Innovative approaches for mobilization of forest biomass for bioenergy

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Innovative approaches for mobilization of forest biomass for bioenergy

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Executive summary

Increasing global demand for energy, a push by governments and industry to reduce greenhouse gases (GHG), and a desire to increase energy independence are driving the demand for renewable alternatives to fossil fuels. As a source of renewable carbon that can be used in the existing energy infrastructure, forest (woody) biomass is an attractive feedstock for the production of bioenergy (meant here to include biomass-based energy carriers in solid, gaseous and liquid forms) for production of heat, power and liquid biofuels.

Based on the definitions of the Intergovernmental Panel on Climate Change, forest biomass feedstocks include:

- Unutilized (or surplus) forest growth that have no taker by conventional forest industries;
- primary residues i.e. by-products of harvesting and silvicultural operations;
- secondary residues, i.e. low-quality by-products of the industrial processing of wood;
- tertiary residues, i.e. post-consumer material such as demolition wood and scrap pallets.

Due to various logistical, social, market and policy challenges, these biomass resources are often left behind in forest value streams of various jurisdictions around the world: they usually end up in open burning, landfill or burned up in boilers with low efficiency for heat and power generation, or left on forest sites. However, they represent opportunities to increase production of bioenergy and therefore contribute to the global energy transition towards renewable sources, and also opportunities to revitalize and diversify regional industrial networks in forest regions.

This report builds on knowledge on the valorization of forest biomass for bioenergy (including heat, power and biofuels) with the aim of providing insights and recommendations for the development of pathways to maximize the value from often underutilized sources of forest biomass. It is presented around case studies that deal with supply, logistics, conversion, social, environmental, market and policy aspects of forest biomass mobilization. It is presented around case studies that deal with supply, logistics, conversion, social, environmental, market and policy aspects of forest biomass mobilization.

Some key recommendations can be drawn from these case studies:

A compilation of the developed knowledge from case studies indicate how taking advantage of modern technologies and innovations in supply chain management can help to valorise underutilized biomass resources. Commercial quantities of underutilized woody biomass resources are available that are currently left behind in the forest, such as the degraded woods in Quebec, or burnt inefficiently by the local sawmills and pulp mills for heat and power generation, as seen with the processing residues in the Vancouver region. These biomass resources traditionally have not been considered as feedstock for biofuels and bioproducts markets due to a combination of logistical disadvantages (high procurement costs) and quality issues (e.g. high moisture content and ash content). Supply chain development, such as the use of adequate pre-treatment technologies for biomass, or a closer integration of forest biomass supply chains within larger forest management systems, can create significant new opportunities for the utilization of this material.

A key element of successful biomass deployment is to ***connect the right biomass to the right value market*** is based on supply chain management and pre-processing to value add the biomass for energy production. In the case presented from Vancouver, very low-quality biomass that could be sourced locally and did not competing uses, was preference to have a secure cost-effective supply that could be managed through a well-planned supply chain to meet energy production needs. In the Italian case, more mature bioenergy markets had been established and local small-scale supply was matched to the local market where the advantages of the location and supply form existing land management used novel supply chain technology and design to meet the specific local market need.

A combination of ***pre-processing solutions can contribute to upgrade the value of the underutilized woody biomass resources***, through managing moisture content, limiting contamination and creating a consistent particle size for energy production systems. These strategies around storage and mixing of resources were used to bring low quality biomass sourced for the Vancouver gasification case to a level that they provided a consistent and reliable energy production, while the Italian case used specific chipping technology as an effective solution at small scale to meet a high-quality biomass supply demand. Pre-processing solutions will add to the cost of biomass delivered to the downstream users and therefore needs to be carefully considered and integrated in the supply chain management. The selection of the pre-processing solutions depends on understanding the feedstock specifications of the bio-processing technology and biomass characteristics. Fractionation, size reduction, drying, densification, torrefaction, blending and washing are examples of the pre-processing solutions.

The location of the upgrading operations is critical to reduce the cost of inbound and outbound transportations and ensuring the right qualities are created and delivered to the bioenergy use of greatest value. In the Italian case logistics were reduced with localised pre-processing of microchips to displace imported pellets; a pre-processing technique that unlocked a local supply. Multiple transportation modes (i.e. road, rail and water) can significantly reduce the biomass delivered cost and where possible it can be most effective to introduce value adding pre-processing operations where these modes of transportation intersect. The Alberta case of pellets for co-firing in coal power energy generation added value to the feedstock through palletisation and then used the now point sources of higher value biomass to leverage logistic cost benefits of rail trainsport to access more biomass at a acceptable cost. Where multiple modes of transportation are not required pre-processing will be better placed either at the point of harvest (road side storage to reduce moisture, infield chipping and grinding, etc.) or within the facility of the final energy producer (active drying with waste heat, palletisation, torification, etc.)

***Agility and flexibility are important to the efficient execution of supply chain plans*.** The reality in the forest sector, and more so in forest biomass supply chains, is that there is a continual need to adapt to changing conditions (e.g. mill closings/openings; natural disturbances). An agile and flexible biomass business case will be able to adapt to multiple sources of feedstocks, and continually move up the technological learning curve through learning-by-doing, as seen in the example of the gasification plant in Vancouver.

Forest biomass supply is inherently complex, so success requires ***right biomass is directed to the right use*** and trying to force what has worked in one region in an area that does not have the same opportunity or conditions increases the risk of failure. In the Quebec case, wood that was otherwise going to be residues on site and create future land management costs and challenges was captured through effective integration with other forest-based supply chains to meet local market at a relatively low cost. In British Columbia the case uses small scale gasification and novel supply management strategies to its advantage to source true low value residues and waste wood as a low-cost supply that other competitors would rather not use; as case that may not work with bigger projects or regions where this low-quality biomass is not readily available.

The priority is to ***displace currently inefficient energy solutions where a biomass feedstock is local to an otherwise remote site***. Where the situation does not a provide clear cut advantaged for bioenergy production and use it is important to work to the identified strengths of bioenergy such as direct heat production and capitalise on other benefits such as regional development, improved forest management outcomes and reliable local energy source. All these strategies for successful biomass supply are enhanced supportive policy and legislation underpin changes in the current forest management practices, organizational behaviour and business models of the forest companies towards supplying a bioenergy industry.

Integration of supply to existing industry and land management needs is key to success. The biojet project in British Columbia relies heavily on integration with forest supply chain to source biomass suited to the specific need as well as downstream supply chain integration to get to market, using already in place and reliable infrastructure to get to market. In Colorado the recovery of pine beetle killed wood was a key tool in the integrated land management strategy to direct as much of the wood that was suitable to high value timber markets but provide viable market to energy use so all the material could be removed and promote regeneration of the forest on site. In Alberta the traditional energy source of coal is a very low-cost solution so high levels of integration with existing supply chains and supply chain infrastructure like rail were needed to deliver at acceptable costs as a renewable component of the co-firing solution.

While biomass supply chains remain, complex and challenging the key elements for success can be quite simple. The first element is to understand the biomass supply including the amount, locations and quality. It then falls on the supply chain to realise the best value by connecting that biomass to the right market and use, while adding the right value at the right place along the supply chain with pre-processing, amalgamations and volume efficiencies. Scaling and integration with existing supply chains that both leverages expertise and creates synergistic efficiency is often the difference between success and failure.

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Introduction

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BACKGROUND

Increasing global demand for energy, a push by governments and industry to reduce greenhouse gases (GHG), and a desire to increase energy independence are driving the demand for renewable alternatives to fossil fuels. As a source of renewable carbon that can be used in the existing energy infrastructure, forest (woody) biomass is an attractive feedstock for the production of bioenergy (meant here to include biomass-based energy carriers in solid, gaseous and liquid forms) for production of heat, power and liquid biofuels.

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Due to various logistical, social, market and policy challenges, these biomass resources are often left behind in forest value streams of various jurisdictions around the world: they usually end up in open burning, landfill or burned up in boilers with low efficiency for heat and power generation, or left on forest sites. However, they represent opportunities to increase production of bioenergy and therefore contribute to the global energy transition towards renewable sources, and also opportunities to revitalize and diversify regional industrial networks in forest regions.

AIM AND OBJECTIVES

This report builds on knowledge on the valorization of forest biomass for bioenergy (including heat, power and biofuels) with the aim of providing insights and recommendations for the development of pathways to maximize the value from often underutilized sources of forest biomass. It is presented around case studies that deal with supply, logistics, conversion, social, environmental, market and policy aspects of forest biomass mobilization.

The specific objectives of the project are:

- to compile information, in the form of case studies, describing challenges and opportunities for the development of successful business cases of mobilization for forest biomass for bioenergy;
- to provide recommendations on best practices and policy for the mobilization and valorization of underutilized forest biomass.

2. Case studies

MOBILIZATION OF UNMERCHANTABLE AND NON-COMMERCIAL TREES IN QUEBEC

Authors : Evelyne Thiffault, Alexis Achim, Julie Barrette, Mathieu Béland, Claude Durocher. Research Centre on Renewable Materials, Université Laval.

INTRODUCTION

Surplus forest growth, i.e. roundwood that could potentially be harvested over and above current harvesting rates while still remaining within the sustainable harvest rate of the forest is a particularly abundant but yet untapped and poorly unaccounted for source of forest biomass. A special case of this category is unmerchantable, non-commercial, low-quality, damaged, or dead trees, together referred here as "unloved woods". A substantial volume of these unloved woods go unutilized despite being part of the forest annual allowable cut (AAC), which represents the biophysical harvest limit of forests from a given jurisdiction, and is usually set by governmental agencies. These unloved woods represent a potential for the sustainable deployment of bioenergy while contributing to the revitalization of the forest sector.

DESCRIPTION OF CURRENT SITUATION

An analysis of Canada's managed forests shows that the ratio of actual roundwood harvest to the Annual Allowable Cut (AAC;) varies among provinces (Figure 1), and highlights the fact that most provinces do not take advantage of the full AAC. Factors explaining this ratio include a combination of: forest product market pricing and broader economic performance; operational difficulties; regulatory framework and restriction; regional structure of the wood processing industrial network; and wood properties and tree/stand characteristics. For example, current harvest levels in the province of Quebec was 63% of the AAC in 2015, which may cause a gradual depletion of the forest resource if stands that have the highest value for conventional products are preferably selected. The harvested proportion of the AAC is particularly low for hardwood species. When these species are mixed with conifers within stands, their present can often hamper the whole forest value chain since operators cannot profitably enter those stands if there is no taker for the hardwood species, causing whole landscapes to go unmanaged.

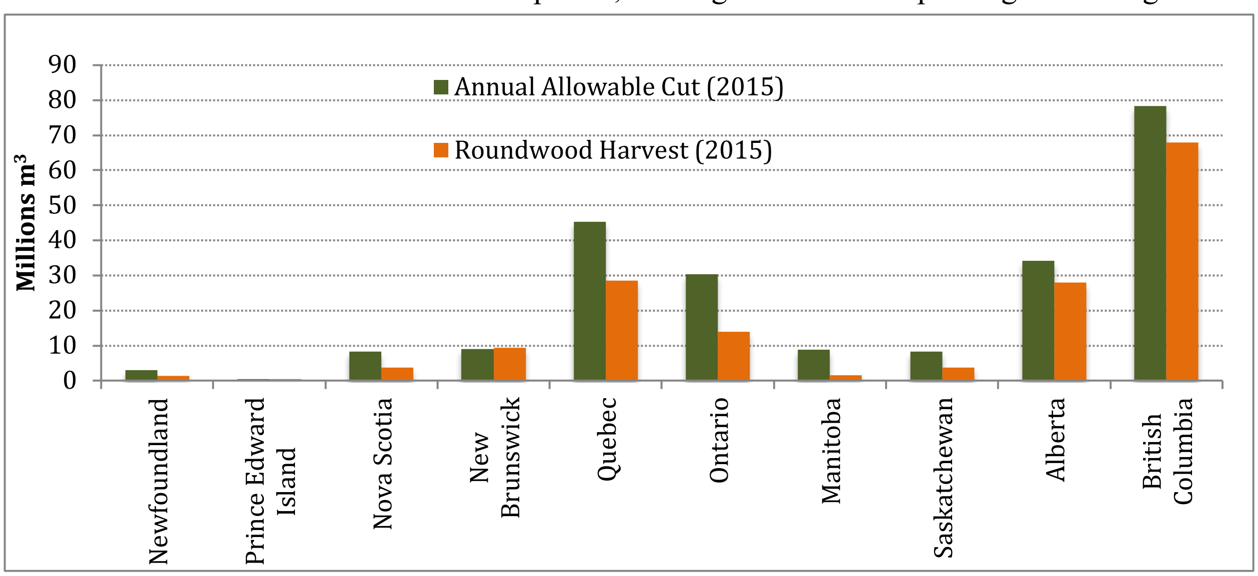

Figure 1: Annual allowable cut and roundwood harvest in 2015. Source: National Forestry Database.

As an example of such under-managed landscapes, simulations of biomass availability from degraded hardwood stands having a stagnant growth and containing only a small proportion of sawtimber-quality logs (less than 20% of total stand biomass) were performed in eastern Quebec, a region where the market for lower-quality (i.e. pulp-quality or less) hardwoods is marginal. The quantity of biomass that can be technically recovered for bioenergy from such stands was estimated at about 58 oven-dry metric tonnes per ha (odt ha^{-1}), i.e. 59% of total stand biomass (Figure 2). Healthier stands with a higher proportion of sawlogs (Figure 3) would yield around 37 odt ha^{-1} of biomass for bioenergy, about the same quantity of sawnwood. As a comparison, conifer stands, which have a strong regional market both for pulp and timber, would yield about 23.02 odt ha^{-1}, or 27% of total stand biomass, as feedstock for bioenergy in the form of tree tops (Figure 4).

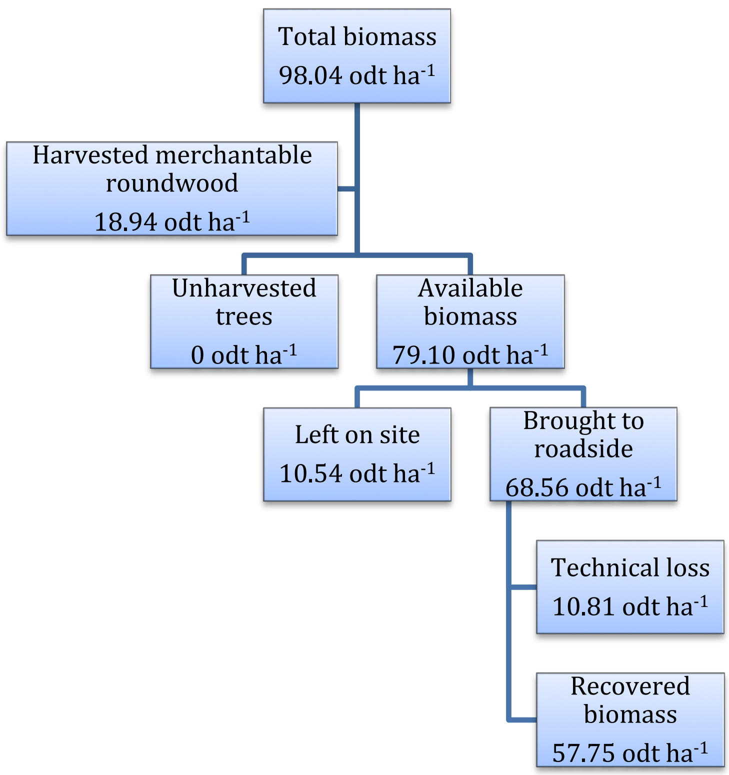

Figure 2: Biomass flow from degraded hardwood stands. Recovered biomass is comprised of whole trees.

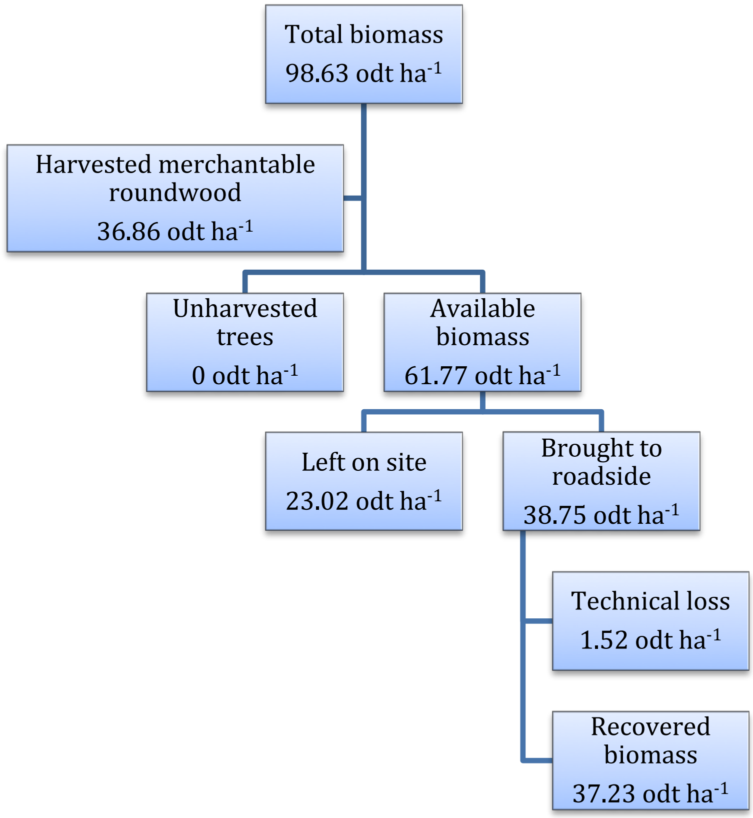

Figure 3: Biomass flow from healthy hardwood stands. Recovered biomass is comprised of low-quality roundwood, and tree tops.

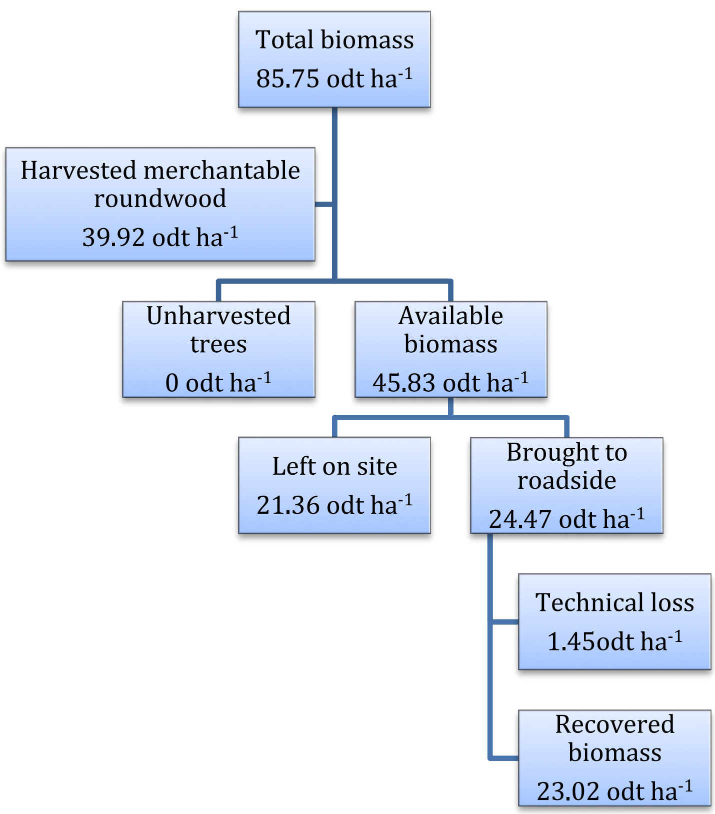

Figure 4: Biomass flow from healthy conifer stands. Recovered biomass is comprised of tree tops.

As another case of unloved woods, the availability of trees killed by natural disturbances is inherently variable because natural disturbances are episodic events and cannot be planned by forest managers. The most recent spruce budworm epidemic started in 2006 in the eastern boreal forest of Canada, and as of 2017, over 3 million of hectares of forest have been affected in Quebec. Affected trees quickly lose their properties for processing into conventional forest products (Barrette, et al. 2015). Wildfires are another important natural disturbance impacting forests and providing potential biomass feedstocks. The theoretical amount of forest biomass from fire-damaged stands across Canada is estimated to be around 47±18 M odt year^{-1} (not accounting for ecological or technical net-down), while that from clearcut harvest (primary) residues is estimated at 14±2 M odt year^{-1} (Mansuy, et al. 2017).

However, biomass sourced from natural disturbances, especially from wildifires, has its drawbacks, the main one being that its availability is highly variable in space and time. Moreover, the areas showing the highest potential (hotspots) for feedstock from wildfires are often located in the northern part of the Canadian managed forests, in regions where a dense road network and industrial structure is lacking relatively to the southern part of the country. Nevertheless, at the scale of large regions, and given that killed wood maintain its quality for bioenergy uses over time, this abundant feedstock could be attractive to users that are agile enough to deal with variability.

Finally, dead trees can also be found sporadically (i.e, interspersed within stands) in undisturbed stands of eastern Canadian forests. In regions bordering the Atlantic ocean or the St. Lawrence Estuary, the maritime climate can induce mean fire return intervals of more than 300 years, which is much longer than the approximate 100-year intervals reported further inland (Bouchard, et al. 2008). In the absence of insect outbreaks, this implies that the period of time since the last major disturbance often exceeds the mean longevity of the trees. Isolated mortality therefore generates significant volumes of standing dead trees interspersed with live trees: for example, in Côte-Nord (northeastern Quebec), dead wood can typically represent about 22% of the total volume in old stands (Barrette, et al. 2013).

OPPORTUNITIES FOR MOBILIZATION OF BIOMASS RESOURCES

ECONOMIC ASPECTS OF MOBILIZATION

Bioenergy offers the forest sector an opportunity to adapt to changing markets and build upon current sawmill and pulp and paper mill infrastructure and activities. Using unloved wood for biomass production can help unlock currently under-managed lansdscapes, offset fixed costs and serve to redistribute timber harvest and forest management costs amongst a wider basket of products. In doing so, the competitiveness of the forest sector as a whole can be increased. It can also help the forest sector to adapt to a changing climate in which natural disturbances such as pests and large wildfire are likely to become more common.

For example, in eastern Canada, companies are required by the government to harvest stands affected by the spruce budworm as part of emergency salvage harvesting plans. A financial analysis of various tree and stand utilization scenarios (Figure 5) performed from the standpoint of an eastern Canadian, independent sawmill (the most prominent wood processing facility in this region) suggested that using budworm affected-stands for lumber and pellets (in which live trees and sections of dead trees with high enough quality would be processed into sawnwood, and highly degraded trees and sawmilling co-products would be pelletized) is almost as profitable as using them for lumber and pulp (Figure 6) (Barrette, et al. 2017). Dead or rotten wood could serve as an interesting feedstock for pellets because wood density is only slightly affected by wood rot, wood calorific value remains untouched (or can even increase), and ash content, although sometimes increasing with rot, should remain within limits of feedstock specifications for pellets. However, the presence, among forest stands, of large trees able to generate value through lumber remains key to the profitability of the forest sector. Nevertheless, for a sawmill to have several alternative pathways for its fibre and co-products increases the resilience of the value chain, making it possible to adapt to temporary or permanent market changes and take full advantage on the emerging bioeconomy.

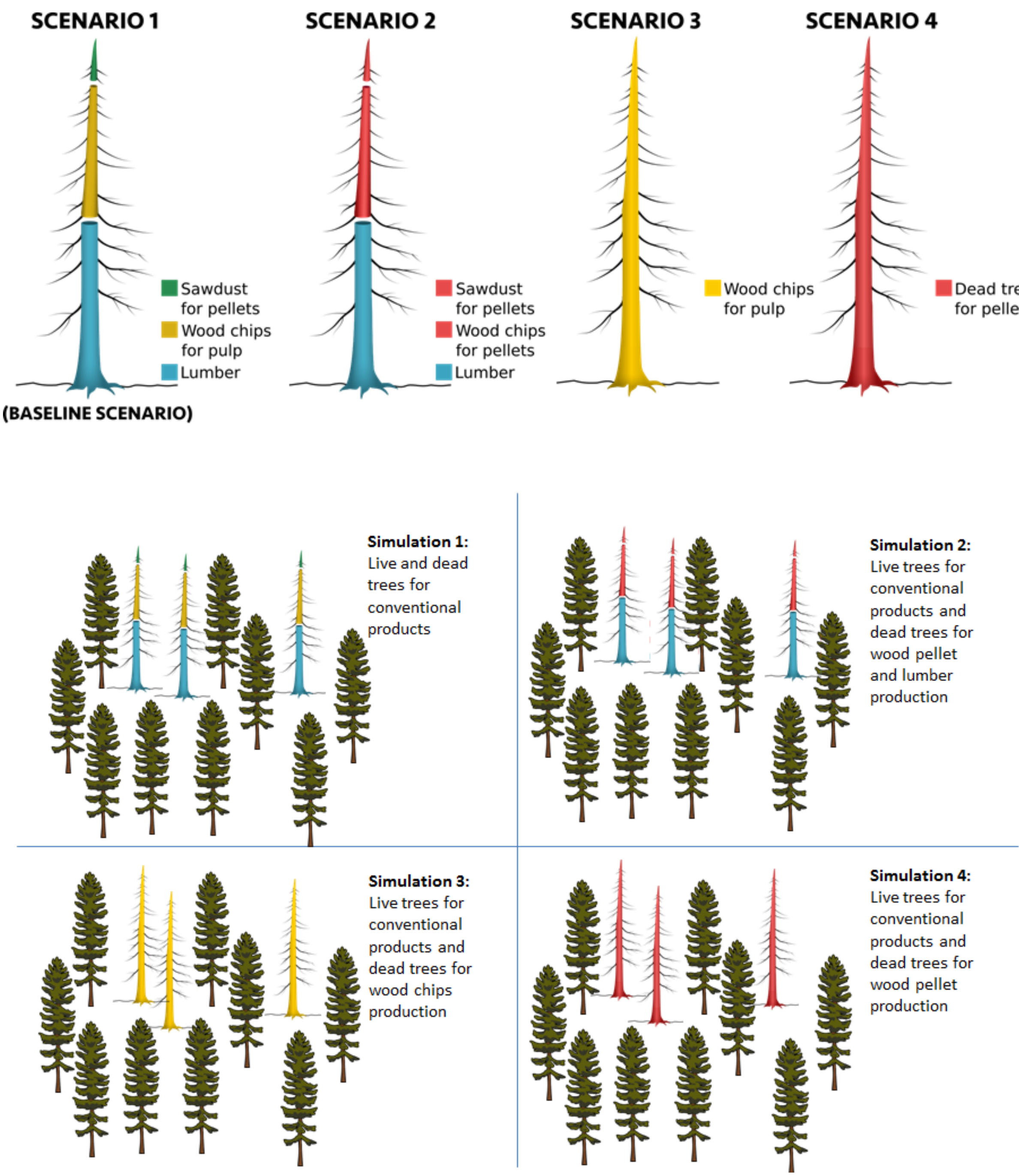

Figure 5: Scenarios of dead tree utilization. Source : [Barrette, et al. (2017)]

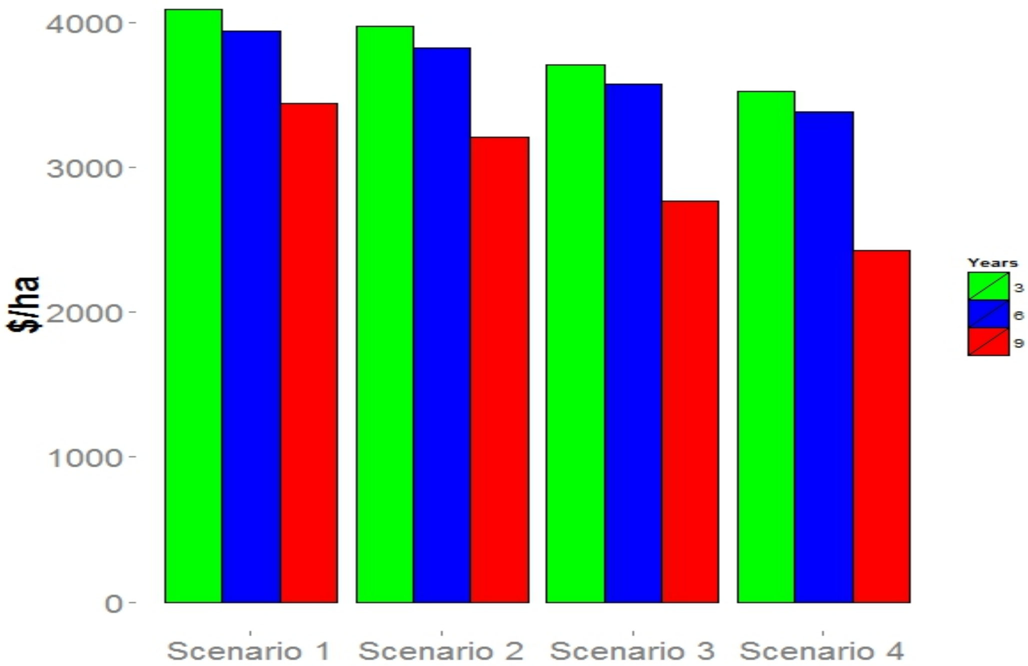

Figure 6: Stand-level profits ($/ha) in typical balsam fir-black spruce stands of Côte-Nord (eastern Quebec) according to time (in years) since the start of the spruce budworm epidemic. Source: Barrette, et al. (2017).

ENVIRONMENTAL ASPECTS OF MOBILIZATION

The increasing contribution of forest biomass to the global energy supply is generating concerns about environmental sustainability. These concerns include risks for deterioration of ecosystem services such as nutrient cycling and soil formation, water purification and flow regulation, biodiversity, and carbon sequestration and climate regulation. The environmental consequences of forest biomass procurement need to be well understood, as limits on biomass extraction set by environmental considerations determine how much biomass can be collected (Batidzirai, et al. 2013,Chum, et al. 2011).

Emerging bioenergy uses typically benefit from availability of low-cost biomass resources, residue streams of various wood processing industries in particular, as well as demolition wood and organic waste. The use of this resource is not likely to compromise sustainability in the forest ecosystem. However, procurement of whole trees, such as unloved woods, implies an increase in harvest intensity, both at the site and landscape level, which may have sustainability implications.

Luckily, the scientific literature, notably from Canada, is abundant on this topic. There appear to be no consistent negative impacts of forest biomass procurement, including unloved woods, on forest ecosystems, and effects appear to be site-specific (Lamers, et al. 2013,Thiffault, et al. 2011). From these scientific bases, planning indicators and guidelines can easily be derived and applied in the design of biomass supply chains (Thiffault, et al. 2014). This was exemplified in a case study on salvage harvesting of wildfire-killed stands for bioenergy in northeastern, which showed that, despite stringent ecological constraints on procurement of unloved woods (along with technical and economic constraints), there are still large amounts of available feedstock, although regional variability is high (Mansuy, et al. 2015) (**Erreur ! Source du renvoi introuvable.**).

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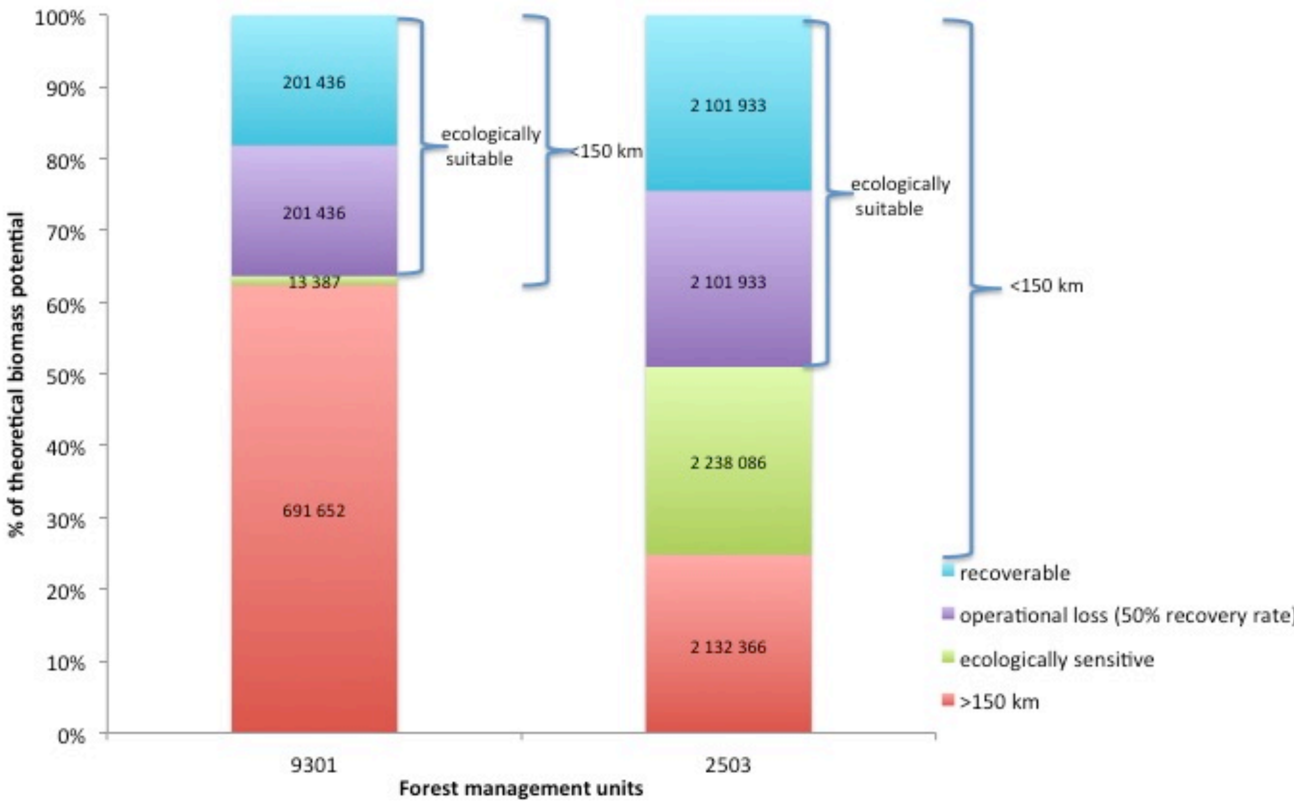

Figure 7: Availability of biomass from wildfire–killed stands and clearcut harvest residues relative to its theoretical potential. Source : Mansuy et al. 2015.

Over the past years, the carbon neutrality assumption of forest bioenergy, especially of roundwood and whole trees, has been the subject of much debate. However, prediction of the timing of the GHG mitigation benefits of forest bioenergy systems relative to reference fossil fuel systems can now be performed using models, therefore allowing the identification of optimal solutions in terms of feedstock choices and procurement strategies. For example, calculations of timing of GHG benefits and GHG savings of forest bioenergy system for process heat showed that procurement of degraded hardwood stands for producing process heat as a substitution to petroleum coke provide GHG mitigation benefits after 12 years or less after implementation of the bioenergy system, with cumulative GHG savings of 5.6-8.5 tonnes of CO_2 eq per gigajoule of bioenergy produced over a 100-year period. Harvesting degraded hardwood stands for bioenergy provides an incentive to replant areas that are otherwise stagnant, with further benefits for the whole regional forest sector, which can hope to restore productive forests. As a comparison, biomass procurement from healthy conifer or hardwood stands, with biomass feedstock comprised of tree tops and low-quality roundwood, would provide GHG mitigation benefits within 6 years or less, with cumulative savings over a 100-year period of 7 to 9 tonnes of CO_2 eq per gigajoule of bioenergy as a replacement of petroleum coke. However, replacing more efficient fossil fuels, such as natural gas, yields fewer interesting results in terms of mitigation benefits; for example, it might take up to 30 years before a bioenergy system based on primary residues from conifer stands and replacing natural gas to provide GHG savings, and would translate into cumulative savings (over 100 years) of 3 to 5 tonnes of CO_2 eq per gigajoule of bioenergy.

CONCLUSION

The best opportunities for unloved wood are likely to be found in integrated forest product chains, where conventional forest products, such as lumber, and bioenergy streams are integrated to optimize the fibre flows and values. These opportunities will only materialize if both the forest and biofuel sectors develop innovative forest management and procurement solutions, which make it possible to extract maximum value from the resource while respecting sustainability principles.

MOBILIZATION OF LOW-QUALITY SAWMILL RESIDUES AND URBAN WOOD WASTE FOR HEAT AND POWER PRODUCTION IN BRITISH COLUMBIA COASTAL REGION

Authors: Ehsan Oviesi, Mahmood Ebadian, Fahimeh Yazdanpanah and Shahab Sokhansanj. Biomass and Bioenergy Research Group, Chemical and Biological Engineering Department, University of British Columbia, Vancouver, BC, Canada

INTRODUCTION

In 2010, The University of British Columbia (UBC) announced its aggressive Greenhouse Gas (GHG) reduction targets for its Vancouver campus. The targets include a reduction of 33% below 2007 levels by 2015, 67% by 2020 and 100% by 2050. 2007 was selected as the baseline as UBC conducted a comprehensive campus GHG inventory which was estimated to be 61 090 tonnes of CO_2 eq. Figure 8 shows the contribution of different energy sources to the UBC campus GHG inventory in 2007.

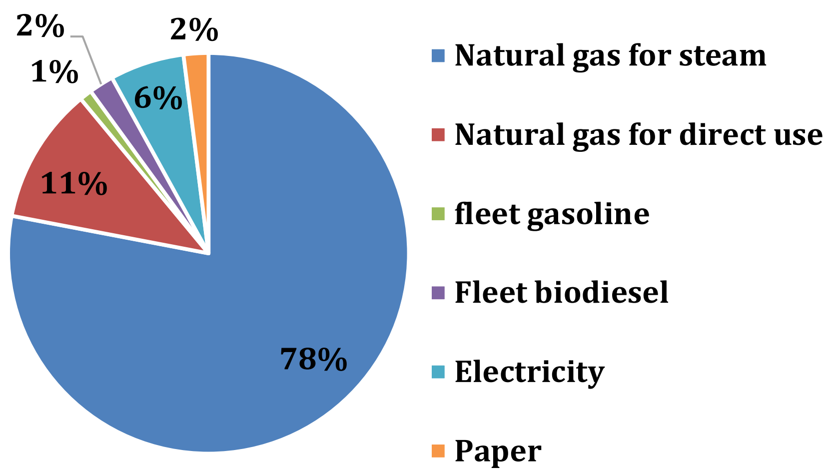

Figure 8: Contribution of different energy sources to the UBC campus GHG Inventory in 2007 (UBC, 2016)

Among the recommended options to reduce GHG was a bioenergy research demonstration facility (BRDF) with the goal of 12% GHG reduction. The construction of this facility was approved in Spring 2009 and the construction was completed in November 2012. This facility uses the urban wood waste and other underutilized wood waste streams in the Lower Mainland as feedstock to produce heat and power. The BRDF is a gasification plant with an annual biomass demand of 12500 oven-dry metric tonnes (odt) (corresponding to 2-4 truckloads/day) and produces 2 MWe of electricity, 4600 lb/hr steam and 1 MWt hot water in the cogeneration mode and 20000 lb/hr of steam in the thermal mode.

Gasification is a thermal process in which the biomass is exposed to an oxygen-deficit air and undergoes two sequences of endothermic transformations. Biomass first breaks down to volatiles and char during the first transformation at around 600ºC. The resulting volatiles contain hydrocarbon gases, hydrogen, carbon monoxide, carbon dioxide, tar and water. The char is mostly made up of fixed carbon and ash. The char is gasified and burned to produce heat during the second transformation at temperature exceeding 1000ºC. The combustible gases are eventually burned in an oxidizer to generate process heat (IEA Bioenergy Task 33 2016).

The Biomass and Bioenergy Research Group (BBRG) worked with both the biomass supplier and the gasification technology developer to measure the quality parameters of biomass delivered to the gasification plant and their impacts on the steam generation. The quality parameters included moisture content, ash content, particle size, heating content and bulk density. The objective 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 and gasification systems.

DESCRIPTION OF CURRENT SITUATION

Figure 9 shows the supply chain of the UBC gasification plant. It 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. The biomass supplier (a waste wood recycling yard, known as depot) is located in Langley, about 50 km from the gasification plant. The sources of feedstock are urban wood waste obtained from within a 100 km radius of depot. The urban wood waste consists of three classes of materials: woody scraps from construction and demolition (C&D), tree trimmings collected from Metro Vancouver's curbsides 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. Figure 10 shows examples of the wood wastes received at the depot. The raw biomass is collected from 114 locations within Metro Vancouver and processed in the depot before being delivered to the gasification plant on UBC campus.

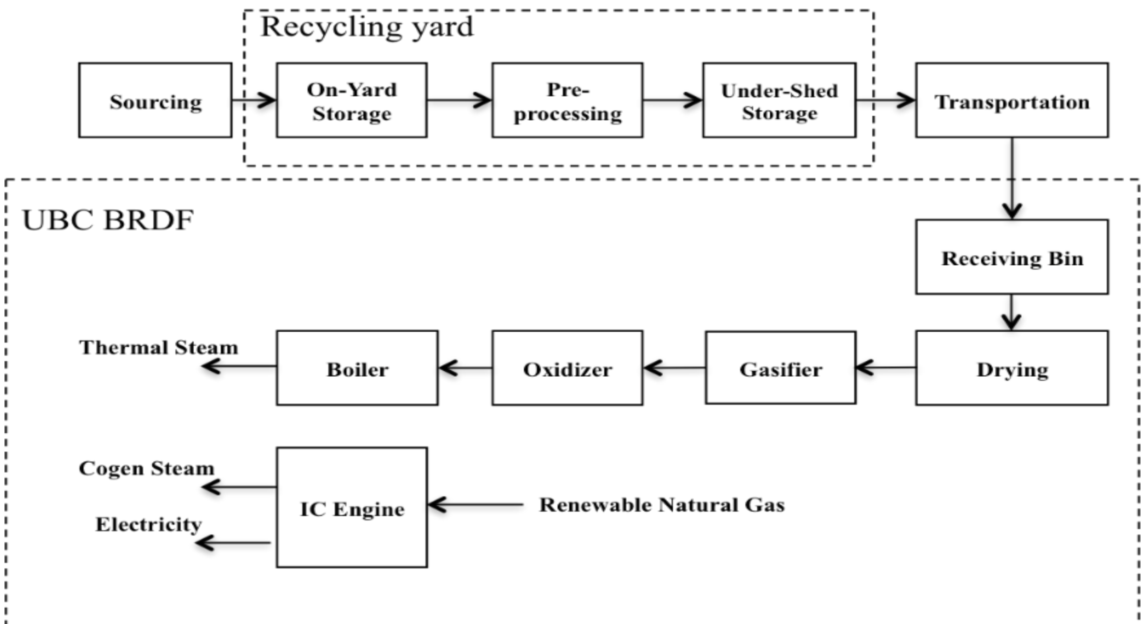

Figure 9: Schematic of the UBC gasification supply chain

Figure 10: Examples of receiving wood waste streams at the recycling yard of the UBC biomass supplier.

The UBC gasification plant requires particle sizes in the range of 6-76 mm and the moisture content in a range of 10-55%. According to the fuel specifications of the plant, the gasifier can tolerate an ash content of 10%. A preliminary analysis showed that the feedstock from recycled clean wood in Metro Vancouver region meets these specifications.

A more detailed analysis of feedstock characteristics and improvements in the performance of the UBC gasifier in terms of operational reliability and thermal output over three years of operation (2012-2015) was also performed. The data on the feedstock quality and the gasifier operation were taken on a regular basis at the depot and the facility.

Table 1 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 (reported on a wet mass basis) was 16.7%, ash content was 0.85% and calorific value was 19.1 MJ/kg. For green biomass, value for moisture content was 40.2% while ash content and calorific value were 0.91 % and 18.9 MJ/kg, respectively. For clean wood, the coefficient of variation (CV) was 23% for moisture content, 35% for ash content and 3% for calorific value. For green wood, the corresponding CV values were 9%, 29%, and 3%, respectively.

Table 1: Feedstock properties (moisture content, ash content and calorific value) of raw clean and raw green materials measured at the depot. Standard deviation and coefficient of variation (CV) are listed under the mean values in the form of (CV, STD). n = number of samples.

Category	**Moisture Content (% wb)**	**Ash Content (% db)**	**Calorific value (MJ/kg)**
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 the material measured at the gasification plant (n = 10)	31.0 (23%, 7.2)	0.83 (20%, 0.17)	19.2 (2%, 0.32)

A commercial tub grinder for wood (Hogzilla Model WC-1354P) comminuted the biomass to small pieces. In addition, an industrial screen with three sieves was used to segregate the ground biomass into three piles of undersize, acceptable/midsize and oversize piles. The data in Table 2 shows that the ash content of the undersize feedstock fraction was several times higher than the ash content in mid- and oversize fractions. The high ash content, which varied from 4.7% to 10.6% in the smaller feedstock fraction, is caused by soil contamination and bark. The ash content of the midsize and oversize was less than 1%. This reinforces the fact that the source of ash mainly comes from contamination with soil.

Figure 11 shows the size analysis for the unscreened and midsize particles. The fuel specifications require that the percentage of particles smaller than 6.7 mm to be less than 25% (as a proportion of mass). 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.

Table 2: Measurements of feedstock properties from the grinder and after the industrial screens.

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

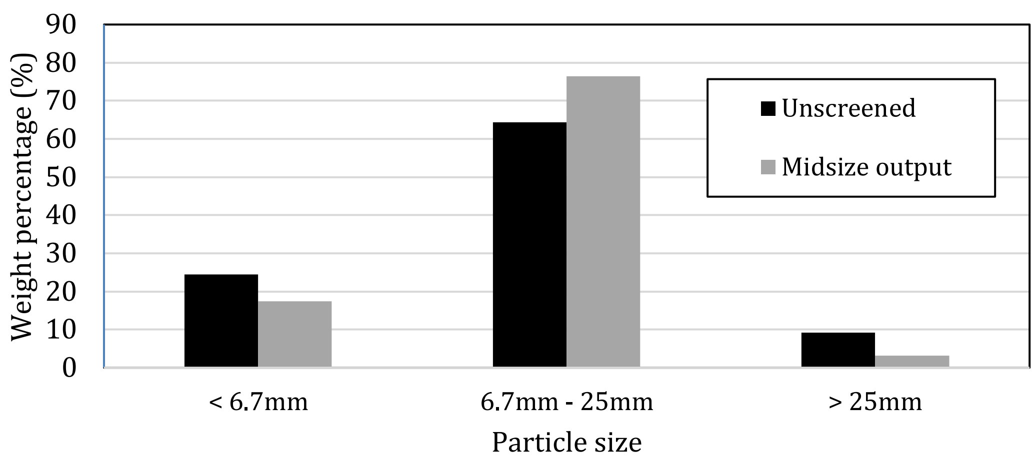

Figure 11 : Distribution of particle size in grinder (unscreened) before screen and in the mid-size fraction after screen.

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

The average and range of variability of daily measurements at the delivery point are listed in Table 3, showing that moisture content had the largest variation among the measured feedstock properties. The average moisture content of the green materials was highest at about 40.2%, while that of clean dry material was 16.7% (Table 3). 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.

Table 3: Descriptive statistics of the feedstock properties from July 2012 to June 2014 (871 samples).

	MC (% wb)	Bulk density (kg/m^3)	Calorific value (MJ/kg)	Ash content (% db)	Fraction of particles larger than 76 mm (%)	Fraction of particles smaller than 6.4 mm (%)
Average	31.0	187.4	19.4	0.8	9.1	17.6
STD	9.6	37.8	0.5	0.2	2.9	7.1
CV (%)	31	20	3	25	32	40
Minimum	10.0	92.0	18.1	0.2	0.0	0.9
Maximum	57.4	327.7	20.9	1.5	18.4	47.6

The UBC gasification plant records operational parameters such as biomass feeding rate to the gasifier, bed temperature, operating hours, and the amount of steam produced over time. Among these parameters, moisture content had a definite negative correlation with steam flow. Figure 12 shows the spread of data with a negative relation between the normalized steam (in kg of steam per tonne of dry biomass) and moisture content, with a correlation coefficient of -0.73. This trend was especially evident for moisture contents above 20%. For every tonne of fuel, the steam generation 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 influencing the heat output of the gasifier.

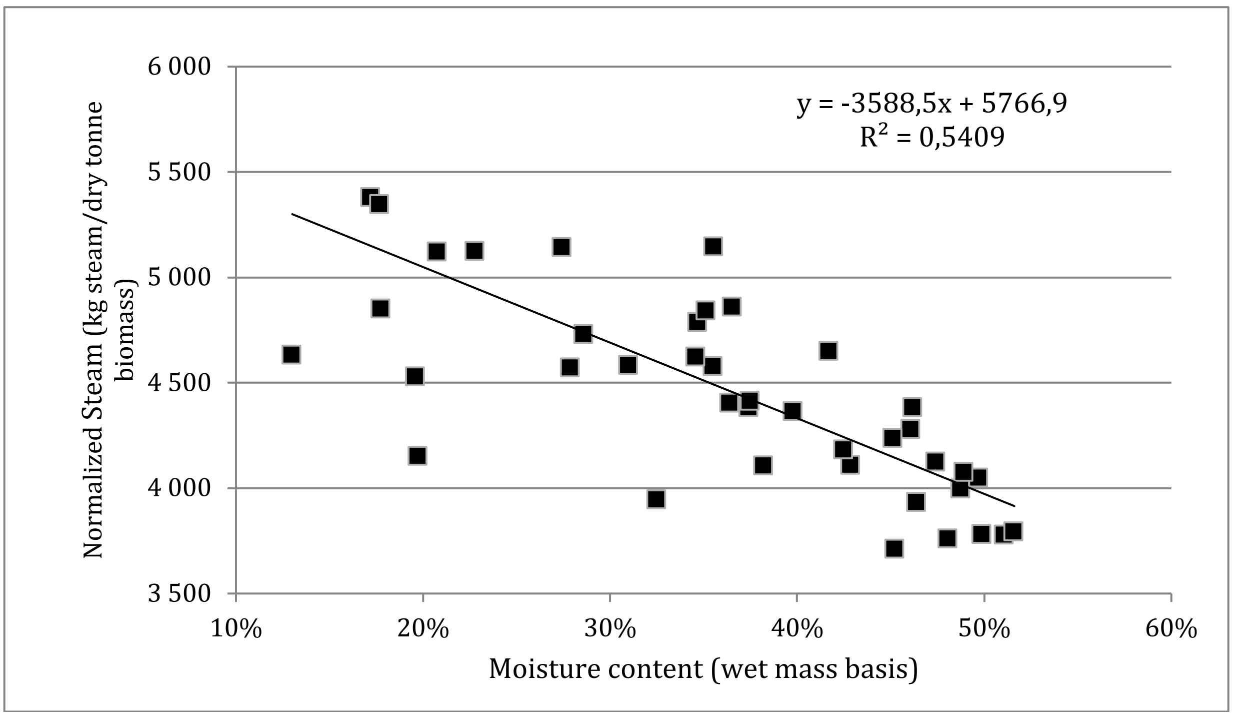

Figure 12: Relationship between normalized steam and moisture content.

The major quality parameters 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 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.

CONCLUSION

- 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.
- Protecting the biomass against rain helps to reduce the level and variation in moisture content.
- 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 changes in moisture content of the feedstock.

SUPPLY OF WOOD PELLETS TO COAL-FIRED POWER PLANTS IN ALBERTA

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INTRODUCTION

Replacement of coal-based generation stations with renewable electricity sources such as wind, solar and biomass has been used in many countries as a strategy to reduce the carbon intensity of the power fleets. Although wind and solar have been attractive and viable options in some regions, their ability to provide reliable base load electricity generation has raised concerns about the fulfillment of the electricity demand of end users, in particular industrial consumers as they demand a continuous power supply (Independent Power Producers Society of Alberta 2015). One potential complementary generation method would be to cofire or completely replace coal with biomass. As of 2009, International Energy Agency (IEA) reported that 234 power plants had been retrofitted to cofire biomass, most only up to a 15% co-firing rate (International Energy Agency 2009). Among the feedstock sources used in co-firing, woody biomass, in particular wood pellets, has been used in large scale power plants due to its similar physical and chemical properties with coal (International Energy Agency 2016).

This Knowledge Translation (KT) project aimed to demonstrate the co-firing of Canadian wood pellets with coal as a compliance strategy to reduce the carbon intensity of the electricity generation in Alberta. The motivation behind this project was the "Climate Leadership Plan" in Alberta to combat the climate change in a province that have the largest GHG emissions in Canada. Replacement of coal-based generation stations with renewable electricity sources such as wind, solar and biomass has been used in many countries as a strategy to reduce the carbon intensity of the power fleets. Although wind and solar have been attractive and viable options in some regions, their ability to provide reliable base load electricity generation has raised concerns about the fulfillment of the electricity demand of end users, in particular industrial consumers as they demand a continuous power supply (Independent Power Producers Society of Alberta 2015). One potential complementary generation method would be to cofire or completely replace coal with biomass. As of 2009, International Energy Agency (IEA) reported that 234 power plants had been retrofitted to cofire biomass, most only up to a 15% cofiring rate (International Energy Agency 2009). Among the feedstock sources used in co-firing, woody biomass, in particular wood pellet, has been used in large scale power plants due to its similar physical and chemical properties with coal (International Energy Agency 2016). In this project, we discuss the logistical implications and the basic costs associated with retrofitting a theoretical 400 MW coal power plant in Wabamum, Alberta, Canada. The locations of potential feedstock supply for wood pellets are analyzed and the direct employment that a wood pellet power plant would provide is also discussed.

The Biomass and Bioenergy Research Group (BBRG) collaborated with the Wood Pellet Association of Canada (WAPC), FPInnovations, and BC Bioenergy Network and the Wood Pellet Sector to introduce biomass as a sustainable and renewable fuel source to decarbonize the power generation in Alberta. The overall objective of this collaboration was to address one single question: "Is co-firing biomass with coal a viable option to reduce the carbon intensity of coal-fired power plants in Alberta?"

DESCRIPTION OF CURRENT SITUATION

Alberta power fleet accounts for about 17% of the total GHG emissions of the province (Government of Alberta 2016). Currently, there are 18 coal-based generating station units in Alberta with a total capacity of 6,271 MW, about 39% of the total power supply in Alberta (Independent Power Producers Society of Alberta 2015). One of the primary goals of the Climate Leadership Plan announced in November 2015 is to phase out coal by 2030 and replace it with renewable and natural gas-fired generation facilities. By 2030, 12 of Alberta's 18 coal-fired generating stations will reach 50 years of operation and will be retired, unless they are able to meet GHG emissions standards set by the federal coal regulations (Independent Power Producers Society of Alberta 2015). The shutdown of the remaining six stations by 2030 will leave the power plants with the stranded assets as the capital invested in these stations will not be earned back by then. In addition, the accelerated shutdown affects the workers in the coal-dependent communities, as well as other sectors that depend on these workers and their families such as healthcare, schools, and grocery stores.

DESCRIPTION OF OPPORTUNITIES FOR MOBILIZATION OF BIOMASS RESOURCES

In the United Kingdom, Drax Power operates as a base load generating station and has retrofitted three of six power generators to burn 100% wood pellets in place of coal. In Canada, the Atikokan and Thunder Bay generating stations have been retrofitted from coal fuel to 100% wood pellet fuel. Both of these generating stations are peak power stations, which are only activated when power demand exceeds or is predicted to exceed base load capacity. These facilities each use approximately 45000 tonnes of wood pellets per year to provide a combined 550 MW of power to the province of Ontario (Strauss, 2014). Employment at wood pellet power plants can be lower than coal power plants, but the entire supply chain creates more direct employment positions (Strauss 2014).

Figure 13 shows the location and the power capacity and the age of six generating station units in Alberta as of 2016. By 2030, when the complete phase-out of coal will be enforced by the provincial government, these units will likely need to continue operating in order to recover the invested capital. The total capacity of these six units is 2570 MW. These units consume approximately 12 M tonnes of coal annually.

Generating Station Unit	Nameplate Capacity (MW)	Age by 2030	Location
Keephills 3	495	19	Wabamun, 70-km west of Edmonton
Genesee 3	495	25	Genesee, 50-km southwest of Edmonton
Genesee 2	410	41	Warburg, 90-km southwest of Edmonton
Genesee 1	410	36	
Sheerness 2	380	40	Hanna, 200-km northeast of Calgary
Sheerness 1	380	46	

Figure 13: Six generating station units that need to operate beyond 2030 to recover the capital invested in these stations and to avoid the stranding assets (IPPSA, 2015).

Wood pellet is considered as a replacement for coal in these facilities. The woody material for the production of wood pellets will be supplied from the home province, Alberta, and from British Columbia. Both provinces have an active forest industry producing various forest products for local, regional and international markets. Due to the massive size of forestlands in these two provinces, large quantities of unutilized wood fibre are available for other industrial uses than the conventional forest industry. Two primarily untapped sources of forest biomass are primary logging residues and non-merchantable timbers. With the current level of Allowable Annual Cut (AAC) (22.45 million m^3) in Alberta, there are approximately 2.9 million oven-dry tonnes (M odt) of unharvested standing timbers (see also Figure 1) and up to 4.0 M odt of logging residues available for other industrial uses than the conventional forest products. In addition, the undersized trees within the merchantable stands are being considered as a source of biomass in the province. It is estimated that there are over 1.8 M odt of this source of biomass available in Alberta (Government of Alberta 2014). In addition to public forestlands, private forestlands can be a source of biomass for coal-fired power plants. The average annual harvest in these forestlands is over one million odt. With the current level of AAC in BC (75 million m^3) there are about 5.4 M odt and 2.9 M odt of unutilized logging residues and standing timbers available in BC (BC Hydro 2013). These unutilized timbers are non-sawlog/non-merchantable timbers within merchantable stands (see also the case study on underutilized « unloved » trees). In total, the potential availability of forest biomass including secondary sawmill residues, primary logging residues and non-merchantable standing timbers is estimated to be over 9 M odt and 8 M odt in Alberta and BC, respectively. In addition, the wood pellet sector in these two provinces is currently producing over 1.7 million tonnes of wood pellets per year. A portion of this capacity may be available for Alberta coal power fleet depending on the market conditions.

Wood pellets can be created through several different supply chain options that are discussed in Figure 14. They can be available at the pellet mill site, if it is co-located with a sawmill or it may need a short hauling from the sawmill site to the pellet plant. Logging residues are piled near the landing, chipped into chip vans and then transported to the pellet mill.

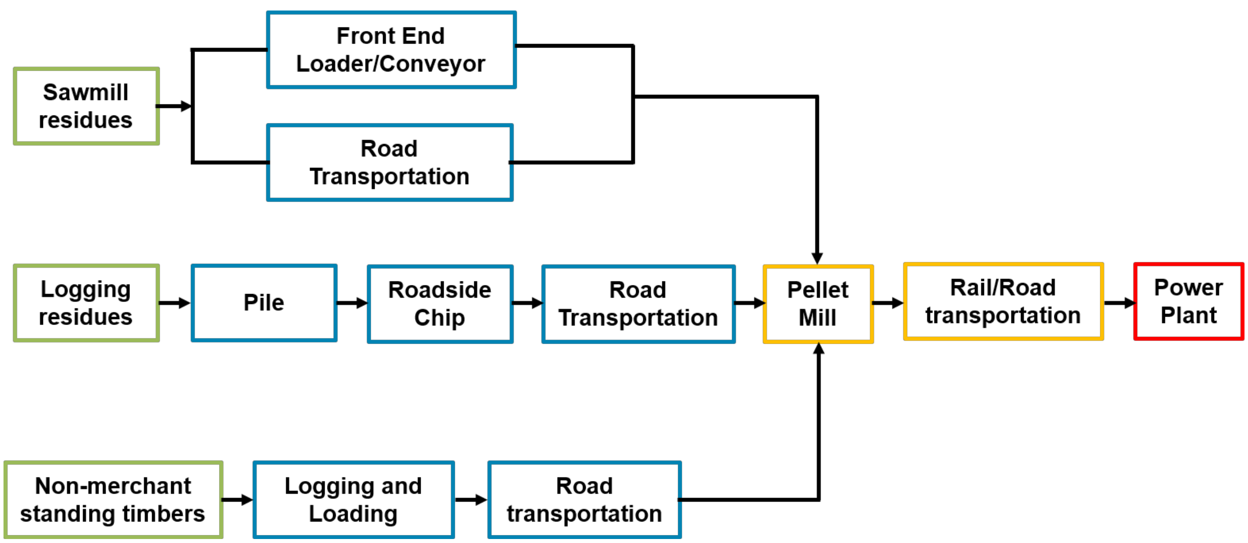

Figure 14: The supply of different available woody biomass in Alberta and BC to the coal-fired power plants

A 400 MW unit represents the average size of the six units under study. Two co-firing fractions are considered: (1) 100% replacement of coal with biomass (2) a co-firing fraction in which the carbon intensity of a coal-based power plant is down to a natural gas combined cycle. This co-firing fraction is used in this study to compare it with 100% co-firing. A 60% co-firing operation of the power plant represents 46% of Canada's total wood pellet production capacity while 100% wood pellet supply represents 78%. A mixture of logging residues and standing timber from the unused Annual Allowable Cut (AAC) in both provinces were used as pellet feedstock in this study, as shown in Table 4. The mixture of residues and standing timber were assumed to be milled into pellets close to the source, with an average travel distance of 100-150 km. The produced wood pellets were assumed to have a heat content of 18 GJ $tonne^{-1}$, replacing coal with an energy content of 20 GJ $tonne^{-1}$.

Table 4: Wood pellet plant configuration and requirements

Wood Pellet Plant Configuration	
Production Capacity (tonne/yr)	200 000
Number of employees	26
Pellet-to-feedstock ratio	0.8
Feedstock composition	70% logging residues and 30% standing timber
Supply radius (km)	100-150
60% Co-firing	
Required Wood Pellet (million tonnes/year)	1.03
Number of wood pellet plants	5
Required feedstock (odt/year)	1,287,500
100% Co-firing	
Required Wood Pellet (million tonnes/year)	1.72
Number of wood pellet plants	9
Required feedstock (odt/year)	2 150 000

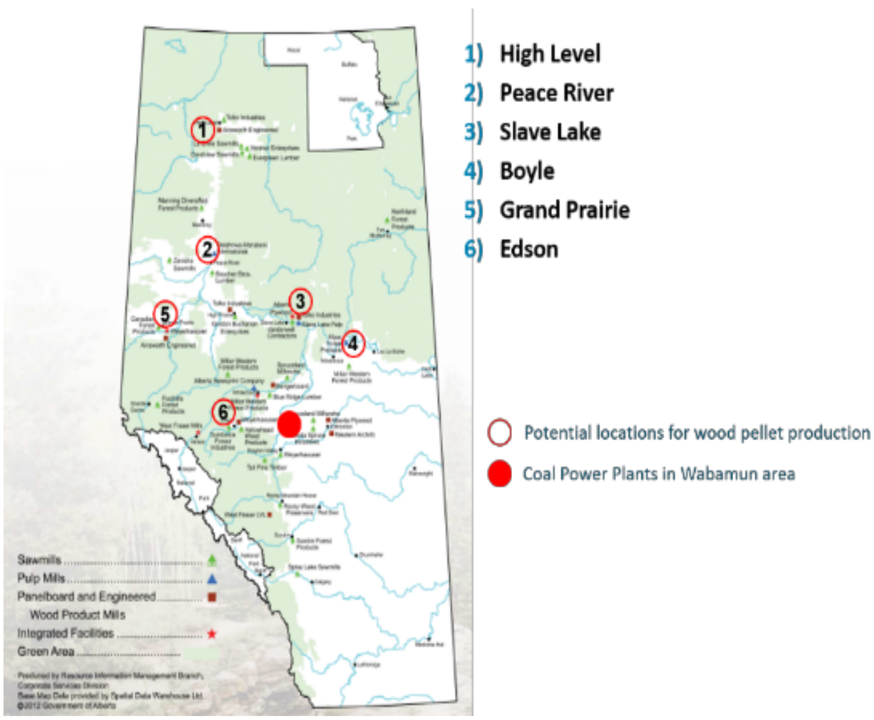

Figure 15: Potential pellet mill locations in Alberta

Each pellet mill established to supply the power plant is assumed to have an annual production capacity of 200000 tonnes and employs 26 people. Each timber/residue crew was assumed to be comprised of 5 people and could produce 10 tonnes hr^{-1} of standing timber or 5 tonnes hr^{-1} of residues. Favorable areas in Alberta for pellet mills identified in this study include: High Level, Peace River, Slave Lake, Boyle, Grand Prairie and Edison, as shown in Figure 15. The capital expenses (Capex) to convert the power plant from coal to wood pellet are assumed to be \$500 kW^{-1} with fixed operations and maintenance (O&M) costs at 2% of the Capex. The capital recovery factor at the end of the power plants life is assumed to be 11%. The O&M costs for the power transmission are assumed to be \$20 MWh^{-1}. The power plant is expected to have a 3% heat derating factor per MW from differences in fuel characteristics between wood pellets and coal, as shown in Table 5.

Table 5: Technical and cost data

Technical and Cost Data	
Plant Capacity (MW)	400.0
Heat Rate (GJ/MWh)	10.0
Capacity Factor (%)	90.0
Coal heat content (GJ/tonne)	20
Cost of coal (\$/GJ)	1.3
Base CO_2-eq intensity (tonne/MWh)	1.0
Wood pellet heat content (GJ/tonne)	18.0
CO_2-eq reduction/co-firing ratio (%)	0.9-1.0
Biomass Processing Data	
Capital Cost (\$/kW)	500
Fixed O&M Cost (% of capital cost)	2
Capital Recovery Factor	0.11
Derate Factor (%)	3
Operational O&M and transmission (\$/MWh)	20

The selling price of power is calculated using the 60% co-firing scenario and the 100% wood pellet scenario. In addition to the selling price, the overall jobs created through the supply system are calculated plus the CO_2 emissions reductions. For this theoretical analysis, a generic 400 MW coal power plant is assumed to be located at the Wabamum, AB where most of the coal-fired power plants are operating. This plant is originally using 1.53 million tonnes coal to produce grid electricity before enacting of Alberta's CLP regulations. The two emission reduction plans analyzed here look at reducing the power plant emissions to match natural gas fueled power plant emission levels (60% co-firing rate), and completely replacing coal with wood pellets. If the 60% co-firing rate is used, 1.03 Million tonnes of pellets would be required. In 100% woody biomass feedstock, 1.72 million tonnes of pellets would be required, as shown in Figure 16. The delivered cost of pellets at the power plant is estimated to be in the range of \$130-170 $tonne^{-1}$ (Table 6).

The 60% co-firing scenario would require 5 pellet mills to be constructed, and the 100% wood pellet power would require 9 pellet mills. In the 60% co-firing scenario, 1.3 million tonnes of feedstock would be required to produce 1.03 million tonnes of pellets annually; in the 100% wood pellet power scenario, 2.2 million tonnes of feedstock would be necessary to produce 1.72 million tonnes of pellets annually. The 60% co-firing scenario would directly employ an estimated 627 personals in the biomass supply chain activities from the forest to the gate of the power plant (Figure 17). Of the 627 direct employment, 440 come from the timber and residue harvesting operations, 57 from transporting biomass feedstocks to the pellet mills, and 130 at the pellet mills. The 100% wood pellet energy scenario would directly employ an estimated 1023 people for the same operations. Of the 1023 direct employment, 735 come from woody biomass harvesting operations, 97 from transport to the pellet mills, and 234 from pellet mill operations. For such large and geographically diverse logistics chains, there is likely to be a significant number of secondary employment opportunities that support operations and this allows the power plant to maintain most or all of the jobs it currently supports.

Table 6: Breakdown of delivered cost at the gate of the power plant

Cost component	Sawmill residues	Logging residues	Non-merchant standing timbers
Feedstock cost at the pellet plant ($/dry tonne)	30-35	60-80	75-150+
Pellet price at the pellet mill ($/tonne)	105-145		
Pellet transportation-rail ($/tonne)	9-36.5		
Delivered cost- power plant ($/tonne)	130-170		
Delivered cost-power plant ($/GJ)	7.07-9.25		

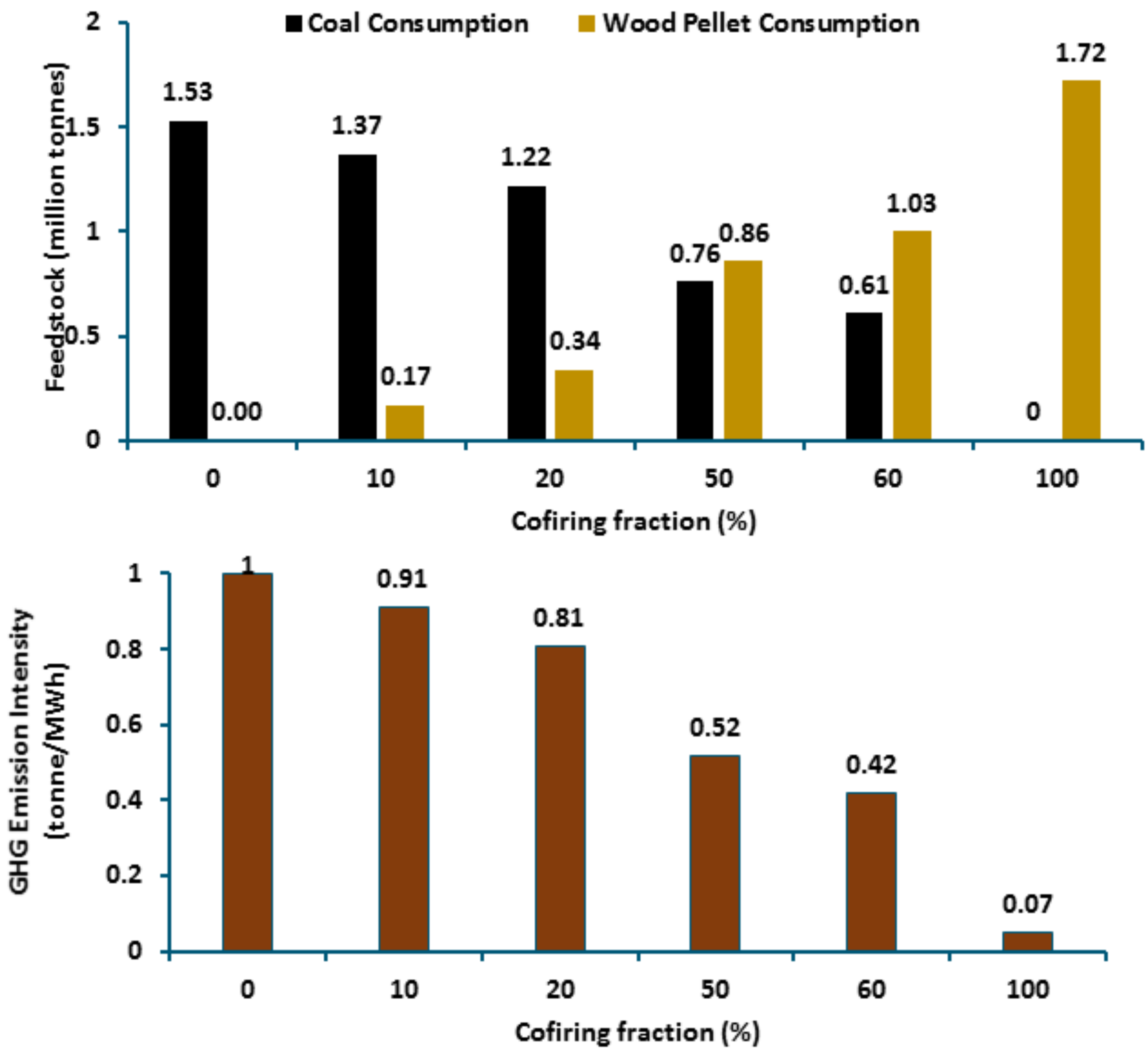

Figure 16 : Coal and CO_2 emissions tonnage displacement with increasing wood pellet usage.

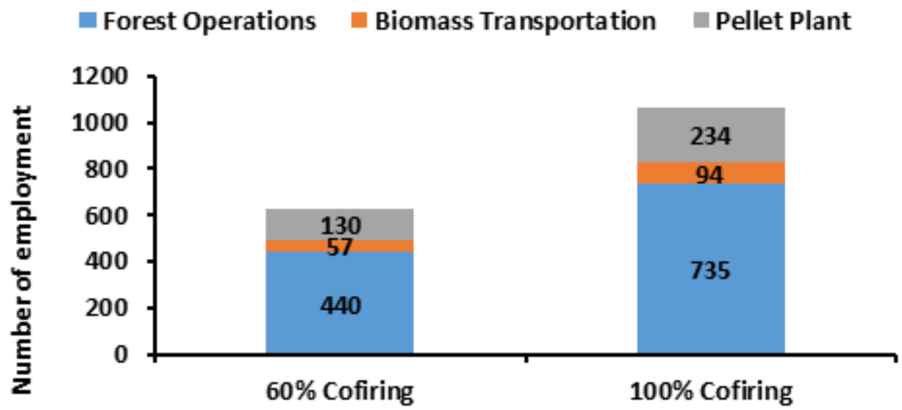

Figure 17: Employment- Wood pellet logistics system

By converting coal power plants to partial or complete wood pellet feedstock, significant amounts of CO_2-eq emissions can be avoided. Using the assumptions of this analysis, the avoided CO_2-eq costs are estimated to be \$70.01 tonne CO_2-eq $^{-1}$ when pellets cost \$130 tonne^{-1} at the power plant gate, but rose to \$92.92 tonne CO2-eq^{-1} when pellets cost \$170 tonne^{-1} at the power plant gate. For every \$5 tonne^{-1} increase in delivered pellet price, an increase of \$2.86 tonne CO_2-eq $^{-1}$ is observed (Figure 18).

There have been several methods of carbon taxes employed globally. For this analysis, we assumed that every tonne of CO_2-e released would be taxed at a given rate (\$15, \$20, or \$30). If the carbon tax on the released CO2-eq is assumed to be \$15 tonne^{-1}, an increase of \$14.52 MWh^{-1} is observed in the cost of electricity if only coal is used to generate power; this increase is \$6.08 MWh^{-1} if natural gas is used to generate power, and \$0.28 MWh^{-1} if only woody biomass is used (Figure 19). If the carbon tax on the released CO_2-eq is estimated to be \$30 tonne^{-1}, an increase of \$29.02 MWh^{-1} is observed if only coal is used to generate power, whereas it is estimated at \$12.17 MWh^{-1} if natural gas is used and at \$0.57 MWh^{-1} with biomass.

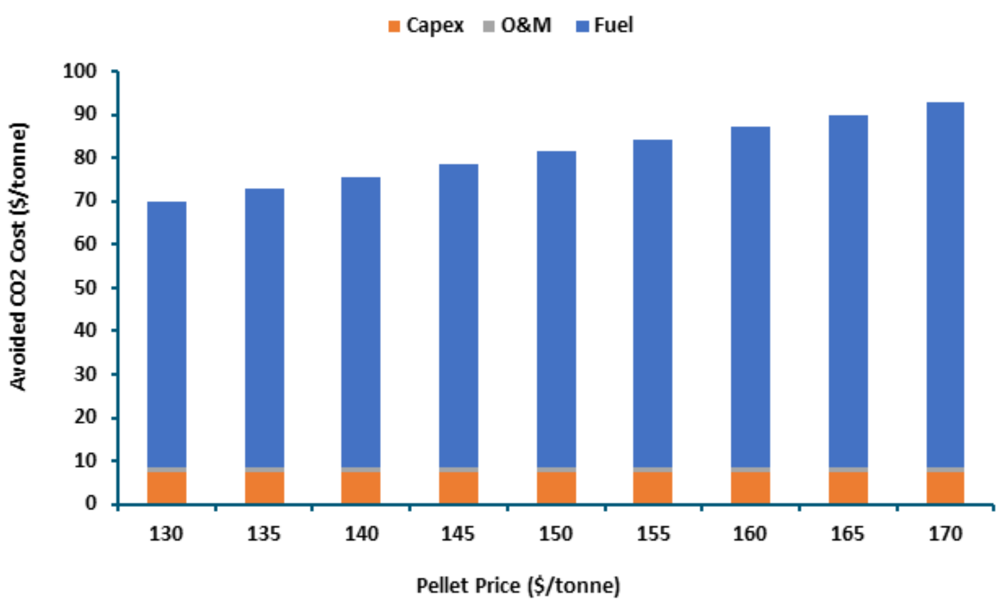

Figure 18: Avoided CO_2 costs

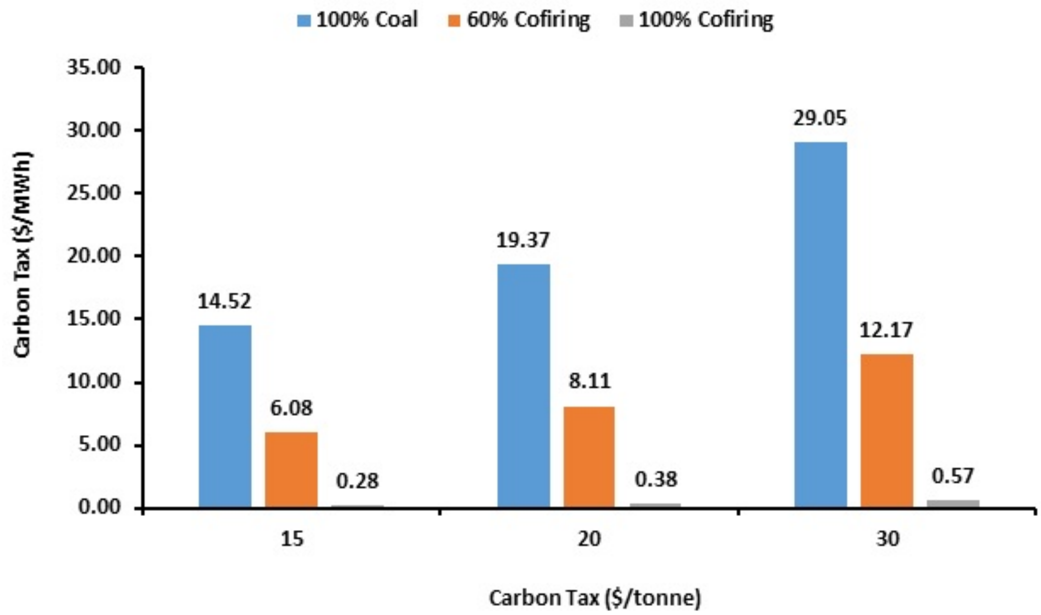

Figure 19: Carbon tax effect on selling price

For the 60% co-firing scenario, the selling price of power ranged from \$73.36 MWh^{-1} when pellets are delivered to the power plant at \$130 $tonne^{-1}$, to \$86.67 MWh^{-1} when pellets are delivered to the power plant at \$170 $tonne^{-1}$. With the conversion capex set to \$500 kW^{-1}, capex accounted for \$4.26 MWh^{-1}, fixed O&M costs accounted for \$0.77 MWh^{-1}, transmission O&M accounted for \$20 MWh^{-1} and the fuel costs accounted for \$48.33-\$61.63 MWh^{-1} (Figure 20). For the 100% wood pellet power, the selling price of power ranged from \$101.45 MWh^{-1} to \$123.89 MWh^{-1} with the delivered pellet price ranging from \$130 $tonne^{-1}$ to \$170 $tonne^{-1}$. With the conversion capex at \$500 kW^{-1}, capex accounted for \$7.19 MWh^{-1}, fixed O&M costs accounted for \$1.31 MWh^{-1}, transmission O&M accounted for \$20 MWh^{-1} and fuel costs accounted for \$72.95-\$95.39 MWh^{-1} (Figure 21).

If the conversion capex is reduced to \$250 kW^{-1}, with a delivered pellet price of \$150 $tonne^{-1}$, the avoided CO_2-eq cost is reduced to \$77.30/tonne. An avoided CO_2-eq cost of \$77.30 allows power to be sold for \$77.60 MWh^{-1} in the 60% co-firing scenario and \$108.59 in the 100% wood pellet power scenario, a 3.0% and 3.6% reduction, respectively. However, if the capex is increased to \$750 kW^{-1}, with a delivered pellet price of \$150 $tonne^{-1}$, the avoided CO_2-e cost is increased to \$85.80/tonne. An avoided CO_2-eq cost of \$85.80 allows power to be sold for \$82.53 MWh^{-1} in the 60% co-firing scenario and \$116.92 in the 100% wood pellet power scenario, and increase of 3.1% and 3.8%, respectively (Table 7).

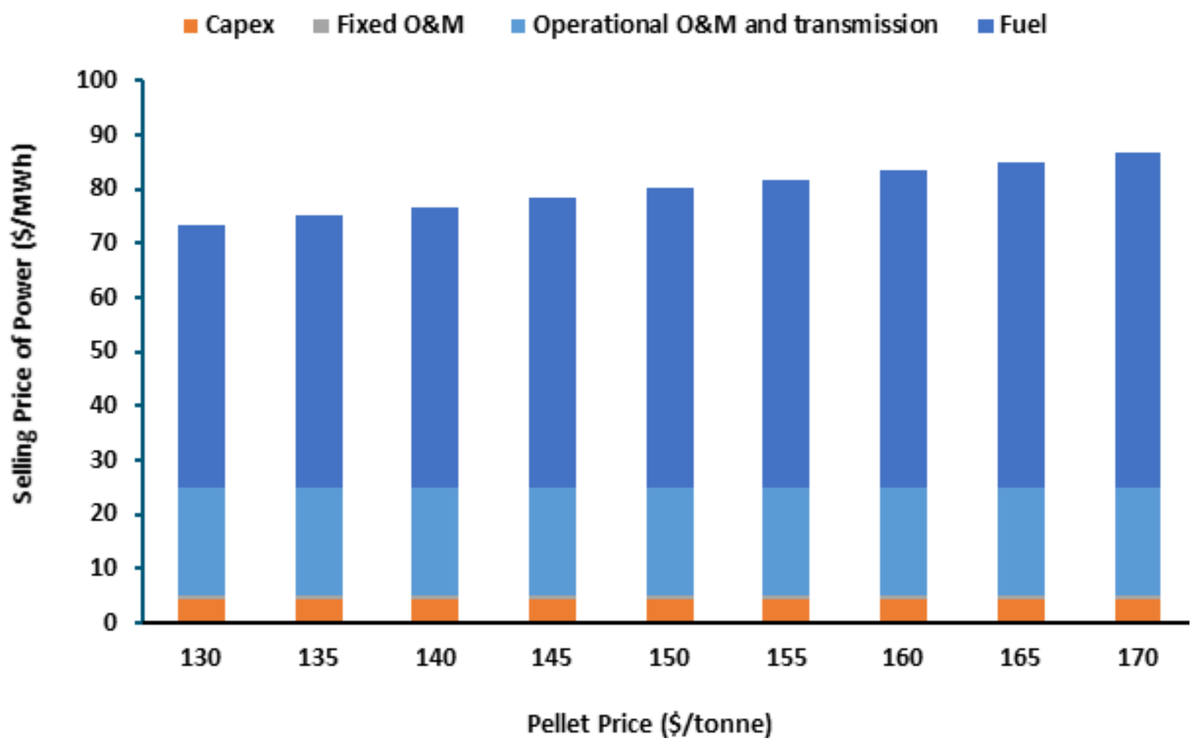

Figure 20: Power selling price - 60% co-firing

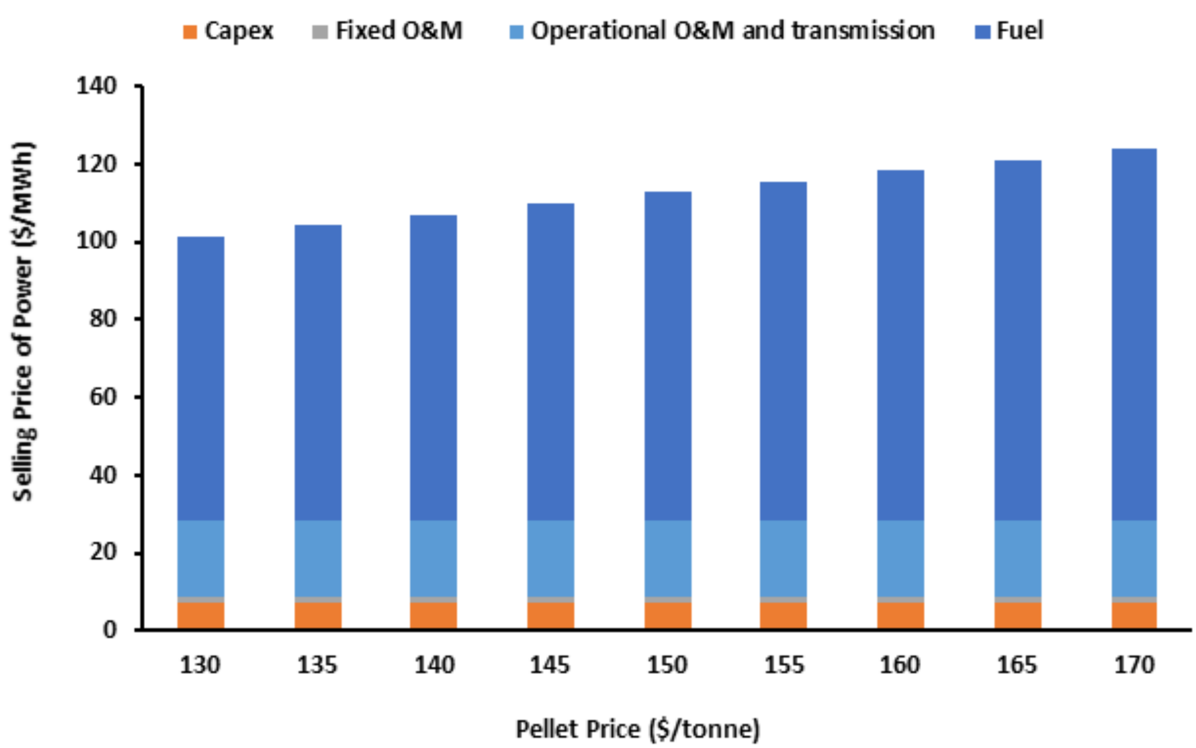

Figure 21: Power selling price - 100% wood pellets

Table 7: Sensitivity analysis on the capital costs of converting to wood pellet

Capital Cost ($/KW)	**250**	**500**	**750**
60% Co-firing			
Avoided CO_2 Cost ($/tonne)	77.30	81.46	85.80
Selling Price of Power ($/MWh)	77.60	80.02	82.53
100% Co-firing			
Avoided CO_2 cost ($/tonne)	77.30	81.46	85.80
Selling Price of Power ($/MWh)	108.59	112.67	116.92

With the assumptions discussed above, the maximum wood pellet usage scenario can provide a significant amount of renewable power. Using both Alberta and British Columbia as feedstock sources, there is roughly 18 million odt of woody biomass feedstock available for coal to wood pellet conversion projects. This is enough feedstock to power 14 power plants at a 60% co-firing rate or 8 power plants with 100% wood pellets. If the maximum number of plant conversions were undertaken, 70-72 pellet mills with an annual capacity of 200000 tonnes would be required, creating a direct employment of 8500-8800. The delivered pellet price at the power plant ranges between \$7.07 GJ^{-1} and \$9.25 GJ^{-1} and the avoided CO_2-eq costs vary accordingly between \$70 $tonne^{-1}$ and \$93 $tonne^{-1}$. The final selling price of power for the 60% co-firing scenario ranges from \$73-89 MWh^{-1} depending on the delivered price of the pellets at the power plant. The final selling price of power for the 100% wood pellet power scenario ranges from \$101-124 MWh^{-1} depending on the delivered price of the pellets at the power plant (Table 8).

Table 8: Summary of logistics and supply chain

	60% Co-firing	**100% Co-firing**
Potential availability of woody biomass in Alberta (public and private forest lands)	~10 million odt	
Potential availability of woody biomass in BC	~8 million odt	
Required biomass to retrofit a 400 MW power facility	1.29 million odt	2.15 million odt
Potential number of retrofitting coal-fired power plants	14	8
Potential number of pellet plants with a capacity of 200 000 tonnes/year	70-72	
Potential employment	8 500-8 800	
Pellet cost at the gate of the power plant ($/GJ)	7.07-9.25	
Avoided CO_2 Cost ($/tonne)	70-93	
Selling price of power ($/MWh)	73-89	101-124

CONCLUSION

Controlling the cost of fuel is critical to ensuring the success of a woody biomass-based green energy project. In our analysis, pellets accounted for 66-77% of the total expenses of a conversion project. Harvesting and collecting feedstock account for over half the cost of the pellets, primarily in the transportation costs from the location of the woody biomass to the pellet mill. Securing long-term, guaranteed feedstock sources is also extremely important to the success of a project of this nature. Locating pellet mills contracted to these power plants in or close to highly productive timberlands ensures the minimum transportation expenses and minimum likelihood of feedstock shortfalls.

A coal to wood pellet conversion project, using the assumptions of this analysis, can produce power for consumer price of approximately \$0.075-0.125 kWh^{-1}. These numbers are higher than generally seen in Alberta's current market. The CO_2 emissions could be reduced by 58% in a 60% co-firing scenario and by 93% in a 100% wood pellet scenario. The supply system for the 60% co-firing can provide over 600 permanent employment opportunities along the supply chain, while the 100% wood pellet scenario can provide over 1200 permanent employment opportunities.

PRODUCTION OF BIOJET FROM WOODY BIOMASS IN WESTERN CANADA

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INTRODUCTION

The aviation sector is responsible for >2% of the world's GHG emissions and this percentage is expected to grow significantly to 2050 as air travel increases. To counteract this possible increased contribution to emissions, the global aviation industry has committed to reducing its anticipated 2020 GHG emissions to 2005 levels and, by 2050, reducing its GHG emissions by 50%. Progress towards these ambitious goals is already being realized through improvements in aircraft design, engine efficiencies, ground transport improvements, air traffic control systems, etc. However, in the mid-to-long-term, aviation fuels will have to be de-carbonized and biojet fuels are the only alternative until well after 2050 as other technologies develop.

Current biojet fuel consumption is less than 0.01% and all based on oleochemical technologies, the upgrading of oils and fats. Significant expansion of this pathway for biojet production is challenged by the high cost of this feedstock, limited opportunities to reduce costs and questions of sustainability and food vs. fuels issues. Meeting mid-to-long-term emission reductions in the aviation sector will require the development and commercialization of biojet technologies using sustainably sourced biomass feedstocks that are available in larger volumes at significantly lower cost, and likely thermochemical conversion pathways.

British Columbia has a high proportion of sustainably certified forests, as well as a track record for developing innovative forest products, such as parallam and oriented strand board (OSB). BC has also been at the forefront of the development of the pellet industry with a current capacity of about 2.1 million tonnes of pellets per year, mostly from secondary mill residues. Existing supply chains established by forest companies are well-developed for removing high value wood from the forest. Mill residues, a cheap feedstock, is produced in limited volumes and are already utilized extensively by the wood pellet sector. The most suitable biomass for biojet production seems to be forest residues that are currently unutilized and burnt in slash piles as a fire mitigation measure. However, supply chains for accessing these residues are not developed yet, although some wood pellet producers are starting to access this resource. Using forest residues for biojet fuel production will therefore require mobilization of this resource through new supply chains piggy-backing on existing wood supply chains or through pellet production supply chains.

The Forest Products Biotech and Bioenergy group and BBRG at the University of British Columbia worked with their industrial partner, Boeing, to evaluate the viability of the establishment of a wood-to-biojet supply chain in Western Canada considering the potential synergies with the existing forestry and fossil fuel supply chains in this region. This case study looked at availability, cost and sustainability of biomass in BC and the potential for domestic production of biojet fuels from forest residues.

DESCRIPTION OF CURRENT SITUATION

CURRENT FEEDSTOCK UTILIZATION AND AVAILABILITY

British Columbia constitutes 18% (55 million hectares) of Canada's total forested area (310 million hectares). The availability of wood fibre and the use of sustainable forest practices have facilitated the development of various industries including the primary (e.g. lumber, panels, engineered wood, etc.) secondary (pulp and paper) and tertiary sectors (bioenergy (i.e. heat and power, wood pellets, etc.).

To ensure sustainable timber supplies and community stability, harvesting of forests in both BC and Alberta are done according to the Annual Allowable Cut (AAC) system on public land and some private land. The approved AAC varies over time as a result of events such as wildfire, insects and diseases, calculation methods, forest inventory and growth, new harvesting and milling technologies, yield information and management strategies. The AAC impacts the availability of wood fibre for the entire industry.

BC, with about 95 million hectares of land has roughly 55 million hectares of forested lands (AEBIOM 2013). The timber production forest area on Crown forest land totals roughly 22 million hectares. The standing timber volume in BC′s forests totals about 11 billion cubic metres (m^3). On private forest lands, an additional 2 million hectares is suitable for harvest. Since 1990, the area harvested on public forest land averaged 180 000 hectares per year. On average, an estimated additional 20 000 hectares are harvested each year on private forest land (BC Ministry of Forests Mines and Lands 2010).

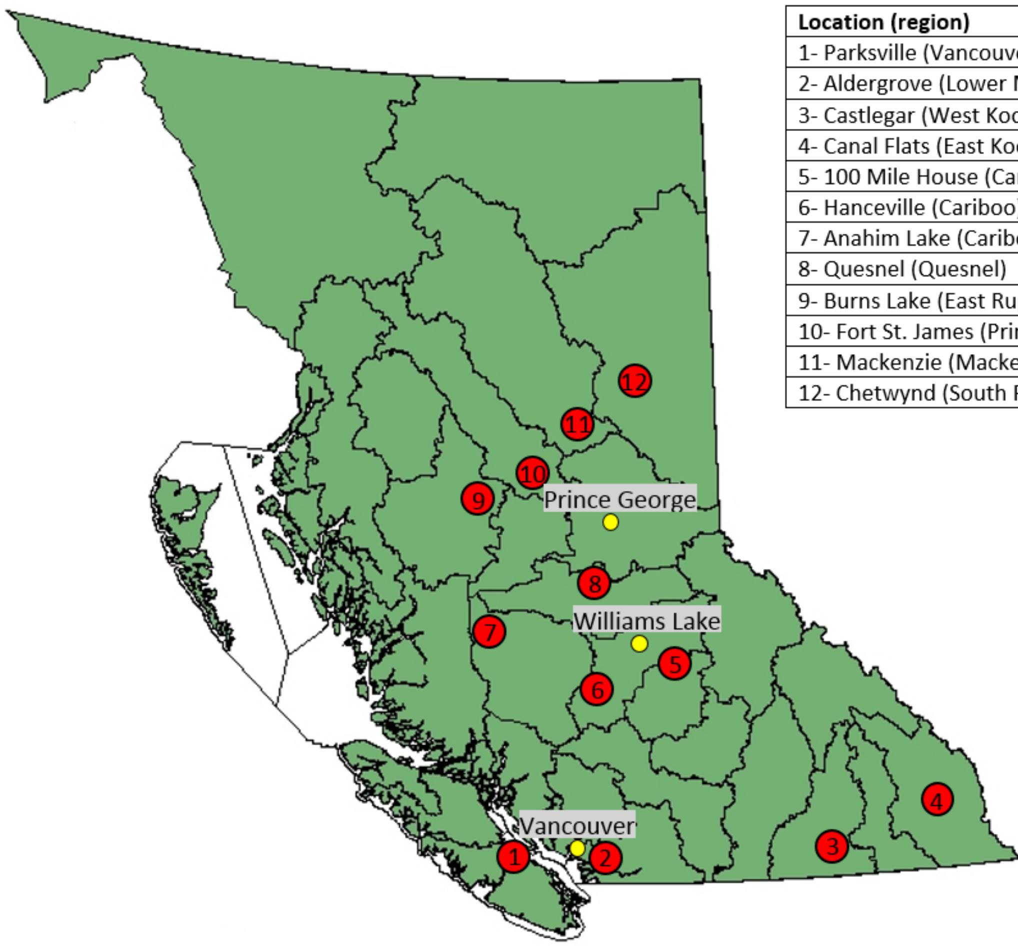
The forest tenure system in BC, which has been in place for over 100 years, presents some challenges to feedstock accessibility and could have some direct and indirect implications for biojet fuel production based upon forest residues. For instance, there is no specific provision or policy for harvesting forest residues, with the only regulations in place being related to fire hazards. Tenure holders are under no obligation to sell residues (which can be left on the roadside or burned), nor to allow third parties to access the residues. This means that while there might be ample residues, not all of it might actually be *available* for the marketplace. Mobilization of forest residues for biojet production requires not only an assessment of physical availability, but also examines economic availability, quality and the policy environment associated with accessing this material.

Forest residues are comprised of primary logging residues that remain on the ground after forest operations have taken place and tend to consist of branches, tree tops, smaller and broken trees. About 6 M odt of forest residues are available annually in BC. To ensure the sustainability and the regeneration and health of future forests at least 25% of these residues must remain behind on the forest floor. Currently about 0.6 M odt of forest residues are utilized in BC for pellet and bioenergy (heat and power) production. The remaining available residues amount to about 4.2 million odt; location and distribution is indicated in Table 9 and Figure 22. The average delivered cost of sourcing these forest residues (based on the supply range indicated) has been estimated to be in the range of 60-82 \$ odt^{-1}. Forest residues are also available in other regions of the province but the available volumes are not significant (less than 100000 odt $year^{-1}$) for industrial applications such as pellet or biofuel production.

Although there are significant volumes of forest residues available, the primary barrier to their economic recovery and use is the lack of logistics systems and enabling policy needed to deliver the large volumes of feedstock of appropriate quality to the end-users at a low cost. Although forest residues can be brought to the roadside during normal logging operations, this does not normally occur. If they are not recovered at this time, it is economically and logistically difficult to justify their collection at a later date. In addition, compositional variations such as tree species, moisture content, ash content, and seasonal fluctuation can lead to large variations in quality and quantity of forest residues, making their use even less attractive. For example, the amount of bark and dirt in the forest residues can vary considerably and the moisture content can range from 20 to 70%. Thus, despite its considerable potential, the utilization of forest residues will require significant improvements in logistical operations and processes that can deal with the variability of biomass quality and delivered costs.

Table 9: Potential locations in BC where large volumes of forest residues are available and their average delivered cost (Industrial Forestry Service Ltd. et al., 2013; FPInnovations, 2011, 2012a,b,c; 2013 and 2014)

Region	**Delivery point**	**Estimated Supply radius (km)**	**Annual availability of forest residues (odt)**	**Average delivered cost ($/odt)**
Vancouver Island	Parksville	155	758 880	66.67
BC Coast-Mainland	Aldergrove	155	758 880	66.67
Cariboo	Hanceville	220	747 519	81.57
Cariboo	Anahim Lake	166	344 626	68.78
Prince George	Fort St. James	195	299 135	75.71
Mackenzie	Mackenzie	178	297 442	71.59
Quesnel	Quesnel	177	236 104	71.32
West Kootenay	Castlegar	216	203,760	80.55
Peace	Chetwynd	192	166 320	75.00
East Rupert	Burns Lake	168	164 473	69.38
East Kootenay	Canal Flats	170	162 000	69.45
Cariboo	100 Mile House	126	110 192	59.50



Location (region)
1- Parksville (Vancouver Island)
2- Aldergrove (Lower Mainland)
3- Castlegar (West Kootenay)
4- Canal Flats (East Kootenay)
5- 100 Mile House (Cariboo)
6- Hanceville (Cariboo)
7- Anahim Lake (Cariboo)
8- Quesnel (Quesnel)
9- Burns Lake (East Rupert)
10- Fort St. James (Prince George)
11- Mackenzie (Mackenzie)
12- Chetwynd (South Peace)

Figure 22: Potential locations in BC where large volumes of forest residues are available

OPPORTUNITIES FOR MOBILIZATION OF BIOMASS RESOURCES

EXISTING INFRASTRUCTURE AND SUPPLY CHAIN SCENARIOS

The development of a regional biojet supply chain in Western Canada needs to integrate the existing wood fibre and fossil fuel supply chains. All these existing infrastructures are reflected in the criteria used for the site selection of the biorefinery and the development of the biofuel supply chains in Western Canada. The criteria to determine the potential location of the biorefinery and to develop the regional biojet supply chain include:

- availability of woody biomass in the area;
- proximity to wood processing facilities, including sawmills, pulp and paper mills, bioenergy plants and pellet plants;
- proximity to oil refineries/upgraders: close proximity of the biorefinery to the existing refineries and upgraders provide an opportunity for co-location and co-processing;
- proximity to petrochemical plants: the synergy between a biorefinery and the petrochemical industry is the share of the infrastructure to produce and store hydrogen as both industries need hydrogen to produce the final marketable products;
- availability of transportation infrastructure;
- proximity to the major airports and populated areas.

Based on these criteria, two regional supply chain scenarios in BC were explored: Vancouver Island (BC) and Coastal Mainland (BC). A third supply chain around Prince George would be suitable, but was not expanded in this case study.

VANCOUVER ISLAND SUPPLY CHAIN SCENARIO

The available feedstocks for biofuel production are forest primary residues and secondary mill residues and the biofuel supply chain scenario for this region are indicated in Figure 23. There are about 0.76 and 0.14 million odt of forest and mill residues available in Vancouver Island. The closest oil refinery is the Chevron facility in Burnaby: this facility is about 120 km away from Parksville on Vancouver Island, as a potential location for the biorefinery site. The refining capacity of Chevron oil refinery can be used to convert the biofuel intermediates produced at the biorefinery into drop-in biofuels. The biojet produced at the Chevron facility (Figure 24) can then be shipped to Vancouver and Victoria International Airports. The diesel co-products could also be distributed via the existing wholesale and retail sites in the Lower Mainland.

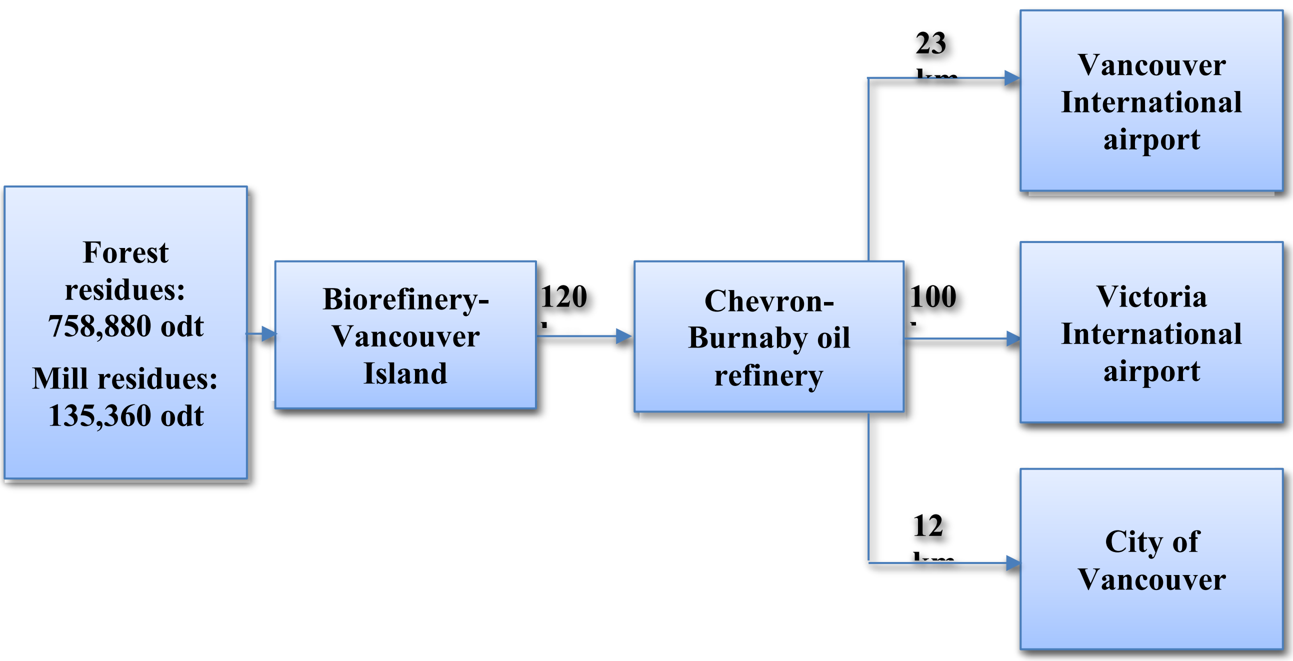


Figure 23: Biofuel supply chain scenario in Vancouver Island, BC

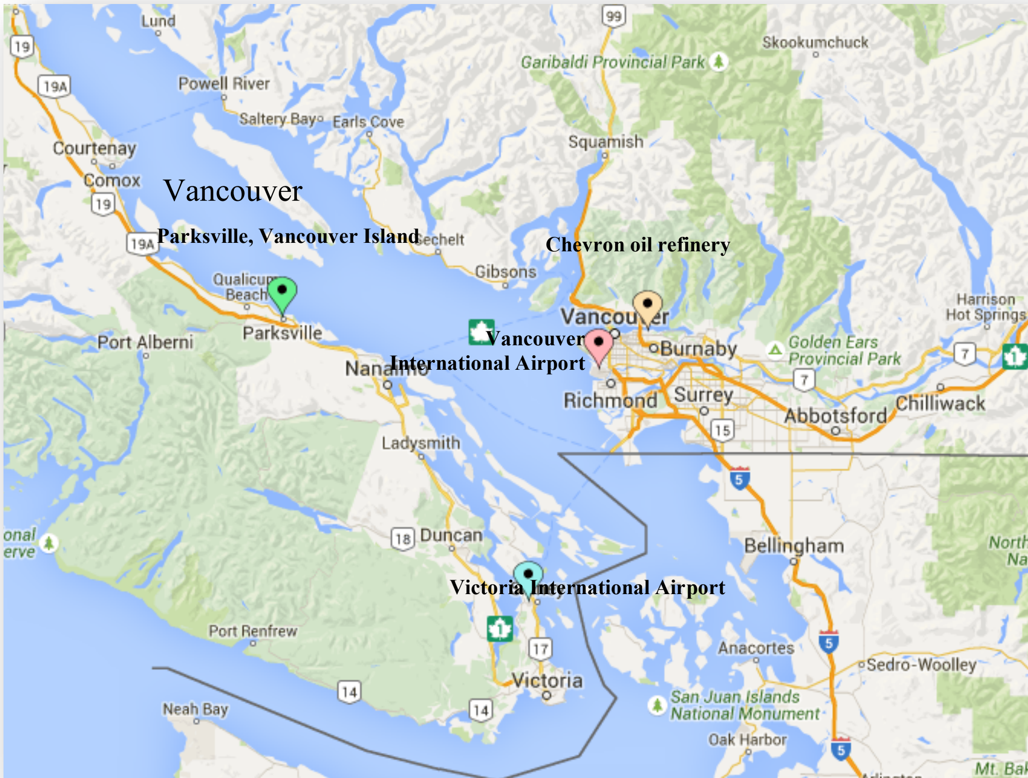


Figure 24: Location of Vancouver Island, Chevron oil refinery and the Victoria and Vancouver International airports in Vancouver Island biofuel supply chain scenario

COASTAL MAINLAND SUPPLY CHAIN SCENARIO

The Coastal Mainland has a similar supply chain to the Vancouver Island biofuel supply chain in terms of available woody biomass and use of the conventional fuel supply chain (Figure 25). The available feedstocks for biofuel production are also primary forest residues and secondary mill residues. There are about 0.76 and 0.14 million odt of forest and mill residues available in the Coastal Mainland. The closest oil refinery is again the Chevron facility in Burnaby. This facility is about 55 km away from Aldergrove within the Coastal Mainland, as a potential location for the biorefinery site. The produced biojet could be shipped to Vancouver and Victoria International Airports from the Chevron facility.

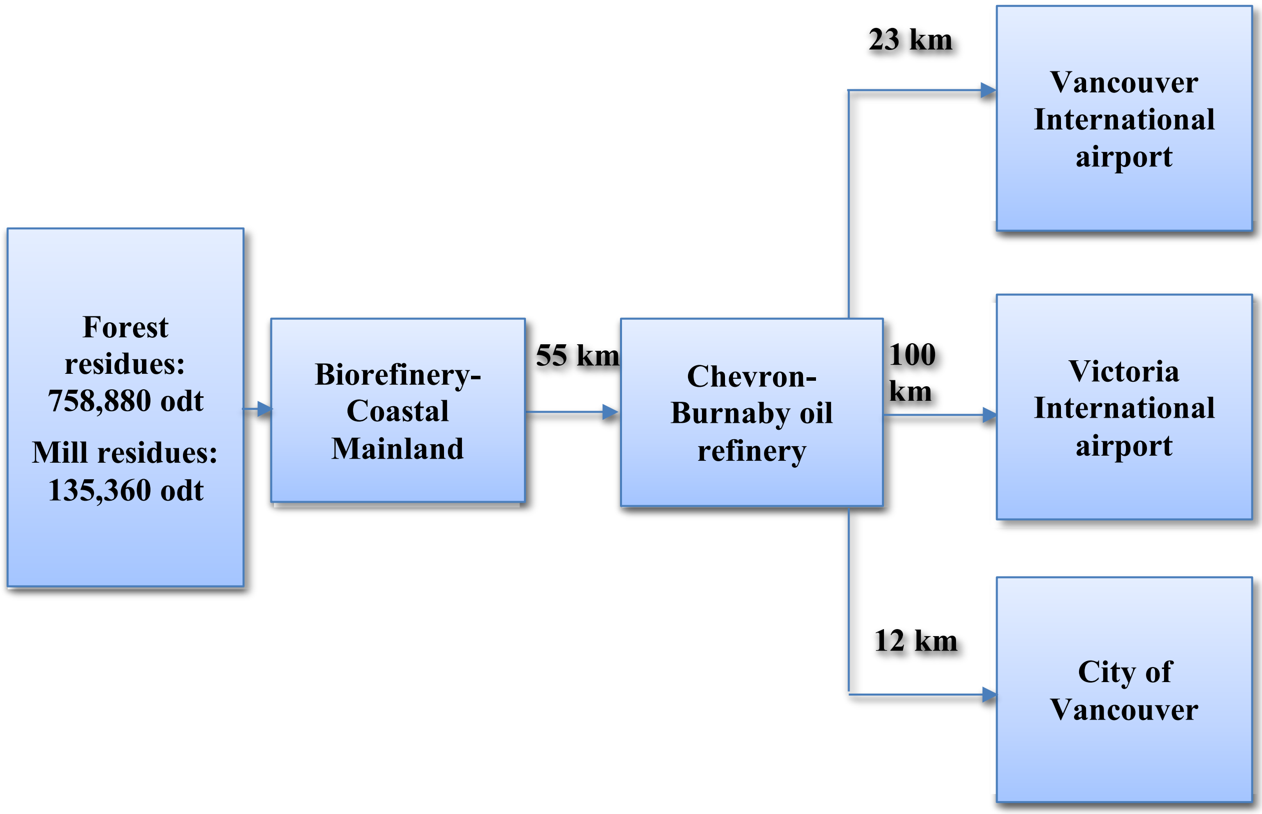


Figure 25: Biofuel supply chain scenario in Coastal Mainland, BC

All of these scenarios provide a high-level view of the potential biofuel supply chains in BC. The selection of the most viable supply chain will require due diligence, including considering the details of economic, social, environmental and political factors. In addition, utilizing the existing infrastructure of both the forest and fossil fuel supply chains depends on the continued health of these two sectors and positive market conditions. Technical challenges also need to be addressed, using the existing transportation infrastructure to ship the intermediate products of the biorefinery to oil refineries. In terms of biomass availability, in addition to market dynamics, the actual realization of the magnitude of dead and non-commercial trees by the mountain pine beetle epidemic in the future will impact the amount of available wood fibre for both the forest products and residual industries.

In order to overcome this problem, the BC government created the Fibre Recovery Tenures in 2012, which allow access to primary residues piled at roadside or on logging landing sites that harvesters don't want or plan to use (standing trees cannot be harvested under these tenures). There are two models of these tenures. The first, and preferred by the government, is a business-to-business approach (B2B), which is based on a market system and has little government involvement. The second is a statutory approach, whereby the primary licensee declares their Landing and Roadside Waste (LRW) as abandoned and therefore may be made available through a fibre recovery tenure to a secondary licensee. However, this tenure innovation hasn't yet been able to fully solve the problem. Access to residues can still be problematic as primary harvesters build and maintain the roads within their tenure and may not allow access or require compensation for access. Thus, lobbying the BC government for specific policies to support biojet production from forest primary residues should be considered as part of an integrated approach.

CONCLUSION

Annually, British Columbia has 4.2 million odt of forest residues available, mainly from softwood. Based on this feedstock and supply chain, a thermochemical based conversion technology is likely the most suitable for the production of biofuels and bioproducts from woody biomass. Softwoods have different chemical structures in their lignin than agricultural biomass which results in inhibition of enzymes and very low sugar hydrolysis yields. Thus, it is not considered feasible for sugar production for further biochemical processing into fuels. Other areas of Canada, where hardwoods occur or where high levels of agricultural residues are available will be more suitable for this type of technology.

Based on pyrolysis and upgrading technology, a potential volume of 700 million litters per year (MLPY) of advanced biofuel could be produced annually in British Columbia alone, including 175 MLPY of biojet. Potential supply chain scenarios were developed for British Columbia lower mainland based on synergistic, integration opportunities with both existing wood fibre and fossil fuel supply chains in BC.

Policy at regional, national and international levels will be required to stimulate and support biojet development. At a national and regional level, policies should focus on promotion of advanced drop-in biofuels in general. This should promote the production and development of biojet and other fuels that will be produced as part of the product blendstock based on thermochemical conversion technologies (i.e. renewable diesel). Specific policies, such as the tenure system which regulates feedstock access, should specifically be considered to allow for tertiary users to economically access this resource.

INTEGRATING ECONOMIC AND ENVIRONMENTAL VALUES INTO FOREST SUPPLY CHAIN MANAGEMENT FOR TIMBER AND BIOENERGY PRODUCTION FROM BEETLE-KILLED BIOMASS IN COLORADO

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INTRODUCTION

The recent mountain pine beetle epidemic has affected a massive area of forests in the Rocky Mountain region. Of Colorado's 9.87 million hectares of forestland, more than 1.38 million hectares of forests were infested between 1996 and 2013. These beetle-killed trees usually result in degradation of wood quality, value loss of forest ecosystem services, and slow natural regener-ation. Dead trees might also increase wildfire risks and contribute to climate change as they decay over time (Kurz, et al. 2008). In contrast, harvesting dead trees provides an opportunity to utilize resources that are otherwise wasted. Woody biomass utilization may also contribute to the economies of rural areas, local wood product industries, natural regeneration and improvement on eco-system services.

DESCRIPTION OF CURRENT SITUATION

According to the U.S. Energy Information Administration (EIA), Colorado is relying heavily on fossil fuels with 64 and 20% of the electricity generated in 2013 from coal and natural gas, respectively. By comparison, the portion of renewable energy sources was only 17%. However, investor-owned electric utilities are requested by Colorado's Renewable Energy Standard to provide 30% of their energy generation from renewable energy resources by 2020. This goal makes logging residues including tree tops, branches and non-merchantable parts of trees, and low-grade logs produced from forest management and restoration activities, attractive as locally available bioenergy feedstock. Forest bioenergy is regarded as a promising "carbon-lean" alternative because carbon emitted during utilization will be recaptured when new biomass feedstocks grow. When used as a substitute for fossil fuels, it can also help reduce emission from fossil carbon.

Until now most studies in forest supply chain management have dealt with exclusively either traditional timber products or bioenergy feedstock, and the linkage between these two important products has not been built yet. For instance, many bioenergy supply chain studies assume biomass residues become available at the landing at free of charge. However, not only technical and economic feasibility of biomass feedstock logistics, but also conventional silvicultural treatments and harvesting methods often become barriers of producing and utilizing forest biomass for bioenergy. In Colorado, *Lop-and-scatter* is a widely used harvesting system for clearcut operations. This ground-based harvesting system employs a feller buncher to cut trees down and stacks them in piles, delimbers to delimb and buck trees to logs at the stump, a skidder to bring logs to the landing, and finally a loader at the landing to sort and deck the logs. Because logs are processed at the stump, logging residue is dispersed over the harvest unit and unavailable for utilization unless an additional biomass collection process is employed. The lop-and-scatter system has been favored up to date because it is easy to implement, more economical for slash management, and leaves nutrients on site. As an alternative to the lop-and-scatter system, a *whole-tree harvesting* system can be employed with the same harvesting equipment, but it is different in that trees are transported by a skidder in the form of whole trees and processed by a delimber at the landing rather than at the stump. Because this harvest system produces logging residue piles at the landing as part of timber harvesting (Figure 26), it has been getting more attention, especially in the Southern Rockies where the mountain pine beetle has caused extensive lodgepole pine mortality. Relative to lop-and-scatter, whole-tree harvesting often requires a larger landing size for residue piles and a higher level of coordination among machines, and may result in lower skidder efficiency (Bolding, et al. 2009).

Figure 26: Harvesting sites in the Colorado State Forest State Park after lop-and-scatter and whole-tree harvesting were carried out.

OPPORTUNITIES FOR MOBILIZATION OF BIOMASS RESOURCES

Although utilizing woody biomass for bioenergy has a potential for reducing greenhouse gas (GHG) emissions and improving other environmental benefits, these benefits are often realized at the expense of higher harvesting costs. As decisions on upstream harvesting operations (e.g., lop-and-scatter vs. whole-tree harvesting) affect the availability and amount of recoverable bio-mass feedstock, such decisions should not be neglected and must be combined with downstream production and supply decisions in biomass supply chain. Furthermore, since economic goals (e.g., minimizing costs, maximizing revenues) and environmental goals (e.g., minimizing GHG emissions) sometimes conflict with each other, balanced and compromising solutions are needed to achieve complex, multi-objectives that landowners, communities and stakeholders may have.

In this study, we applied a multi-objective optimization (MOO) approach to integrate the economic and environmental objectives into forest supply chain management for both timber and bioenergy production while taking into account options in the upstream timber harvesting operations. This approach provides an opportunity to investigate a wide range of decisions throughout the timber and biomass supply chains and their trade-offs in a regional context.

STUDY AREA

As a part of research project of the "Bioenergy Alliance Network of the Rockies (BANR)", which has been supported by the USDA National Institute of Food and Agriculture (NIFA) bioenergy program, the study area was selected in the State Forest State Park in northern Colorado (40°57´N, 105°98´W). Lodgepole pine (*Pinus contorta*) stands impacted by the mountain pine beetle outbreak since 2008 were selected for salvage harvest in this study. For modeling harvesting operations, we divided the dead pine stands into 627 harvest units with an average size of 5.4 ha per unit. The amount of timber and logging residues recoverable from each unit were estimated using the allometric equations of live and dead trees developed for the study area (Chung, et al. 2017). Harvest units were assumed to be clearcut using a ground-based system, i.e., either conventional lop-and-scatter or whole-tree harvesting. We conducted a detailed time study on both lop-and-scatter and whole-tree harvesting in the forest in winter 2015 to develop harvesting productivity and cost estimating models (Han, et al. 2018). Using our cost estimates of each harvest unit, we determined preferred (i.e., more cost-efficient) harvesting systems across the study area (Figure 27).

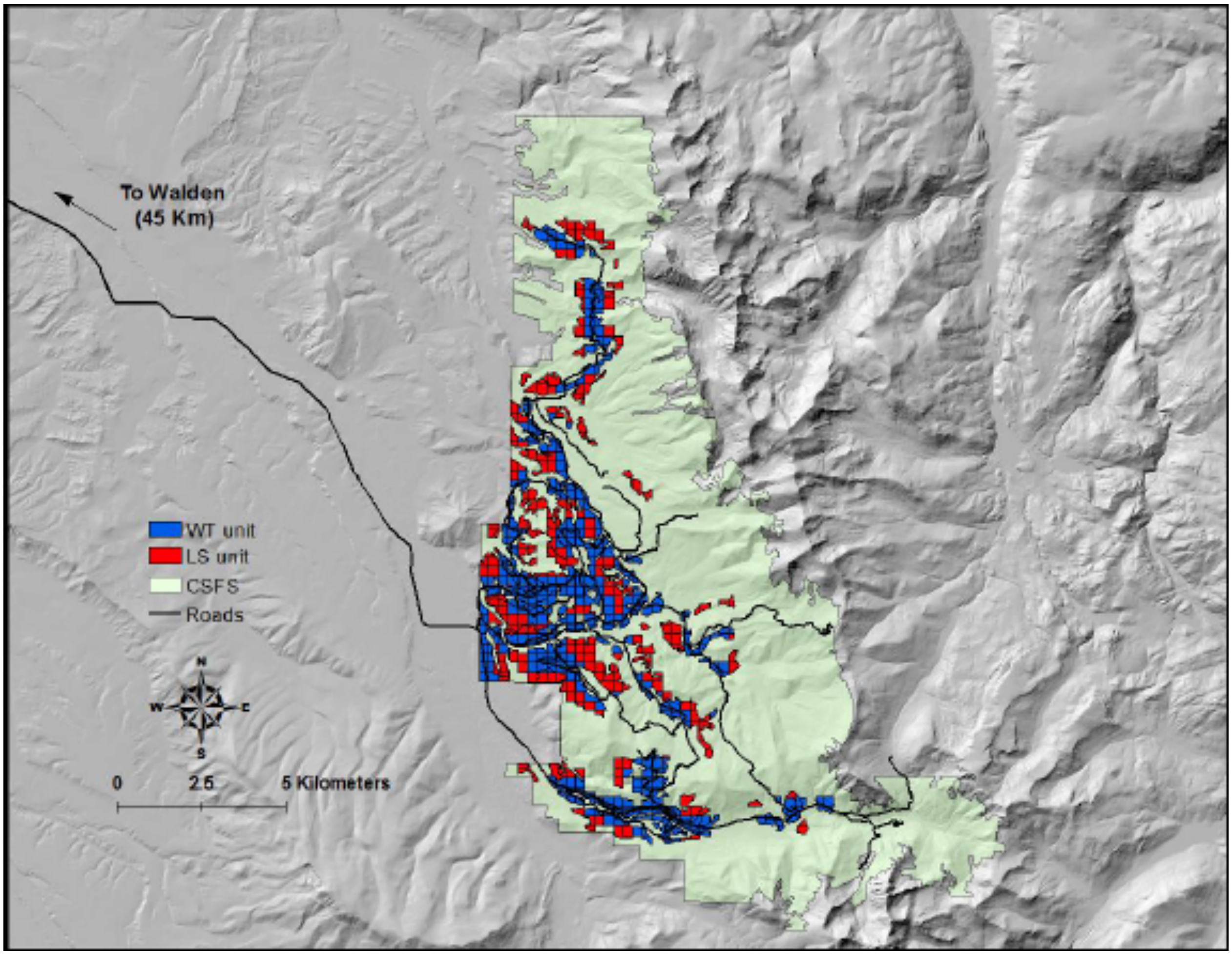

Figure 27: Map of the study area presenting harvest units and their preferred harvesting sys-tems (WT: whole-tree harvesting; LS: lop-and-scatter).

It was assumed that the primary timber product from harvesting operations was sawlog, and that logging residues were a by-product and could be used as feedstock for pellet production. We also assumed both materials were transported to Walden, CO, located approximately 50 km north-east of the study area, for processing and pellet manufacturing. Wood pellet production was chosen as a suitable bioenergy product in this study because of the existing pellet mill with an annual production capacity of 110 000 tons in Walden. In addition, pellets are known as an efficient way to use wood fuels for heat and/or power generation (Pa, et al. 2011) because pelletization prior to combustion brings a number of advantages, such as low moisture content (less than 8%), high net calorific value (17 GJ $tonne^{-1}$ or 4.8 kWh kg^{-1}), low ash content (1% by weight) and homogeneity in shape and size. In our study, pellets produced from logging residues were assumed to be used only for industrial purpose (i.e., co-firing with coal) and transported to Hayden Station, a coal-fired power station located near Hayden, CO, approximately 136 km away from Walden.

In our study, sustainability was defined to comprise three components, which were net revenues (economic aspect), reduction in GHG emissions (environmental aspect), and contribution to local industry and employment (socio-economic aspect). Both quantitative and qualitative evaluations were applied to assessing the performance of the supply chain.

METHODS

MODEL FRAMEWORK AND FORMULATION

The quantitative evaluation of integrated economic and environmental aspects of forest supply chain management is a relatively new research area. Mathematical programming helps in finding the optimal solution considering these multiple aspects. By using MOO approaches, some studies have integrated economic, environmental and social objectives in the optimization of forest biomass-to-bioenergy supply chains (Cambero and Sowlati, 2014). Instead of a single optimal solution optimizing all objectives, the solution output of a MOO problem can be a set of "Pareto optimal solutions" where in each solution one of the objectives cannot be improved without sacrificing one or more other objectives. Kanzian et al. (2013) presents a bi-objective optimization model where the profit must be maximized and the CO_2 emissions must be minimized. You, et al. (2012) optimized the design and planning of cellulosic ethanol supply chains considering economic, environmental, and social objectives, which are measured by the total annualized cost, the life cycle greenhouse gas emissions, and the number of accrued local jobs, respectively. The ε-constraint method they used is the most commonly used solution approach for a MOO problem which produces Pareto optimal curves showing the potential trade-offs and compromises among objectives (Cambero, et al. 2014).

In order to apply the MOO approach to our study, we designed a model framework as shown in Figure 28. This framework includes multiple components to represent different stages in the supply chain of products for the region. The model selects optimal harvesting options for each harvest unit by considering the economic and environmental values along with product pathways over the supply chain in the study area. For example, sawlogs produced by harvesting operations are sent to sawmill and then converted to lumber for their use. Production cost and revenue of lumber as well as the amount of carbon emissions and reductions along the product pathway are calculated. Logging residues are screened and ground on site and then transported to facility for pellet production. Carbon emissions and reductions from co-firing at coal plant are incorporated to consider the environmental aspect of using wood pellets for bioenergy in the region.

The primary goal in our study was to build an optimization approach that considers a supply network with multiple entities and corresponding processes. Details of equations, functions and notation can be found in Appendix A.

The problem was formulated using 5 the multi-objective mixed integer programming method. Before solving the MOO problem, values of maximum revenue ($(f_r)_{max}$) and maximum GHG reduction ($(f_e)_{max}$) are found using a single objective optimization method. Then, Pareto optimal solutions are retrieved using the weighted sum scalarization approach, where the sum of the two conflicting objectives have to be maximized as shown in Eq. (1). Under this approach, the objective functions are scaled with non-negative weights (λ_r, λ_e) which sum up to one. We select 11 weight combinations where values of λ_r and λ_e change from 1.0 to 0 and 0 to 1.0, respectively, with an increment of 0.1.

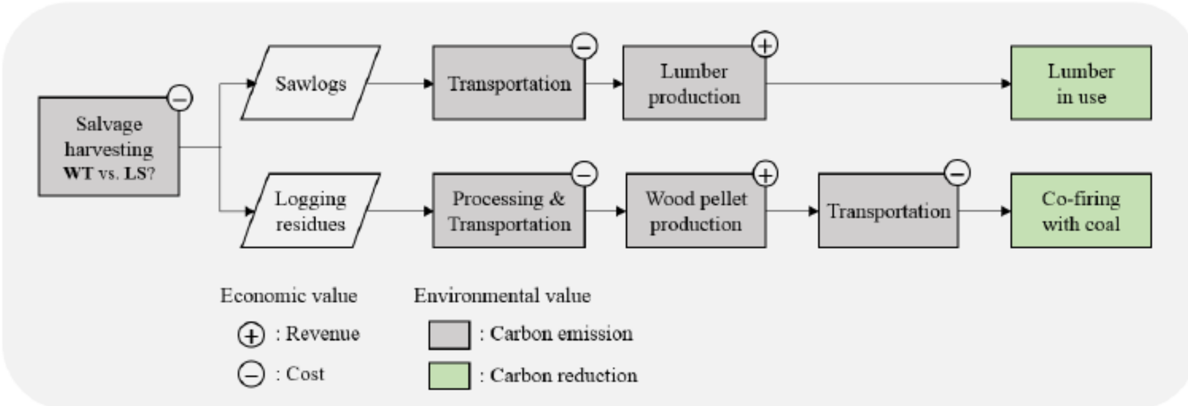

Figure 28: Model framework and product pathways employed in this study.

The economic objective f_r (Eq. 2) describe the total net revenue generated from harvesting operations. It is calculated by summing up revenues from selling lumber (Eq. 3) and revenues from selling wood pellets (Eq. 4), and subtracting costs of harvesting operations (Eq. 5), costs of pur-chasing sawlogs (Eq. 6), costs of screening and grinding operations (Eq. 7), costs of transportation (Eq. 8), and costs of lumber and pellet manufacturing (Eq. 9). Similarly, the environmental objec-tive f_e (Eq. 10) accounts for the total GHG emissions after accounting for the substitution effects of using bioenergy. Emissions considered in our model are GHG emission reduction through using lumber and wood pellets (Eq. 11 & 12), GHG emissions from harvesting operations (Eq. 13), GHG emissions from screening and grinding operations (Eq. 14), GHG emissions from transportation (Eq. 15), and GHG emissions from pellet manufacturing (Eq. 16). The goal is to minimize the total GHG emissions. However, since the combined objective is to be maximized, we turned the original minimization problem into a maximization problem by considering the reduction in GHG emissions as a positive contribution to the objective function.

RESULTS AND DISCUSSION

MOO MODEL

As the focus of the objective moves towards the environmental aspect (i.e., λ_e increases), more units are harvested and the whole-tree harvesting system gains preference (Figure 29). Corre-spondingly, more lumber and bioenergy products are produced (Figure 30). When the supply chain is fully economic-drive, no pellets are produced because production cost exceeds its revenue for all harvest units. This indicates monetary incentives or subsidies might be necessary to facilitate the utilization of locally available biomass for bioenergy production. When the harvest decisions are fully derived by the environmental objective, all units are harvested by the whole-tree harvest-ing system and all logging residues are removed for pellet production. Harvesting maps describing all 11 scenarios are shown in Figure 31.

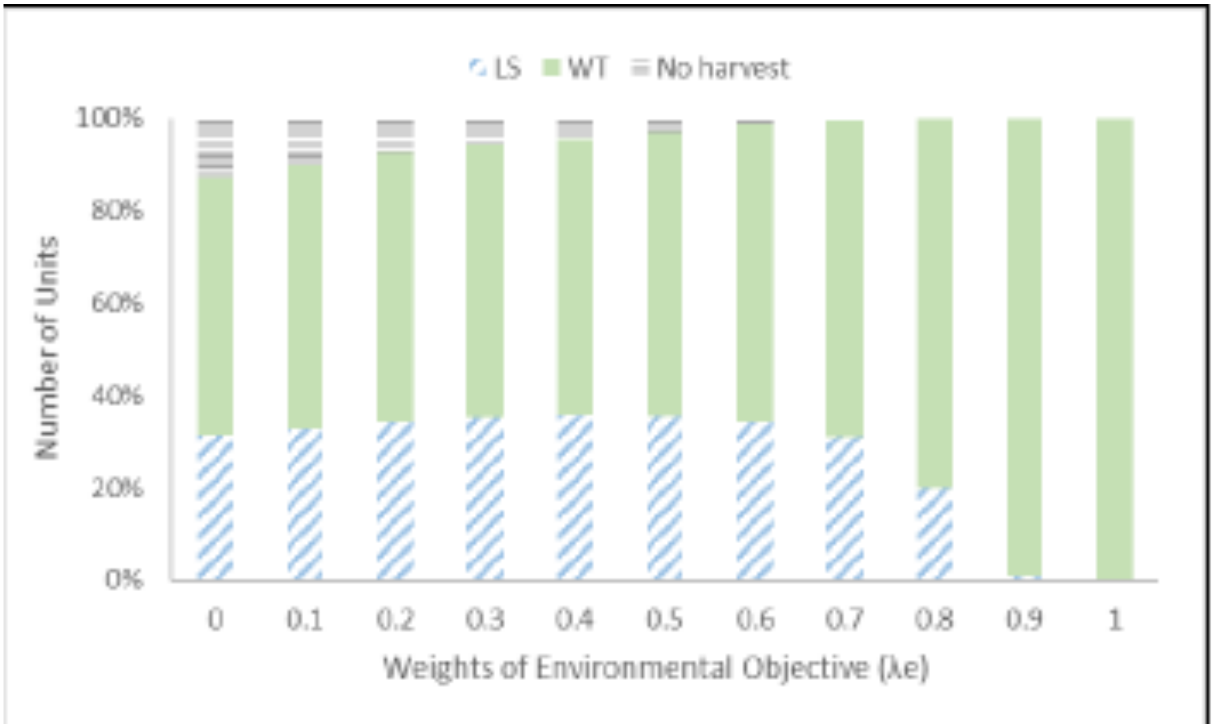

Figure 29: Response of harvest decisions to changing λ_e.

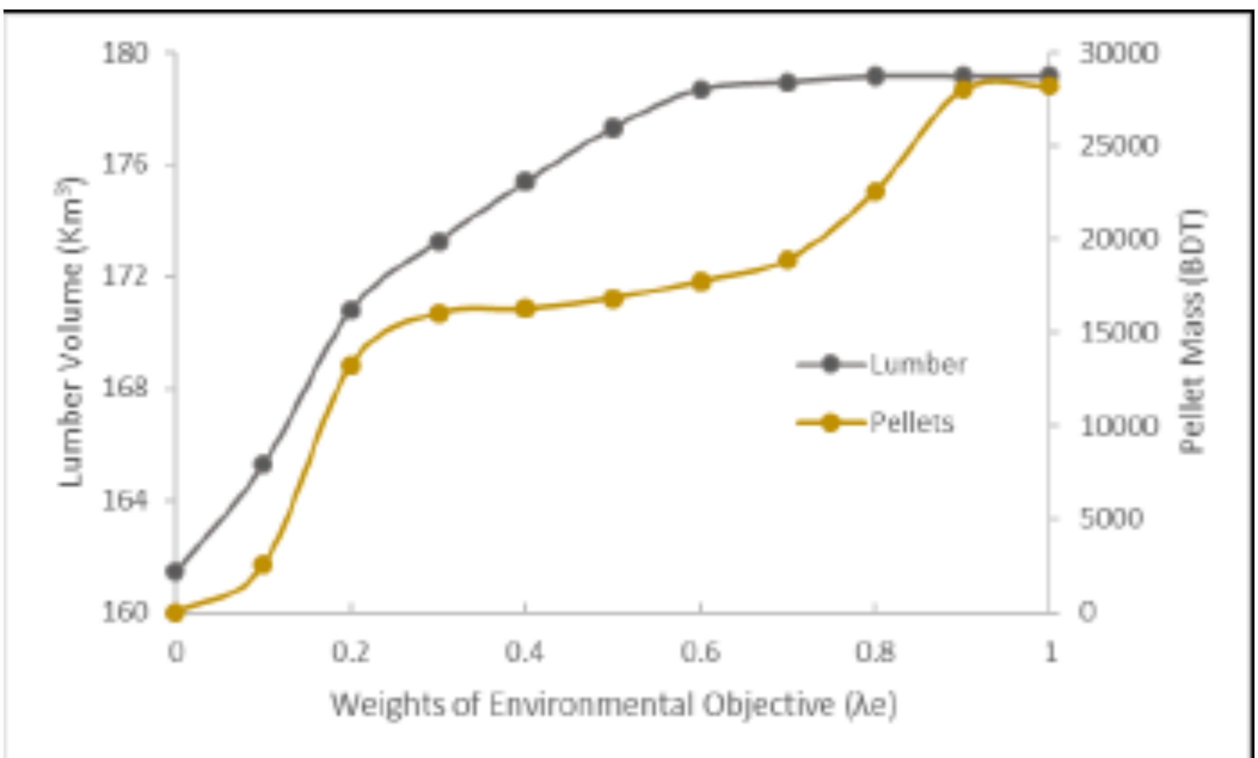

Figure 30: Response of forest products to changing λ_e.

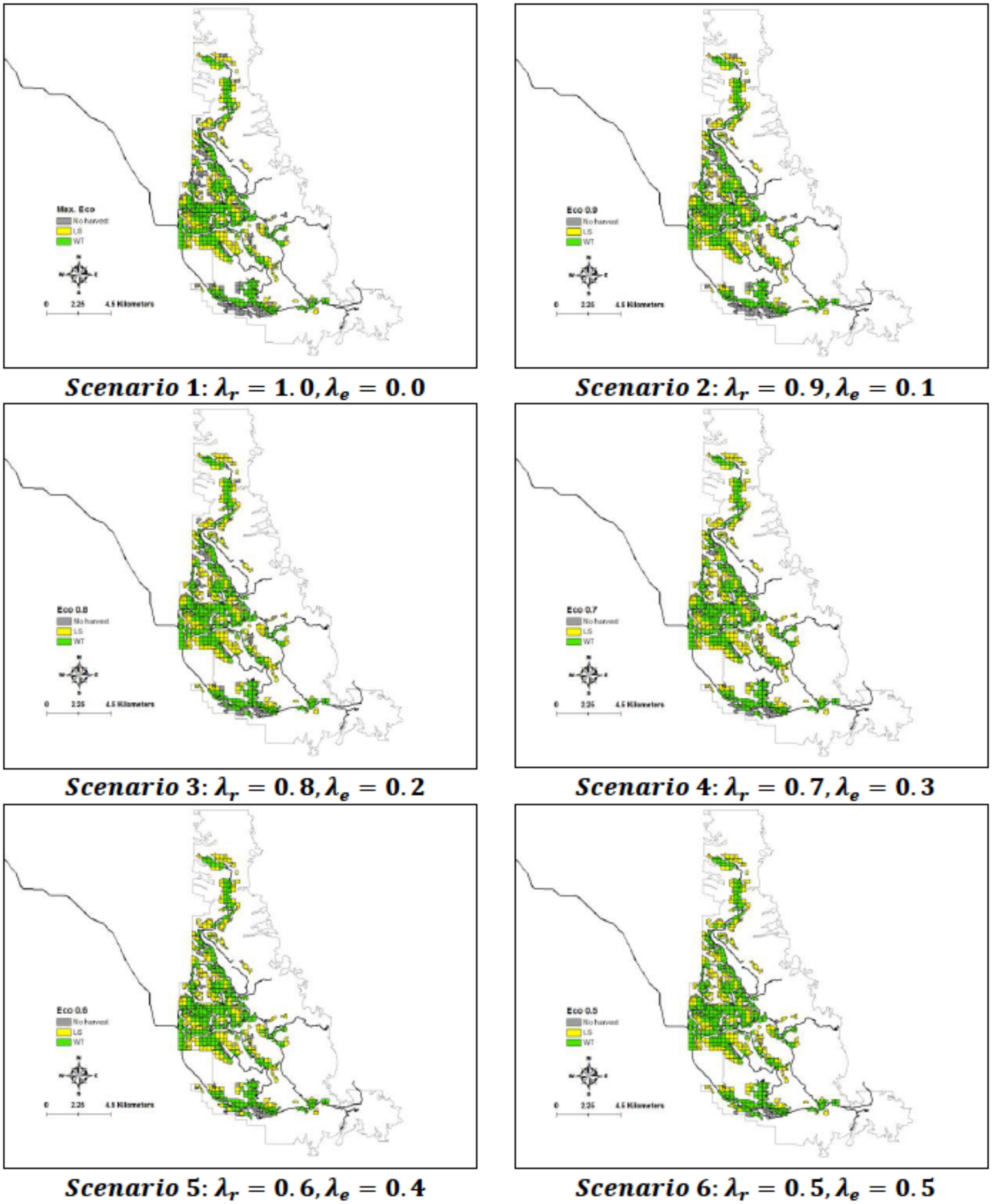

Figure 31: Harvesting maps with decisions depending on different weights.

As the weight of environmental objective increases from 0 to 1.0, the economic objective value decreases from \$4.42 million to \$3.19 million, representing 27.8 percent reduction in net revenues. Meanwhile, the amount of carbon reduction increases from 166 kton CO_2-eq to 211 kton CO_2-eq, representing 27.1 percent increase. When the objective switches from being fully "economic" to fully "environmental", the marginal loss in economic objective trades for the marginal gain in environmental objective while changes in marginal rate are inconstant across the range of objective weights (Figure 32). In particular, when λ_e is between 0 and 0.2, the environmental ob-jective improves quickly, whereas the economic objective declines moderately. The Pareto Curve in Figure 33 presenting the trade-offs between economic and environmental performances also suggests that carbon reduction more than 200 kton CO_2-eq requires a large reduction in net revenue.

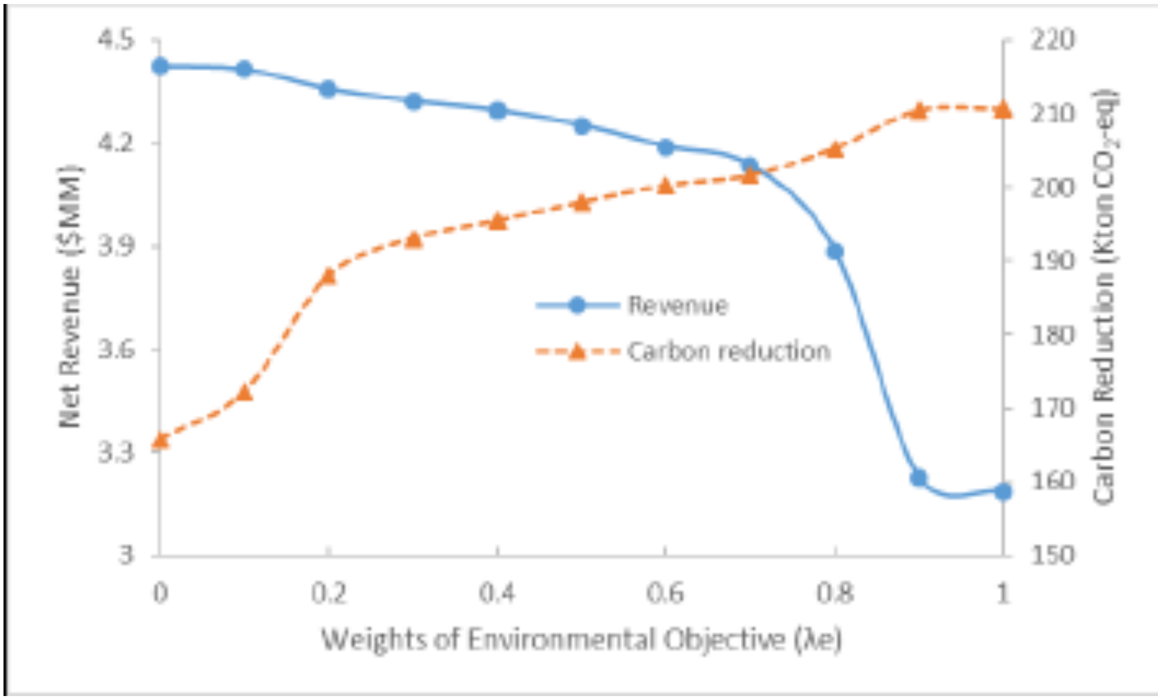

Figure 32: Response of revenue and carbon reduction to changing λ_e.

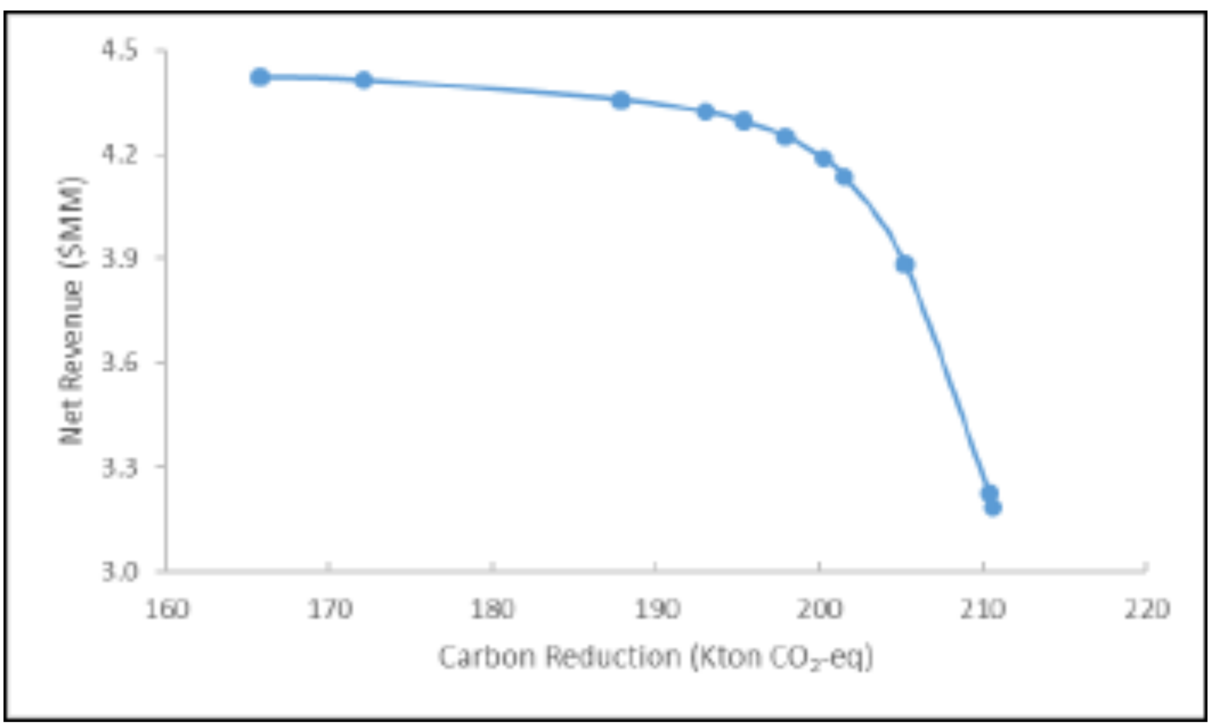

Figure 33: Trade-offs (pareto curve) between revenue and carbon reduction.

As harvesting operations and supply chain management are mainly economic-driven, it is important that the economic objective is not sacrificed acutely to obtain improvements in environmental objective. As an example, the scenario where λ_e=0.5 was chosen to illustrate this forest industry supply chain and issues related to sustainability. In this case, lumber production volume is 177 303 m^3 and pellet production amount is 16 835 bdt. Applying our timber harvesting time study results, we estimate the total time needed to harvest all selected units (607 out of 627) are about eight years. The amount of annual lumber production would be then 22 163 m^3 and the annual pellet production would be 2 104 bdt, or 2 338 t at 10% moisture content. This represents only 2% of the 110 000 t capacity at the pellet manufacturing facility in Walden, CO. However, this only represents feedstock from one harvesting site. Once the framework of utilizing logging residues for pellet production is constructed, feedstock from other harvesting sites may also be collected and delivered to the facility. This may help to revive the local bioenergy industry (only one third capacity of the facility was running in 2010) and contributes to the enhancement of local employment. From the landowner's perspective, producing sawlogs in excess of the maximum economic amount, as well as processing logging residues becomes an economic burden and thus may require monetary incentives. For logging contractors, additional production work (saw-log production and biomass pre-processing) represents extra income sources, extended work con-tract, and enhanced job security. From the power plant's perspective, we assumed the delivered price of bituminous coal to be \$60 t^{-1}, equal net converting efficiency (i.e., from HHV to generated electricity) of 35% for coal and pellets, and same handling procedures and costs by weight for coal and pellets. Then the electricity production cost is \$0.02145 kWh^{-1} by coal and \$0.06298 kWh^{-1} by pellets when used exclusively. Even at 10 percent cofiring ratio (i.e., 10 percent of electricity output comes from pellet combustion), the electricity production cost is \$0.02560 kWh^{-1}, which is 19.4% higher than coal-fired generation. In addition, it has been estimated that for an around 10% cofiring ratio, the modification cost of power generation equipment per kW capacity output is \$500 on combustion system[1] However, environmentally this provides significant benefits since the reduction of carbon emission is 2241.9 kg CO_2-eq when substituting 1 t of coal with pellets, or 0.33 kg CO_2-eq kWh^{-1}.

CARBON CREDITS

When carbon credit is introduced, the positive effect on carbon reduction is very significant when the credit level is in the range of \$0-8 per ton CO_2-eq. Nevertheless, the negative impact on net revenue from timber and biomass production is minimal. Further improvement on carbon reduc-tion beyond this range becomes marginal, but at the large expense of net revenue. For instance, at \$8 per ton CO_2-eq carbon credit rate, the improvement in carbon reduction is 17% compared to the base case (i.e., zero carbon credit rate) while the decrease in lumber net revenue is only 3%. In addition, the loss in net revenue will be well compensated by earned carbon credits. This indicates that carbon credit method contributes to carbon reduction effectively even at a low credit price.

CONCLUSION

Constrained by long-term forest management plan, silvicultural practices, harvesting legislations, etc., forest harvesting operations are often managed independently and isolated from downstream wood product and bioenergy production. The absence of linkage results in sub-optimality in forest supply chain management. Since performances in multiple aspects are assessed in nowadays supply chain management, this sub-optimality becomes more severe when issues related to sustainability are addressed. This study demonstrates how upstream harvesting decisions affect the performance of the entire supply chain and shows the trade-offs between net revenues and reduction of GHG emissions. However, the study did not consider customer demands, product mix, fiber flows from different sources, etc. and thus needs further improvement. In particular, the dynamic change of forest stands regarding the beetle infestation should be included in future studies because it directly affects availability of biomass, use of biomass, harvesting costs, and sale revenues.

VERTICALLY-INTEGRATED SMALL-SCALE OPERATIONS IN ITALY

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INTRODUCTION

Beginning in the mid 1990s, the Italian Government has invested much effort into developing an effective bioenergy industry, and today Italy hosts over 60 wood-fired power stations (CHP), with a power between 1 and 40 $MW_{electric}$ each. These plants account for a total power output capacity estimated at 436 $MW_{electric}$ and they use approximately 4.5 million tons of fresh wood chips. Furthermore, over 90 large (≥1 MW) wood-fired district heating (DH) plants operate in Northern Italy, with a total power output of 430 $MW_{thermal}$. Additional ca. 100 smaller (< 1 MW) district heating systems have been commissioned, especially in Central and Southern Italy. On top of that, firewood is still a very popular fuel for residential heating and cooking, and pellet has enjoyed an unprecedented boom over the last 5 years. The following numbers can help appreciate the scale of the Italian wood energy sector: in 2013, the Italian National Statistics Agency (ISTAT) has estimated to 10 million the number of firewood and pellet stoves being used in Italy, for a total annual consumption of 19 million tons of firewood and 1.3 million tons of pellets. In fact, Italy is the largest consumer of wood pellets in Europe, and the wood pellet market promises the largest growth in the next future. These developments reflect peculiar conditions, which can be listed as follows:

- Italy enjoys a relatively mild climate, which limits the operation hours of most heating systems, except in the Alps. That constrains the amount of capital families are willing to invest on efficient heating plants, because a large investment can be hardly depreciated. In contrast, users can accept relatively high fuel cost (or plant inefficiency) because in most cases the amount of fuel used in a season is somewhat limited. The result is a strong preference for simple plants (e.g. firewood stoves and pellet stoves or boilers), even when these plants must be fed with relatively expensive fuel - i.e. more expensive than wood chips;

- the Italian Government releases generous subsidies for renewable energy generation, and the same time the cost of fossil fuel and of electricity is very high. For instance, the price of natural gas to household users in 2015 was 0.091 €/kWh, which was the third highest in Europe, after Sweden and Spain (Eurostats 2017). At 0.23 €/kWh Italian households also need to match the fourth highest electricity price in Europe after Denmark, Germany and Ireland (Eurostats 2017). Subsidies and the high price of electricity and gas motivate people to move towards biomass energy;

- Italy has a very large population (> 60 Million), which implies that the relatively small energy wood consumption of each household combines into a very large accumulated demand and represents a great market opportunity.

All the above combine into limiting the potential of classic district heating schemes to the Alpine regions, and in general to high mountain settlements. Outside those areas, and especially in the Mediterranean regions of Central and Southern Italy, forest owners and enterprises have two main customer targets: power stations and individual residential users - the latter generally skeptical about woodchips opportunities, due to the difficulty in depreciating the large investment cost required for the installation a woodchip plant in the face of a relatively limited heating season.

At present, power stations are mostly large plants that are beyond the investment capability of most primary producers - forest owners or logging companies. Currently, the smallest power plants use the ORC technology and deliver slightly less than 1 $MW_{electric}$, but the cost of such plants runs in the 10 M€ range. On the other hand, the pellet market is almost entirely fed with import product, sourced outside Italy (and generally outside the EU) and manufactured in large industrial plants. Furthermore, the overwhelming success of pellet heating has impacted the firewood market, so that the demand and the price for firewood are declining rapidly. Paradoxically, the eroding margins on firewood production have supported irregular operators, who remain the only ones who can still make it under current conditions. Pressed down by the encroaching pellet and undercut by irregular operators, small-scale logging companies struggle to survive and they need to find a new game.

Among the main strategies, the following ones seem most viable: a) increasing production efficiency, which is generally obtained by investing in new machinery in order to match the requirements of the new industrial users (power stations), and in particular competitive price and sustained supply; b) capturing a larger proportion of the added value, which can be achieved through vertical integration - i.e. by manufacturing the final product rather than the raw material.

DESCRIPTION OF CURRENT SITUATION

The global consumption of wood pellets has increased very rapidly in recent years, exceeding 18 million t in 2014, and scholars predict further dramatic growth by year 2020. That is the consequence of a resolute EU bioenergy policy, aimed at curbing on greenhouse gas (GHG) emissions. Since the supporting measures are European, so are the consumers, and the growing unbalance between supply and demand has generated a lively global trade, where biomass is shipped to Europe from wherever it is available at competitive cost and quality. Pellets are especially suitable for long-distance transport, due to their high energy density and market price, and it is estimated that 50% of the global pellet production is the object of cross-border trading. That includes a substantial flow of pellets from outside the EU and into her borders, since the EU represents 85% of the global pellet consumption, but only 60% of production. Italy is the largest global consumer of pellets in residential heating applications, with an annual demand estimated at 1.4 million tons. This large demand is matched only in part by national production, quantified at 0.8 million t and largely supplemented by imports.

This success is gained at the expenses of traditional firewood, and there might be good reason to rejoice: traditional firewood installations are flawed with low energy efficiency and high emission levels, and pellet plants offer a marked improvement in that regard. However, firewood is generally sourced in the immediate vicinities, supporting local entrepreneurs and forest owners, which is seldom the case of pellets. One of the goals of the European bioenergy strategy is to support rural development within the EU, and the rapid shift from firewood to pellet seems to defy it: in fact, the decreasing demand for firewood represents a challenge for an already fragile forest economy.

OPPORTUNITIES FOR MOBILIZATION OF BIOMASS RESOURCES

In the years between 2005 and 2010, when the market for pellets first started expanding in Italy, many entrepreneurs considered installing a pellet manufacturing facility fed with the local primary wood resource rather than with sawmill residues. A number of feasibility studies were performed in order to gauge the potential of such endeavors. Most studies returned a negative forecast, further confirmed by the premature closure of a few plants commissioned in those years. Shortly afterwards, few small-scale local forest entrepreneurs cautiously started experimenting with the same concept, but on an even smaller scale. Today, an increasing number of small-scale pellet manufacturing plants fed with log material is operating successfully, and this study surveyed four such plants spread over much of Northern and Central Italy (Figure 34).

Figure 34: Location of case study plants

The term "Microchips" describes a very small homogeneous wood chip product that can be used to feed common pellet stoves and boilers - possibly after minor modifications of the stove or bolier feeding system and combustion settings (Figure 35). Microchip production matches the need for replacing industrial pellets with a new product that can be manufactured by small enterprises, using locally available raw materials and low-investment technology. Microchips cannot match the quality of pellets in terms of high energy density, extremely low moisture content and even piece size: however, microchips are still dry, dense, small (length ≤ 10 mm) and homogeneous enough for feeding plants that were originally designed for pellet fuel, and that are much cheaper to purchase compared with a classic chip-fired heating plant (Table 10). Furthermore, microchips are cheaper than pellets and their origin is easier to trace, because entirely local. For this same reason, microchips contribute to local economy, which is not always true for pellets. Pellet-stove worthy microchips can be produced in several ways, which are described in this study.

Table 10: Comparison between microchips and A1+ chips

Sample	#	Microchips	A1+ Chips
Moisture content	%	10.4	11
Density	kg m^{-3} chips	190	233
Ash content	% on dry	2.0	0.7
Heating value	MJ kg^{-1}	15.8	14.5
Heating value	kWh kg^{-1}	4.39	4.03
< 3.15 mm	% weight	6	0
3.15-15 mm	% weight	94	35
16 mm-31 mm	% weight	0	65
>31 mm	% weight	0	0

Figure 35: Microchips (left), modified burner (centre), modified bottom feeding (right)

THE STUDY PLANTS

This study surveyed 8 existing commercial operations, equally divided between pellet manufacturing operations and microchipping operations. These operations had been running long enough for gaining meaningful experience, so that reliable information could be obtained, despite the pioneer character of this new activity. All the initiatives presented here have been launched by forest enterprises, alone or in partnership with some other parties. The study excludes projects managed by other company types that have no direct connection with raw material production, but are managed by industrial or capital concerns and buy the wood raw material on the market (Table 10).

Regardless of product type, all operations present the following common characteristics: they all use low-grade hardwood material, especially sweet chestnut (*Castanea sativa* L.), which is the dominant feedstock in all cases except for Pellet 2; chipping is always performed with a mobile forestry chipper, owned by the operator or contracted for the purpose, and used for a number of other jobs besides processing feedstock for the pellet or microchip production plant. Concerning chipping, it is worth noting that all chippers used for microchip production are disc types, except for the machine used in operation Microchip 4. Operators state that disc chipper are cheaper to operate and offer better product quality than drum chipper when used on log material, and their statements are supported by existing literature.

PELLET PLANTS

All the pellet plants in this study have a capacity below 1 t pellets h^{-1} and are fed with forest products or by-products, not sawdust or shavings (Figure 36). The sample covers a relatively wide range in plant size, capital investment and annual production, but all plants in this study deliver a standard product, matching the quality specification set for commercial pellet (6 or 8 mm diameter, 9% moisture content) (Table 11). As customary for any commercial pellet plant, the plants in this study are equipped with one or more refining mills and with a dryer, which is fired with chips, pellets or firewood - never with gas or other fossil fuels. The availability of refining mills, makes screening unnecessary. No debarking facility is included, because most operations use thin-barked hardwood logs, and those that also use conifer logs keep them in storage for at least one year in order to reduce moisture content and favor the loosening of bark, which is easily shed during handling.

Table 11 : General description of the pellet operations

Operation	#	Pellet1	Pellet2	Pellet3	Pellet4
Commissioned	Year	2010	2013	2013	2014
Output	$t\ h^{-1}$	0.3	0.1	0.4	0.8
Work	$h\ year^{-1}$	1333	550	500	1125
Production	$t\ year^{-1}$	400	55	200	900
Raw material	%	100 H	66 H/33 S	66 S/33 H	100 H
Raw material	$€\ t^{-1}$	40	30	40	55
Raw material	Origin	Bought	Own	Bought	Bought
Storage	months	2-4	24-36	12	4
Product	type	8 mm pellet	6 mm pellet	6 mm pellet	6 mm pellet
Moisture	%	9	9	9	9
Investment	€	200000	46000	120000	630000
Screening	type	None	None	None	None
Drying	type	Chip boiler	Firewood boiler	Chip boiler	Pellet boiler
Bagging	type	15-kg	15-kg	15-kg	15-kg
Fine removal	step	-	-	-	-
Electricity	kW	33	19	55	122
Main product	%	100	100	100	100
Certified quality		No	No	No	No
Status		Expanding	Stable	Stable	Ceased

Notes to the table: Raw material is H = hardwood, S =softwood; the investment cost does not include the chipper, the tractors and the loaders when owned by the same operator, as these machines are acquired and used for other main tasks; 15-kg is the standard small plastic bag used for pellets; Electricity represents the cumulated power of all electric motors in the plant; main product represents the % of the main target product (pellet or microchip) issued from the plant.

Figure 36: Small-scale pellet manufacturing plant

MICROCHIP PLANTS

The microchip operations in this study are even more diversified than the pellet operations, representing a very large variety in capital investment (from 1500 to 345000 €), production capacity and technical characteristics (Table 12). Yet, they are all harnessed to manufacture the same general product type, and for the same use. Since no refining mills are deployed, all plants include screening as a crucial stage in the process. Different solutions are adopted, but most screens are self-constructed, and are often obtained through the ingenious adaptation of other equipment common to different sectors, such as agriculture (adapted fruit selection screen) or construction (adapted cement mixer) (Figure 37). The drying of microchips (Figure 38) is obtained in different ways, often exploiting solar energy and only in one case through a chip-fired boiler. That also explains the large variety recorded for the moisture content of microchips. The most advanced microchip production systems also perform dust removal at some stage along the process, which is not the case for the simplest operations.

Figure 37: Micro-chipping and screening on the farm yard

Figure 38: Air-drying and bagging microchips

Table 12: General description of the microchip operations

Operation	#	Microchip1	Microchip2	Microchip3	Microchip4
Commissioned	Year	2008	2015	2015	2014
Output	$t\ h^{-1}$	0.8	1.1	1.0	0.8
Work	$h\ year^{-1}$	130	80	5000	500
Production	$t\ year^{-1}$	100	90	5000	400
Raw material	%	100 H	100 H	100 H	50 H/50 S
Raw material	$€\ t^{-1}$	30	30	45	75
Raw material	Origin	Own	Own	Bought	Bought
Storage	months	12	12	12	3
Product	type	Microchips	Microchips	Microchips	Microchips
Moisture	%	18	16	11	15
Investment	€	38000	1500	345000	90000
Screening	type	Oscillating	Rotating	Both types	Rotating
Drying	type	Solar pad	None	Chip boiler	Solar barn
Bagging	type	15-kg	Big bags	Sacks	Big bags
Fine removal	step	at bagging	none	at sieving	at sieving
Electricity	kW	5	3	35	3
Main product	%	80	80	30	30
Certified quality		No	No	Yes	Yes
Status		Expanding	Ceased	Expanding	Ceased

Notes to the table: Raw material is H = hardwood, S =softwood; the investment cost does not include the chipper, the tractors and the loaders when owned by the same operator, as these machines are acquired and used for other main tasks; 15-kg is the standard small plastic bag used for pellets; Electricity represents the cumulated power of all electric motors in the plant; main product represents the % of the main target product (pellet or microchip) issued from the plant.

FINANCIAL SUSTAINABILITY

Production cost averaged 228 € t^{-1} for pellets (9% moisture content) and 134 € t^{-1} for microchips (moisture content between 11 and 18%). For each process type, three entrepreneurs out of four accrued meaningful profits, and the average profit was estimated at 10% and 6% for pellets and microchips, respectively (Table 13). However, profitability differences between the two production chains were deprived of statistical significance.

In particular, the cost difference between pellet production and microchip production depends on process cost, which is 7 times higher for pellets compared with microchips, or 101 € t^{-1} vs. 14 € t^{-1}. Raw material cost accounted for 28% and 50% of total cost respectively for pellets and microchips, and it was significantly lower for forest owners (30 € t^{-1} vs. 51 € t^{-1}).

Table 13: Cost, revenues and profit for the 8 sample operations

Operation	#	Pellet1	Pellet2	Pellet3	Pellet4	Microchip1	Microchip2	Microchip3	Microchip4
Wood	€ t^{-1}	61	49	63	84	39	44	76	107
Chipping	€ t^{-1}	18	42	24	12	31	38	17	21
Process	€ t^{-1}	86	104	86	127	16	2	10	27
Bagging	€ t^{-1}	32	44	44	35	50	17	20	17
Total cost	€ t^{-1}	197	238	216	258	136	101	124	173
Sale price	€ t^{-1}	240	270	240	240	146	131	135	136
Profit	%	22	13	11	-7	7	29	9	-21

Notes: all costs and revenues are referred to the metric ton of final product, at the water mass fraction recorded at the end of the process; wood cost includes immobilization of capital; sale price = mean price of all products issued from the plant, weighed by their contribution to total production.

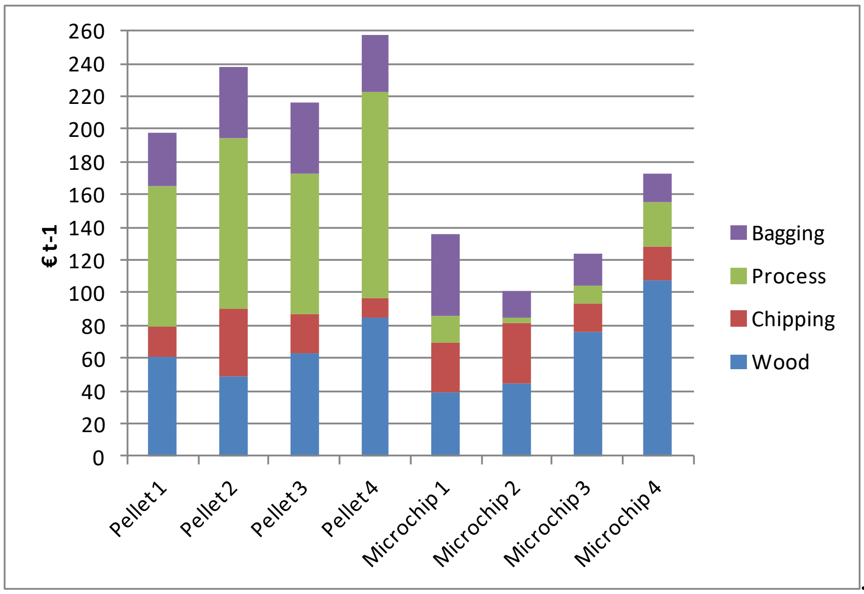

Figure 39: Cost breakdown for the 8 sample operations

Mean raw material cost, chipping cost and bagging cost are not significantly different for the two product options (Figure 39). The pelletizing process incurs significantly higher depreciation, fuel, power and labour costs than microchipping. While capital cost is the dominant component of total process cost for both options, differences are highest for energy cost, since fuel and power cost are respectively 14 and 17 times higher for pellet production than for microchip production (process stage only). The fuel used for drying the chips before pressing (pellets) or screening (microchips) is always renewable and consists of reject firewood, screened out chips or pellets. In general, the heat demand of all plants in the study is met with renewable sources.

The higher price obtained by pellets results in pellet operations being more profitable than microchip operations, although the difference is deprived of any statistical significance due to the very large variation in the data pool. Conversely, the much lower investment required by a microchip operation pushes mean return on investment (ROI) slightly above 9%, against the 5% figure recorded for pellet operations (values estimated for successful operations only, after removing those operations that had to shut down). But this difference is not significant either, and for the same reasons. In fact, one can lose money or make good profits with both products, depending on plant management and local market conditions.

Figure 40: Industrial-scale microchip plant (operation Microchip 3)

CONCLUSION

Small-scale pellet and microchip production (Figure 40) may represent a viable opportunity for forest owners and operators confronted with a declining firewood market. These new products may support rural development more effectively than the massive import of industrial pellets does.

This study describes clear differences between the two operation types. Microchip production is a simple process, which can be implemented with a very small investment. Screening is the characterizing step, present in all operations. For the same investment level, a microchip operation will yield a larger product volume than a pellet operation, serving more users and utilizing larger forest areas. Microchipping is often a part-time job, conducted during seasonal lulls in activity. Microchips represent a new product, largely unknown, which currently arouses much curiosity but still needs to gain widespread trust. In contrast, pellet production is a relatively complex process, which incurs larger capital and operating cost. Drying, refining and pressing are the characterizing steps, and pellet production is a parallel job that can improve time use of labour engaged with low-intensity tasks, rather than a part-time job for the seasonally idle. Pellets are a well-known product, very popular and easily traded on all markets.

Both systems are implemented at a pioneering stage, and are based on flexible models that can be adapted to the disparate array of rural entrepreneurs, each facing his/her own peculiar local market and working conditions. Optimized chipping could further decrease the impact of two process chains where chipping represents the main consumer of fossil fuels, while the large energy demand generated from drying is already covered with renewables, as recommended in previous studies. Use of renewable electricity would boost the environmental performance of pellet operations, since electricity accounts for 90% of the impacts derived from pellet production. Renewable power could be generated on site with a small-scale wood gasification plant, which could also offer process heat, thus offsetting the energy cost incurred with drying. However, commissioning such a plant would incur relevant additional investment and may be outside the reach of the smallest entrepreneurs.

RECOMMENDATIONS AND CONCLUSIONS

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This report presented case studies describing challenges and opportunities for the development of successful business cases of mobilization of forest biomass for bioenergy, biofuels and bioproducts. Some key recommendations can be drawn from them.

A compilation of the developed knowledge from case studies indicate how taking advantage of modern technologies and innovations in supply chain management can help to valorise underutilized biomass resources. Commercial quantities of underutilized woody biomass resources are available that are currently left behind in the forest, such as the degraded woods in Quebec, or burnt inefficiently by the local sawmills and pulp mills for heat and power generation, as seen with the processing residues in the Vancouver region. These biomass resources traditionally have not been considered as feedstock for biofuels and bioproducts markets due to a combination of logistical disadvantages (high procurement costs) and quality issues (e.g. high moisture content and ash content). Supply chain development, such as the use of adequate pre-treatment technologies for biomass, or a closer integration of forest biomass supply chains within larger forest management systems, can create significant new opportunities for the utilization of this material.

A key element of successful biomass deployment is to ***connect the right biomass to the right value market*** is based on supply chain management and pre-processing to value add the biomass for energy production. In the case presented from Vancouver, very low-quality biomass that could be sourced locally and did not competing uses, was preference to have a secure cost-effective supply that could be managed through a well-planned supply chain to meet energy production needs. In the Italian case, more mature bioenergy markets had been established and local small-scale supply was matched to the local market where the advantages of the location and supply form existing land management used novel supply chain technology and design to meet the specific local market need.

A combination of ***pre-processing solutions can contribute to upgrade the value of the underutilized woody biomass resources***, through managing moisture content, limiting contamination and creating a consistent particle size for energy production systems. These strategies around storage and mixing of resources were used to bring low quality biomass sourced for the Vancouver gasification case to a level that they provided a consistent and reliable energy production, while the Italian case used specific chipping technology as an effective solution at small scale to meet a high-quality biomass supply demand. Pre-processing solutions will add to the cost of biomass delivered to the downstream users and therefore needs to be carefully considered and integrated in the supply chain management. The selection of the pre-processing solutions depends on understanding the feedstock specifications of the bio-processing technology and biomass characteristics. Fractionation, size reduction, drying, densification, torrefaction, blending and washing are examples of the pre-processing solutions.

The location of the upgrading operations is critical to reduce the cost of inbound and outbound transportations and ensuring the right qualities are created and delivered to the bioenergy use of greatest value. In the Italian case logistics were reduced with localised pre-processing of microchips to displace imported pellets; a pre-processing technique that unlocked a local supply. Multiple transportation modes (i.e. road, rail and water) can significantly reduce the biomass delivered cost and where possible it can be most effective to introduce value adding pre-processing operations where these modes of transportation intersect. The Alberta case of pellets for co-firing in coal power energy generation added value to the feedstock through palletisation and then used the now point sources of higher value biomass to leverage logistic cost benefits of rail trainsport to access more biomass at a acceptable cost. Where multiple modes of transportation are not required pre-processing will be better placed either at the point of harvest (road side storage to reduce moisture, infield chipping and grinding, etc.) or within the facility of the final energy producer (active drying with waste heat, palletisation, torification, etc.)

***Agility and flexibility are important to the efficient execution of supply chain plans*.** The reality in the forest sector, and more so in forest biomass supply chains, is that there is a continual need to adapt to changing conditions (e.g. mill closings/openings; natural disturbances). An agile and flexible biomass business case will be able to adapt to multiple sources of feedstocks, and continually move up the technological learning curve through learning-by-doing, as seen in the example of the gasification plant in Vancouver.

Forest biomass supply is inherently complex, so success requires ***right biomass is directed to the right use*** and trying to force what has worked in one region in an area that does not have the same opportunity or conditions increases the risk of failure. In the Quebec case, wood that was otherwise going to be residues on site and create future land management costs and challenges was captured through effective integration with other forest-based supply chains to meet local market at a relatively low cost. In British Columbia the case uses small scale gasification and novel supply management strategies to its advantage to source true low value residues and waste wood as a low-cost supply that other competitors would rather not use; as case that may not work with bigger projects or regions where this low-quality biomass is not readily available.

The priority is to ***displace currently inefficient energy solutions where a biomass feedstock is local to an otherwise remote site***. Where the situation does not a provide clear cut advantaged for bioenergy production and use it is important to work to the identified strengths of bioenergy such as direct heat production and capitalise on other benefits such as regional development, improved forest management outcomes and reliable local energy source. All these strategies for successful biomass supply are enhanced supportive policy and legislation underpin changes in the current forest management practices, organizational behaviour and business models of the forest companies towards supplying a bioenergy industry.

Integration of supply to existing industry and land management needs is key to success. The biojet project in British Columbia relies heavily on integration with forest supply chain to source biomass suited to the specific need as well as downstream supply chain integration to get to market, using already in place and reliable infrastructure to get to market. In Colorado the recovery of pine beetle killed wood was a key tool in the integrated land management strategy to direct as much of the wood that was suitable to high value timber markets but provide viable market to energy use so all the material could be removed and promote regeneration of the forest on site. In Alberta the traditional energy source of coal is a very low-cost solution so high levels of integration with existing supply chains and supply chain infrastructure like rail were needed to deliver at acceptable costs as a renewable component of the co-firing solution.

While biomass supply chains remain, complex and challenging the key elements for success can be quite simple. The first element is to understand the biomass supply including the amount, locations and quality. It then falls on the supply chain to realise the best value by connecting that biomass to the right market and use, while adding the right value at the right place along the supply chain with pre-processing, amalgamations and volume efficiencies. Scaling and integration with existing supply chains that both leverages expertise and creates synergistic efficiency is often the difference between success and failure.

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Appendix A. notation, Equations and functions from case study:Integrating Economic and Environmental Values into Forest Supply Chain Management for Timber and Bioenergy Production from Beetle-killed Biomass in Colorado

Sets:
$U-set\ of\ candidate\ harvesting\ units\ i$
$M-set\ of\ timber\ mills\ j\ purchasing\ timber\ products$
$K-set\ of\ bioenergy\ plants\ k\ using\ biomass$
$F-set\ of\ facilities\ utilizing\ bioenergy\ product$
$S-set\ of\ harvesting\ systems\ s$
$P-set\ of\ timber\ products\ p$
$O-set\ of\ final\ wood\ product\ o$
$Q-set\ of\ bioenergy\ products\ q$

Parameters:
$\lambda_r-weight\ coefficient\ of\ the\ economic\ objective$
$\lambda_e-weight\ coefficient\ of\ the\ environmental\ objective$
$ro_{jo}-sale\ price\ of\ wood\ product\ o\ at\ mill\ j$ ($\$/m^3$)
$rq_{fq}-sale\ price\ of\ bioenergy\ product\ q\ at\ plant\ k$ ($\$/bdt$)
$eo_{jo}-net\ reduction\ rate\ of\ GHG\ emission\ by\ using\ wood\ product\ o\ produced\ from\ mill\ j$ ($kg\ CO_2eq/m^3$)
$eq_{fq}-reduction\ rate\ of\ GHG\ emission\ by\ using\ bioenergy\ product\ q\ at\ facility\ f$ ($kg\ CO_2eq/bdt$)
$m_{ip}-volume\ availability\ of\ timber\ product\ p\ at\ harvest\ unit\ i$ (bdt)
$n_i-mass\ availability\ of\ logging\ residues\ at\ harvest\ unit\ i$ (bdt)
$hc_{sp}-harvesting\ cost\ rate\ of\ timber\ product\ p\ using\ system\ s$ ($\$/bdt$)
$he_{sp}-harvesting\ GHG\ emission\ rate\ of\ timber\ product\ p\ using\ system\ s$ ($kg\ CO_2eq/bdt$)
$price_p-stumpage\ price\ of\ timber\ product\ p$
$sgc-cost\ rate\ of\ grinding\ and\ screening\ logging\ residues$ ($\$/bdt$)
$sge-GHG\ emission\ rate\ of\ grinding\ and\ screening\ logging\ residues$ ($kg\ CO_2eq/bdt$)
$dist_{ij}-distance\ between\ harvest\ unit\ i\ and\ mill\ j$ (km)
$dist_{ik}-distance\ between\ harvest\ unit\ i\ and\ plant\ k$ (km) $dist_{kf}-distance\ between\ plant\ k\ and\ facility\ f$ (km)
$tcp_p-transportation\ cost\ rate\ of\ timber\ product\ p$ ($\$/bdt*km$)
$tep_p-transportation\ GHG\ emission\ rate\ of\ timber\ product\ p$ ($kg\ CO_2eq/bdt*km$)
$tcb-transportation\ cost\ rate\ of\ logging\ residues$ ($\$/bdt*km$)
$teb-transportation\ GHG\ emission\ rate\ of\ ground\ logging\ residues$ ($kg\ CO_2eq/bdt*km$)
$tcq_q-transportation\ cost\ rate\ of\ bioenergy\ product\ p$ ($\$/bdt*km$)

Decision variables:
1) Continuous variables:
$z_{isp}-amount\ of\ timber\ product\ p\ produced\ in\ system\ s\ at\ harvest\ unit\ i$ $x_{ijp}-amount\ of\ timber\ product\ p\ transported\ from\ harvest\ unit\ i\ to\ mill\ j$
$u_{jo}-amount\ of\ wood\ product\ o\ produced\ at\ mill\ j$
$w_{ik}-amount\ of\ logging\ residues\ transported\ from\ harvest\ unit\ i\ to\ plant\ k$
$v_{kfq}-amount\ of\ bioenergy\ product\ q\ transported\ from\ plant\ k\ to\ facility\ f$
2) Integer variables:
$y_{is}=\begin{cases} 1, if\ harvest\ unit\ i\ is\ harvested\ using\ system\ s \\ 0, otherwise \end{cases}$

$$Maximize\ z = \lambda_r f_r/(f_r)_{max} + \lambda_e f_e/(f_e)_{max} \tag{1}$$

Economic aspect:

$$f_r = R^O + R^Q - C^{har} - C^{material} - C^{s\&g} - C^{trans} - C^{prod} \tag{2}$$

$$R^O = \sum_{j\in M}\sum_{o\in O} u_{jo} * ro_{jo} \tag{3}$$

$$R^Q = \sum_{k\in K}\sum_{f\in F}\sum_{q\in Q} v_{kfq} * rq_{fq} \tag{4}$$

$$C^{har} = \sum_{i\in U}\sum_{s\in S}\sum_{p\in P} z_{isp} * hc_{sp} \tag{5}$$

$$C^{material} = \sum_{i\in U}\sum_{s\in S}\sum_{p\in P} z_{isp} * price_p \tag{6}$$

$$C^{s\&g} = \sum_{i\in U}\sum_{k\in K} w_{ik} * sgc \tag{7}$$

$$C^{trans} = \sum_{i\in U}\sum_{j\in M}\sum_{p\in P} x_{ijp} * dist_{ij} * tcp_p + \sum_{i\in U}\sum_{k\in K} w_{ik} * dist_{ik} * tcb + \sum_{k\in K}\sum_{f\in F}\sum_{q\in Q} v_{kq} * dist_{kf} * tcq_q \tag{8}$$

$$C^{prod} = \sum_{j\in M}\sum_{o\in O} u_{jo} * pco_{jo} + \sum_{k\in K}\sum_{f\in F}\sum_{q\in Q} v_{kfq} * pcq_{kq} \tag{9}$$

Environmental aspect:

$$f_e = E^O + E^Q - E^{har} - E^{bio} - E^{s\&g} - E^{prod} \tag{10}$$

$$E^O = \sum_{j\in M}\sum_{o\in O} u_{jo} * eo_{jo} \tag{11}$$

$$E^Q = \sum_{k\in K}\sum_{f\in F}\sum_{q\in Q} v_{kfq} * eq_{fq} \tag{12}$$

$$E^{har} = \sum_{i\in U}\sum_{s\in S}\sum_{p\in P} z_{isp} * he_{sp} \tag{13}$$

$$E^{s\&g} = \sum_{i\in U}\sum_{k\in K} w_{ik} * sge \tag{14}$$

$$E^{trans} = \sum_{i\in U}\sum_{j\in M}\sum_{p\in P} x_{ijp} * dist_{ij} * tep_p + \sum_{i\in U}\sum_{k\in K} w_{ik} * dist_{ik} * teb + \sum_{k\in K}\sum_{f\in F}\sum_{q\in Q} v_{kq} * dist_{kf} * teq_q \tag{15}$$

$$E^{prod} = \sum_{k\in K}\sum_{f\in F}\sum_{q\in Q} v_{kfq} * peq_{kq} \tag{16}$$

$$\sum_{s\in S} y_{is} \le 1 \quad \forall\, i \in U \tag{17}$$

$$z_{isp} = m_{ip} * y_{is} \quad \forall\, p \in P, s \in S, i \in U \tag{18}$$

$$\sum_{j\in M} x_{ijp} = \sum_{s\in S} z_{isp} \quad \forall\ p \in P, i \in U \tag{19}$$

$$u_{jo} = \sum_{i\in U}\sum_{p\in P} x_{ijp}/density_p * ratioo_{jpo} \quad \forall\, o \in O, j \in M \tag{20}$$

$$\sum_{k\in K} w_{ik} \le y_{i2} * n_i \quad \forall\, i \in U \tag{21}$$

$$\sum_{f\in F}\sum_{q\in Q} v_{kfq}/ratioq_{kq} = \sum_{i\in U} w_{ik} \quad \forall\, k \in K \tag{22}$$

$$y_{is} \in \{0,1\} \quad \forall\, s \in S, i \in U \tag{23}$$

$$z_{isp} \in Z_+ \quad \forall\, p \in P, s \in S, i \in U \tag{24}$$

$$x_{ijp} \in Z_+ \quad \forall\, p \in P, j \in M, i \in U \tag{25}$$

$$u_{jo} \in Z_+ \quad \forall\, j \in M, o \in O \tag{26}$$

$$w_{ik} \in Z_+ \quad \forall\, k \in K, i \in U \tag{27}$$

$$v_{kfq} \in Z_+ \quad \forall\, k \in K, q \in Q \tag{28}$$

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Further Information

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