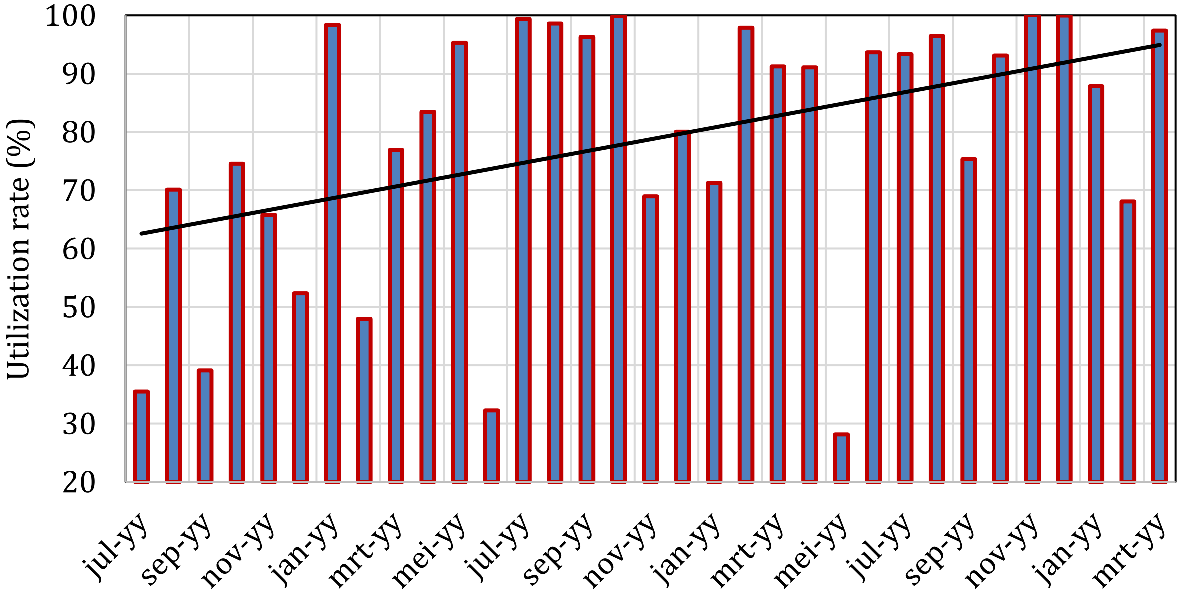

Figure 26: Monthly utilization rate (percent working hour).

Part of the improvement in the performance of the gasifier and the increase in the steam generation observed on Figure 25 is due to the increase in the quality of biomass delivered to the UBC gasification plant over time. It would be difficult to specifically quantify the impact of the fuel quality on the plant performance due to the impact of other parameters such as operation conditions and the maintenance of the equipment. However, in this study, the historical data for the moisture content, the performance of the gasifier and the steam generation were collected for three years to quantify the impact of the moisture content of delivered wood fuel on the steam generation and the associated revenue and profit. The indications are as expected: the level and variability of moisture content had a large effect on the plant's performance. Figure 27 shows the monthly mass of wood fuel delivery to the gasification plant. There was a slight increase in biomass delivery over the 3 years of operation. Monthly variations became smaller in 2014 compared to variations in 2012 and 2013. The payload of delivery trucks ranged from 13 to 30 metric tonnes. As expected, the payload increased with the increase in the moisture content of delivered wood fuel.

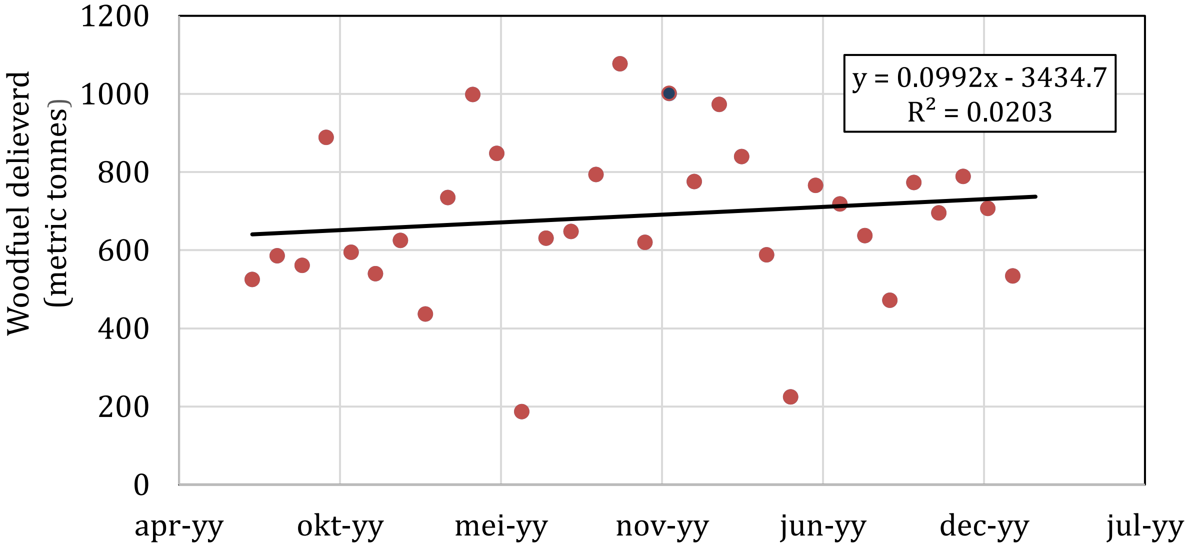

Figure 27: Monthly mass of wood fuel delivery to the gasification plant.

Figure 28 shows the distribution of moisture content of wood chips delivered to the UBC gasification plant. This distribution was developed from 1 253 truckloads of wood chips delivered to the UBC gasification plant from January 2015 to December 2016. The average moisture content was 35.7% with a standard deviation of 10.2%. The minimum and maximum observed moisture content was 12% and 58%, respectively. During this period, the wood recycling company installed a shed as a storage and protective structure to house and protect the wood chips from getting wet due to rainfall. It also installed sets of screens on the grinder to increase the proportion of particles larger than 6.4 mm (1/4") and less than 75 mm (3").

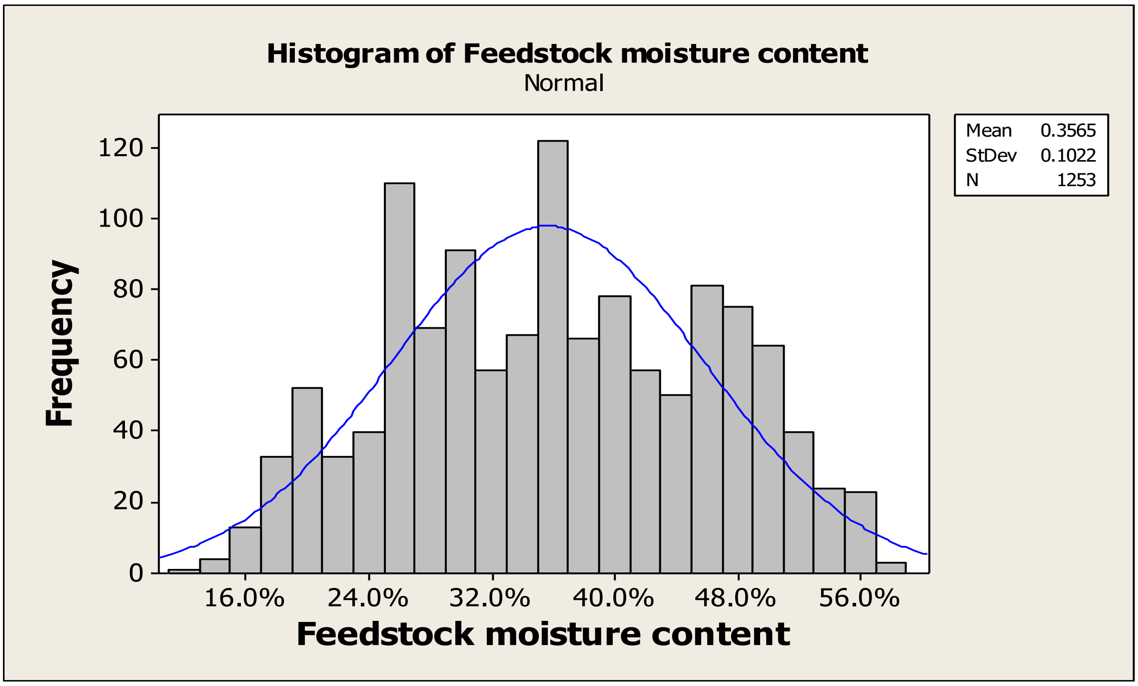

Figure 28: Distribution of moisture content of wood chips delivered to the UBC gasification plant. This distribution was developed from 1,253 truckloads of wood chips delivered to the UBC gasification plant from January 2015 to December 2016.

3.5.3 Cost Benefit analysis of using wood fuel at the gasification plant: Wood fuel supplier's perspective

Regardless of the moisture content of delivered wood chips, the contract between UBC and the biofuel supplier stipulates that the UBC pays the supplier based on the dry mass of wood chips delivered at the gate of the gasification plant. In this study, it is assumed that the wood fuel price paid to the supplier is 56.63 USD dry tonne^{-1} (75 Canadian dollars (CAD) dry tonne^{-1}). The wood recycling company delivers wood chips to UBC using its own trucks. Thus, the moisture content impacts its transportation cost. To meet the daily biomass demand of the gasifier (~40 dry tonnes per day), 2-4 truckloads of wood chips per day need to be delivered. The weight of wood chips at 20% moisture content is measured to be about 15.65 dry tonnes per truckload, while at 50% moisture content, it is around 11.5 dry tonnes. Thus, on average, the supplier is paid about 886 USD per truckload if the moisture content of delivered wood chips is at 20% and 651 USD if the moisture content of the truckload is at 50%, with a difference of 235 USD per truck load.

Reduction in the moisture content of delivered wood chips has another benefit for the supplier. In the period of 2015-2016, 16 800 dry tonnes of wood chips were delivered to the gasification plant, using 1 253 truckloads (average 13.40 dry tonnes per truckload). If it is assumed that moisture content of delivered wood chips is 20% for the entire delivered truckloads, the number of truckloads would reduce to 1 074, i.e. a reduction of 14% of the number of truckloads. The operating cost of each truckload for the supplier is estimated at \$140 hr^{-1} and it takes about 2 hours to leave the supplier site, dump wood chips at UBC plant and then travel back to the supplier site. Thus, a 14% reduction in the number of truckloads (i.e. 179 truckloads) can result in over 50 000 USD annually for the supplier. This could be the minimum saving as the supplier can use its truck fleet more efficiently to deliver biomass to other customers.

Particle size of the fuel is another factor influencing the logistics system. Operators at the UBC gasification plant collect oversize wood fuel particles when the fuel is delivered by the wood recycling company. All the oversize materials are collected into a container, and once the container is full, the supplier takes the materials back to reprocess it. Transporting and handling of container costs the supplier roughly 500 CAD (378 USD). Table 24 lists the annualized capital cost of pre-processing wood chips at the supplier site in order to maintain the moisture content and particle size within the range of specifications. It is estimated that the annual cost of the protective storage structure at the supplier site, extra screens for sorting wood fuel and dealing with oversize material amounts to 23 271 USD. The capital cost does not include the operating costs for operating the grinder, loading and unloading (power use and operator time).

Table 24: Annualized costs incurred in order to improve the quality of wood fuel supplied to the gasification plant. All values were converted from CAD to USD$_{2016}$

Description	Purchase price (USD)	Expected life (years)	Annual cost (USD)
Protective structure to store UBC's wood fuel	27 184	23	906
Screens for sorting fuels	94 388	15	4 719
Grinder for fuel size reduction	188 777	15	9 439
Cost of handling (oversize) rejects	378 per load		8 306
Total annualized capital cost			**23 371**

Cost Benefit analysis of using wood fuel at the gasification plant: UBC Gasifier's perspective

As discussed above, moisture content impacts the steam generation at the gasification plant (with steam being the only source of revenue in this facility). Figure 29 shows the impact of the moisture content on the steam generation. Revenue is then calculated by multiplying the steam mass by the price of steam; the latter is estimated to be 24 CAD per 1000 lbs of steam (equivalent to 18.12 USD per 1000 lbs of steam). Figure 31 suggests that the average daily revenue decreases from 8 800 CAD to 7200 CAD (6645 USD to 5437 USD) as moisture increases from 20% to over 50%, i.e. a 17% decrease in revenue.

As mentioned before, UBC pays 56.63 USD dry tonne^{-1} (75 CAD dry tonne^{-1}) and the daily biomass demand is ~40 dry tonnes; thus the total daily cost for feedstock for UBC is about 2 265 USD. However, this amount may vary depending on the number of delivered truckloads and moisture content of delivered wood chips. Given the daily feedstock cost and the daily steam revenue in Figure 31, the daily profit of steam generated at the UBC gasification plant can be calculated, as shown in Figure 31. As seen on this figure, on average, an increase in moisture content from 20% to 50% can result in a 14% reduction in profit for UBC.

In summary, reduction in the moisture content of delivered wood chips can bring cost savings for the biofuel supplier and increase the benefits for the UBC as end-user. Reduction in moisture content from 50% to 20% can result in a minimum cost saving of over 50 000 USD annually for the supplier in terms of reduction in transportation costs (reduction of 14% of the number of truckloads needed to supply the end-user) and rejection of oversize wood chips. This cost saving is considerable for a small-sized wood recycling facility; it could be the minimum saving as the supplier can also use its truck fleet more efficiently to deliver biomass to other customers. On the other hand, reduction in moisture content from 50% to 20% can result in an increase of daily profit of 642 USD (850 CAD), i.e. a 16% profit increase, for UBC by generating more steam.

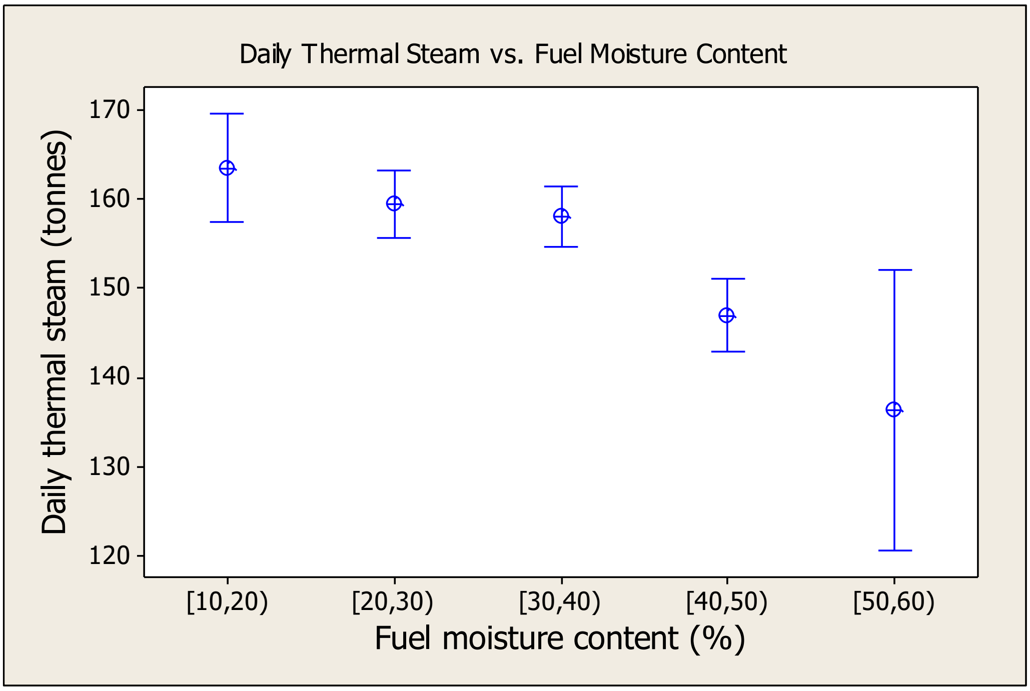

Figure 29: Relationship between generated steam (in metric tonnes) and feedstock moisture content from January 2015 to December 2016.

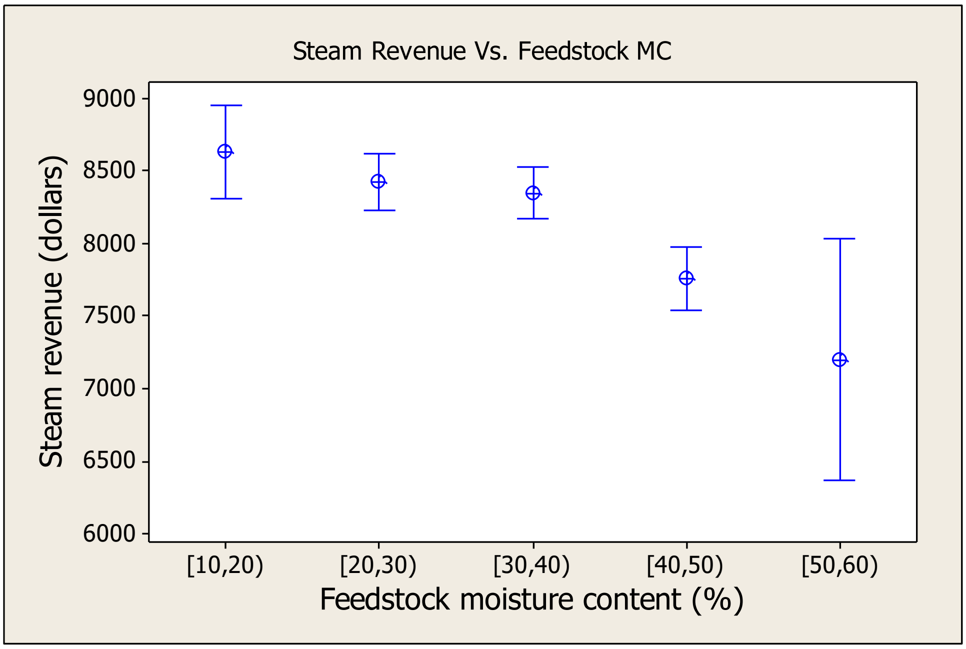

Figure 30: Impact of feedstock moisture content on the daily revenue of generating steam at UBC gasification plant. Revenue is expressed in Canadian dollars. 1 Canadian dollar (CAD) = 0.755 USD$_{2016}$

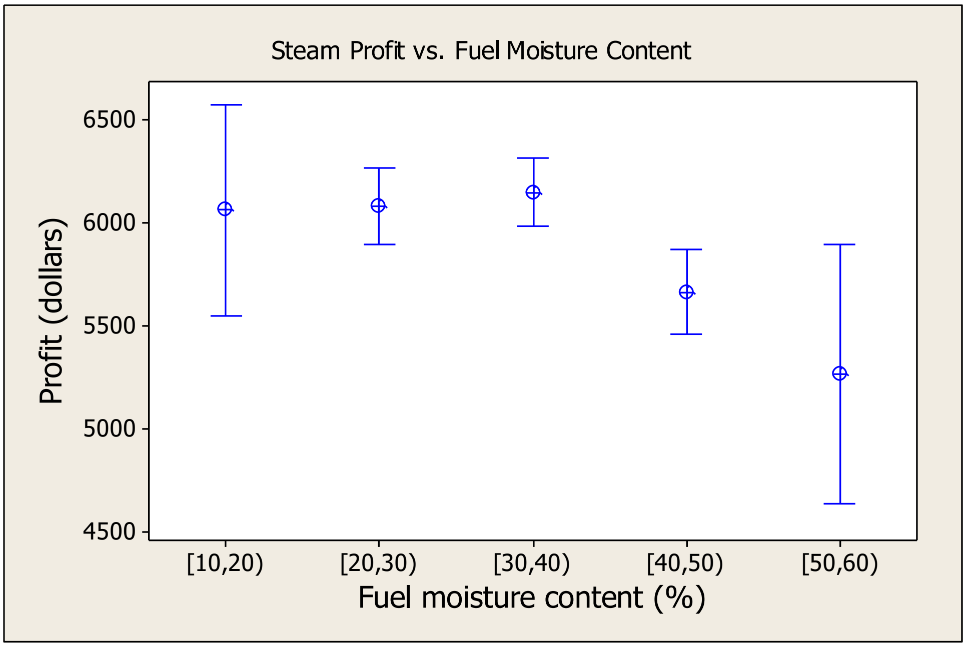

Figure 31: Impact of feedstock moisture content on the daily profit of generating steam at the UBC gasification plant. Daily Profit is expressed in Canadian dollars, and is calculated by subtracting feedstock costs from the steam generation revenue. 1 Canadian dollar (CAD) = 0.755 USD$_{2016}$

In summary, the financial aspects and cost savings of pre-processing technologies in forest biomass supply chains will vary greatly depending on the expected (or historical) variation of properties of forest biomass feedstocks, especially moisture content, for which large variations are most often the norm, the feedstock specification of the bio-conversion facility, the impact of off-spec properties on the performance of the conversion process, and also the feedstock transport distances and the storage and production capacity of the facility.

Gautam et al.[140] assessed the feasibility of incorporating biomass depots within forest biomass value chains, using a forest area in Quebec as a case study. A biomass depot makes it possible to gather biomass from various locations within a regional network and provide services such as biomass pre-treatment for it to meet quality requirements of end-users, and also serve as a biomass storage and as a node for intermodal transportation. Gautam et al.[140]'s study suggests that adding a biomass depot can lead to cost reductions of 11-31% relative to a reference value chain without a depot, notably because it dramatically increases the capacity for moisture management of feedstock (with benefits for transportation and energy conversion). However, although the depot increases the likelihood of delivering biomass at a lower cost, actual cost savings are very dependent on the overall configuration of the value chain, such as transport distances and production capacities of yards and conversion plants. Combinations of biomass depot location relative to feedstock sources and bio-conversion facilities, pre-treatment services offered within the depot, and storage and production capacity of the depot and bio-conversion facilities should therefore be carefully considered.

4 Summary and recommendations

In Canada, the average annual production of bioenergy from forest biomass is 0.48 EJ $year^{-1}$ [4]. Mobilisation of forest biomass feedstocks that can be provided by primary, secondary and tertiary residues could vary from 0.68 to 4.43 EJ $year^{-1}$. Projected production for similar scenarios applied to selected North American, European and Oceanian countries that are part of the boreal and temperate biomes could reach 4.94 to 28.01 EJ $year^{-1}$.

However, compared to fossil fuels, forest biomass as an energy source has many drawbacks, which include lower bulk density, higher moisture content, inferior heating value, and poorer grindability. Due to these disadvantages, the overall costs for handling, transport, and storage of forest biomass might be significantly high.

The usability and value of forest biomass for various end-uses can nevertheless be increased by appropriate pre-treatments: they can significantly improve the quality, storability and transportability of biomass and enable more versatile end-uses, as well as cleaner combustion and energy production especially for small users.

Figure 32 summarizes opportunities for using pre-treatment methods and technologies along the reference forest value chain that were discussed in previous sections. These opportunities include:

- moisture management by passive and active drying, covering, blending, and monitoring and modelling of moisture content;
- physical property management by chipping, grinding, sieving and machine visualization;
- ash content management by washing;
- density management by pelletizing.

Several pre-treatment processes can be implemented at the beginning of the forest value chain (passive drying of residues on the forest cutblock and/or by roadside; covering to prevent re-moistening; monitoring and modelling of moisture content; chipping). This can be made easier by close integration of biomass operations with planning of stemwood procurement for conventional wood products, which can ensure that the utilization of available machinery is optimized, and that biomass feedstocks are handled and piled in a way that facilitate downstream processes. Proper implementation of pre-treatment at this early stage in the chain can considerably increase the energy density of the material and therefore significantly reduce transportation costs per unit of energy, a key aspect of bioenergy profitability. This is especially relevant for the economic sustainability of forest biomass in Canada where feedstock sources are spread in low densities across large areas [141, 142]. Development of a modelling capacity for predicting seasonal evolution of moisture content should also be particularly relevant, and can be easily done using available weather data and drying curves, as experiences from other countries such as Finland have shown.

On Figure 32, several pre-treatment processes are set to be performed at a biomass depot or yard. The role of biomass depots for the mobilisation of profitable forest biomass supply chains is increasingly being demonstrated. They make it possible to access low-grade and diffuse forest biomass feedstock resources across a region and offer a buffer against variation in feedstock supply and quality. Research results suggest that a biomass depot within a supply chain can lead to cost reductions of 11-31% relative to a reference value chain without a depot, notably because it increases the capacity for moisture management of feedstock, with consequent benefits for transportation and energy conversion. Larger biomass volumes make it easier to justify the investments needed for the implementation of biomass pre-treatment equipment with which biomass characteristics and quality can be actively addressed and improved.

Supply costs of biomass from primary forest residues, which do not include any significant pre-processing technologies, were estimated at 1.70-3.18 USD GJ^{-1} for heat plants, 7.21-41.39 USD GJ^{-1} for power plants, and 13.39-29.45 USD GJ^{-1} for combined heat-and-power plants [25]. Case studies in British Columbia and Quebec suggest that the cost of pre-processing operations for pellet production ranges from 1.78 to 2.96 USD GJ^{-1}. Assuming that end-users could use pellets, the pre-processing operations leading to pellet production would add a proportionally high cost for heat plants, but a more reasonable cost to combined heat-and-power plants.

Another case study for a gasification plant in British Columbia estimated at 23 371 USD the total annual capitalized costs of simple pre-processing technologies for moisture and physical property. Reduction in the moisture content of delivered wood chips at the gasification plant can bring cost savings for the supplier and increased benefits for the end-user. Reduction in moisture content from 50% to 20% can result in a minimum cost saving of over 50 000 USD annually for the supplier in terms of reduction in transportation costs (reduction of 14% of the number of truckloads needed to supply the end-user) and rejection of oversize wood chips. This cost saving is considerable for a small-sized wood recycling facility; it could be the minimum saving as the supplier can also use its truck fleet more efficiently to deliver biomass to other customers. On the other hand, reduction in moisture content from 50% to 20% can result in an increase of daily profit of 642 USD (850 CAD), i.e. a 16% profit increase, for UBC by generating more steam. Overall, the investment in pre-processing technologies can therefore lead to substantial benefits for the whole value chain.

The energy efficiency (ratio of recovered energy in the end-use and energy content of green biomass) is a crucial component of economic sustainability and should be an important indicator for overall efficiency of pre-treatment methods. The costs associated with pre-treatments should be connected to the energy efficiency evaluations. These costs should be based on the monetary value per MJ or kWh delivered, and not on the monetary value per tonne of forest biomass delivered to the plant. These costs should include implicit costs like breakdowns, repairs, and stoppages due to feedstock characteristics.

In addition to the value of final product, the return on pre-treatment investment should be carefully investigated. It should be pointed out that it is not difficult to achieve good energy yield, but it is rather difficult to achieve good yields at low energy input and investments. During the storage , the raw material losses can be markedly reduced by proper timing and matching with the demand cycles of end-users. For its part, pelletization densifies the energy and mass of biomass, and homogenizes its physical properties, with effects on downstream processes. There is a general agreement that drying at a lower temperature (less than 60 °C) has no adverse effect on the quality of wood pellets. More generally, a clearer understanding of the effects of properties of raw or pre-treated feedstocks on efficiency of downstream processes and bio-conversion is needed.

It is therefore of utmost importance to critically evaluate the needs for pre-treatment in the specific conditions of supply and value chains. For example, in local supply chains with short distances between feedstock and final end-user, as might be the case for several forest-based communities across Canada, a direct sourcing of green biomass from forest to energy production facility, without any significant pre-processing phases, may give the highest overall efficiency both in thermal and economic terms. For example, Finland is currently experimenting the Fast Track model [143], an alternative operational model where part of the forest biomass feedstock is taken to the CHP plant directly from forest without drying and storing. Fast Track is focused on summer and early autumn harvests because top performance of boilers is not needed at that time of the year. Procurement costs of logging residue supply for energy use can be decreased by using Fast

Track, but it can be profitably used only for very specific supply needs. There is therefore a need to fine-tune the entire forest value chain to ensure the profitability of bioenergy production, especially in countries like Canada where generally low fossil fuel and energy prices call for high levels of agility and ingenuity.

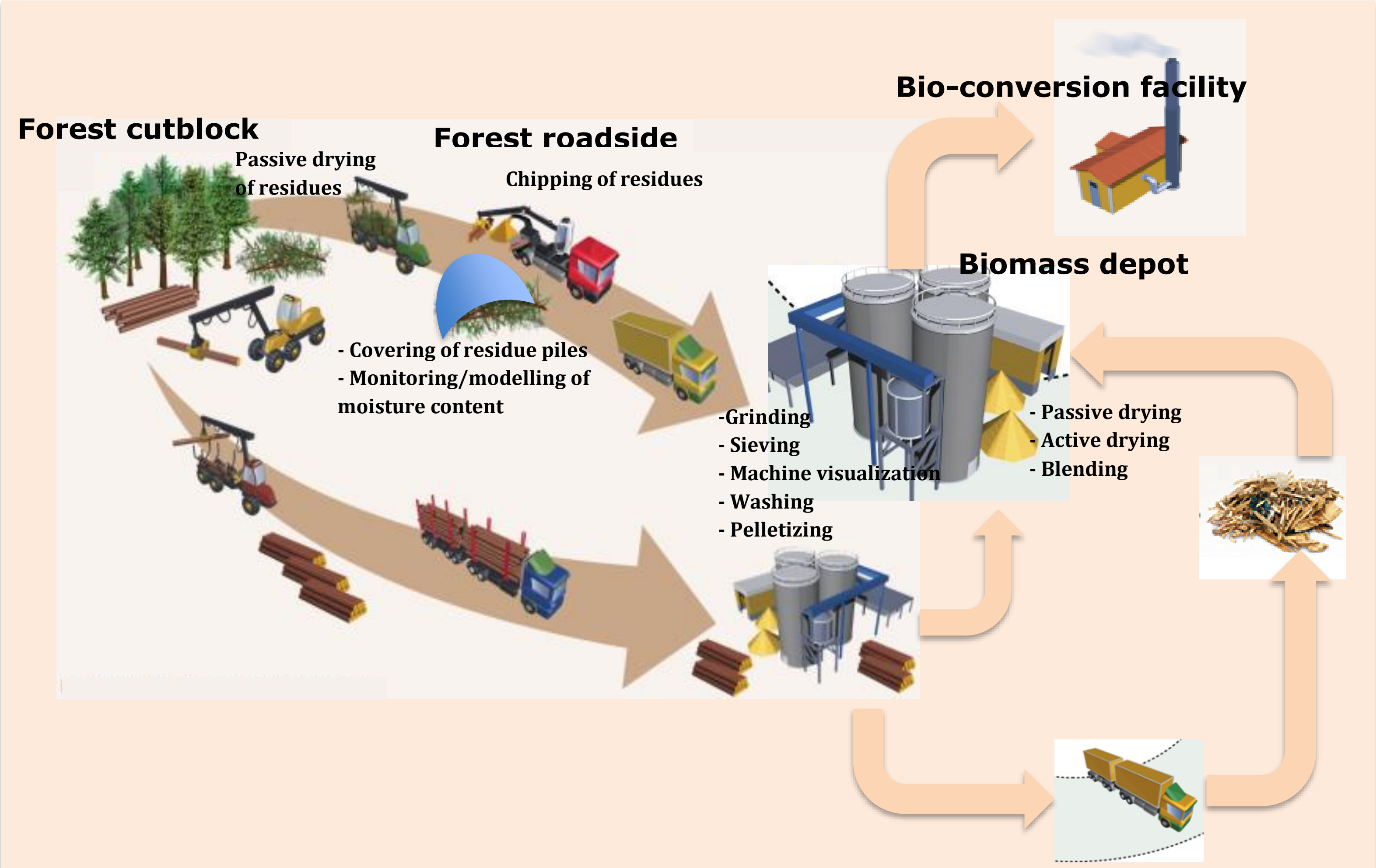

Figure 32: Opportunities for biomass pre-treatment methods within the forest biomass value chain.

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