*Utrecht University*

# Current and future trade opportunities for woody biomass end-products from British Columbia, Canada

MSc. Thesis

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# Preface

It is astounding how much can be learned from a single project. When I started thinking about a MSc. thesis, it was hard for me to comprehend the extensiveness of work involved. More than a year later, I come to the conclusion that a Master thesis, the crown on your student career, should not be underestimated at all times. Moreover, the research process has shown personal capabilities in sometimes stressful situations, with help of the pool of knowledge and skills acquired over the last years. However, the realization of this thesis would not have been possible without the valuable contribution and support of others. Therefore, I would like to address the people who have guided me through the process, from the first idea to the final version.

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Andre, thank you for your refreshing insights regarding biomass and providing me the knowledge of biomass supply chains. As overall supervisor, you have shown me the importance of keeping guard of the main structure during my research, which is vital for academic writing.
Paul McFarlane, also many thanks to you for providing me an internship position at UBC. Thank you for helping me to settle down in Vancouver and providing me essential guidance during my research. Your help and encouragements made my stay in Vancouver one of the best times of my life.
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I would like to thank Warren Mabee (UBC) for his willingness to help me out when I encountered difficulties. Your clarifying insights were very helpful to me, particularly the topics of ethanol and model construction. Jack MacDonald (FPInnovations), for your time and provision of a clear understanding regarding BC forestry operations and its characteristics. Staffan Melin (UBC/WPAC), for your precious time, research support and useful information regarding pellets. Thank you for arranging fieldtrips, which highly contributed to get a clear view on the recent developments in the pellet industry and its supply chain. Shahab Sokhansanj, for helping me out in dealing with biomass supply chain issues. Cathe Koot, for the enlightening tour through the UBC research forest. I want to thank CFS/NRCan for financially supporting my internship and providing me data and articles of great value to my research. People involved are: Thomas White, Rebecca Ewing, Janice Larsson, Tony Lempriere, Georgian Lorraine and also thanks to Christian Wolfe who made this internship possible. Moreover, I would like to thank the experts from sawmills and pellet mills that have provided me with most valuable data: Len Fox, Wally Aiken, Spencer Martin, Andy McGowan, Richard White and also John Swaan (WPAC).

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To finalize, I want to thank my supporting family for their concern for me and my thesis and especially my Amy, for caring a lot and doing the final grammar and spelling check of this document, together with my friend Paul Voerman. However, even by mentioning all these people I couldn't have done this all without the help of God. Therefore, Soli Deo Gloria!

# Executive Summary

## Purpose and relevance of thesis

A substantial part of Canada's biomass reserves could be used as a feedstock for bioenergy production. Important feedstock categories include sawmill residues, roadside residues and mountain pine beetle (MPB) killed trees. As the domestic demand is limited, trading biomass end-products from Canada to regions in the world could be a viable alternative. The main aim of this study is ***to investigate the market potential for the biomass end-products pellets and ethanol for the province of British Columbia (BC), Canada***. Pellets are primarily being used for co-firing in Europe and ethanol principally serving the US transportation fuel market. To do so, the maximum availability of feedstock, cost of final products and potential volumes of end-products were assessed for the current (2008), near future (2012) and future (2020) situation. By estimating future demand volumes and prices, future market production volumes and related prices of pellets and ethanol for BC are derived. Designed scenarios (elaborated in thesis) provide a range of outcomes regarding different assumptions taken for possible developments in the biomass industry. These outcomes illustrate the biomass trade potential from BC which may provide very useful insight on potential biomass import volumes and biomass prices for the Canadian and European biomass industry and policy makers alike.

## Approach and Methodology

An integrated analysis has been conducted incorporating both provincial conditions (e.g. BC's forest practices) as well as continental demand figures (e.g. EU pellet demand), resulting in a comprehensive overview of the biomass implications concerning BC. The feedstock potential was mapped geographically to assess the location-specific availability along the province. By using a supply chain approach, a pathway from the feedstock source to the consumer was developed which includes a breakdown of end-product costs. The feedstock availability and the supply chain steps were incorporated into a dynamic spreadsheet which determined mass flows and costs per taken step. Regarding the supply chain the distinction was made between 'feedstock delivered at a production plant' and from 'production plant to the end-user' to include competition for feedstock since other industries in BC require similar feedstocks. Accordingly, four feedstock scenarios and four end-product scenarios were evaluated and cost supply curves were developed.

## Results and conclusions

### Feedstock

Results show significant differences in feedstock delivered at the production plant: sawmill residues are by far the cheapest feedstock (currently starting at \$17.0/Odt) whereas roadside residues (\$43.7/Odt) and MPB killed trees (\$99.7/Odt) would start at considerably higher costs (ES Table 1). At present, only the heavily competed sawmill residues are being used, however availability is limited. A growth in production volume of biomass end-products has increased the demand for feedstock substantially, which may lead to a shift towards other, more expensive and widely available, feedstock in the near future. It is expected that when demand for feedstock grows, increasingly investments would be made on research and development to attain cost reductions in total feedstock cost. Future prospects for feedstock show considerable cost reductions in roadside residues and MPB killed trees for the years 2012 and 2020, according to an optimistic feedstock scenario (FS 1).

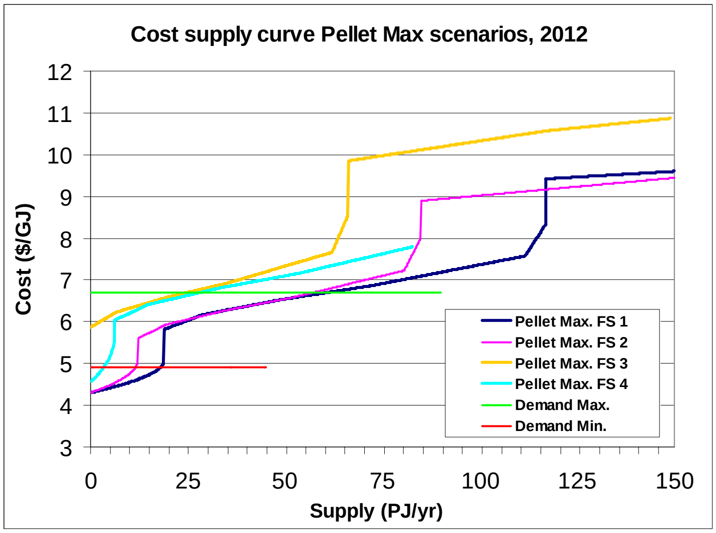
**ES Table 1: feedstock end-results for FS 1, BC**

| *Feedstock costs* | | **2008** | **2012** | **2020** |
|---|---|---|---|---|
| **Sawmill residues** | Costs (US$/Odt)<br>Volume (Million Odt/yr) | 17.0-28.4<br>1.3 | 17.0-28.4<br>1.3 | 17.0-28.4<br>1.3 |
| **Roadside residues** | Costs (US$/Odt)<br>Volume (Million Odt/yr) | 43.7-86.2<br>5.0 | 40.3-79.0<br>5.5 | 34.3-67.4<br>5.9 |
| **MPB trees** | Costs (US$/Odt)<br>Volume (Million Odt/yr) | 99.7-…<br>n.a. | 95.9-109.7[a]<br>36.7 | 81.7-103.0[a]<br>15.0 |

[a] Higher end value presented for a level of 10 million Odt MPB killed trees. However, the total volume of MPB killed trees is much higher

## Pellets market potential

Pellet production has been ongoing for more than a decade and future demand is expected to grow steadily[1]. In 2006, BC produced 650.000 Odt pellets (i.e. ~11,7 PJ/yr.) at production costs starting from $4.8/GJ. Regarding feedstock availability and costs of scenarios in this study, the pellet production could expand significantly. The total assumed EU's demand[2] for 2012 is 90 PJ/yr from which BC could supply in the highest case 60.9 PJ/yr and in the lowest case 24.8 PJ/yr (ES Figure 1). For the year 2020, FS 1 and FS 2 show outcomes that meet the entire projected EU demand of 218 PJ/yr considering favourable market conditions (price level of $8.2/GJ). This is 20% more than the global wood pellets production volume estimated for 2007[1]. However, moderate scenarios for 2020 show trade potentials of approximately 50 PJ/yr (FS 4).

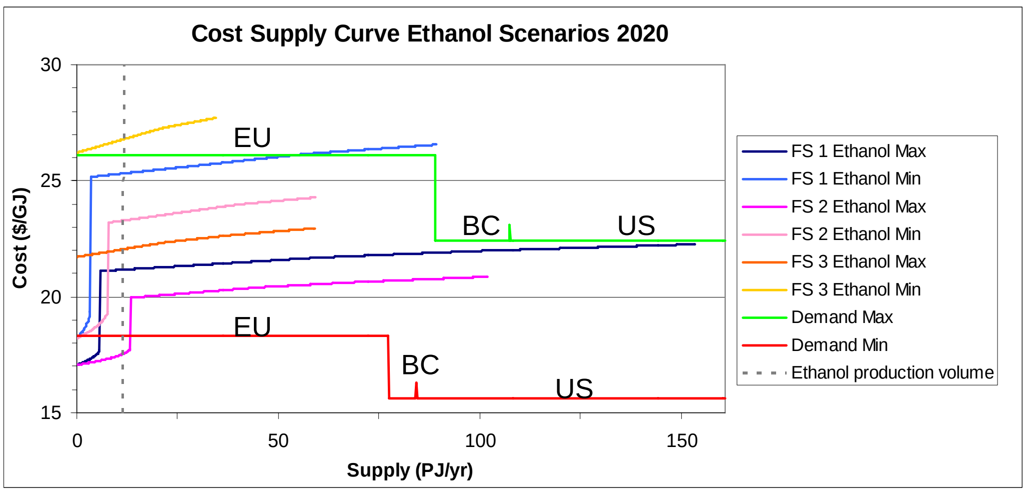



**ES Figure 1: cost supply Pellet-Max scenario BC, 2012. Four feedstock scenarios are depicted (FS 1/ FS 2/FS 3/FS 4) each having defined feedstock availabilities and cost levels and form the base of the shown Pellet-Max scenario. Demand lines show market prices and demanded volumes for the EU.**

[1] Wood & Pellet Association in Canada
[2] Demand from outside the EU

## Ethanol market potential

For 2012, ethanol-Max scenarios show limited production potential, even regarding the higher assumed price levels. The ambitious expectations in improvements of conversion efficiencies and cost reductions for the ethanol-Max scenarios for 2020, leads to very large ethanol trade potentials from BC to other markets in the world. Optimistic ethanol production scenarios (ethanol-Max) are economically feasible up to 154 PJ/yr[3] and would meet the assumed demand of the EU, BC, and partly the US demand (ES Figure 2). This equals approximately 21% of the global ethanol production volume for fuel use in 2005[4]. The lower case (ethanol-Min) production capacity ranges at 0-59 PJ/yr regarding highest price assumptions. There is limited potential assuming ethanol at the lowest price level, configured by the demand-Min line.




**ES Figure 2: cost supply curves ethanol scenarios, BC, 2020. A 400MW ethanol output plant is assumed (i.e. 11.5 PJ/yr). Three feedstock scenarios are depicted (FS 1/FS 2/FS 3) each having defined feedstock availabilities and cost levels and form the base of the ethanol scenarios. Demand lines are drawn which show market prices and demanded volumes for EU, BC and the US market.**

Increasing the plant scale results into significant costs reductions and increases the market potential substantially (elaborated in thesis). However, large scale ethanol production volumes could only be achieved by using large volumes of MPB killed trees as feedstock besides sawmill residues. The Prince George region has the biggest share of the potential ethanol production in BC; an approximate 39% of the total produced volume.

In conclusion, ***BC has significant opportunities for biomass trade within the stated timeframe (2008-2020)***. A substantial share of the available feedstock in BC could be converted into profitable biomass end-products. Cost reduction throughout the supply chain and increases in market prices creates potential for extensive expansion in the biomass industry in BC. ***In 2020, pellet production potentials for BC exceed the global pellet production*** (estimated for 2007) ***and ethanol production volumes could reach 21% of global ethanol production volumes*** (estimated for 2005)[4]. BC, therefore, could play a significant role on the global biofuels market.

[3] At an average total cost of $21.6/GJ regarding a 400MW ethanol output plant.
[4] Source: Walter et al., 2007

# Outline

## List of abbreviations

| | |
|---|---|
| BC | = British Columbia |
| EU | = European Union (refers to 25 member states) |
| US | = United States |
| MPB | = Mountain Pine beetle |
| TSA | = Timber supply area |
| TFL | = Tree farm licence |
| LRF | = Lumber recovery factor |
| NRL | = Non recoverable lumber |
| R&D | = Research and development |
| O&M | = Operation and maintenance |
| FS | = Feedstock scenario |
| GHG | = Green house gas emissions |
| GJ | = Gigajoule ($10^9$ joule) |
| PJ | = Petajoule ($10^{15}$ joule) |
| Odt | = Over dry tonne |
| MW | = Megawatt |
| km | = kilometer |

# 1. Introduction

## *1.1 Introduction*

The growing energy demand in the world influences the current energy supply security. Today's fossil fuel-based western economies will face significant problems if energy prices rise to unprecedented values, caused a.o. by scarcity of supplies. Countries importing energy are debating how to solve this foreseen problem in the future. At the same time, considering the issue that most energy reserves are purchased from unstable regions in the world makes the quest of a secure energy supply even more relevant.

The other main issue is the growing evidence of climate change, related to the combustion of fossil fuels. The increasing need for energy to meet the world's demand, results in an increase of fuel consumption. In a fossil fuel-based society, this implies an increase in the amount of emissions of the greenhouse gas $CO_2$ into the atmosphere causing climate change.

In order to tackle the above mentioned main two problems simultaneously, a renewable energy source like biomass could be one of the solutions. Biomass is considered a $CO_2$ neutral fuel (when produced and used sustainably) and resources are available in many parts of the world, also in more politically stable regions (Hoogwijk et al., 2005).

Power plants, for instance large scale co-firing installations, require a steady supply of biomass resources from forest rich regions. Since a large part of the industrialized countries (e.g. Western Europe) lack these conditions, international trade in biomass is taking off (Peksa-Blanchard et al., 2007)[5].

Canada (British Columbia) could play an important role in this context since it has vast woody biomass reserves and one of the largest paper and timber industries in the world[6] (Bradley, 2006a). Residues from the wood processing industry, roadside residues[7] and mountain pine beetle (MPB) infested trees are further investigated in this thesis as feedstock for the production of biomass end-products. Due to low energy prices in Canada, the economic feasibility of large scale biomass projects for domestic usage is limited, regarding the current (2008) situation. Therefore, trading Canadian biomass to regions in the world that are willing to pay more for biomass products could be a viable alternative.

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[5] Associated with *Task 40* (www.bioenergytrade.org).

[6] Canada is the largest exporter of forest products in the world: 17.3% of the total world trade turnover (NRCan, 2006b).

[7] Biomass leftovers after delimbing trees at the roadside, a substantial part of harvesting residues.

## 1.2 Problem Description

The biomass trade implies two sides; the supply side, and the demand side. Both sides have their specific drivers which determine the production capacity of biomass end-products and on the other side the demanded capacity (Box 1).

| | |
|---|---|
| *Drivers for supply side:* | |
| - Excess of biomass | : sawmill residues/ roadside residues/ MPB trees |
| - Increasing biomass demand | : rising prices of biomass end-products |
| - Supply chain developments | : reduction in costs of supply chain steps |
| - End product developments | : new markets stimulated by forestry industry |
| *Drivers for demand side:* | |
| - Environmental policy (Kyoto) | : tax redemptions/ incentives biomass usage |
| - Price developments | : price of biomass vs. other energy carriers (e.g. oil) |
| - System adaptation for biomass | : adaptation end-user eases trade possibilities |

**Box 1: drivers for biomass supply and demand (IEA, 2006)**

Canada already produces and exports biomass end-products for international biomass trade. Considering its extensive unutilized biomass feedstock volumes, more export of end-products could be expected in the near-future (Bradley, 2006a). Furthermore, evident demand for biomass end-products (especially in the US and the EU) results in possibilities for international biomass trade (Bradley, 2006b; Swaan, 2006). Benefits could be achieved in this market if the supply side anticipates to this growing biomass demand. Simultaneously, a growing supply side could contribute at a higher level to greenhouse gas (GHG) emission reductions[8].

Currently, it is still hard to determine in which direction the biomass market will develop, regarding the selection of end-products and the potential production capacity. Consequently, an overview of future supply-demand scenarios for biomass end-products results in a range of possible outcomes to be used as guidance to policy makers and entrepreneurs for taking appropriate measures in stimulating the biomass industry.

Defining the different pathways, including all individual steps from biomass at the source to domestic end-users or international transfer sites (e.g. international terminals), will provide a comprehensive overview of supply chains and their characteristics (including costs).

Increasing biomass demand creates an incentive for technological development within this industry and could generate economies of scale. This could lead to decreasing production costs and a more competitive market position, thus growth in the biomass industry. Eventually, supply and demand of biomass may develop towards a stage of stabilization in which biomass resources are extracted from forests, and converted into profitable end-products.

[8] Unutilized biomass residuals will decay which generate greenhouse gasses without any recovery of energy. Moreover, a greater risk of forest fires is expected when residues are left behind in forests .

**Previous work**

A supply chain consists of individual components, or steps, which all have their specific features in terms of cost and constraints. Regarding biomass supply chains previous research has been undertaken. The following studies have been conducted by other researchers, describing supply chains in general terms or addressing specific individual components.

The Canadian biomass forest situation and resource quantity have been determined by studies initiated by the Canadian natural resources institutes (CFS/NRCan). Furthermore, biomass feedstock assessments have been conducted in the past and at present for sawmill residues, harvesting residues and MPB tree volumes (Bradley, 2006a; MacDonald, 2006; NRCan/CFS, 2005).

Long term experience has been gained in biomass harvesting and transportation methods in Scandinavian countries. Although Canadian harvesting systems differ from the ones in Scandinavia, information could contribute as reference material (Alakangas, 2000; Johansson J. et al., 2003). Canadian harvesting and transportation methodologies have been researched as well, although in comparison to Scandinavian practices less profoundly (Forrester et al., 2006; MacDonald, 2006; Ryans & Desrocher, 2006; Wood & Layzell, 2003).

The main pre-treatment technologies have been described as well: pelletization (Uslu & Faaij, 2006), bio-oil (Bradley, 2006b), ethanol (Faaij, 2006; KEMA, 2005; Uslu & Faaij, 2006). Some of the mentioned main pre-treatment technologies are subjected to location specific conditions, which should be taken into account when applying this information for Canada or BC.

Most data regarding transportation and forest practices in BC has been studied at FPInnovations (MacDonald, 2007). Biomass supply chains have been studied a.o. at Utrecht University (Hamelinck et al., 2005) and UBC (Sokhansanj et al., 2006).

The economical feasibility of long distance international biomass trade has been proven by several studies. Moreover, limited energy losses were found throughout the supply chain giving rise to the effectiveness of reducing $CO_2$ emissions through biomass trade (Agterberg & Faaij, 1998; Wasser & Brown, 1995).

From the above, most studies focused at one particular part of the supply chain, or whole supply chains at a high aggregation level. Therefore, an integral analysis which incorporates all individual processes, availability of feedstock, for the current and future situation on a regional scale (BC), provides new insights. Bio-oil is the only bioenergy product that has been studied for Canada throughout the supply chain, although in a relatively general way, excluding different regional specific characteristics regarding harvesting and pre-treatment technologies (Bradley, 2006b; Bradley, 2007).

Furthermore, future regional demand projections of biomass end-products (prices and volumes) have not been taken into account in earlier research, whereas this component is the main driver for biomass trade. Factors concerning policy, competition of feedstock, energy prices and demand chain developments are still lacking in most publications. This study does include these factors in the designed scenarios.

## 1.3 Research Objective and Scope

This research aims to provide an overview of how cost of feedstock/end-products relates to increasing production volumes. Regarding these costs, potential future production volumes (supply) and export volumes of biomass end-products for BC can be derived. Designed scenarios (described in chapter 2.4 and 4) provide a range of outcomes regarding different assumptions taken for possible developments in the biomass industry. These outcomes will illustrate a possible biomass trade potential from BC to other parts in the world (mainly Europe and the US). Decision makers in the biomass industry and governments could use outcomes as a tool for founding further developments and steering the biomass industry into the most preferable direction.

From the rationale as described in the sections 1.1 and 1.2, the following research objective is defined:

**Objective**

The objective of this thesis is to identify opportunities to develop the biomass market potential for the province of British Columbia (Canada) under varying scenarios projected from the present until the year 2020, taking into account:

- Different biomass feedstocks: sawmill residues, roadside residues and mountain pine beetle infested trees.
- Different pre-treatment technologies: chipping, pelletization and ethanol production.
- Different end-products: pellets, ethanol.
- A pre-defined supply chain describing the pathway from source to final destination of the biomass end-product for BC.
- Different markets:
  - Product markets: heat supply, co-generation and transportation fuel (ethanol)
  - Spatial markets: British Columbia (Canada), United States, overseas markets (Europe and Asia)

- The *Market potential,* is defined by Blok (2006) as 'the part of the technical potential that is likely to be implemented, taking into account all barriers and stimuli for adopting new technology' (see also Appendix 1).

For this research, a 'case study' approach is applied which implies that the selected province has been analyzed in great detail. The actual situation, region specific constraints and opportunities are evaluated for the province of British Columbia regarding biomass, providing outcomes for this province in particular. A case study approach is appropriate for this research since it conducts an in-depth assessment of the current state of the supply chain and its future potentials. Furthermore, provinces (and even regions) differ significantly in terms of practices and geographical characteristics, making a general approach less suitable to draw accurate conclusions.

**Demarcations**

- The main focus of this research will be the supply side of biomass feedstock and end-products which mainly includes mass flows, costs calculations and technical specifications. The future demand of biomass end-products is difficult to determine and will only include rough demand estimations. The focus, therefore, is less on the demand side (approximately 80% of time and effort is put in supply side vs. 20% in demand side).
- 'Future development' implies in this thesis, scenarios constructed for the years 2008 (current), 2012 (short term) and 2020 (medium term).
- Canada is an enormous country having various geographical and climate conditions across the provinces. The focus of this study will be on the province of British Columbia (BC). This province has vast woody biomass supplies (largest in Canada) and several other factors making this area suitable for this research: substantial amount of residues from sawmills, still largely unutilized woody biomass at road sides and the current mountain pine beetle (MBP) devastation (NRCan/CFS, 2005).
- This study is conducted on a 'meso-level'. This implies that the area of BC will be divided into smaller regions (five regions have been selected based on existing lumber activities and sawmill residues surpluses (NRCan/CFS, 2005): Prince Rupert, Prince George, Cariboo, Kamloops and the US-border)[9] and assessed individually at feedstock potential, pre-treatment possibilities and trade implications. Results will provide detailed information of the future developments of biomass supply curves in BC. Although this study focuses at the province of BC alone, the methodology (as described in section 2.5) is composed in such a way that this study can be applied for other provinces of Canada as well.
- The supply chains will be assessed from harvesting biomass at the forest to an (international) terminal, and all the steps in between. This could be for international trade or domestic usage of the end-product. In this study, the final use of biomass as end-product is not part of the supply side and therefore is excluded from the analysis. For supply chain inventories and calculations, the most common pathways of forest practices for BC are applied in this study (further explained in Chapter 3). This demarcation has been made to reduce the complexity of accounting for various different practices, changing from location to location across BC. Moreover, the so described 'common pathway' covers most part of BC and therefore is taken here as being most applicable (MacDonald, 2007). In this study, this common harvesting method is assumed to keep in practice till at least 2020, although taking into account improvements for each step in the supply chain.
- This study focuses on main biomass pre-treatment technologies by using already widely available information from literature. Pre-treatment technologies taken into account in this study are: chipping, pelletization and ethanol production. End-products that will be taken into account are: pellets (current, short term, medium term) and ethanol (short term, medium term). Considering the limited amount of time, the scope of this study has been narrowed down to investigate only two end-products fabricated from the feedstock as mentioned in the previous section; an existing end-product and an end-product with great potential for the near future. Pellets are

[9] The Vancouver (coastal) area is not included in this study since this area has no significant sawmill residues surpluses. In addition, no extensive MPB outbreaks have been reported so far .

selected as end-product since the production of pellets is ongoing for more than a decade in BC and has grown into a mature pellet market. Substantial experience has been gained over this time period in the production process and supply chains. Moreover, pellets already are exported to Europe and the demand for pellets is growing increasingly (Melin, 2007).
Ethanol has been selected as second end-product even though this product (in this study 2nd generation: made of woody biomass) is not commercially available yet on large scale. However, high expectations regarding the future are there. In recent years, ethanol as a gasoline substitute, has been in high demand especially in the US.

- Several other end-products could have been selected here to investigate as well, regarding the utilization of the same feedstock sources. For instance, torrefied wood pellets or bio-oil. However, ethanol has been selected as future end-product since it has very different properties compared to pellets (solid vs. liquid). Furthermore, ethanol serves a different market (transportation fuel market) unlike torrefied wood or bio-oil (heating/co-firing market). This results into some fundamental differences in the supply chain of the two end-products. Ethanol has a very different production process incorporated, and transportation requires tanker vehicles, capable of storing liquids. Furthermore, the production process and scale of the ethanol production plants will have considerably different implications for feedstock requirements than pellet plants. These differences, as mentioned in the above, make this study look into the diversity of possibilities woody biomass has as feedstock in BC.
- Accordingly, the markets which will be taken into account in this research are: heating, co-firing and transportation fuel.
- Other influencing factors concerning biomass demand and supply side will be addressed as well; supply chain developments, competition in feedstock, policy and energy prices.

# 2. Theoretical Approach & Methodology

In this study the market potential of biomass in BC is assessed. Biomass is considered here as woody biomass derived directly or indirectly from the forest. A location specific inventory forms the foundation to map biomass potentials for BC. This inventory comprises a detailed overview of the supply chain typically characterized for BC. Moreover, local conditions and constraints will be dealt with in this study (for instance policy, competition and geographical constraints). This detailed view is combined with a broader demand view which covers the inventory in biomass end-product demand from regions outside of BC (US, EU and Asia). Together, those two views provide insight into how the biomass industry in BC could develop in the near future. The approaches and methods applied to conduct this study are addressed in this section.

Region specific data and information has been obtained from related scientific literature and reports from research institutes in BC have been scrutinized. Moreover, fieldtrips have been undertaken and interviews with experts have provided relevant information regarding this study (see also *References*).

## *2.1 Supply chains*

A supply chain model provides an overview of the different phases and physical steps in the process, from feedstock extraction till the production of the product and finally, the pathway to the end-user. In order to map the entire supply side, all the individual components in the chain should be included (regarding the scope of this thesis, the final step in the supply chain will be ‘transport to a (international) terminal’). After describing those components in terms of costs, mass flows and technical characteristics, pathways of the biomass supply chain can be constructed by connecting individual steps. This provides a clear picture of total costs and mass flows in the system. In Figure 1, common pathways of biomass supply chains for BC are depicted with help of expert knowledge and relevant literature (MacDonald, 2007). One should read this figure starting from the top, making decision steps on the way down. Possibilities in pathways created by decision steps form the main supply chains assessed in this thesis.

The focus of this study is at existing feedstock supply chains in BC and distinguishes the whole supply chain into two parts:

*Feedstock supply chain ‘till plant gate’*
→ Includes **harvesting**, **comminuting**[10] and **transportation** from source till production plant

*End-product supply chain ‘till (international) terminal’*
→ Includes **storage**, **processing** at plant and **transportation** from plant to (international) terminal

[10] Comminuting is the process of reducing the size of woody biomass; making chips.

This focus has been chosen to account for competition in feedstock with other industries and furthermore to be able to investigate an end-product, given certain feedstock prices.

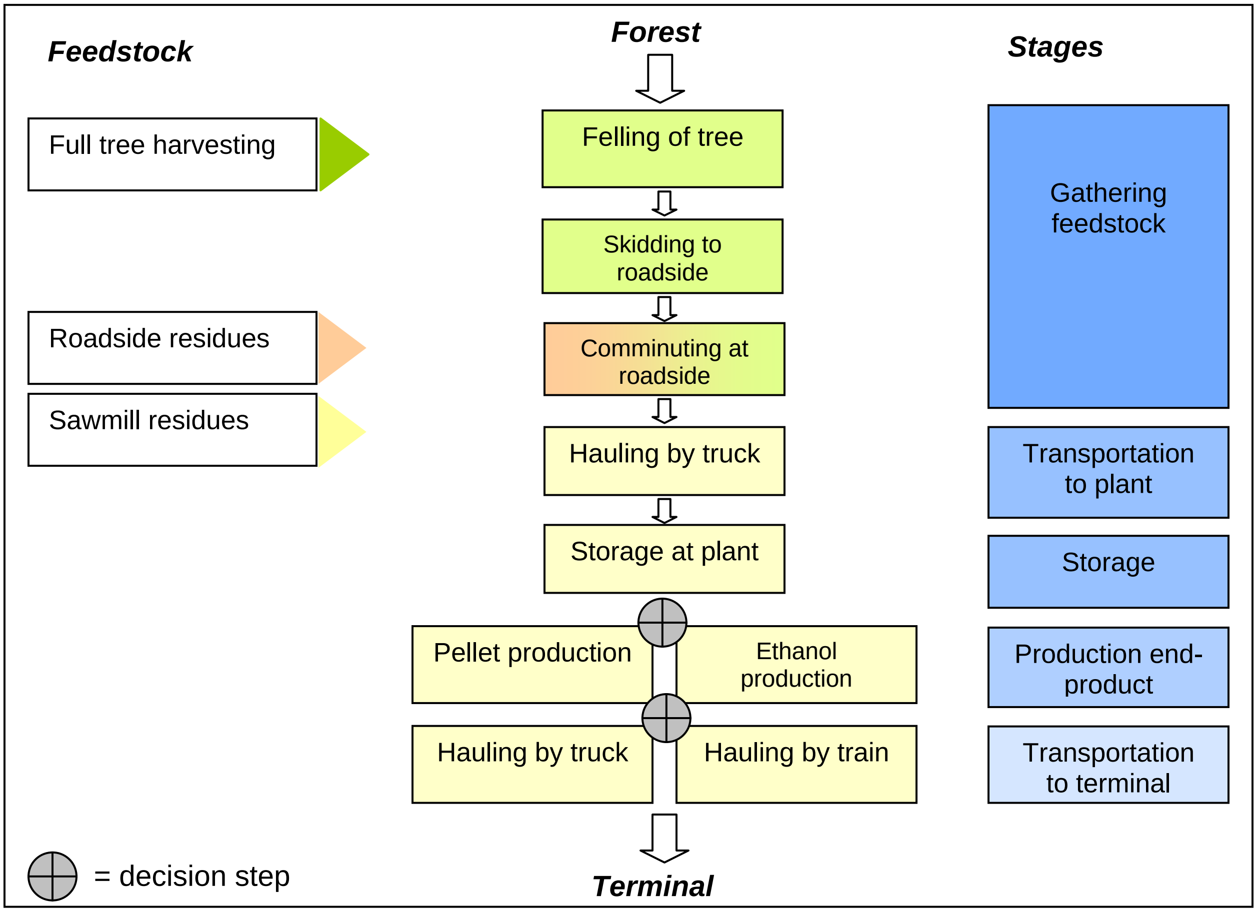


**Figure 1: supply chains woody biomass**

Depending on the source of feedstock used for an end-product, several processes could take place at the *gathering feedstock* stage. For instance, when using sawmill residues as feedstock, it is obvious that the trajectory through the *gathering feedstock phase* boxes is omitted; hence *transportation to plant* would be the first step.
A possible pathway could take place from *forest* to *terminal* as situated in Figure 2:

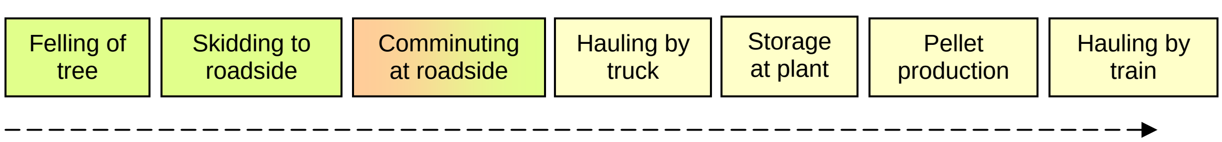


**Figure 2: supply chain whole tree harvesting and pellet production**

## 2.2 Cost supply curve

A cost supply curve is a tool that shows how costs of a product are connected to increasing quantities in supply. An increase in biomass feedstock demand inherently leads to gathering feedstock from longer distances. This results into higher transport costs at increasing production volume. Therefore, the curve is expected to rise continuously when production capacity increases. This effect is also recognized in other studies assessing biomass supply (Dam et al., 2005). An example of a cost supply curve is given in Figure 3, clearly presenting increasing marginal costs when enlarging the demand.

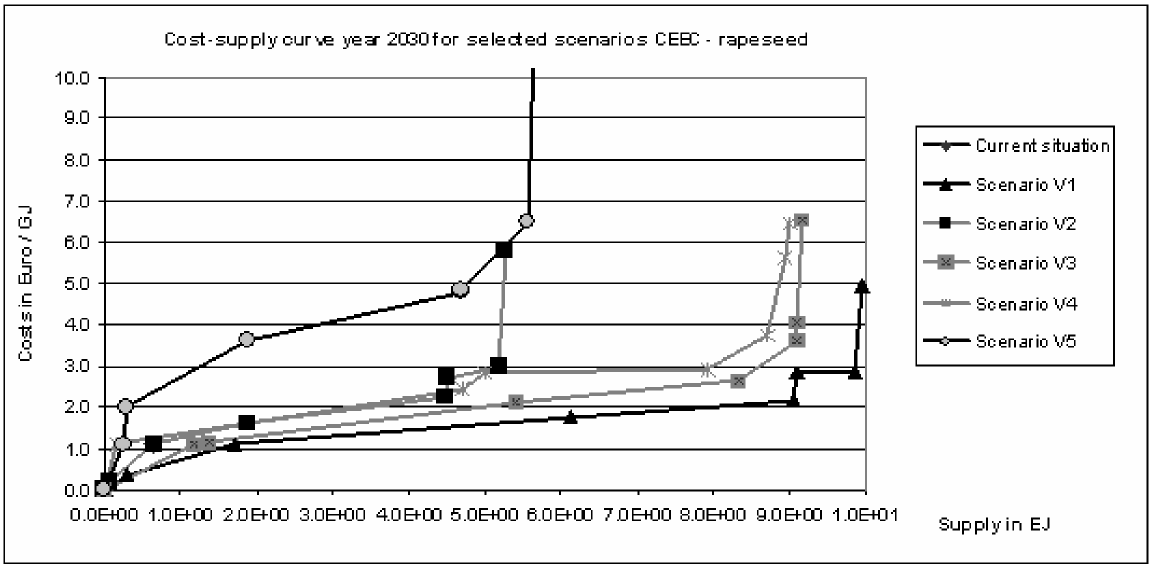


**Figure 3: cost supply curve for rapeseed produced in CEEC countries (Dam et al., 2005)**

In this study, cost supply curves play a key role in presenting outcomes for feedstock, pellets and ethanol potentials for BC. Comparisons between products and between production pathways can be shown in these curves.

Prerequisite for establishing cost-supply curves is a detailed set of specific costs data at a defined supply level. To mark out points in a graph, costs are defined for every step in the supply chain to indicate maximum feedstock supply potentials. Input data is acquired from on-site research, expert knowledge and literature studies.

## 2.3 Modeling feedstock and end-products potentials

Modeling the feedstock supply for BC first requires an inventory of the availability of biomass feedstock. This provides the hypothetical feedstock availability (sawmills residues, roadside residues, MPB killed trees) for every region within BC. Provincial databases on tree yields and mass flows across BC were consulted to find accurate information. However, a more realistic picture of biomass end-product possibilities in the near future requires an economic outlook that includes cost projections. Therefore, costs need to be defined regarding collection of feedstock and every single other step in the supply chain to finally come up with a total cost structure of a biomass end-product. To do so, BC's commonly used pathways from resource to end-user are defined. Pathways (i.e. supply chains) include average hauling distances per truck load to account for changes in costs when requiring more feedstock. Mass flows of feedstock and its characteristics (moisture content and density of products) are taken into account as well.

**Supply chain spreadsheet**

For this study, a customized supply chain spreadsheet has been constructed in Excel. This describes every step of the supply chain taken from source to end-product for BC in terms of mass flows and costs. The spreadsheet provides the option of decision steps to conduct mass flows to a particular end-product (in this study pellets or ethanol). A snapshot of the spreadsheet is provided in Appendix 2.

The spreadsheet works as follows (see Figure 4). First, a feedstock is selected (based on least costs) and the maximum volume is defined according to a selected feedstock scenario for a specific region. Next, depending on the selected feedstock and region a defined BC supply chain is chosen for in which mass flows and costs for every included step are assessed[11]. To calculate final costs for each end-product, the costs of every included step in the chain is aggregated from source till the terminal. This sequence of steps is repeated for a next unit of end-product until there is no more feedstock available. Costs of end-products tend to increase when transportation distances become larger at increasing feedstock demand. When a cheap feedstock is depleted, another subsequent lowest cost feedstock will be selected instead.

Compared to the Chains study of Hamelinck et al. (2005), this study focuses exclusively at one main supply chain, with three different feedstocks, each starting at a different stage in the chain, whereas Hamelinck et al. describes a large variety of chains from several locations in the world. These chains include mass flows, cost calculations, energy calculations and emission values. Moreover, the Chains model includes the final transport to the end-user, which is beyond the scope of this study. Furthermore, this study does not define energy numbers nor emission values. However, this study does include specific local conditions in costs and practices in BC. It also provides a range of cost when increasing the production volume (as in cost supply curves), which is not addressed in the Chains study (Hamelinck et al., 2005).

[11] A transportation step is included for every feedstock, but for instance using MPB trees as feedstock includes additional steps: felling of tree, skidding to roadside etc.

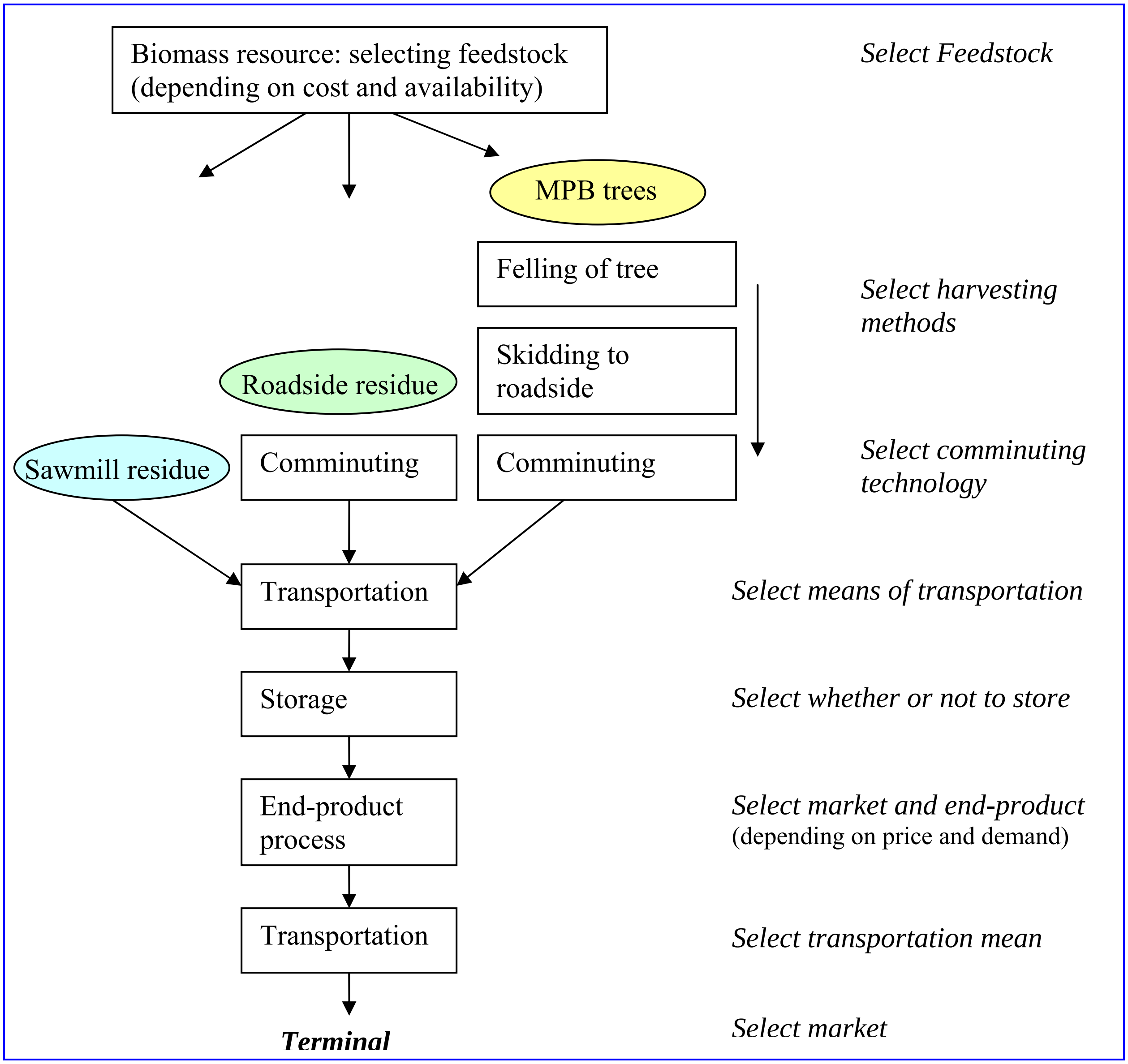

**Figure 4: running through the spreadsheet**

## Specific parameter description

In the spreadsheet, the availability and volumes of feedstock to be used for biomass end-products for each region is constrained to several influencing factors as described in terms of parameters. In the following section, the formulas applied for the spreadsheet are presented.

The sawmill residues volume is given by formula (1):

$$V_{sawmill} = [(V_{harv} * r_{sawm} * r_{resi}) - V_{used}] * r_{appl} * r_{biom} \quad (1)$$

Where $V_{sawmill}$ is the sawmill residues volume (in $m^3yr^{-1}$) dedicated to biomass end-products. A starting point is the annual harvesting volume $V_{harv}$ (in $m^3yr^{-1}$). From the total harvested volume a share is destined for sawmills given in a specified ratio ($r_{sawm}$ in %).

A ratio of the incoming volume in sawmills is converted into sawmill residues given by $r_{resi}$ (in %). A share of the sawmill residues is used for sawmill applications or being sold to other industries given by $V_{used}$ (in $m^3y^{-1}$). Due to differences in quality and characteristics (for instance bark content) of the sawmill residues only a part of this residue can be applied for biomass end-products, given by $r_{appl}$ (in %). To account for competition for this applicable sawmill residue a factor $r_{biom}$ is included representing the ratio (in %) of applicable sawmill residues destined for biomass end-products taken into account the demanded sawmill residues by other industries.

The roadside residues volume is given by formula (2):

$$V_{roadside} = V_{harv} * r_{left} * r_{biom} \qquad (2)$$

Where $V_{roadside}$ is the roadside residues volume (in $m^3yr^{-1}$) dedicated to biomass end-products. This volume is determined by multiplying the annual harvesting volume $V_{harv}$ (in $m^3yr^{-1}$) with the ratio of the tree (applicable part) left at the roadside (in %). Furthermore, competition in feedstock from other demanding industries is taken into account by the factor $r_{biom}$, given in % of total applicable volume roadside residues destined for biomass end-products alone.

The MPB killed trees volume is given by formula (3):

$$V_{MBP} = V_{kill} * r_{extr} * r_{avail} * r_{appl} * r_{biom} \qquad (3)$$

Where $V_{MBP}$ is the mountain pine beetle killed trees volume (in $m^3yr^{-1}$) dedicated to biomass end-products (in $m^3yr^{-1}$). The total volume of MPB killed trees is given by $V_{kill}$ (in $m^3$). The extraction rate is given by $r_{extr}$ (in %) and is defined as the annual supply volume with regard to the total available volume to account for a steady supply over a longer period of time. From this annual volume a certain part is made available by the government $r_{avail}$ (in %). A share of the tree volume may not be used due to reduced wood quality or bark content. Therefore, the usable share is given by $r_{appl}$ (in %). To account for competition for this applicable feedstock a ratio factor ($r_{biom}$) is included giving the percentage of the MPB trees volume destined for exclusively biomass end-products.

Feedstock costs are calculated by adding up the costs of every step in the supply chain (from source till plant gate), as stated in formulas (4), (5) and (6).

$$C_{sawmill} = C_{purch} + C_{load} + C_{trans} + C_{store} \qquad (4)$$

Where $C_{sawmill}$ are total costs for sawmill residues to 'plant gate'. This is a summation of cost to purchase the sawmill residues from a sawmill ($C_{purch}$), loading and unloading costs ($C_{load}$) transportation costs ($C_{trans}$) and storage costs ($C_{store}$). All cost components are given in \$/Odt delivered. No losses are accounted for due to short term storage.

$$C_{roadside} = [C_{com} + C_{load} + C_{trans} + C_{store}]/r_{loss} \qquad (5)$$

Where $C_{roadside}$ are total costs for roadside residues to 'plant gate'. This is an addition of comminuting costs ($C_{com}$), loading and unloading costs ($C_{load}$) transportation costs ($C_{trans}$) and storage costs ($C_{store}$). Due to long time storage of roadside residues, material losses occur at the plant site. Therefore, for every Odt of feedstock used in the production process, more than one Odt needs to be delivered at the plant. This is defined by $r_{loss}$ (in % remained). All cost components are given in \$/Odt delivered.

$C_{MPB} = [C_{harv} + C_{com} + C_{store} + C_{load} + C_{trans}]/r_{loss}$ (6)

Where $C_{MPB}$ are total costs for MPB killed trees to 'plant gate'. This is an addition of harvesting costs ($C_{harv}$), comminuting costs ($C_{com}$), loading and unloading costs ($C_{load}$) transportation costs ($C_{trans}$) and storage costs ($C_{store}$). Due to long time storage of MPB killed trees, material losses occur at the plant site which is defined by $r_{loss}$ (in % remained). All cost components are given in \$/Odt delivered.

Transport cost for sawmill residues remains the same regardless of the demanded volume since assumed in this study is that these residues are acquired from the same sawmill. Therefore a set cost component is selected for transportation of sawmill residues. For roadside residues and MPB killed trees transportation cost till plant gate are calculated by first estimating the transportation distance for every delivered feedstock volume[12]. Hence, the total transportation cost can be calculated by applying formula (7).

$C_{trans} = d_{pg} * C_{spec}$ (7)

Where, $C_{trans}$ is the transportation cost in \$/Odt delivered at the 'plant gate'. The one-way haul distance from source to 'plant gate' is given by $d_{pg}$ (in km) and $C_{spec}$ represent specific cost per traveled km (\$/tonnekm).

Calculating transportation costs of end-products to the terminal is applied by formula (8).

$C_{trans\_ter} = d_{ter} * C_{spec}$ (8)

Where $C_{trans\_ter}$ is the transportation cost is \$/Odt delivered at the terminal. The one-way haul distance for biomass end-products form plant to terminal is given by $d_{ter}$ in formula (8) (in km). $C_{spec}$ determines the specific cost per km for every Odt transported (\$/tonnekm) depending on the mean of transportation and influenced by system improvements.

Total costs for the production of end-products are presented the formulas (9) and (10).

$C_{total\_pel} = (C_{feed} / \eta_p) + C_{pellet} + C_{stor} + C_{trans\_ter}$ (9)

Where $C_{total\_pel}$ is the total cost of pellets delivered at the terminal (\$/Odt). This is a summation of feedstock costs ($C_{feed}$) divided by the production efficiency ($\eta_p$ in ratio), production costs of pellets $C_{pellet}$, storage costs $C_{stor}$ (in case of roadside residues or MPB killed trees as feedstock) and the transportation cost to the terminal ($C_{trans\_ter}$). All cost components are given in \$/Odt delivered.

$C_{total\_eth} = (C_{feed} / \eta_{eth}) + C_{eth} + C_{stor} + C_{trans\_ter})$ (10)

[12] In section 5.2 and Appendix 7, these steps are further elaborated.

Where $C_{total\_eth}$ is the total cost of ethanol delivered at the terminal ($/GJ). This is an addition of feedstock costs ($C_{feed}$) divided by the production efficiency[13] ($\eta_{eth}$ in ratio), production costs of ethanol $C_{ethanol}$, storage costs $C_{stor}$ (in case of roadside residues or MPB killed trees as feedstock) and the transportation cost to the terminal ($C_{trans\_ter}$). All cost components are given in $/GJ delivered. Converting cost components from $/Odt to $/GJ is done by taking into account the caloric values of the different materials.
Demand price figures are calculated by applying formula (11):

$$P_{ter} = P_{loc} - C_{trans\_fin} \qquad (11)$$

Where $P_{ter}$ is the price level at the terminal in BC (in $/GJ)[14]. This price is calculated by subtracting the final transport costs ($C_{trans\_final}$ in $/GJ) from the price at the market in the region where it is sold $P_{loc}$ (in $/GJ). Final transport signifies transport of the end-product from terminal in BC to final market (for instance, ocean freight transport when trading pellets to EU).

[13] Typically, in terms of energy content, more than one unit (e.g. 1 GJ) of feedstock is required to generate one unit of end-product (e.g. ethanol). Therefore, the conversion efficiency should be taken into account when calculating feedstock costs for production. The conversion efficiencies are mentioned in section 5.2.
[14] For pellets both $/GJ and $/Odt are used to express costs.

## 2.4 Scenario construction

Scenarios outline possible developments, made up by different input values for a series of storylines. An effective way of constructing scenarios is to select realistic upper and lower boundaries for main parameters influencing the model. This could result in a positive Max-scenarios and a negative Min-scenario.

A well known example of using scenarios as tool for analyzing future projections are the scenarios created by the IPCC (Faber et al., 2007). The IPCC distinguishes the scenarios (worldviews) A1, A2, B1 and B2, each having a certain perception of the world and a direction of possible developments. This allows policy makers to act according to certain perceived behavior in society and a desired state.

In this study, scenarios form the foundation for the final outcomes. First, a set of feedstock scenarios will provide an overview how, under certain conditions, feedstock availability (for biomass end-products e.g. pellets and ethanol) and costs could evolve from the current situation till 2020. On top of that, an end-product scenario can be placed, by using the outcomes of a selected feedstock scenario as input data in total cost calculations. A range of end-product scenarios will capture positive and negative developments in this industry (Max vs. Min scenarios). Characterizing main drivers for growth in the biomass industry will help constructing those different scenarios.

**Methodology for scenario construction**

By translating the (main) influencing factors into parameter values for each scenario (see also Chapter 5), a supply curve can be constructed representing feedstock costs and end-product costs. Cost-supply curves for ‘feedstock till plant gate’ exclusively, could look like the thin curves as presented in Figure 5.

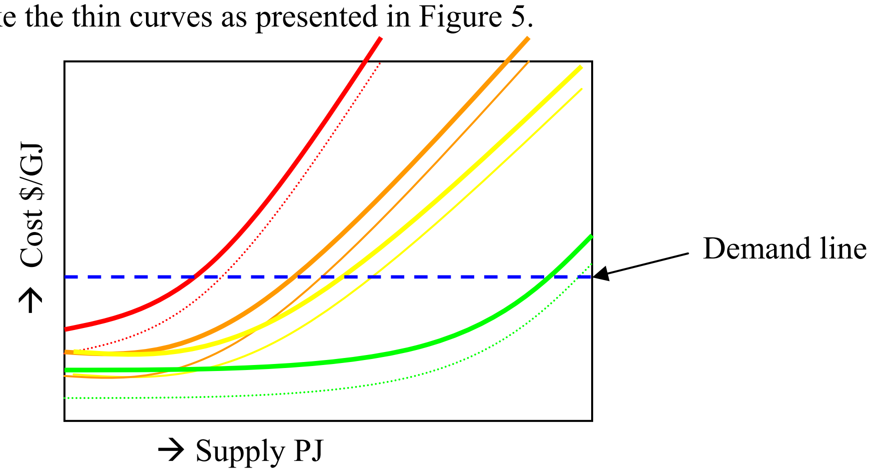


**Figure 5: cost supply curves including demand line**

To obtain the total costs for a product till international terminal, end-product production costs and transport costs (till terminal) should be added to feedstock costs as well. This results in the thick curves in Figure 5. All the lines have been lifted up in comparison to the original line (thin line). This is the case for both the Max-scenario and the Min-scenario, although the increase differs depending on the way the parameters are set for each scenario. Furthermore, from the scenario description, later on in this thesis, a demand line can be determined which represents the market price (dotted line) for either a Max or a Min scenario. This is done for the years 2008, 2012 and 2020, for both pellets and ethanol. The point in which the cost-supply curve and the demand line intersect represents the hypothetical market potential.

As stated in section 1.3, five regions were selected within BC to focus at. To account for the regional differences, cost-supply curves are constructed for each of the five selected regions, besides an overall cost-supply curve for the province as a whole. This has some implications for input values to run the model in accordance with the different regions. For instance, BC's feedstock availability is broken down into the feedstock availability per region. Similarly, transportation costs (to terminal) is region specific since different regions have different transportation distances to deliver their products to a terminal.

The total overview (cost-supply curve) for BC's potential represents an integration of all individual cost-supply curves from the selected regions in BC.

## 2.5 Step by step plan

This section describes in chronological order the steps to be taken to come up with final outcomes. The different steps involved in the supply and demand side assessments have separately being outlined in this study. Considering the scope of this research, steps 7 and 10 are of less importance and will be addressed in the discussion section.

***Supply side***

1. Select province

2. a. Define geographical constraints; how can this province be divided into regions with regard to forest resources, distances from forest to plants, lumber industry, distances from plants to cities/ terminals, transportation means, markets for biomass end-products.

   b. Define in the distinguished areas the volume per feedstock for biomass end-products. This gives an overview of the amount of sawmill residues, forest residues and biomass MPB-wood in the selected area at present until 2020. The volume per feedstock can be considered as the technical potential for this province which is the amount of feedstock that could be harvested using current forest practices in BC (Blok, 2006).

   c. Investigate existing data of currently used and most promising pre-treatment technologies and means of transportation subjected to the selected areas. This will provide present and future information of these technologies in terms of costs, efficiencies and capacity. At this stage, the focus is at the economic potential. Define and map supply chains for the biomass feedstock in the region including all different steps currently applied.

3. Define cost-supply curves for every feedstock 'till plant gate' in every selected area, to assess total feedstock costs. Included are possible harvest and pre-treatment operations in forest and transportation costs (including loading/unloading) of biomass to processing plant.

4. Map the competition for feedstock between the lumber industry and the biomass end-products industry. Additionally, present competition within biomass industry.

5. Constructing cost-supply curves which incorporate all costs of the individual components of end-products in the supply chain from forest to the (international) terminal.

The influences of BC's policy and its implications can be assessed for every single step at the supply side.

***Demand side***

6. Define present and future biomass markets demanding Canadian biomass:
   - Spatial division of markets: Domestic, US-market and overseas markets.
   - Types of biomass market: heating, co-firing and transportation fuel (ethanol).
   - Alternative product usage else than energy market.

7. Assess to what extent change in demand is caused by influencing factors.
   - Estimate price development other fuels.
   - Estimate overseas transportation development.
   - Estimate the willingness of regions to comply with emission reduction targets

8. Define demand curves for BC's biomass for the current and the future situation. Performing a quick policy scan from existing literature could facilitate in giving future prospects for biomass demand taken into account certain policy measures.

***Supply-Demand***

9. Link supply and demand to create final scenarios. This linkage is performed by considering the market price under different circumstances. The market price determines the equilibrium of future supply and demand. Scenarios that are generated in this step will incorporate (example in Figure 6):
   - Biomass fuel type
   - Biomass fuel quantity
   - Costs/GJ
   - Final market destination
   - Year of projection
   - Demand line

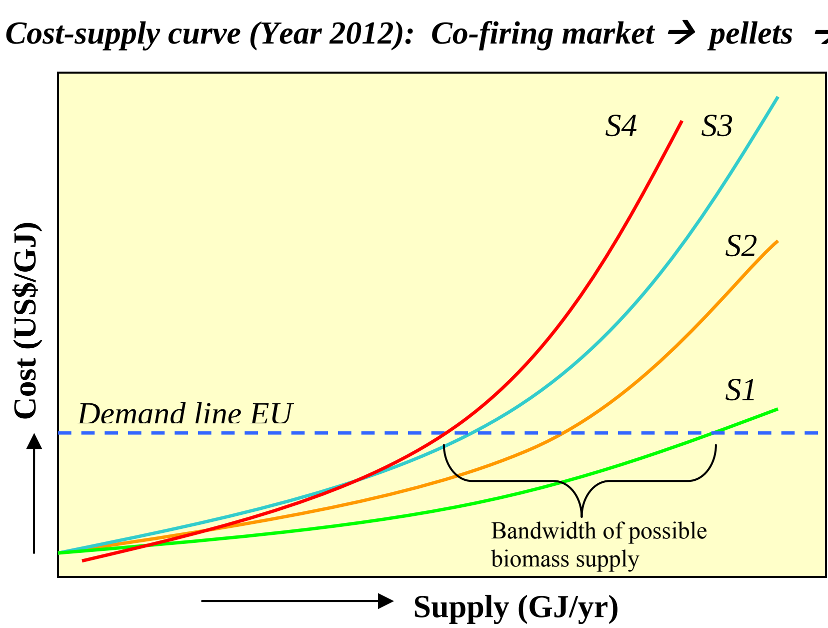


**Figure 6: cost supply curve pellets trade to the EU for co-firing market for the year 2012, including demand line.**

***Strategy definition phase***

10. a. Define strategies for the selected province according to potential biomass demand growth. Strategies should take into account when a change should be made to a more expensive biomass feedstock, and how many pre-treatment plants could be build to fulfill demand.

    b. Evaluate possibilities to extrapolate finding over Canada. This implies using the outcomes of this research to give rough estimations of all of Canada, without much more in depth research.

All steps are presented in a comprehensive overview in Figure 7.

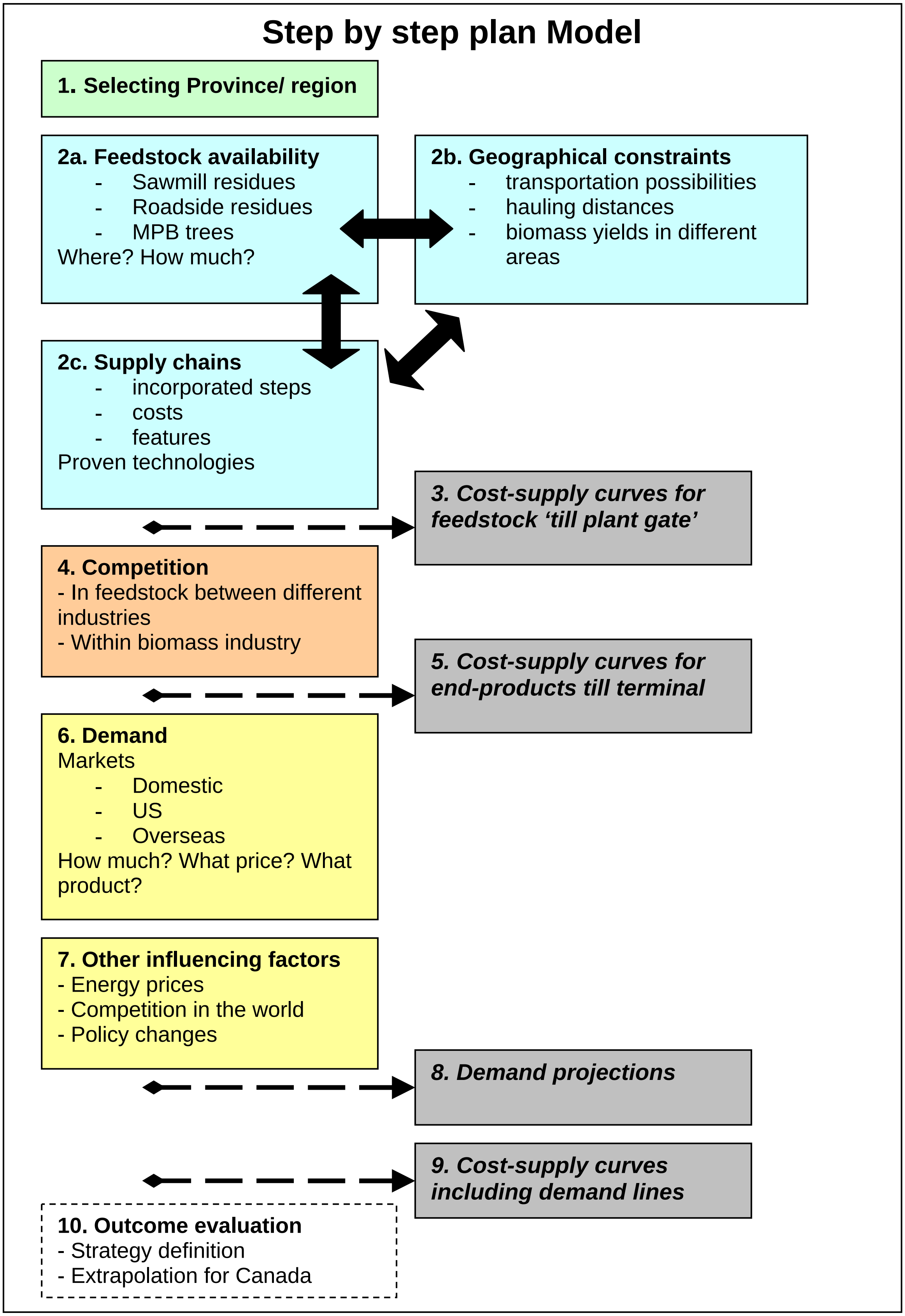


**Figure 7: methodology representation**

# 3. Case study: British Columbia (BC)

## BC background

British Columbia (BC) is located on the west side of Canada and has approximately 4.4 million inhabitants (Statcan, 2007a). The provincial capital of BC is Victoria; however the largest city is Vancouver. BC varies in landscapes and climates across the province, from rain forest to very dry areas. Most prominent is the widespread coverage of forests in every part of the province.

BC covers 94.6 million ha of land from which at least 60 million hectares is forest land and other wooded land[15]. The protected boreal forest comprises 35 million ha including 25 million ha of old-grown forests (+250 years on coast, 120-140 years in interior) covering a substantial area in BC (FII, 2007). The remaining part of forest land (ca. 25 million ha) is being used by the lumber industry (BCMOF, 2007a). This industry plays a significant role in BC's economy with an export of Can$13.7 billion (2005) of lumber products (mainly to the US market) and serving 79.700 direct jobs across the province (NRCan, 2006b).

Five forest regions have been selected to investigate in this study: Prince George, Prince Rupert, Cariboo, Kamloops and the US border region (Figure 8). This selection is based upon geographical constraints, logistical opportunities and feedstock availability. Furthermore, every region has a coverage rate which implies that a defined part of the selected region is taken into account in this study. This is further explained in section 5.1. In addition, Figure 8 shows the international terminals from where ocean freights can be loaded for international transport: Prince Rupert and North-Vancouver terminal.

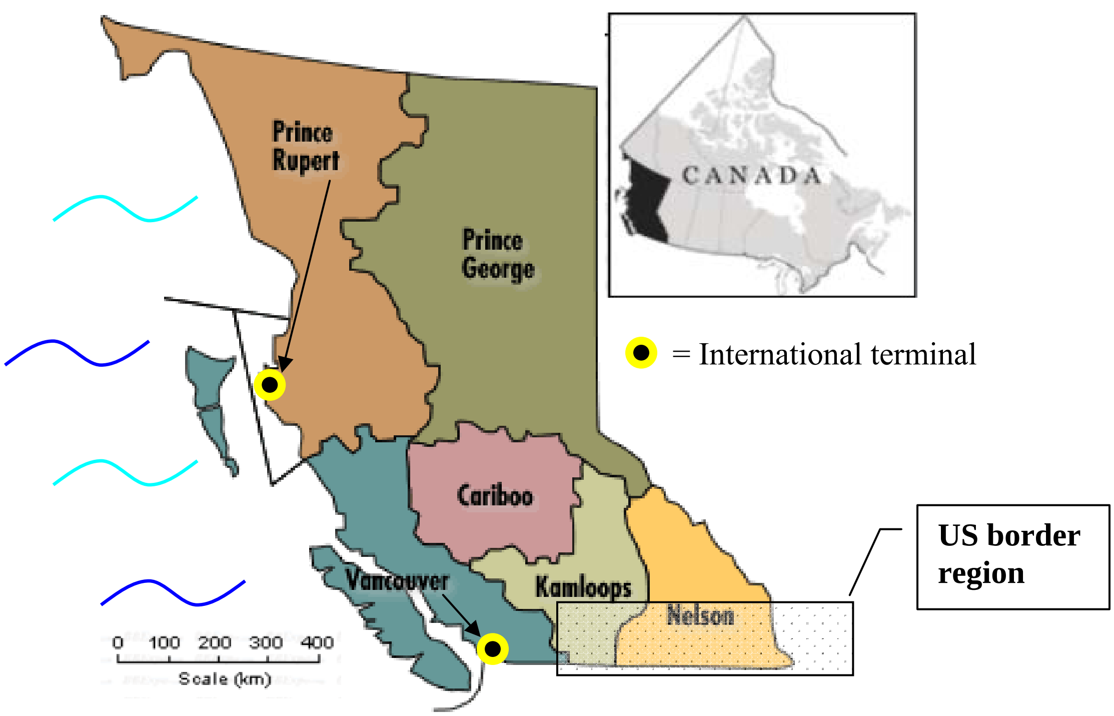


**Figure 8: map regions BC**

[15] In comparison, the land surface of the Netherlands is only 3.4 million hectares (VROM, 2007)

## Forest ownership British Columbia

The part of forest land being used by the lumber industry is divided into three different categories of ownership (BCMOF, 2007a).

- 96% of the harvestable forest land is owned by the province; the 'Crown land'
- 3% of the harvestable forest land is owned by private owners
- 1% of the harvestable forest land is owned differently (federal, community etc.)

The Crown land is governed by the provincial government on behalf of the citizens of BC. The intention of the province is to manage this land in a sustainable way both from the natural and socio-economic perspective. Regarding the Crown land, the province has determined a total of 6 forest regions comprising 37 Timber Supply Areas (TSA). The private owned forest areas comprise in total 34 different areas and are given a license to harvest trees, the Tree Farm License (TFL). Most of the TFL's are owned by companies from the lumber industry. In total, there are 71 management units in BC.

## Determining the Annual Allowable Cut (AAC)

AAC levels reflect the maximum volume of trees to be harvested each year in $m^3$/year. Since most of the feedstock for biomass end-product industries currently comes from sawmills, the inclusion of harvesting levels in this study is relevant. Every specific area in BC is assessed individually and given a permit for the AAC[16]. By adding up the individual AAC rates, the total AAC for BC can be calculated (Figure 9). At least once every five years an evaluation is undertaken to assess whether harvesting volumes need to be adjusted in each of the management units. Occurrences in BC, for instance tree diseases and bug infestations, will be considered when addressing the AAC. Over the last five years such adjustments took place as a result of the mountain pine beetle (MPB) epidemic, increasing the AAC in some regions considerably[17].

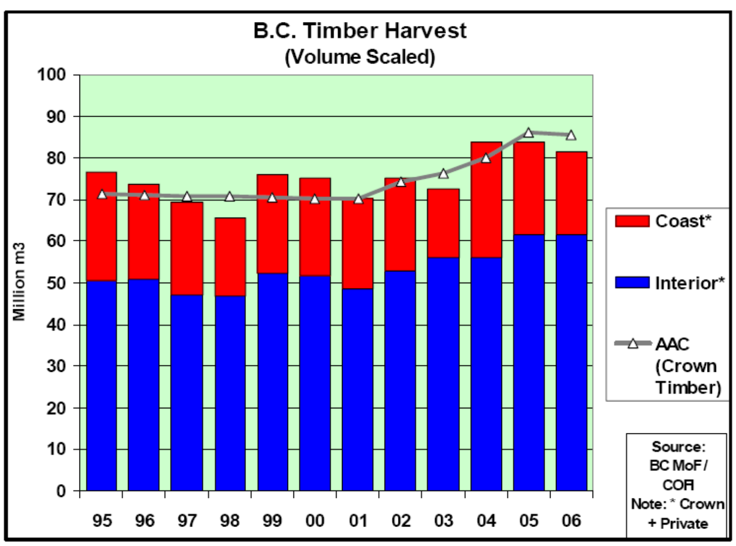


**Figure 9: AAC levels BC (International_wood_markets_group, 2006)**

[16] In 'the Forest Act', made by the Ministry of Forestry, guidelines are presented regarding sustainable forestry management together with harvesting levels for BC regions.
[17] As presented in the Rationale for AAC determination for the Meritt sub-region by Chief Forester

Assumption regarding future AAC levels for BC will facilitate in assessing the future sawmill residues availability. Moreover, future roadside residues availability can be determined, which comprises a share of the total harvested volume. However, the total AAC level is not always harvested by lumber companies, due to fluctuations in lumber prices. Current numbers for AAC in the main areas in BC are situated in Table **1**[18].

**Table 1: AAC levels of main areas in BC (BCMOF, 2007b)[19]**

| (in million $m^3$) | TSA | TFL | Total |
|---|---|---|---|
| *Prince George* | 23.59 | 2.27 | 25.86 |
| *Prince Rupert* | 7.42 | 1.01 | 8.43 |
| *Cariboo* | 13.05 | 0.87 | 13.92 |
| *Kamloops* | 6.37 | 0.49 | 6.86 |
| *US-border* | 8.25 | 1.71 | 9.96 |
| *Total* | 58.68 | 6.35 | 65.03 |

Furthermore, not all harvested trees are destined for the production of timber. Currently, 75.7 % of the AAC volume is used by sawmills, 17.8 % to other industries (e.g. paper industry) and 6.5 % is directly processed into chips for the pulp and paper industry (Melin, 2007).

Due to the mountain pine beetle (MPB) epidemic, the current AAC is higher than the average over the last 10 years. The expectation is that the current AAC level will stay at this high rate or slightly increase over the coming 5 to 10 years (BCMOF, 2007c). After 10 to 15 years most MPB trees will have been decayed to such extend that utilizing for any purpose is not possible anymore (MacDonald, 2006). Therefore, by that time, AAC levels most likely will be lowered (even lower than pre-outbreak levels after 2 decades) in order to restore the condition of the forest as depicted in Figure 10 (BCMOF, 2007c).

[18] Volumes for specific areas are presented in Appendix 3.

[19] Coverage area is not used here to define AAC rates but rather whole regions since logs are extracted from the entire region and brought to sawmills located within the defined coverage area. To avoid double counting, the US border includes total AAC from sub-region Okanagan (located in Kamloops region) and 70% of AAC from Merritt sub-region. 30% of the AAC from Merritt is allocated to Kamloops.

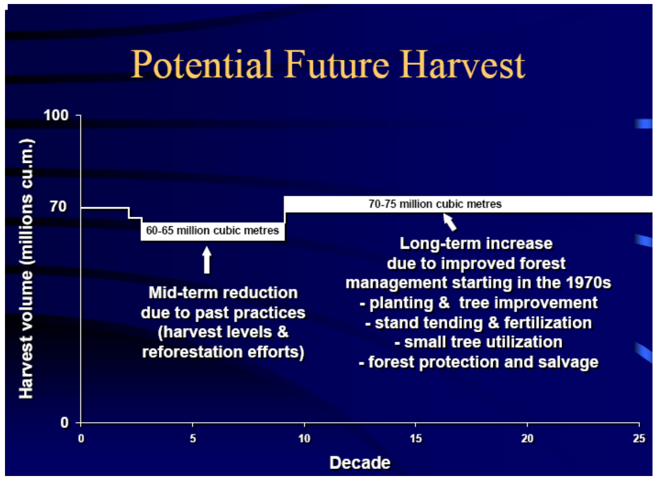

**Figure 10: Potential future harvest AAC levels for BC (Bogle, 2007)**

## *3.1 Feedstock assessment*

### Feedstock: Sawmill residues

During the process of lumber production in sawmills, a certain part of the incoming log is not sawn into merchantable lumber as a result of defects of the log or by delivery constraints. All parts of the initial log not leaving sawmills as lumber are called *sawmill residues*. In sawmills the log undergoes many stages to end up as commercial lumber, and in the process a proportion of the roundwood input log is converted into by-products such as sawmill residues.

In general, two kinds of sawmills can be distinguished; dimension lumber mills and stud mills. Dimension lumber mills produce boards in all kinds of sizes and grades, whereas stud mills produce one size of lumber with high speed capacity. A short step by step overview is given of the processes in a dimension lumber mill (Box 2).

***Description***

Logs enter the plant and are temporarily stored and dried in a log yard. Then, the logs go through a debarker which separates most bark from the log.
Next, the log enters the sawmill and is scanned by computerized lasers to guide cutting patterns for highest throughputs.
Then, the log is cut into a side board and a cant board. The boards are scanned again for their optimal pattern and sawn into lumber.
Trimming takes place and afterwards the boards are sorted into stacks comprising equal grade boards.
After that, the boards are kiln dried to get the right moisture content.
The boards then go through a planer and afterwards the boards are graded and trimmed again if necessary.
Finally the loads of lumber of the same grade are packed and stacked, and ready for transport to the consumer.

| ***Process*** | ***Residue*** |
|---|---|
| Log yard | |
| Debarking | → Bark |
| Scanning process | |
| Cut into boards | → Sawdust |
| Scanning process | |
| Sawn into lumber | → Sawdust<br>→ Chips |
| Grading and trimming | → Trim ends<br>→ Sawdust<br>before kiln dry process |
| Kiln drying | ------------------<br>after kiln dry process |
| Planing | → Shavings |
| Grading and trimming | → Trim ends<br>→ Sawdust |
| Packing | |
| | → Hog |

**Box 2: description of the sawmilling operation (Ackom et al., 2007)**

As described in Box 2, different kinds of sawmill residues can be distinguished; bark, sawdust, chips, trim ends and shavings. Residues produced before the kiln drying process all have about the same moisture content, similar to the incoming log. This typically is situated in the range of ~20% (MPB-killed trees) to ~50% (fresh trees) (Tampier et al., 2006). Residues obtained after the kiln drying operation have moisture contents in the range between 9% and 20%, depending on the required quality and the purpose. Throughout the whole process pieces of wood and other residues accidentally are discarded from the process. The mixture of different types of residue is called 'hog'.

## Lumber recovery

The volume of sawmill residues is subjected to several constraints. First, the residue volume is directly related to the throughput of logs in sawmills. Second, the quality of logs determines which share can be used for quality lumber and which share will end up as residue. Third, the Lumber Recovery Factor addresses the efficiency of the process in sawmills due to technical improvements (see Box 3). The given relationships are shown in Table 2.

**Lumber Recovery Factor**

Performances of individual sawmills are assessed by their Lumber Recovery Factor (LRF). This factor implies the amount of produced board feet meters (bfm) lumber per $m^3$ input of logs. Average lumber recovery rates for BC interior mills are at 274 Fbm/$m^3$ (Feet board meter per cubic meter) (for 2007) which implies a recovery of 48% of the log volume for dimension lumber sawmills producing commercial lumber. The trend in Figure 11 shows a steady increase in LRF over the past twenty years. However, a further continuous growth is unlikely due to the reduction in wood quality as a result of MPB infestations.

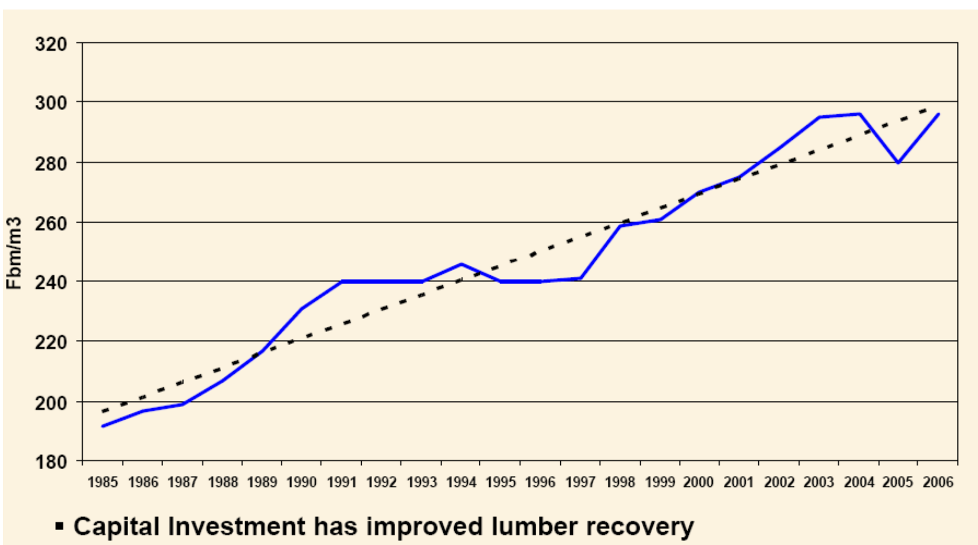


**Figure 11: Lumber Recovery Factor timeline (West Fraser timber, 2007)**

**Box 3: Lumber Recovery Factor explained**

**Table 2: relationships sawmill residue and constraints**

| *Constrain* | *Effect on residue volume* | *Current development* |
|---|---|---|
| Throughput of logs | Linear related; twice the amount of logs, twice the sawmill residue volume | AAC is temporarily at a high level due to MPB but it is forecasted to reduce in the near future |
| Quality of logs | Increased intake of poor log quality by sawmills subsequently result in higher amount of residues | MPB killed trees are currently being used for sawmilling |
| Lumber recovery rate | Higher recovery rates result in fewer sawmill residues | Technological developments for yield optimization and cost reduction are in progress |

The wood quality has lowered since the MPB outbreak, which affects the Lumber recovery factor (LRF). MPB wood is dryer and contains more cracks and flaws than normal wood, therefore blunting the saw teeth much faster. This all contributes to a larger proportion of produced sawmill residues per processed log[20]. At a certain rate of deterioration of trees by MPB, the logs cannot be converted into merchantable lumber anymore. Therefore, it could be the case that in the near future the increasingly deteriorating log quality might nullify technological improvements made in sawing practices, resulting in even lower LRF rates than currently proven (McFarlane, 2007). After the MPB outbreak, total sawmill residues is probable to decrease in volume as a result of future LRF gains and a reduction in roundwood log intake by mills.

Table 3 presents the amount of sawmill residues produced and consumed for BC (see also Appendix 4). A significant part of the total sawmill residues (mainly chips) goes directly to pulp and paper mills. The remaining part of the sawmill residues can be used by other industries. The surplus represents the still available volume for potential biomass end-products in the current situation

**Table 3: production, consumption and export of sawmill residues in BC 2008, further explained in Appendix 4 (NRCan/CFS, 2005)**

| **region** | AAC | part for sawmills[21] | total sawmill residues[22] | consumed 2008 | surplus 2008 |
|---|---|---|---|---|---|
| | Mill. m3 | Mill. m3 | Mill.Odt[23] | Mill. Odt | Mill. Odt |
| *Prince George* | 25.86 | 19.58 | 3.871 | 2.859 | 1.013 |
| *Prince Rupert* | 8.43 | 6.38 | 1.262 | 1.163 | 0.099 |
| *Cariboo* | 13.92 | 10.54 | 2.083 | 2.057 | 0.027 |
| *Kamloops* | 6.86 | 5.19 | 1.027 | 0.974 | 0.052 |
| *US border* | 9.96 | 7.54 | 1.490 | 1.415 | 0.076 |
| total | 65.03 | 49.23 | 9.733 | 8.467 | 1.266 |

## Bark

[20] Dryer logs have other implications too, namely: dryer sawmill residues (favorable for biomass industry), less time needed for kiln drying process (energy saving; potentially biomass saving).

[21] 75,7% of total AAC volume destined for sawmills (Melin, 2007)

[22] A LR of 48% is applied (McFarlane, 2007)

[23] 1 Odt wood = 2.63 $m^3$ wood (Stennes & McBeath, 2006)

The share of bark in the total volume of residues is important to look at, since not all bark residues are applicable for biomass end-products. An average of 55% of the total surplus (weight) consists of bark material (NRCan/CFS, 2005). A share of the bark is contaminated with sand and rocks which is not desired in the production of end-products. It is assumed that 10% of the total bark content is contaminated with sand and rocks (MacDonald, 2007). Bark has a high lignin content resulting in a higher energetic value (23.4 $GJ_{hhv}$/Odt) compared to whitewood (16-19 $GJ_{hhv}$/Odt). Combusting of bark generates higher ash concentrations compared to whitewood and ethanol production from bark is very difficult due to the high lignin values (Rhén et al., 2007).

## Feedstock: Roadside residues

Roadside residues are the non-merchantable parts of the tree to be found at the roadside in a whole-tree harvesting system and consist of tree tops, butts and limbs. Roadside residues piles are located on average 10-13 m from the road, providing enough space for loading machines and trucks during the operations. These piles typically have a rectangular shape or a teepee shape, and differ in size. The dispersion of residues and the shape of the piles is controlled by the operator of the dangle-head processor[24]. Quantities of roadside residues depend on the quality of trees (the ratio utilized for the lumber industry) tree yields in a certain harvesting cut block and the skills of the operator (MacDonald, 2006).

An estimated 14-55% of the standing tree ends up as roadside residue, with an average of 24% (MacDonald, 2006). The amount of roadside residues per hectare ranges between 22-144 Odt/ha depending on the density of trees located in a cut block. Other residues dispersed over the cut block range between 8-30 Odt/ha (average 20 Odt/ha). However, these residues are considered not economically to harvest as it takes to much time and effort to collect (MacDonald, 2006).

**Table 4: roadside residue volumes selected within coverage area for selected regions[25]**

| Region | million $m^3$/yr | million Odt/yr |
|---|---|---|
| | Total | Total |
| Prince George | 5.50 | 2.09 |
| Prince Rupert | 1.97 | 0.75 |
| Cariboo | 2.40 | 0.91 |
| Kamloops | 1.65 | 0.63 |
| US Border | 1.75 | 0.67 |
| **Total** | **13.26** | **5.05** |

Currently, roadside residues are not utilized by the lumber industry and are usually considered as waste. Therefore, piles are being burned in a controlled way to prevent forest fires and to clear the area, to make room for silviculture. Ironically, a part of the actual forest fires initiate due to burning roadside residue piles (Baxter, 2004).

**Biomass implications**

[24] Machine used to cut and delimb (remove branches) the stand.

[25] Based on AAC rates Appendix 3 and a roadside residue percentage of 24% of total harvest (1 Odt = 2.63 $m^3$ wood)

Roadside residues have gained interest from the biomass industry over the last few years as a result of projected scarcity in the availability of sawmill residues in the near future. Currently, sawmill residues are being used exclusively as feedstock which induces competition and the rise of feedstock prices. Therefore, it is valuable for the biomass industry to know which volume of roadside residues is available and how much will it cost to collect.

The main disadvantage of roadside residues in comparison to sawmill residues is the significant transportation distance. The required comminuting step also increases costs for this feedstock. However, if sawmill residues are not available anymore, roadside residues might become a potential candidate for the biomass industry since there is plenty of proven feedstock available.

**Bark**

The relatively high bark content (estimated at 20-25% of total weight (MacFarlane, 2007)) needs to be considered when assessing roadside residues as feedstock for biomass end-products. Debarking roadside residues is very difficult due to the small stem sizes and branches, and only could be achieved with expensive machinery (MacDonald, 2007).

**Thinnings**

This study does not include feedstock assessment regarding thinning, since this practice is not being applied in the main forestry sector in BC and is perceived as time consuming and not economically feasible (Koot, 2007). Therefore, no experience exists on large scale thinning practices. However, in other parts of the world (e.g. Finland) the thinnings derived from this operation do serve as biomass feedstock. At the same time thinning the forest is beneficial for the growth of the trees (Hakkila, 2003).

## Feedstock: Mountain Pine Beetle invested trees

Currently (2008) an immense part of the British Columbian forests is being devastated by the Mountain Pine Beetle. Mainly due to relatively warm winters, the highly susceptible forest lands (mono crop), the lack of predators and the slow response of governments made this epidemic spread along the interior rapidly (Stennes & McBeath, 2006). Currently, more than 500 million $m^3$ of the 1.8 billion $m^3$ of pine in BC has been killed and 8 million hectares have been infested already. In a substantial part of the interior almost every mature Lodgepole Pine tree is infested (Figure 12). Predictions indicate that by 2013, more than 80% of the total Logdepole Pine trees will be killed in the interior of BC (CFS/NRCan, 2007a).

The effects of this MPB infestation are enormous because a substantial part of the harvestable timber in the interior comprises the susceptible pine trees (Tampier et al., 2006). After the tree has been infested and killed, it dries out and deteriorates over the years. The economic value of logs decreases considerably over time and has major implications for the lumber industry. Within three years after mortality, most trees could still be utilized for the production of lumber, though with a reduced LRF. Depending on the regional climatic conditions killed trees can stand for another 3 to 15+ years before they eventually fall down and decay completely.

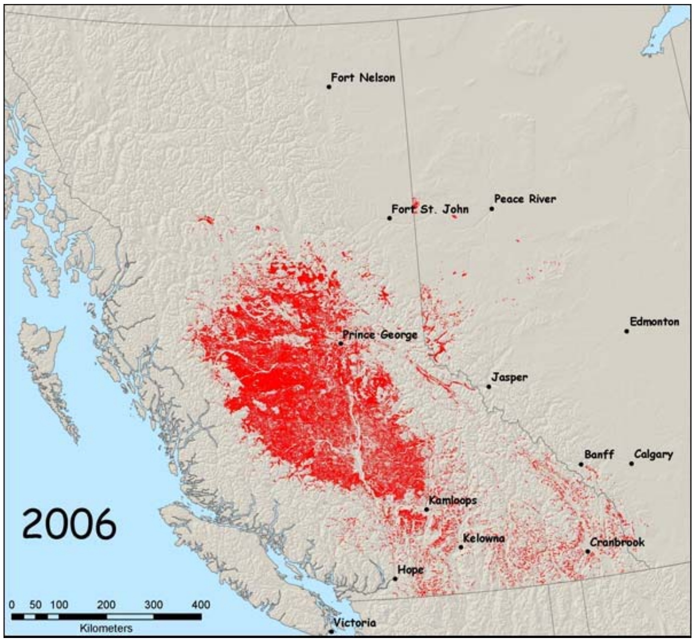

**Figure 12: affected areas by MPB, given in red (CFS/NRCan, 2007a)**

Other consequences of MPB infestation (CFS/NRCan, 2007b):

- Impacts on landscape aesthetics
- Changes to wildlife habitat
- Future reduction of Allowable Annual Cuts
- Potentially higher-intensity forest fires

In Figure 13, the course of the epidemic is situated (given in annual attacked trees in $m^3$) and the peak of the outbreak is shown for the year 2005. However, it takes several years (±4 years) before the tree is killed after being attacked by the MPB.

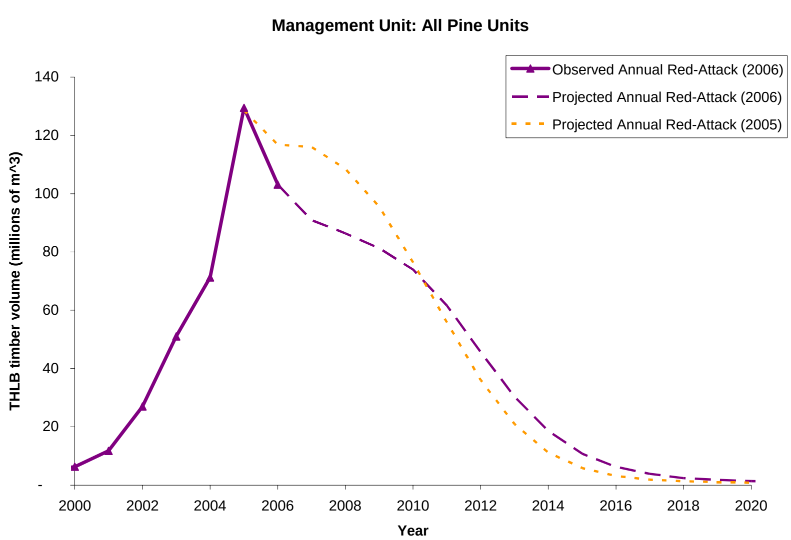


**Figure 13: MPB infestation projections, 2000-2020 (BCMOF, 2007c)**

The accumulation of dead trees results in a significant source of potential biomass feedstock. Table 5 shows the accumulated volumes of MPB killed trees for three different years. After the MPB attack, the killed trees will remain in the forest and slowly decays for at least several years. Therefore, the peak in accumulated volume is expected to be between 2010 and 2018 (see also Appendix 5).

**Table 5: current and expected MPB killed trees volumes (BCMOF, 2007d)**

| (in million $m^3$) | **2006** | **2010** | **2018** |
|---|---|---|---|
| *Prince George* | 145.3 | 276.2 | 284.8 |
| *Prince Rupert* | 72.9 | 109.9 | 113.6 |
| *Cariboo* | 147.7 | 172.2 | 175.5 |
| *Kamloops* | 33.1 | 77.4 | 81.0 |
| *US-border* | 15.2 | 77.6 | 92.6 |
| *Total* | 414.2 | 713.3 | 747.5 |

**Biomass implications**

Despite having severe impacts on the lumber industry and the province as a whole, the MPB infestation has created opportunities for the emerging biomass industry. The amount of killed trees is far beyond the capacity the lumber industry could possibly handle in the mills. Utilization of dead trees for energy recovery and biomass end-product applications has been proposed by BC's provincial government and other stakeholders (BCMOF, 2007e). Practically this would imply: whole tree harvesting, comminute the tree into chips, transport the chips to the plant. Due to the additional steps in the supply chain, total costs are higher compared to roadside residues and sawmill residues.

**Bark**

The bark content of MPB trees is estimated at 12% of the weight (MacFarlane, 2007) and should be considered when assessing the availability of this feedstock for end-products. A debarking process could be implemented before chipping takes place in case demanding industries do not accept bark.

## 3.2 *Logistic assessment*

### Harvesting practices

Two main methods of tree harvesting can be distinguished: *whole tree harvesting* and *cut-to-length harvesting*. However, the *whole tree harvesting* method is most applied for BC (Bradley, 2007). Furthermore, clear cut harvesting has been proven most efficient and cost effective. This implies cutting every single tree in a selected cut block, leaving this area as an open patch in the forest. The two methods of harvesting are explained below.

*Whole tree harvesting*
The feller-buncher cuts the tree and bunches the trees together. In some cases 'roundwood' is separated from 'non-merchantable trees' at the forest operation site. Next, the grapple-skidder grabs the bunch of trees and skids the trees from the forest to the roadside. At the roadside a dangle-head processor delimbs and tops the trees. The tops and the other residues are accumulated on a second pile, the so called 'roadside residues pile'. At the roadside the cleared log is loaded onto a truck by a log-loader and the log is hauled by truck to the sawmill.

*Cut to length harvesting*
In this case the harvester (machine) is doing three tasks subsequently. First, the tree is felled and delimbed. Whilst running over the log, the machine measures the diameter and at certain diameters, it cuts the log and separates the different parts from the tree. Typically, a pile of sawlogs, a pile of pulpwood and a pile of slash is produced. A forwarder carries the three different products separately to the roadside to be loaded onto trucks. When slash is brought to the roadside it is first being processed into chips at the roadside before loaded onto trucks (Gingras & Favreau, 1996; MacDonald, 2006).

A significant difference between the two harvesting systems is that piles of residues are created at different locations at the harvesting site. The whole tree harvesting system generates residues piles at the roadside whereas the cut-to-length system generates the piles in the forest. Therefore, when recovering the residues (the slash) in the cut-to-length system, an additional transportation step is required.

**Harvesting costs**
A cost structure of the harvesting of trees includes both the machinery and operators to do the actual harvesting. This also includes preliminary steps, overhead costs, regeneration steps and permit costs, which are mentioned in the section below.

– <u>Planning and layout</u>

Before the actual harvesting can take place the terrain has to be mapped. Field engineers will investigate the forest area with a Global Positioning System (GPS) and the cut block is marked and assessed on its geographical conditions. The stage of planning and layout is essential before starting harvesting operations but also implies additional costs (Dunham, 2004).

– Road construction

Most harvesting operations take place in remote areas, which requires road construction to haul logs from the cut block to sawmills. From main roads, new branches are constructed. Since on average forests have a life cycle of at least 60 years, small forest roads only have a one-season function. Costs for road construction are fairly high (Kumar et al., 2005).

– Silviculture

After the harvest has taken place, the company given the permit to harvest is also responsible for the regeneration of the forest. This is done by means of planting seedlings at the clear cut area (i.e. silviculture) and taking care of those until the new trees are mature enough to sustain themselves. This stage is called 'free growth' and typically takes 12 years to attain. The costs of silviculture are very high (Koot, 2007).

– Stumpage fee

The stumpage fee is an additional amount of money to be paid to the province of BC for every cubic meter harvested Crown land trees owned by the province. This fee is subject to change and is location specific. In the current situation, the province lowered the stumpage fee in certain parts of BC with large amounts of MPB-killed trees to provide an incentive for lumber industries to process the devastated trees first (Tampier et al., 2006).

**Harvesting window**

Harvesting practices are constrained by weather conditions. The heavy equipment and trucks have a severe impact on roads and the terrain. Therefore harvesting practices only can take place when the terrain is solid. This is the case during wintertime (December-February) when the ground is frozen and occasionally in specific regions during the summer after a long dry period (July-August). If temperatures in wintertime drop below -25˚F (-32˚C), operations are ceased due to engine and fuel constraints (Koot, 2007).

## Pre-treatment

### Comminuting

Comminuting refers to the sizing of wood in order to increase the density of the material, which reduces transportation costs. A common way to comminute wood is by using a chipper; stationary units and mobile units are applied. Currently, fresh chips are used for the pulp and paper industry. However chips could be a suitable feedstock for the biomass industry as well.

### Increasing density

The packing ratio describes the ratio of a pile that consists of wood (rather than air), to determine the net volume of woody biomass. Residues piles typically lie between 6%-25%, depending on the size of stems, tree species and method of stacking (Hardy, 1996). Softwood trees (e.g. logdepole pine) typically have densities of 400-500 kg/m$^3$. In case the packing ratio is 10%, the average density of a load woody biomass would be approximately 45 kg/m$^3$. Chipping will increase the packed woody biomass density from 45 kg/m$^3$ to 250-350 kg/m$^3$ (Badger & Fransham, 2005). This improvement in density makes this resource more economic to utilize. Figure 14 shows how differences in density affect transportation conditions.


**Figure 14: comparison same mass different densities (BBRG, 2007)**

### Composite Residue Logs (CRL's)

In Canada composite residue logs are still in experimental phase, whereas in Finland and Sweden this system is already in use for the last few years (P. Hakkila, 2006). This method of increasing the density is based upon compressing wood residues. A machine with a mechanical arm feeds slash into the compressor, forming the slash into a bundle, and tying it together with string. However, due to differences in harvesting practices, forest floor residues are less available in BC in comparison with, for instance, Finland (MacDonald, 2007).

### Cost structure

The costs included in the comminuting process are mainly the capital cost and the operation and maintenance costs. Running the chipper at full capacity is most economic, though, requires an optimized logistical plan to maintain a continuous feed of input and uptake of output.

## Transportation

A major part in the total cost of the biomass end-product is associated with transportation. Generally, transportation can be distinguished into two separated stages: transportation from feedstock source till production plant and transportation to deliver the end-product from plant to the consumer (or terminal). Currently, most pellet mills are supplied with feedstock from nearby located sawmills, which minimizes transportation till plant. However, using other feedstock will induce more transportation contingencies.

Typically, sawmills and biomass plants are located in forested areas, remote from end-users (>800km in many cases) making transport a logistical challenge. The three ways to transport biomass in BC are, by truck, by train, by barge (over inland waterways). Every option has its advantages and limitations elaborated below.

*Transport by Truck*

Trucks are the most commonly used transportation means in BC, mainly because of their flexible handling abilities. Trucks can reach almost every site, even areas with poor maintained roads and steep hills. Truck transport is expensive per km and truckloads are fairly small. In most biomass feedstock situations trucks transportation is only feasible within a range of 150 km (MacDonald, 2007). Beyond this distance, costs become too expensive and emissions from the truck offset a substantial part of the avoided $CO_2$ emissions, gained by using biomass as a fuel. Too much truck transport on roads could result in congestion, which reduces average speeds. Truck usage on forest roads is limited to the harvesting window, due to the road conditions.

*Transport by train*

A substantial part of the lumber industry in the interior of BC is connected to the railway network. The cost of transportation over long distances is relatively cheap in comparison to truck transport. Currently, every major pellet mill is connected to the railway network and is able to load rail cars with biomass end-products. At the terminal, the cars are unloaded and the end-product is stored. Fuel usage and emissions during transport of biomass are less compared to trucks and also loads can be very large. A disadvantage of train transportation is that existing railways determine potential places to establish new to build plants. The costs to expand railway systems are very high and very limited detour possibilities exist when there is maintenance on the tracks (Forrester et al., 2006).

*Transport by barges (over inland waterways)*

Unlike the coastal area, the interior of BC has limited availability of barge transportation. Only in areas where there is connection to waterways barge transportation is possible. The costs per traveled km are the least for barge transport compared to the other options, however loading and unloading takes time and increase costs substantially. In most cases new waterway systems need to be implemented. Moreover, weather conditions could make a year round supply difficult (Forrester et al., 2006). This study excludes inland waterway transportation due to limitations in waterways and a lack of established systems in the interior of BC.

Most lumber industries (61% of total in BC) are located in the interior of BC (BCMOF, 2006). Two sea terminals in BC provide possibilities to load biomass end-products into international freights; North Vancouver and Prince Rupert (Figure 15). In general, all the plants located southern of Quesnel are in proximity to the terminal in Vancouver. All the plants northern of Quesnel are closest to the terminal in Prince Rupert. However, the actual situation in the rail transport sector is more complex than mentioned here. In reality, contracts have been made between pellet producers and freight companies, based on lowest cost and security of supply, not distance. Moreover, some lumber and pellet companies own specific sections of an international terminal and will only go to this terminal to unload (Melin, 2007).


*Distances from end-product plant to international terminal:*

- Quesnel → North Vancouver 660 km
- Quesnel → Prince Rupert 850 km

**Figure 15: map terminals BC**

### Calculating transportation costs

Roadside residues and MPB trees involve transportation from forest till plant gate. Increased feedstock demand at a production plant requires larger feedstock extraction areas. In this study it is assumed that the first demanded feedstock volumes will be collected from nearby located areas. When this feedstock has been used, feedstock will be collected from more remote areas. At the same time, with expanding the collection area, a much larger volume becomes available (see Appendix 6). Costs calculations are further explained in section 5.2 and Appendix 6.

## Storage

In current practices sawmill residues is the only feedstock used for biomass end-products (Melin, 2007). Since most sawmills provide a continuous supply of sawmill residues, the need to store is limited. Most pellet mills have storage capacities to account for only several weeks of production. Short storage times reduce the chance for deterioration of sawmill residues considerably (Premium Pellet, 2007).

Due to the constrained harvesting window, roadside residues and MPB killed trees can only be extracted from the forest during specific months of the year (mainly December-February). Therefore, in order to run a production plant year round, long term storage is required (MacDonald, 2007). The main implications for long term storage are losses in biomass through decay and a reduction in quality of the chips. Moreover, the risk of self-ignition of chip piled must be considered. However, storage could also be beneficial in terms of reducing the moisture content when stored under coverage material (Melin, 2007).

Fungi growth is the main cause of heat development and decay of the wood. Material losses for fresh pine trees can reach up to 20% per year for small chips in uncovered piles without ventilation (Scholtz et al., 2005). However, when ventilation of air is applied together with rain protecting coverage, material losses could be reduced to less than 1% a month (Jirjis, 1995).

Storage of chips adds to the total costs in terms of monitoring costs and construction costs for preparing a large terrain to stockpile chips (Suurs, 2002).

## 3.3 Conversion technologies to end-products

In this study, two biomass end-products have been selected to investigate: pellets and ethanol. This section describes the production process and characteristics of the two products.

### Pellet production

Sawdust and shavings are hammer milled, mixed and dried until the feedstock mixture has the right size and moisture content (ca. 9%) before being converted into pellets. In this pelletizing process the woody particles are heated and compressed through a dice into small cylindrical shapes (moisture content drops to 4-6%). The lignin, a natural compound of wood, forms the glue-like composition on the outside of the pellet. After that, the pellets are cooled, screened and monitored on their quality (higher heating value and moisture content) before loaded into train cars (Premium Pellet, 2007).

Pellet plants prefer feedstock of low moisture content which saves energy required for the drying process. Several pellet mills use a portion of their purchased sawdust to fuel their heaters, whereas other mills use natural gas. This share could be in the range of 10-15% of the total purchased sawmill residues. Typical conversion efficiencies for pellet production is 86.5%. This implies that 86.5% of the incoming feedstock (in Odt) is converted into pellets and the remaining part used for the drying process. The pelletizer is powered by electricity from the grid[26]. Currently, it is still too costly to build an installation that provides power and heat for the pelletizing process at the same time (Premium Pellet, 2007). Several other developments are assumed to take place in the near future, for instance, the steam explosion method to increase the density of pellets, which increases the density of pellets to significantly (Melin, 2007).

Contracts are made between sawmills and pellet mills for feedstock trade. Since sawmill residues are perceived as 'waste streams', sawmills are glad to sell these residues for a low price to pellet mills rather than burn it in beehive burners. Sawmill and shavings currently (2008) can be purchased for approximately \$12/Odt (Premium Pellet, 2007).

**Bark pellets**

Bark could become a potential feedstock for pellet production when (whitewood) sawmill residues become scarce. Theoretically, pellets could be produced from 100% bark. However, in practice bark pellets (>20% bark content) tend to break easily and the forming of dust could create problems in handling the product (Melin, 2007). Co-firing industries (based on coal) should not have problems in dealing with high ash-contents of bark material since the combustion of coal generates much higher ash contents than bark. Bark pellets for residential purposes (e.g. stoves) are less appropriate regarding the high ash contents (Melin, 2007).

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[26] Approximately 0,54 GJ electricity is required per Odt pellets (Bradley, 2006).

## Ethanol production

Concerning the scope of this thesis, the assessment of ethanol potentials is constrained to 2nd generation ethanol production. This refers to the process of ethanol production based on ligno-cellulosic biomass (woody biomass).

A large part of woody biomass consists of ligno-cellulosic molecules, providing strength to the plant or tree. This ligno-cellulose is a combination of cellulose, hemicellulose and lignin with a typical distribution for softwood of respectively 44%, 22% and 28%. Cellulose consists of C6 glucose strands whereas hemicellulose comprises many different glucose compounds (a.o. C6 and C5). Lignin can not be used for ethanol production itself but instead could be used for electricity or steam generation at the plant site. Moreover, lignin could be sold as co-product[27] which help this technology to become economically feasible (Mabee, 2006).

Generally, two 'platforms' can be distinguished regarding the production of ethanol from biomass (see also Appendix 8). The first platform is based on enzymatic processes in which biomass is broken down into parts by enzymatic hydrolysis and subsequently fermentation takes place. The second platform is the thermo-chemical platform in which high temperatures force the biomass components to fall apart. Exclusively the enzymatic pathway will be elaborated in this study (Mabee, 2006).

### Enzymatic platform

*Pretreatment*

First, an increase of the surface area of the feedstock is required in order to facilitate the enzymatic hydrolyses process in the subsequent step (Figure 16). This is achieved by removing or loosening the lignin in biomass resulting in the release of individual fibers into its main components; cellulose, hemicellulose and lignin. Several techniques are currently being investigated based on performance and efficiencies including steam explosion, acid treatments and alkaline treatments (Mabee, 2006).

*Hydrolysis*

The next step is hydrolysis, which basically implies the breakdown of larger cellulose compounds into its carbohydrate components (cellulose C6 sugars/ a.o. hemicellulose C5 + C6 sugars). This is accomplished by an enzyme called cellulose, produced by fungi.

*Fermentation*

The C6 sugars are easy to ferment into ethanol by ordinary yeast. The C5 sugars derived from hemicellulose, however, cannot be converted into ethanol by this type of yeast. Therefore, a new type of yeast is being developed which is able to ferment this C5 glucose strand. In this stage of the process other end-products could be made by the use of reactive matter, like bacteria.

After fermentation, a purification and separation step is undertaken to separate the produced ethanol from other final products.

[27] Lignin could be used for the production of dispersing agents, animal feed binders, concrete additives, drilling mud additives and soil stabilizers (Pan et al., 2004).

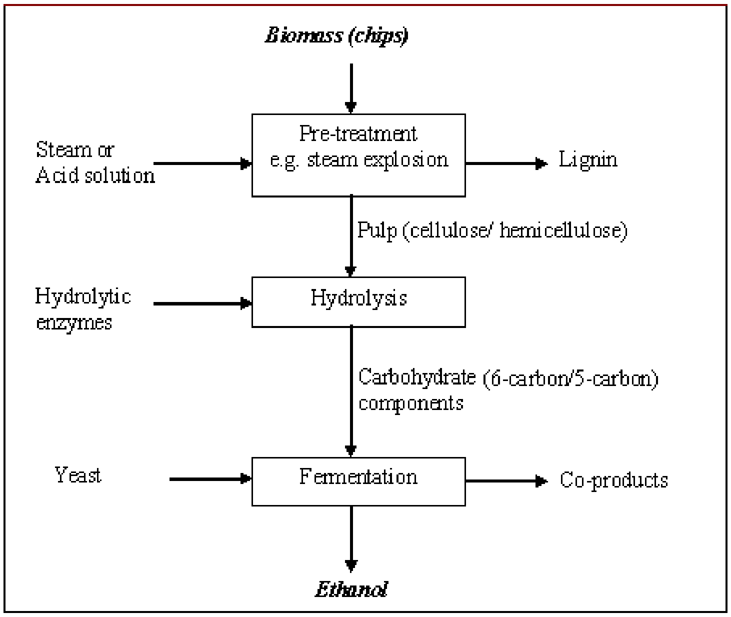


**Figure 16: ethanol production process**

## Feedstock

Clean whitewood chips (i.e. without bark) from whole tree harvesting and from sawmills are most preferred to use as feedstock for ethanol production (Mabee, 2006). The moisture content should not be too low in order to let the wood components fall apart easier and the size of chips is suitable for this process. Roadside residues consist of small sized wood and contain parenchyma cells which are currently not well suited for ethanol production (Mabee, 2006). Currently, especially MPB killed trees have a great potential to be used for ethanol production regarding the extensive availability. However, the bark volume should be excluded from the total MPB killed trees volume. In the long term short rotation trees (e.g. hybrid willows) could secure a future biomass feedstock supply for ethanol production (Melin, 2007).

## Conversion efficiencies

In Table 6, the efficiencies of the several conversion processes are presented. *Wood to ethanol* represents the process deduced from the enzymatic platform. The lower ranges are the currently achieved efficiencies in laboratories (small-scale) whereas the higher range numbers refer to the mid term (2020) prospects.

**Table 6: ethanol conversion efficiencies**

| | **Avg. energy recovered** *(GJ/Odt wood)* |
|---|---|
| *Wood-to-ethanol* | 2.6 - 6.4 |
| *Syngas-to-ethanol* | 3.1 |
| *Fischer-Tropsch fuels* | 2.9 - 7.6 |

**(Hahn-Hagerdal et al., 2007; Mabee, 2006; Tijmensen et al., 2002)**

## 3.4 Competition for feedstock

### Markets demanding feedstock

Defining the different markets is required to gain knowledge about the competition of biomass feedstock, prices and end-product demand. The following specific biomass demanding markets are included in this assessment: BC market, US-market and the outside North-America market (Europe and Asia). It is anticipated that this will facilitate decision making processes in recommending location specific expectations in future growth of biomass demand.

Figure 17 shows how markets are interconnected. There is competition in feedstock in the orange surface area between the lumber industry on the left side and the biomass industry on the right side. Furthermore, there is competition within the biomass industry situated in the yellow surface area (lower right side). This means, for instance, that pellet manufacturers are competing with ethanol producers for feedstock. The red dashed line implies the policy regarding both demand for feedstock, development in industries and resources availability.

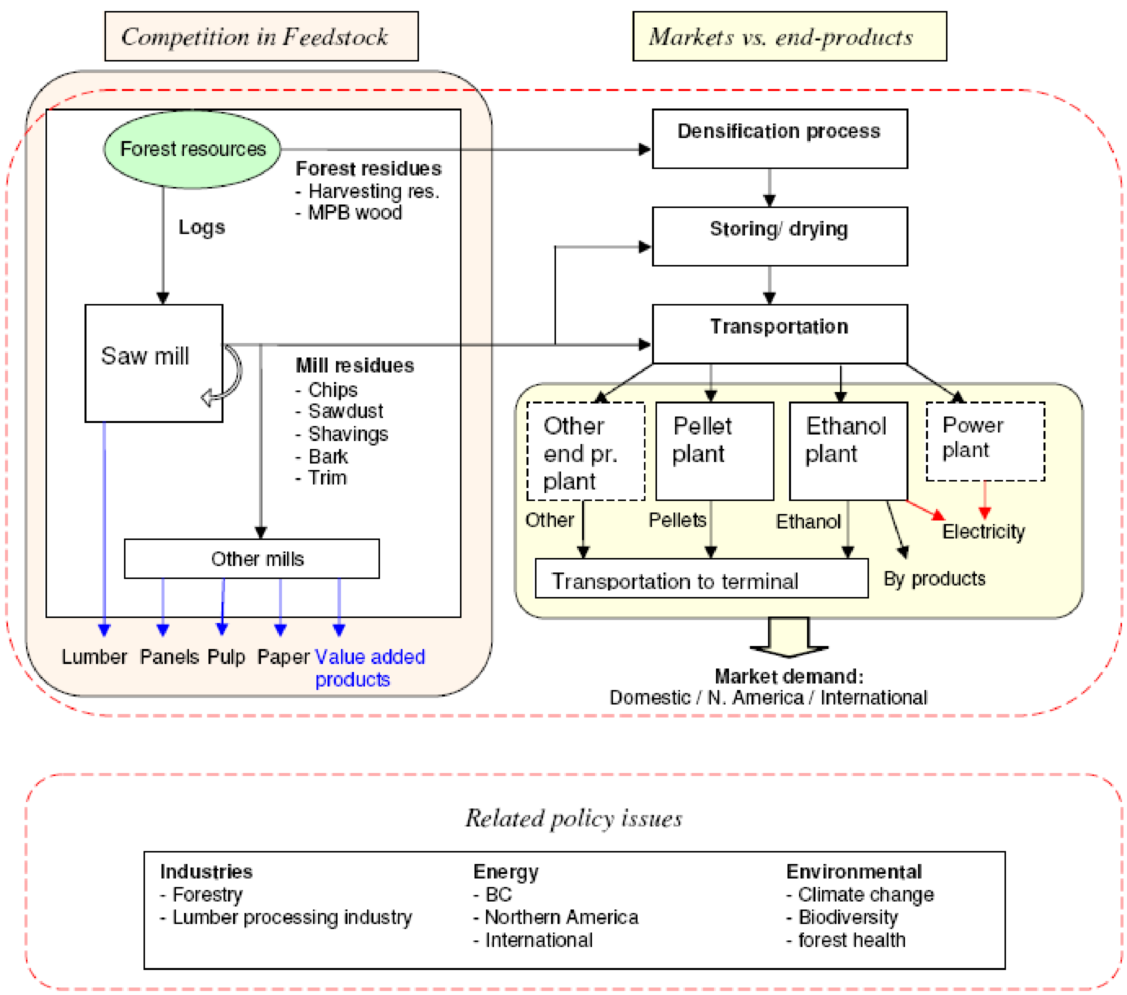


**Figure 17: biomass supply chain including competition (Ackom & McFarlane, 2007)**

**Competition in fiber**

An extensive lumber (forest product) industry has been established in BC over the last century. Currently a diversified range of products is manufactured; a.o. dimension lumber, panels, pulp & paper, shakes and shingles and other biomass products. One can distinguish industries utilizing virgin forest resources, from industries using sawmill residues as main feedstock. Driven by increasing energy (natural gas) prices, increasingly sawmills use a share of their residues to fire their kilns to dry lumber, mostly chips and sawdust. Figure 18 displays the main industries in BC in which pellets are embodied by 'other products'. The red numbers represent changes in material flows with regard to the year 2007 compared to the 2005 situation.

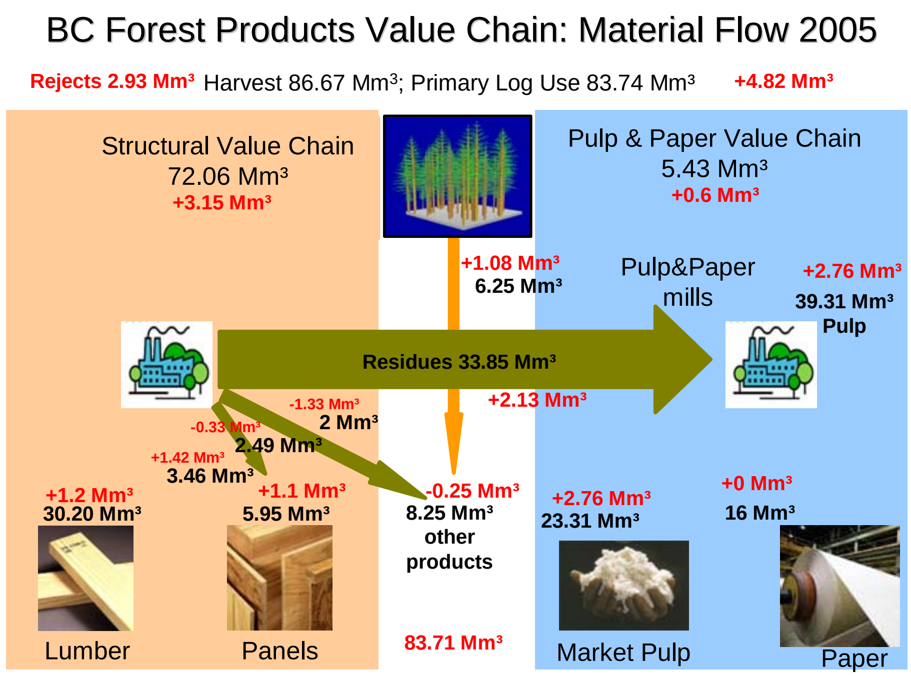


**Figure 18: competition in feedstock BC (Ackom et al., 2007)**

Considering the sawmill residues as finite, competition in feedstock will occur when demanding industries start to grow and increase their feedstock demand. Therefore, in order to assess the future sawmill residue potential for biomass, it is valuable to consider possible developments of various industries as well (Table 7 & Appendix 9).

**Table 7: drivers for other industries**

| Industry | Requiring what feedstock | Main driver | Where? |
|---|---|---|---|
| *Timber industry* | Logs from forest | Housing market<br>Price of lumber | US, Japan<br>(potential China) |
| *Panels* | sawdust, chips, shavings | Housing market | US, Japan<br>(potential China) |
| *Pulp & Paper* | Clean chips, sawdust from sawmills but also from forest | Paper and packaging markets linked to GDP growth | BC, US |
| *Biomass end-products* | Sawdust, shavings (currently) | Energy targets | Europe |
| *Energy industry (co-generation plant)* | bark, sawdust, chips, hog | Energy targets | BC |

**Biomass implications**

Currently the biomass end-product industry completely relies on sawmills providing them cheap sawmill residues. Other kinds of feedstock, for instance harvesting residues, are exceedingly expensive, and at this time not economically feasible to utilize. At present, sawmills are still producing enough sawmill residues to meet the demand from the different mentioned industries. However, in the case the biomass end-product industry would expand, the demand for feedstock will also grow. In this situation, in which several industries require the same kind of residue, competition is inevitable. Competition will increase the price of residues, which affects the total costs of end-products for all the before mentioned industries also.

Future expectations in feedstock demand could be made by analysing trends in the different industries. However, there are some influencing factors which are hard to take into account, for instance future economic growth. Ranges in future expectations regarding demand are translated into scenarios elaborated in Chapter 5.

## 3.5 End-product demand

Biomass demand is directly related to biomass supply. Therefore, in order to assess the volume of biomass end-product for potential trade in the near future it is essential to have an understanding of current markets and near future demand projections. For every market, the current situation and the underlying assumptions of the demand projections are discussed in the section below. Future market projections are elaborated in Chapter 5.

**Pellet markets**

The BC pellet market is very limited due to the widely available alternative energy sources. However, emission reduction targets gain interest in the provincial government and economic growth induces an increase in energy demand as well. Unlike BC, the US has to deal with a shortage in domestic energy sources to meet the growing energy demand. The US has not ratified the Kyoto agreements and therefore is not in particular focusing on more expensive energy sources (e.g. biomass options). Similar to the US, Asia has to deal with shortages in domestic energy supply, but also does not prioritize the emission reduction issue. Therefore, biomass demand is expected to be low in these regions since prices of biomass options are currently higher than alternative energy sources (e.g. coal).

Currently (2008), pellet consumption in the EU is growing exponentially due to favorable policy conditions, high heating oil prices and the willingness to comply with Kyoto targets (Figure 19). The EU is by far the biggest buyer of BC pellets in the current situation but also in the projected situation (Swaan, 2006). Therefore, this study focuses at the EU pellet demand.

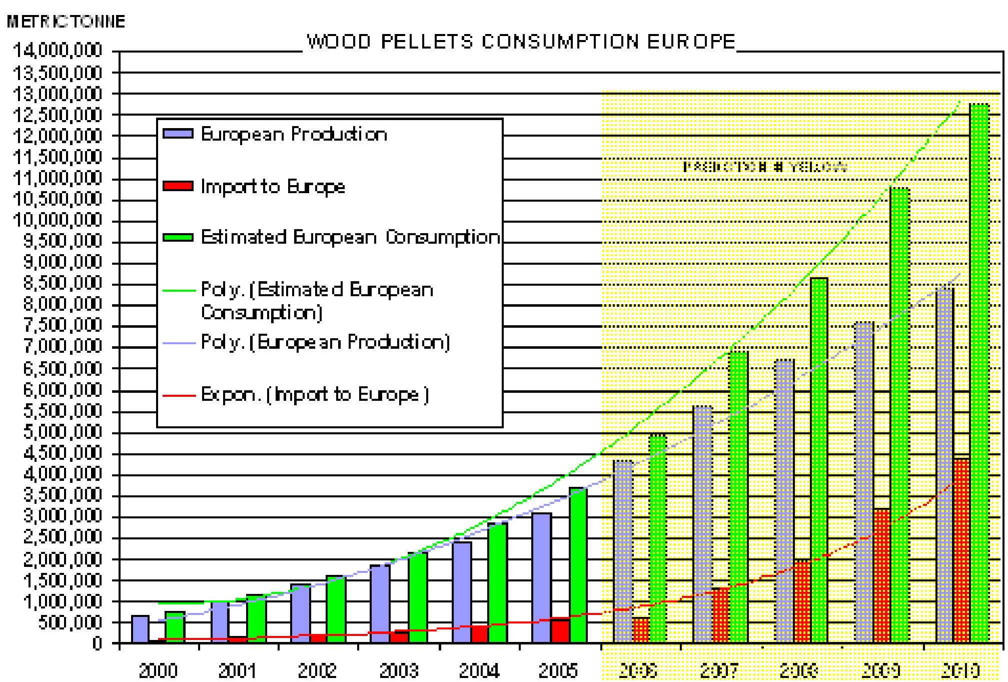


**Figure 19: wood pellets consumption Europe and projection consumption for 2006-2010 in shaded area (Melin, 2006).**

**Ethanol markets**

Ethanol demand, as a transportation fuel, is related to the consumption growth (GDP growth, which leads to an increase in transportation (Mantzos et al., 2003)) and the ratio of ethanol in the gasoline mixture. The latter is strongly driven by governmental policy aiming at the reduction of greenhouse gas emissions and addressing the energy security issue. Production costs of ethanol without subsidy are currently considerably higher compared to gasoline. Hence, ethanol in a free market would not lead to an increase in demand. Thus, demand projections should be based upon consumption growth and subjected policy.

This study distinguishes three different markets for ethanol; BC market, US market and EU market. These markets will be explained in the below. Trade will occur when parts of the world cannot produce sufficient ethanol to cover their own demand. Geographical constraints could induce trade, for instance regarding the situation of the EU which is unable to fulfill biofuel needs in the near future by itself.

**US market**

The US ethanol market has continued to expand rapidly over the last 5 years (Walter et al., 2007). Due to substantial governmental subsidies plants are increasingly being built to produce first generation ethanol. Furthermore, the government has set targets to increase the ratio of ethanol in blended gasoline. For 2006 a target of 2.86% ethanol as ratio in gasoline blends was set. For the same year, the US produced approximately 16.2 Giga Liter (GL) and the US government has set a new target of 28,4 GL to be used in gasoline blends by 2012 (Szklo et al., 2007). An important reason for the US government to stimulate ethanol production is to reduce the dependency of foreign energy sources derived from unstable regions in the world. Ethanol is a potential substitute for gasoline which constrains the fuel outlooks to gasoline only. Figure 20 depicts the expected gasoline consumption for the US showing a steady growth in consumption.

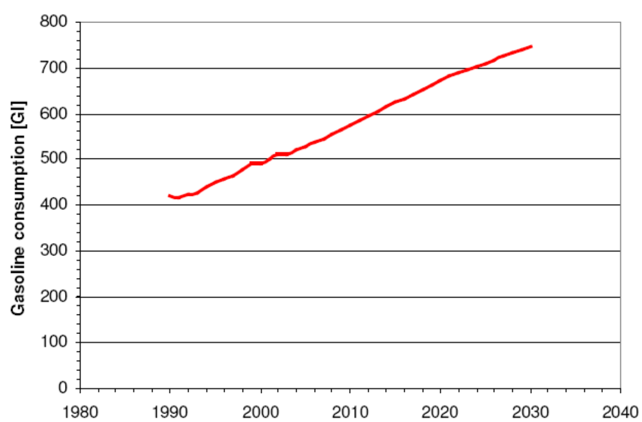


**Figure 20: US gasoline fuel demand estimates (Walter et al., 2007)**

## EU market

Driven by EU mandates ethanol production in member countries has increased in the last few years. Current production is about 1,6 GL and is expected to grow in the coming decade (Walter et al., 2007). For 2010, a target of 5.75% biofuels in the total transportation fuel consumption is set, and for 2020 a level is set at 10%. A stringent policy regarding efficiency of car engines results into a decrease of gasoline consumption per traveled km and at the same time more efficient diesel cars are expected to take over the market share of gasoline cars (from 30% in 2005 to 43% in 2011). This will result into an overall reduction in gasoline consumption and therefore a relative reduced demand in ethanol in Europe (Figure 21) as compared to the increase in gasoline demand for the US (Figure 20) above.

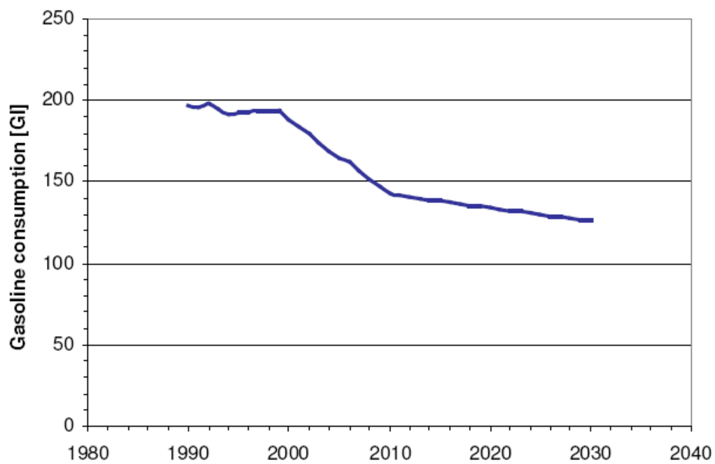


**Figure 21: estimated gasoline demand EU (Walter et al., 2007)**

Since future EU production is not expected to fully cover the ethanol demand, international trade becomes a potential alternative.

## BC market

There is an increasing demand for ethanol as transportation fuel to comply with emission reduction targets in Canada. The government of British Columbia has agreed upon an ethanol ratio target of 5% by 2010 (NRCan, 2006). Current production is very limited and a breakthrough in 2$^{nd}$ generation biofuels could give a boost to this new market in BC. Evidently, in comparison to the EU or the US, the ethanol demand of BC is currently very small.

## Asian market

China's economy thrives currently and this is expected to continue for the coming decades. Due to an increase in socio-economic status and the need for locally available energy, China is considering investments in renewable energy sources as well (Junfeng & Lingjuan, 2007). Already China imported 1 Mega Liter (ML) ethanol from Brazil in 2006. However, it is expected that the demand in the EU will be approximately 4 times higher than China's ethanol demand, even in 2020. Furthermore, EU prices for ethanol are significantly higher. Therefore, China is not taken into account in further calculations (Walter et al., 2007).

# 4. Defining scenarios

For this study, four feedstock scenarios and four end-product scenarios were defined with help of literature studies and expert knowledge (see also *References*; personal communication). The four feedstock scenarios are described in Table 8 and will be explained first, in terms of a 'storyline' description. Each of the scenarios reflects a hypothetical feedstock potential given specific determined parameters which outline a certain development in the forestry industry in line with the storyline. Next, the four end-product scenarios will be explained together with storylines which describes costs trends for processing end-products and include future demand trends. In chapter 5, all scenarios will be quantified (given values for parameters).

**Table 8: Feedstock scenarios**

| Name | Description |
|---|---|
| Scenario 1: Availability-Max | Technological potential; all sources full available |
| Scenario 2: Pro-active | Governmental support to utilize all feedstock |
| Scenario 3: Reduced cheap feedstock | Strong competition for feedstock |
| Scenario 4: Limited sources | Feedstock sources are constrained by government |

*Scenario 1: Availability-Max*

This scenario is characterized based on technical potential (i.e. maximum availability) of feedstocks together with a progressive technological development regarding forestry practices. The availability of sawmill residues remains the same with regard to the current situation, due to constant harvesting levels and no competition for sawmill residues from other industries. Furthermore, the Lumber Recovery Factor is assumed to stay at the same level: technological developments at sawmills offset an increase in low quality (MPB) logs. The volume of roadside residues will slightly increase due to lower quality of MPB trees causing more residues at roadsides per harvested stand. The full potential of MPB trees is made available by the provincial government to utilize this feedstock for the recovery of economic value. Technical developments in forestry practices (i.e. harvesting operations, transportation, comminuting etc.) result into cost reductions at a progressive level. Furthermore, in scenario 1, it is assumed that there is no competition for any of the three mentioned feedstock from other industries. Therefore, the whole potential feedstock volume is available for ethanol or pellet production.

*Scenario 2: Pro-active*

Scenario 2 is characterized by an active standpoint from the provincial government towards the utilization of all the three mentioned feedstock. This is translated into governmental policy which attains to recover the maximum economic value from any of the unutilized feedstocks. First of all, all feedstock sources are made available (e.g. MPB harvesting permits) and the AAC harvesting volume increases. Furthermore, recovery of feedstock for utilization is encouraged by providing subsidies (low stumpage price) and by initiating extensive R&D programs to achieve significant costs reductions throughout the supply chain. This results in lower costs for feedstock extraction and transportation till plant gate. However, besides ethanol and pellet production, other industries benefit as well from the relatively cheap feedstock inducing competition for feedstock. Therefore, a substantial share of the total available feedstock is allocated to other industries other than biomass end-product industries.

*Scenario 3: Reduced cheap feedstock*
Competition for biomass feedstock between various industries portrays scenario 3. Lumber industries require all surpluses of sawmill residues by 2012 to the disadvantage of the biomass industry. As a result, the biomass industry has to cope with more expensive feedstock sources (i.e. roadside residues and MPB trees). It is assumed that there is a modest technological development in forest practices, slightly reducing operation costs towards 2020. The harvesting volume (AAC) is assumed to stay at current levels, which also has its consequences on the availability of roadside residues (directly related). A modest part of the whole MPB killed trees source is made available by the provincial government. However, no financial support is granted to salvage affected areas.

*Scenario 4: Limited sources*
In scenario 4, the total feedstock potential for biomass end-products is considered very low and there is a lack of provincial governmental support towards biomass industries in BC. AAC levels are expected to be lowered towards 2020 to let forests areas recover from the MPB epidemic. This has direct consequences regarding the amount of sawmill residues produced. Moreover, sawmill residues are subjected to moderate competition as a result of increasing demand from other industries. This increasingly reduces the availability for biomass end-product purposes. The availability of roadside residues is relatively low due to poor synchronization of harvesting operations. However, no competition for roadside residues exists from other industries. Since there is no technological development, the availability of this feedstock could only increase by deterioration of MPB log quality. Furthermore, MPB trees are not allowed to cut by the provincial government. There are no technological developments expected throughout whole supply chain (i.e. no cost reductions).

### Scenarios for Pellets and Ethanol

For each of the end-products pellets and ethanol, two scenarios have been constructed; a positive scenario (Max) and a negative scenario (Min). These scenarios will be placed on top of the feedstock scenarios to provide a complete overview how cost supply curves could look like (Table 9). The 'storylines', as described in the below, form the foundation for costs structures regarding the production of the end-product and *transport till terminal*. In addition, demand lines can be deduced from these storylines, i.e. market prices and volumes.

**Table 9: End-product scenarios**

| Name | Description |
|---|---|
| Scenario 1: Pellet-Max | Favorable conditions in pellet production and demanding markets |
| Scenario 2: Pellet-Min | No significant improvements in technology, no beneficial market conditions |
| Scenario 3: Ethanol-Max | Favorable conditions in ethanol production and demanding markets |
| Scenario 4: Ethanol-Min | No significant improvements in technology, no beneficial market conditions |

*Scenario 1: Pellet-Max*

Substantial technological improvements are expected to take place regarding the pellitizing process. Intensive R&D programs and learning effects reduce production costs over time. Moreover, transportation of end-products to a terminal becomes more efficient, reducing costs. A favorable market outlook for pellets is expected towards 2020. Increasing fossil fuel prices in the EU will cause higher costs for electricity production. In addition, the energy security issue gains priority in EU member states, as well as emission reduction targets to mitigate climate change. The characteristics of pellets (being compatible in co-fired installations) as an alternative fuel, together with the above mentioned developments gives rise to an increasing pellet demand in EU countries. In a globalized world, trade of goods is not constrained by taxes or any other barriers, which is expected to happen in this scenario as well.

*Scenario 2: Pellet-Min*

In this Pellet-Min scenario a very modest level of technological development is expected to take place in the production and transportation phase. Also, market conditions are not as favorable as in the Pellet-Max scenario. Assumed here is that EU's electricity prices stay on a low level, due to low fossil fuel prices (e.g. coal). Also long term agreements with fossil fuel contractors (e.g. gas from Russia) reduce the uncertainty of energy supply. Furthermore, emission reduction targets loose priority which makes the stimulation of renewable energy sources less important. In this 'moderate globalization' scenario, trade barriers will result in higher trading costs, having a detrimental effect on competitiveness of pellets from BC.

*Scenario 3: Ethanol-Max*

A high rate of technological development is expected in the production of ethanol, increasing the conversion efficiency. Assumed here is that commercial ethanol production will take off in 2012 and increases in capacity extensively. The market displays high petrol prices and ambitious ethanol production capacity targets are set for the US. This makes ethanol a strong competitor on the transportation fuel market. The energy security issue in the US forms a mayor driver to conduct policy with regard to utilization of alternative energy sources (other than fossil fuels). The current debate of food vs. energy gains the interest of using forest residues as feedstock for ethanol. This induces in increase in support in the development of 2$^{nd}$ generation ethanol. This scenario assumes a highly globilized world without trade barriers.

*Scenario 4: Ethanol-Min*

This scenario assumes a low rate of technological development in the ethanol production process, constraining costs reductions. No extensive R&D programs are initiated and breakthroughs regarding ethanol production efficiencies are small. An increase in ethanol demand is impeded by stable petrol prices and new discoveries of large oil fields, which reduces the need to secure the energy demand. Furthermore, long term agreements with oil suppliers make a more expensive renewable fuel (e.g. ethanol) less attractive for trade. A lack of concern to meet emission reduction targets around the globe, limits governmental support to use ethanol. Trade is constrained to some extent as a result of a less globilized world. This increases trade costs and therefore reduces trade potentials.

# 5. Input data

This chapter elaborates on the data which is applied for modelling the scenarios (Ch. 4) in the constructed spreadsheet and describes the underlying reasoning and assumptions made.

## 5.1 Region definition

BC’s railroad system is presented in Figure 22 including the two terminal locations for international trade; Prince Rupert and Northern Vancouver (red underlined). The railway system is a key condition to transport forest products from the interior to a terminal (Melin, 2007). In BC, truck transport of feedstock for biomass end-products beyond 150 km is considered not economically feasible (MacDonald, 2007). The green area in Figure 22 encompasses the locations within a 150 km range to the railway system in which roadside residues or MPB trees harvesting is potentially feasible. The blue line separates the province into two delivery zones based on least distance from plant to terminal by train transport. All end-products produced above the blue line (Prince Rupert and Prince George forest region) are assumed be delivered at the Prince Rupert terminal whereas all end-products produced beneath this line are delivered at the terminal in North Vancouver. Figure 23 depicts a potential area (in yellow) to be used for ethanol production in addition to the area already depicted in Figure 22. Since this area is hardly connected to the railroad grid only truck transportation could take place. Therefore, it is assumed that in the US border area ethanol production could be feasible exclusively for trade to the US, within a range of 200 km for the US border.

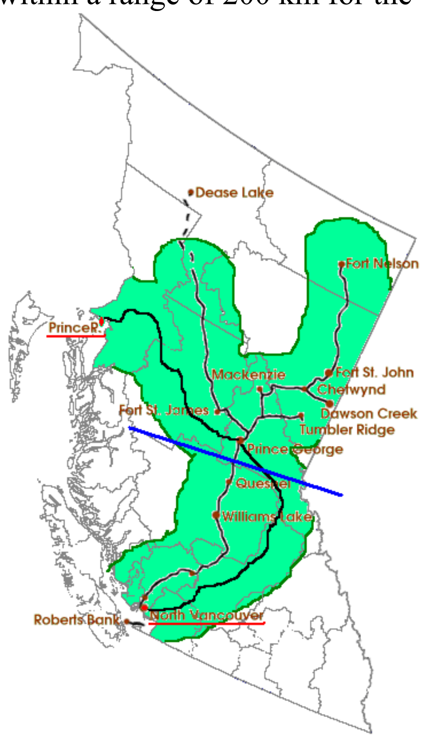


Figure 22: BC railroads and selected research area


Figure 23: potential 'US border' for ethanol production

In Appendix 3, harvesting volumes and volumes of MPB killed trees of are defined for the selected regions by using a coverage rate. The coverage rate is the estimated percentage of a region's area which is coloured in Figure 22 and Figure 23. This percentage is translated into feedstock available in that particular region within the scope of this study in terms of AAC levels and MPB killed trees volume. Assemble

## 5.2 Quantification of scenarios

Based on the defined scenarios in Chapter 4, a specific set of data can be gathered for each of the scenarios. This collection of data is used as input data for the spreadsheet and comprises data from literature studies and assumptions given by experts. All data sheets for every scenario can be found in the Appendices (9-16). To demonstrate, one feedstock scenario (Table 12) and one end-product scenario (Table 18) are presented in this paragraph.

### Feedstock availability

**Harvesting levels**

Table 10 presents the current AAC levels for the selected regions, taken into account the coverage rate for each region (further elaborated in Appendix 3).

**Table 10: current AAC per region (BCMOF, 2007b)**

| Region | In million $m^3$/yr | | |
|---|---|---|---|
| | TSA | TFL | Total |
| **Prince George** | 20.65 | 2.27 | 22.92 |
| **Prince Rupert** | 7.20 | 1.01 | 8.21 |
| **Cariboo** | 9.11 | 0.87 | 9.98 |
| **Kamloops** | 6.37 | 0.49 | 6.86 |
| **US Border** | 5.58 | 1.71 | 7.29 |
| Total | **48.91** | **6.35** | **55.26** |

Changes in future AAC levels for the assessed regions are defined in the feedstock scenarios according to the assumed policy stance (Table 11). The AAC for scenario 2 shows an increase in volume of 10% for the years 2012 and 2020 compared to the current situation. To reduce complexity, this increase in AAC is expected to occur equally throughout the selected regions. Therefore, every region gains 10% in AAC with regard to the current situation in this scenario.

**Table 11: Assumed future AAC levels for each feedstock scenario with regard to current AAC levels**

| **Name** | **2008** | **2012** | **2020** |
|---|---|---|---|
| Scenario 1: Availability-Max | Current | + 0% | + 0% |
| Scenario 2: Pro-active | Current | + 10% | + 10% |
| Scenario 3: Reduced cheap feedstock | Current | + 0% | + 0% |
| Scenario 4: Limited sources | Current | - 10% | - 15% |

**Table 12: data sheet feedstock scenario 2**

| | | Scenario 2 | | | Pro-active | | |
|---|---|---|---|---|---|---|---|
| *Year* | *Unit* | *2008* | | *2012* | | *2020* | |
| **Feedstock availability** | | Coverage[28] | Sawmill R[29] | Coverage | Sawmill R | Coverage | Sawmill R |
| - AAC rates (total) | $Mm^3/y$ | 55,26 | 65,03 | 60,79 | 71,53 | 60,79 | 71,53 |
| Prince George | $Mm^3/y$ | 22,92 | 25,86 | 25,21 | 28,45 | 25,21 | 28,45 |
| Prince Rupert | $Mm^3/y$ | 8,21 | 8,43 | 9,03 | 9,27 | 9,03 | 9,27 |
| Cariboo | $Mm^3/y$ | 9,98 | 13,92 | 10,98 | 15,31 | 10,98 | 15,31 |
| Kamloops | $Mm^3/y$ | 6,86 | 6,86 | 7,55 | 7,55 | 7,55 | 7,55 |
| US border | $Mm^3/y$ | 7,29 | 9,96 | 8,02 | 10,96 | 8,02 | 10,96 |
| - LR[30] | % | | 48 | | 49 | | 50 |
| - **Sawmill residues surplus (total)** | MOdt[31] | | **1,27** | | **2,03** | | **1,83** |
| Prince George | MOdt | | 1,01 | | 1,32 | | 1,24 |
| Prince Rupert | MOdt | | 0,10 | | 0,20 | | 0,17 |
| Cariboo | MOdt | | 0,03 | | 0,19 | | 0,15 |
| Kamloops | MOdt | | 0,05 | | 0,13 | | 0,11 |
| US border | MOdt | | 0,08 | | 0,19 | | 0,16 |
| - **Roadside residues (total)** | MOdt | **5,05** | | **5,78** | | **5,78** | |
| Prince George | MOdt | 2,09 | | 2,40 | | 2,40 | |
| Prince Rupert | MOdt | 0,75 | | 0,86 | | 0,86 | |
| Cariboo | MOdt | 0,91 | | 1,04 | | 1,04 | |
| Kamloops | MOdt | 0,63 | | 0,72 | | 0,72 | |
| US border | MOdt | 0,67 | | 0,76 | | 0,76 | |
| - Roadside residues[32] | % | 24 | | 25 | | 25 | |
| - **MPB trees (total)** | Mm3 | **0,00** | | **35,66** | | **14,95** | |
| Prince George | Mm3 | 0,00 | | 13,81 | | 5,70 | |
| Prince Rupert | Mm3 | 0,00 | | 5,50 | | 2,27 | |
| Cariboo | Mm3 | 0,00 | | 8,61 | | 3,51 | |
| Kamloops | Mm3 | 0,00 | | 3,87 | | 1,62 | |
| US border | Mm3 | 0,00 | | 3,88 | | 1,85 | |
| - Policy figures[33] | +/- | + | | + | | + | |
| - Rate of Cut of total MPB[34] | % | 0[35] | | 50 | | 50 | |
| **Cost minus transport** | | | | | | | |
| - Techn. development (cost reductions)[36] | % | 4 | | 15,07 | | 38,73 | |
| - **Sawmill residues** | $/Odt | **17** | | **17** | | **17** | |
| - Price at sawmill | $/Odt | 12 | | 12 | | 12 | |
| - Loading/short transportation | $/Odt | 4 | | 4 | | 4 | |
| - Storage costs | $/Odt | 1 | | 1 | | 1 | |
| - **Roadside residues** | $/Odt | **23,00** | | **19,53** | | **14,09** | |
| - Comminuting costs | $/Odt | 23,00 | | 19,53 | | 14,09 | |
| - **MPB trees** | $/Odt | **80,31** | | **67,74** | | **48,87** | |
| - Harvesting costs[37] | $/Odt | 33,73 | | 28,65 | | 20,67 | |
| - Comminuting costs | $/Odt | 17,25 | | 14,65 | | 10,57 | |
| - Stumpage fee | $/Odt | 0,55 | | 0,00 | | 0,00 | |
| - Development costs[38] | $/Odt | 7,86 | | 6,68 | | 4,82 | |
| - Silviculture | $/Odt | 7,10 | | 6,03 | | 4,35 | |
| - Overhead | $/Odt | 13,82 | | 11,74 | | 8,47 | |
| **Transportation cost + loading (truck)** | $/Tkm[39] | Formula: 0,236*D+13.5 | | | | | |
| - Mean distance | km | 100 | | | | | |
| - costs of mean distance | $/Odt | 37,10 | | 31,51 | | 22,73 | |
| **Competition** (Lumber industry etc.) | | | | | | | |
| - **Sawmill residues surplus (total)**[40] | MOdt | **1.27** | | **0.81** | | **0.732** | |
| - Biomass end-products[41] | % | 100 | | 40 | | 40 | |
| - Others | % | 0 | | 60 | | 60 | |
| - **Roadside residues** | MOdt | **5.05** | | **4.05** | | **4.05** | |
| - Biomass end-products | % | 100 | | 70 | | 70 | |
| - Others | % | 0 | | 30 | | 30 | |
| - **MPB trees** | MOdt | **0,00** | | **21.40** | | **8.97** | |
| - Biomass end-products | % | 100 | | 60 | | 60 | |
| - Others | % | 0 | | 40 | | 40 | |

[28] Applying the AAC of the regions confined by the coverage rate as stated in Appendix 3
[29] Applying the AAC of the whole regions for sawmill residues since mills are located within the coverage area but haul logs from the whole region to the mills (Appendix 3).
[30] Lumber Recovery (in % of incoming log volume leaving sawmill as timber) dependent on technological development in sawmills and quality of logs.
[31] MOdt = million oven dry tones; $Mm^3$ = million cubic meters
[32] Percentage of the tree that is left behind at the roadside calculated as a percentage of the wood volume taken away to be used for the lumber industry.
[33] The standpoint of governmental policy towards utilizing MPB trees for the industry.
[34] Percentage of the total available MPB trees which is harvestable (assumed is 50% max. harvest potential due to geograph. constraints) and allowed by governmental regulations.
[35] In the current situation MPB trees are not utilized yet due to policy constraints, however, costs are calculation in case when harvesting would take place.
[36] Cost reduction in % per year as a result of technological development, numbers for 2012 and 2020 are a cumulative cost reduction with regard to 2008.
[37] This includes cutting, felling and skidding the tree to the roadside
[38] This includes road construction, lay-out costs and other capital costs
[39] $/tonne/km
[40] It is assumed that industries currently utilizing sawmill residues will continue to do this in future. Therefore, a set amount (8.47 mill. Odt for BC) is reserved for this industry and is subtracted from total sawmill residues. The surplus is the available sawmill residue after subtraction. See also Appendix 4 for amounts reserved for each region.
[41] The percentage of the stated total (surplus) destined as feedstock for biomass end-products (pellets and ethanol).

### Sawmill residues

Table 12 presents for each individual region the volumes and cost of feedstock, for the years 2008, 2012 and 2020. The sawmill residues were calculated by formula (1) given in section 2.3.

$$V_{sawmill} = [(V_{harv} * r_{sawm} * r_{resi}) - V_{used}] * r_{appl} * r_{biom} \qquad (1)$$

$V_{harv}$ is defined by the AAC for each separate region.
$r_{sawm}$ is the ratio of total AAC dedicated to lumber production, here assumed 75.7% of the total AAC (Melin, 2007).
$r_{resi}$ is defined by the Lumber Recovery percentage as given in Table 12 at 48% in 2008.
$V_{used}$ is defined by the volume of the sawmill residues being used by other industries (Table 3). The amount of sawmill residues currently used by other industries is subtracted from the total produced sawmills. The part of formula (1) within brackets results in the sawmill residues surplus volume.
$r_{appl}$ is defined by the share of the surplus of high enough quality to use for pellet or ethanol production. In the values for Table 12 no reduction is taken into account to present full availability of sawmill residues surplus.
$r_{biom}$ defines the competition factor for feedstock. In feedstock scenario 2, for instance, it is assumed that 60% of the total sawmill residues surplus volume cannot be used for biomass end-products since other industries claim this feedstock (for 2012 and 2020). Therefore, only 40% of the sawmill residue surplus volume is dedicated to biomass end-products and presented in Table 12.

### Roadside residues

Roadside residues are calculated by formula (2).

$$V_{roadside} = V_{harv} * r_{left} * r_{biom} \qquad (2)$$

$V_{harv}$ is defined by the AAC levels for each region.
$r_{left}$ is the percentage of the felled tree which is left at the roadside, adjusted to calculate with AAC levels. In Table 12, a value of 24% is given for feedstock scenario 2 regarding 2008. For 2012 and 2020 this value increases due to technological improvements together with an assumed rate of discarded biomass from MPB killed trees (Table 13).
$r_{biom}$ is defined by competition for this feedstock from other industries. In this feedstock scenario the value of 70% of the total roadside residues is dedicated to biomass end-products.

**Table 13: percentage roadside residue with regard to AAC levels for defined scenarios**

| Name | 2008 | 2012 | 2020 |
|---|---|---|---|
| Scenario 1: Availability-Max | 24% | 26% | 28% |
| Scenario 2: Pro-active | 24% | 25% | 25% |
| Scenario 3: Reduced cheap feedstock | 24% | 25% | 28% |
| Scenario 4: Limited sources | 24% | 26% | 30% |

## Mountain Pine Beetle killed trees

The five selected regions each have an estimated and expected volume of killed trees for the years 2006, 2010 and 2018 as shown in Table 14 (BCMOF, 2007c). These numbers represent volumes within the specific research area for each region given by the coverage rate. Since data is limited, this study applies the shown volumes of 2006 for the 2008-scenarios, volumes of 2010 for the 2012-scenarios and volumes of 2018 for the 2020-scenarios.

**Table 14: MPB volumes per region (BCMOF, 2007c)**

| Region | volume dead trees (million $m^3$) | | |
|---|---|---|---|
| | 2006 | 2010 | 2018 |
| **Prince George** | 145.3 | 276.2 | 284.8 |
| **Prince Rupert** | 72.9 | 109.9 | 113.6 |
| **Cariboo** | 147.7 | 172.2 | 175.5 |
| **Kamloops** | 33.1 | 77.4 | 81.0 |
| **US Border** | 15.2 | 77.6 | 92.6 |
| Total | **414,3** | **713,3** | **747,4** |

The total volume available for biomass end-products is given by formula (3):

$$V_{MBP} = V_{kill} * r_{extr} * r_{avail} * r_{appl} * r_{biom} \qquad (3)$$

$V_{kill}$ is defined by the MPB killed trees volume in the specific region.
$r_{avail}$ is defined by the percentage of the MPB killed trees volume made available by the governmental policy. In Table 12, a value of 50% is made available for the years 2012 and 2020 according to the policy assumed for feedstock scenario 2.
$r_{biom}$ is defined by the proportion of total MPB killed trees volume dedicated for biomass end-products which accounts for 60% regarding feedstock scenario 2.
$r_{extr}$ is defined by the yearly MPB killed trees extraction rate. Instead of the whole standing tree volume in a particularly year, the feedstock is distributed over several years. This allows processing plants to have a steady supply of biomass during a certain period. For the scenarios for 2012 the time span of 10 years has been selected, according to decay rates of MPB killed trees. On average this is 1/11 of the tree volume each year, starting four years past mortality (Tampier et al., 2006).

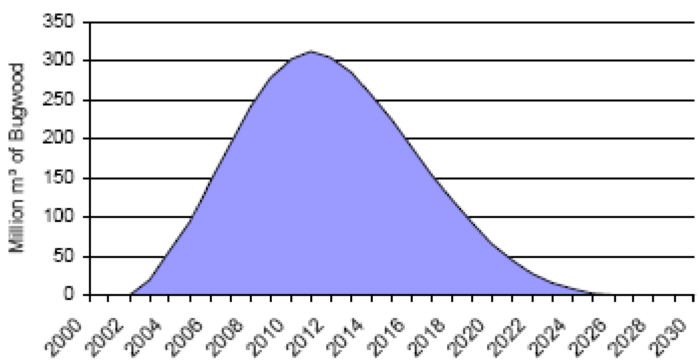


**Figure 24: cumulative availability of still harvestable MPB killed trees for BC (Tampier et al., 2006)**

Starting at 2012, a ten year period of MPB killed wood extraction could supply a yearly feedstock volume of approximately 10% of the total aggregated volume for 2012 (Figure 24). Regarding 2020, only a small share of MPB killed trees is left for another 5 years, which is approximately 20% of the cumulative total given (Figure 49). Therefore, this volume is allocated over 5 years to provide a 5 year long steady supply. For this situation, 4% (0.2*1/5) of the MPB killed trees volume is taken as annual supply rate. Considering the estimations from Tampier et al. (2006), the MPB killed trees feedstock may have disappeared after 2025. These projections and assumptions were applied for every BC region.
$r_{appl}$ refers to the part of the available MPB killed which can be used considering the characteristics. For instance, the bark content could be undesired. In Table 12, 100% is assumed to depict the total available volume regardless of the unwanted parts.

Governmental policy determines the availability of MPB killed to be used as feedstock for energy purposes. In Table 15, a *plus* implies a positive governmental stance and gives rise to a larger percentage to be cut. A *minus* implies a negative governmental standpoint. The maximum assumed harvestable percentage (Availability-Max scenario) for MPB killed trees is 50% due to geographical constraints in BC (MacDonald, 2007; McFarlane, 2007). The current (2008) situation shows that no MPB trees are made available for energy purposes (Table 12).

**Table 15: MPB available feedstock due to policy**

| Feedstock Scenario | Governmental stance | % of total MPB trees made available for period 2012-2020 |
|---|---|---|
| Scenario 1: Availability-Max | + | 50% |
| Scenario 2: Pro-active | + | 50% |
| Scenario 3: Reduced cheap feedstock | +/- | 25% |
| Scenario 4: Limited sources | - | 0% |

## Technological development

In this study, it is assumed that feedstock costs and end-product costs will be reduced as a result of technological development. The rate of technological development is expressed in percentage and is assumed to be directly related to the cost reduction percentage with regard to the base-line costs (current costs). The assumed technological developments for all scenarios are presented in Table 16.

**Table 16: Assumed technological development rates for constructed scenarios**

| *Name of scenario* | *Technological development rate* | | | | | |
|---|---|---|---|---|---|---|
| **Feedstock scenarios** | **2008** | | **2012** | | **2020** | |
| Scenario 1: Availability-Max | 2% | | 7.8% | | 21.5% | |
| Scenario 2: Pro-active | 4% | | 15.1% | | 38.7% | |
| Scenario 3: Reduced cheap feedstock | 1.5% | | 5.9% | | 16.6% | |
| Scenario 4: Limited sources | 0% | | 0% | | 0% | |
| **End-product scenarios** | **Process** | **Transp.** | **Process** | **Transp.** | **Process** | **Transp.** |
| Scenario 1: Pellet-Max | 3% | 2% | 11.5% | 7.8% | 30.6% | 21.5% |
| Scenario 2: Pellet-Min | 1% | 0% | 3.9% | 0% | 11.4% | 0% |
| Scenario 3: Ethanol-Max | n.a. | 2% | 0% | 7.8% | 0% | 21.5% |
| Scenario 4: Ethanol-Min | n.a. | 0% | 0% | 0% | 0% | 0% |

A distinction has been made between feedstock scenarios and end-product scenarios to account for differences in technological development throughout the supply chain (Bradley, 2007). Moreover, within the end-product scenario a distinction has been made between the processing phase and the 'transportation to terminal' phase. Relatively low cost reductions are assumed regarding the transportation phase due to the maturity of transportation systems

In Table 16, the percentages for 2008 represent annual technological development rates, expressed in annual cost reduction percentages with regard to the current (2008) situation. Cost reductions shown for the year 2012 are calculated by multiplying the percentage given in the base-year by the number of years into the future. For instance, feedstock scenario 1 shows an annual cost reduction of 2% and gives the following calculation to generate a cost reduction percentage for 2012.

Cost reduction compared to the base-year = $1 – (1-0.02)^4 = 0.078 = 7.8\%$

The assumed cost reductions for the feedstock scenarios are based upon Scandinavian experiences in forestry practices (Junginger et al., 2005). In this study, these costs reductions apply to all the cost adding components in the supply chains concerning roadside residues and MPB killed trees, except for stumpage fee (which is set by the government). Sawmill residues is not considered to be subjected to cost reductions since only few steps are involved and cost (price) is mostly determined by sawmills. A 4% annual cost reduction is a valid figure as a benchmark in the most positive scenario (feedstock scenario 2) creating un upper boundary and corresponds with the assumptions which Bradley (2007) presented with regard to the Canadian situation (Bradley, 2007).

Ethanol is not commercially available yet. Therefore, the assumed base-year for starting up large scale ethanol production is 2012. Cost reductions are assumed to take place exclusively through efficiency improvements of the conversion process, which reduces feedstock costs considerable.  Therefore, until 2020 no cost reductions are assumed regarding Operation and Maintenance (O&M) costs and capital costs (for equal plant sizes). The assumed efficiency improvements for the ethanol production process are relatively high (Table 22). However, since substantial research is currently undertaken, technological breakthroughs are assumed to occur with regard to ethanol-Min scenarios.

**Feedstock cost calculations**

Table 12 presents for the base (2008) situation the costs for the three selected feedstocks, broken down into sub parts. Apart from transportation, the costs for roadside residues are mainly determined by the comminuting costs. It is assumed that comminuting takes place at the roadside (most cost efficient method (Bradley, 2007)) and that costs, as presented in Table 12, includes all cost made at the roadside: machinery, labour, O&M. The cost for comminuting ($23/Odt)[42] is provided by MacDonald (2006) and includes all costs made till loading chips unto the truck (MacDonald, 2006). The MPB killed trees are subject to various processes before they are ready for transport, including harvesting operations, which increases the total cost considerably. A breakdown of costs is presented

[42] Based on Morbark chipper 20-30 Odt/hr (load factor 2400 h/yr)

in the data sheet (Table 12). The stumpage fee is in this pro-active scenario abolished, having limited impacts on costs. The entailed costs for harvesting steps (all shown apart from comminuting) are provided by Stennes and McBeath (2006) and the comminuting step by MacDonald (2006) (MacDonald, 2006; Stennes & McBeath, 2006).
Sawmill residues costs are determined by the purchase price at sawmills together with loading and transportation costs (Premium Pellets, 2007). The current (2008) average price of sawmill residues is $12/Odt (Premium Pellets, 2007). However, the price of sawmill residues is assumed to double (see also Appendix 20) towards the last Odt sawmill residue available due to scarcity in supply (Gaston et al., 1995; Roberts et al., 2007). Furthermore, competition from other industries increase price levels, for instance from the sawmill residues demanding pulp industry (RBC, 2007).

### Transportation costs

Transportation costs regarding 'forest till plant gate' are calculated by formula (12)[43] which refers to hauling of wood chips by truck in the base case (2008).

$$C_{trans} = 0.236 * d_{pg} + 13.5 \qquad (12)$$

Where $C_{trans}$ is the transportation cost in $/Odt delivered at the 'plant gate'.
$d_{pg}$ is defined by the one-way transportation distance from forest till plant gate (in km) in which 0.236 signifies the specific costs per tonnekm (in $/Odt) and 13.5 the base costs for loading, unloading and others (in $/Odt). In Table 12, the costs for a 100 km distance (source to plant) are presented to show in what range average transportation costs will be.

### Competition for feedstock

The last section of Table 12 outlines the competition for feedstock between other feedstock demanding industries. According to the characteristics of the scenarios the feedstock is allocated to industries. Feedstock scenario 2 has a pro-active characteristic which gives rise to competition for feedstock, since utilization of residues is stimulated by the government. The percentage of biomass end-products is shown, resembling the percentage of the surplus to be used for additional pellets or ethanol production in BC. It is assumed that these competition figures exist for all regions equally for the years 2012 and 2020. In this scenario, for instance, 40% of the total sawmill residues surplus is available for pellet and ethanol production. In Table 17, the assumptions regarding competition are presented for each defined scenario. Exclusively in Scenario 1 the full feedstock potential is available for pellet and ethanol production.

**Table 17: Allocation feedstock for Pellet and Ethanol production**

| *Name of scenario* | *Allocation feedstock (% of total surplus for pellets & ethanol)* | | |
|---|---|---|---|
| | **Sawmill residues** | **Roadside residues** | **MPB killed trees** |
| Scenario 1: Availability-Max | 100% | 100% | 100% |
| Scenario 2: Pro-active | 40% | 70% | 60% |
| Scenario 3: Reduced cheap feedstock | 0% | 70% | 80% |
| Scenario 4: Limited sources | 50% | 100% | n.a. |

Further assumptions regarding the feedstock scenarios can be found in Appendix 20.

[43] provided by FPInnovations (J. MacDonald)

## End-products

Table 18 shows the input data for the pellet-Max scenario for the years 2008, 2012 and 2020. First, the production costs are presented and broken down in several sub-parts. Furthermore, the conversion efficiency is given representing the amount of end-product (pellets) produced from one unit (GJ) of feedstock fed into the process. A technological development of 3% in 2008 implies a yearly cost reduction in all production processes of 3% per year.

**Table 18: data sheet Pellet-Max scenario**

| | | *Scenario 1* | *Pellet-Max* | |
|---|---|---|---|---|
| *Year* | *Unit* | *2008* | *2012* | *2020* |
| - **Production cost** | $/Odt | **43,94** | **38,90** | **30,49** |
| - O&M costs | $/Odt | 19,55 | 17,31 | 13,56 |
| - Labor cost | $/Odt | 8,16 | 7,22 | 5,66 |
| - Capital | $/Odt | 13,03 | 11,54 | 9,04 |
| - Overhead | $/Odt | 3,20 | 2,83 | 2,22 |
| - Storage (feedstock) | $/Odt | 1.65 | 1.45 | 1.15 |
| - Conversion efficiency[44] | % | 86,50 | 87,00 | 89,00 |
| - Technological development[45] | % | 3,00 | 11,47 | 30,62 |
| - **Transportation plant to terminal** | $/Tkm[46] | Formula: 0.025*d+3.8 | | |
| - Mean of transportation | - | train | train | train |
| - Average distance (average) | km | 625 | | |
| Prince George (train) | km | 850 | | |
| Prince Rupert (train) | km | 380 | | |
| Cariboo (train) | km | 560 | | |
| Kamloops (train) | km | 350 | | |
| - Cost of average distance (average) | $/Odt | 19.43 | 17.92 | 15.24 |
| Prince George (train) | $/Odt | 25.00 | 30,94 | 30,94 |
| Prince Rupert (train) | $/Odt | 13,33 | 15,99 | 15,99 |
| Cariboo (train) | $/Odt | 17,78 | 21,69 | 21,69 |
| Kamloops (train) | $/Odt | 12,45 | 14,87 | 14,87 |
| - Technological development | % | 2,00 | 7,76 | 21,53 |
| - **Demand for biomass** | | | | |
| *EU* | | | | |
| - Energy market prices (pellets) | $/GJ | 6,1 | 6.7 | 8,2 |
| - Pellet demand volume | PJ | 12,6 | 90 | 216 |

### Pellet production cost

Pellets typically have a higher heating value (hhv) of 18 GJ/Odt and production costs have been estimated at $44/Odt for the Max-scenario (Stennes & McBeath, 2006) and $60/Odt for the Min-scenario (Primium Pellets, 2007), both for a 80.000 tonnes/yr pellet mill[47]. A slight cost reduction in pelletizing process could take place by the learning effect and by up scaling production (for Max-scenario). Minor conversion improvements are assumed to occur when efficiencies of drying systems will increase and fewer feedstock is required for the heating process. In the base situation (2008) 13.5% (3,13 $GJ_{th}$/Odt) of all incoming feedstock is used for the drying process (Premium Pellets, 2007) and for electrical appliances 54 $MJ_e$/Odt (Bradley, 2006c). The cost of storage refers to the storage of chips from roadside residues or MPB killed trees. Costs to store sawmill

[44] Feedstock output (GJ) / feedstock input (GJ)
[45] Cost reduction in % per year as a result of technological development influencing production costs and storage costs.
[46] In $/tonne/km. In the formula the d = number of kilometers one-way haul. The fixed costs include capital, loading and unloading.
[47] Producing 10 Odt/hr, load factor 8000 hours/yr.

residues are included in the feedstock scenarios and is considered less costly than storage over a longer period of time (Suurs, 2002).

## Production costs ethanol

The costs data and assumed characteristics for the ethanol-Max scenario are presented in Table 19.

**Table 19: data sheet Ethanol-Max scenario**

| | | *Scenario 3* | *Ethanol-Max* | |
|---|---|---|---|---|
| *Year* | *Unit* | *2008*[48] | *2012* | *2020* |
| - **Production cost** | $/GJ | | **19.4** | **19.4** |
| - O&M costs | | | 1,75 | 1,75 |
| - Labor cost | | | 0,62 | 0,62 |
| - Enzymes and chemicals | | | 3,26 | 3,26 |
| - Capital & taxes | | | 12,07 | 12,07 |
| - Overhead | | | 1,71 | 1,71 |
| - Storage (feedstock) | $/Odt | | 1,53 | 1,30 |
| - Revenues (electricity & lignin)[49] | $/GJ | | 4.27[50] | 4.27 |
| - Conversion efficiency[51] | % | | 32 | 55 |
| - **Transportation plant to terminal** | $/Tkm | Train = 0,045*d vs. Truck = 0,04*d | | |
| - Mean of transportation | - | | train/truck | train/truck |
| - Technological development[52] | % | 2,00 | 7,76 | 21,53 |
| - Mean distance (Total average) | km | 625 | | |
| Prince George (train) | km | 850 | | |
| Prince Rupert (train) | km | 380 | | |
| Cariboo (train) | km | 560 | | |
| Kamloops (train) | km | 350 | | |
| US Border (truck) | km | 200 | | |
| - Cost of mean distance (Total average) | $/L | 0,0166 | 0,0151 | 0,0128 |
| Prince George | $/L | 0,0301 | 0,0278 | 0,0237 |
| Prince Rupert | $/L | 0,0135 | 0,0125 | 0,0106 |
| Cariboo | $/L | 0,0199 | 0,0183 | 0,0156 |
| Kamloops | $/L | 0,0123 | 0,0113 | 0,0097 |
| US border | $/L | 0,0142 | 0,0131 | 0,0112 |
| - **Demand for biomass** | | | | |
| *BC* | | | | |
| - Energy market prices (petrol) | $/GJ | 15,6 | 18.1 | 22.2 |
| - Ethanol demand | PJ | 0 | 9.8 | 19.6 |
| *EU* | | | | |
| - Energy market prices (petrol) | $/GJ | 18.3 | 20.6 | 26.1 |
| - Ethanol demand | PJ | 0 | 208.3 | 88.9 |
| *US* | | | | |
| - Energy market prices (petrol) | $/GJ | 15,6 | 18.1 | 22.2 |
| - Ethanol demand | PJ | 0 | 77.2 | 294.8 |

Since no large commercial 2nd generation ethanol plants exist at present, cost calculations are primary based on development projections from several other studies ((S&T)[2] et al., 2004; Hamelinck, 2004; Tampier et al., 2006). The main costs for the production of ethanol are feedstock costs capital costs and processing supplies, which include specific enzymes (Table 20). Increasing the size of ethanol production plants influences the production costs significantly due to economies of scale. This relationship is shown in Figure 51 (Appendix 8) and provides the ethanol production cost data for four selected sizes (Table 21).

[48] Currently there is no commercial cellulose-based ethanol facility economically running in BC. In this thesis, it is assumed that in 2012 production will take off.
[49] Co-products of ethanol production are a major part of the revenues generated.
[50] Revenues are assumed at $0,10/liter produced ethanol
[51] Feedstock output (GJ) / feedstock input (GJ)
[52] Cost reduction in % per year as a result of technological development, numbers for 2012 and 2020 are a cumulative cost reduction with regard to transportation and storage in 2008.

Costs in the ethanol scenarios are based on a 400MW ethanol output plant (8000 hrs/yr load, 492.3 million liters/yr, 15 year lifespan) and include all cost components as stated in Table 20 (Hamelinck, 2004).

**Table 20: ethanol production cost as a percentage of total capital and O&M costs (Hamelinck, 2004)**

| Ethanol production costs *(based on 220 million liter ethanol/yr)* capital + O&M cost excluding biomass feedstock | |
|---|---|
| **item** | % |
| - O&M costs | 9,0 |
| - Labor cost | 3,2 |
| - Enzymes and chemicals | 16,8 |
| - Capital & taxes | 62,2 |
| - Overhead | 8,8 |
| **total cost of production** | 100,0 |

**Table 21: ethanol production costs for different plant sizes (Hamelinck, 2004)**

| Production costs ($/GJ) | | | | |
|---|---|---|---|---|
| | **100MW** | **200MW** | **400MW** | **1000MW** |
| *Production costs* | 29.7 | 24.0 | 19.4 | 14.7 |

Conversion efficiencies for ethanol production are important to take into account since feedstock costs are form a significant share of the total costs. The higher the efficiency of the process the less feedstock is required per unit output (Table 22). In this scenario it is assumed that the efficiency will increase to a rate of 55% by 2020 (Hamelinck, 2004). Regarding the ethanol-Min scenario, an efficiency of 22.5% is used for 2012 and 32% for 2020 (Table 6).

**Table 22: feedstock requirements for different plant sizes (Hahn-Hagerdal et al., 2007; Hamelinck, 2004; Mabee, 2006; Tijmensen et al., 2002)**

| Feedstock requirements (in PJ) | | | | |
|---|---|---|---|---|
| Efficiency (ratio) | **100MW** | **200MW** | **400MW** | **1000MW** |
| *0.225* | 12.8 | 25.6 | 51.2 | 128 |
| *0.32* | 90 | 18.0 | 36.0 | 90.0 |
| *0.55* | 5.2 | 10.5 | 20.9 | 52.4 |

In addition, revenues from selling lignin and electricity account for $0.10/liter ($4.27/GJ) ((S&T)$^2$ et al., 2004).

## Transportation

Table 23 shows the costs for transporting goods by different means for different distances. Costs are calculated in \$/tonnekm, included a fixed cost for loading and unloading and a variable cost depending on the distance (Forrester et al., 2006; Tampier et al., 2006).

**Table 23: transport costs BC sawmill residues, one way haul distance (Forrester et al., 2006)**

| Costs (\$/tkm) | **50km** | **100km** | **300km** | **1000km** |
|---|---|---|---|---|
| *Truck* | 13.60 | 19.80 | 44.60 | 131.40 |
| *Rail* | 35.90 | 37.00 | 41.70 | 57.90 |
| *Barge* | 8.00 | 10.30 | 19.60 | 52.10 |

Transportation by barge, however, is excluded from this research due to limited potential and geographical constraints concerning BC. This study assumes that feedstock is transported to processing plants by trucks whereas end-products are transported to an international terminal by rail. However, an exception is made for ethanol transport from the US-border region to a terminal. Due to limited railway possibilities in this region, ethanol is being transported by (tanker) truck.

To find the accompanying distance for each delivered tonne of feedstock, the total feedstock volume is divided into segments and given an average transportation distance. Regarding roadside residues, this is conducted according to the distances and volumes of log transport destined for sawmills. Since roadside residues constitute a certain percentage of the total harvested trees, estimations in transportation distances can be made accordingly. Regarding MPB killed trees, it is assumed that transportation distances increase with increasing gathered volumes, as in rings in a circular coverage area. Every further segment in this ring increasingly contains feedstock. In appendix 7, presents the allocation of feedstock over distances. However, costs for transportation of sawmill residues from sawmill to plant is fixed, since it is assumed that new end-product plants will be located adjacent to sawmills which limit transportation costs significantly.

Cost calculations for transport to an international terminal by train are determined firstly by defining the distance from a central point in a region (main city in region connected to the railroad grid) to the terminal (Appendix 6). Table 24, shows distances for every region and transportation costs are calculated according to the equation as presented in Table 18.

**Table 24: transport distances for every region (Google Maps, 2007)**

| Region | Average distance till terminal[53] |
|---|---|
| | **Km** |
| **Prince George** | 850 |
| **Prince Rupert** | 380 |
| **Cariboo** | 560 |
| **Kamloops** | 350 |
| **US Border** | 200 |

[53] Measured from central railway station in every region to closest international terminal; North Vancouver or Prince Rupert.

For modelling the province as a whole the distance of 625 km is taken, which is an approximate average distance. Furthermore, an assumed reduction in transportation cost can be obtained from Table 18. Cost reductions can be justified by learning effects in large scale cargo transport and system improvements.

## Demand

Price projections for ethanol and pellets in 2012 and 2020 are based upon an energy outlook of the IEA (2006) presented for fossil fuels. Prices of other energy products, like ethanol or pellets, are directly connected with fossil fuel prices when substitutable (Appendix 18). Pellets are a proven substitute for coal in co-firing power plants and ethanol a substitute for gasoline. For the 'Max' scenarios a price increase is expected, 2.5% per year for pellets[54] and 3% per year for ethanol. This is a result of assumed rising energy prices and financial support from governments towards renewable energy sources and corresponds with energy price rises over the last decades (Pigath et al., 2005). For the 'Min' scenarios a stable price is projected according to the IEA outlook. Furthermore, it is expected that fossil fuel energy supply will be stable and the need to comply with Kyoto targets is not perceived as important.

### Pellets

This study assumes that every additional produced pellet in BC is dedicated to the EU market. By extrapolating the demand line for the EU to 2012 as presented by the Wood and Pellet Association of Canada (Figure 19), a shortage in volume of approximately 5 million Odt of pellets is expected to occur. BC could compensate for this shortage through export. For the pellet-Max scenario it is expected that the energy security issue in the EU will result in more trade with stable regions. Therefore, in the year 2020 more than a doubling of capacity and imported pellet volume is assumed compared to 2012 (an increase of 7.6% per year; 240% over 12 years). For the pellet-Min scenario a reduced growth rate is expected (doubling in 12 years; 5.9% per year). In Table 25, the pellet scenarios are presented including the assumed prices and total demanded volumes for the EU. However, the import value represents the potential trade volume since the EU has pellet production capacity as well to cover a share of the total demand.

**Table 25: Demand volumes and prices for pellets EU**

| **EU pellet prices ($/GJ)** | **Current*** | | **2012** | | **2020** | |
|---|---|---|---|---|---|---|
| Pellet Max<br>Pellet Min | 6,1<br>4,9 | | 6,7<br>4,9 | | 8,2<br>4,9 | |
| **EU pellet demand (PJ)** | **Demand** | **Import** | **Demand** | **Import** | **Demand** | **Import** |
| Pellet Max<br>Pellet Min | 126[55]<br>126 | 12,6<br>12,6 | 288<br>162 | 90<br>45 | 576<br>216 | 216<br>90 |
| **EU pellet demand (Mill. Odt)** | **Demand** | **Import** | **Demand** | **Import** | **Demand** | **Import** |
| Pellet Max<br>Pellet Min | 7,0<br>7,0 | 0,7<br>0,7 | 16,0<br>9,0 | 5,0<br>2,5 | 32,0<br>12,0 | 12,0<br>5,0 |

*(2007 data)

[54] Coal prices tend to be more stable since there is still plenty of this resource available in the world (IEA, 2006). Therefore, the price increase for pellets is assumed to be less than the price increase for pellets.
[55] *Source: (Pigath et al., 2005)*

Current (2008) market prices for delivered pellets for the Norwegian residential market are $13.2/GJ (166euro/Odt)(Pigath et al., 2005) whereas delivered pellet to Rotterdam (CIF)[56] are $9.4/GJ (Melin, 2007). A lower estimate price is given for Europe of $8.8/GJ (Pigath et al., 2005). Current prices in Table 25 are shown for pellets bought at the terminal in North Vancouver or Prince Rupert. Ocean freight rates are assumed to be $3.3/GJ for the pellet-Max scenario, and $3.9/GJ for the pellet-Min scenario. This includes costs for insurance, freight and terminal costs (Melin, 2007). Therefore, this study assumes a current price level between $4.9[57]-6.1/GJ[58] (FOB[59] Vancouver) for large scale industrial utilization (bulk).

## Ethanol

*United States*

Future US ethanol demand figures are deduced from Walter et al. (2007), which defines two scenarios; one projecting a strong growth in ethanol consumption and the second describing a conservative ethanol demand. The difference in growth rate is mainly caused by the assumed ratio of ethanol in gasoline blends and the developments in 2nd generation bio-ethanol from cellulose. In the ethanol-Max scenario, it is assumed that the government stimulates the use of richer ethanol blends in gasoline. Table 26 shows the assumed import potential including commodity prices (FOB US). The import value represents the trade potential for BC's ethanol production.

**Table 26: US ethanol demand ((Walter et al., 2007))**

| **US ethanol prices ($/GJ)** | **Current** | **2012** | | **2020** | |
|---|---|---|---|---|---|
| Ethanol Max[60]<br>Ethanol Min | 15,6[61]<br>15,6 | 18,08<br>15,6 | | 22,24<br>15,6 | |
| **US ethanol demand (PJ)** | **Demand** | **Demand** | **Import** | **Demand** | **Import** |
| Ethanol Max<br>Ethanol Min | 482,0<br>482,0 | 762,8<br>514,8 | 77,2<br>39,8[62] | 1808,8<br>776,9 | 294,8<br>147,4 |

*Europe*

In Table 27, import projections and prices are provided for the EU. Assumptions for the ethanol-Max scenarios are based upon a continuation of the current strong policy to increase the share of biofuels in EU member states. EU's gasoline consumption is estimated by using Walter et al. (2007) and the import potential is provided by scenarios Dunham et al. (2004). The 'biodiversity scenario' has been selected for the ethanol-Max scenario which has the most expected ethanol imports (ECN, 2007). The ethanol-Min scenario shows limited ethanol import opportunities to the EU (see also Appendix 19).

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[56] CIF = Cost Insurance and Freight. The costs for all handlings to delivery point are borne by the seller (i.e. cost of production, transport to buyer and insurance during transport).
[57] Pellet Max price =Pellets price Rotterdam - Pellet Max freight rate.
[58] Pellet Min price = Lower estimate Europe - Pellet Min freight rate.
[59] FOB = Free On Board, in which the seller of the product will pay for all handlings until loaded on a ocean freight. Costs for sea transport and insurance is borne by the buyer.
[60] The ethanol-Max scenarios assume a price increase of 3% per year.
[61] (Source: Ethanol market, 2007)
[62] For the Min scenario, half of the potential import is expected.

**Table 27: demand ethanol EU**

| EU ethanol prices ($/GJ) | Current | 2012 | | 2020 | |
|---|---|---|---|---|---|
| Ethanol Max | 18,3[63] | 20,6 | | 26,1 | |
| Ethanol Min | 18,3 | 18,3 | | 18,3 | |
| **EU ethanol demand (PJ)** | **Demand** | **Demand** | **Import** | **Demand** | **Import** |
| Ethanol Max | 37,4[I] | 346,3[II+64] | 208,3 | 610,7[III] | 88,9 |
| Ethanol Min | 37,4 | 88,9[2] | 44,5[65] | 152,1[IV] | 77,2 |

I (Ebio, 2007); II (Mantzos et al., 2003); III (Intersience, 2007); IV (Walter et al., 2007)

*British Columbia*

In Table 28, equal prices are shown for all the ethanol scenarios with regard to the US market. Given the location of BC (adjacent to US), it is assumed that trade is relatively easy and prices are assumed to be similar in an open market. However, if there is a demand, BC's produced ethanol will likely first go to the BC's market when prices of ethanol equal US prices. This is assumed since trading to other countries adds to handling costs and paperwork costs which results in additional costs.

For the ethanol-Max scenario, an ethanol ratio of 7.5% and 15% in gasoline is expected for respectively 2012 and 2020 due to proactive governmental policy. In the ethanol-Min scenario a ratio of 2.5% and 5% is assumed for the years 2012 and 2020, in which it is assumed that the government is not addressing the issues of climate change.

**Table 28: demand ethanol BC**

| BC ethanol prices ($/GJ) | Current | 2012 | 2020 |
|---|---|---|---|
| Ethanol Max | 15,6[a] | 18,08 | 22,24 |
| Ethanol Min | 15,6 | 15,6 | 15,6 |
| **BC ethanol demand (PJ)** | **Demand** | **Demand** | **Demand** |
| Ethanol Max | n.a. | 9,8[b] | 19,6[b] |
| Ethanol Min | n.a. | 3,3[c] | 6,5[c] |

a (Statcan, 2007b) b (Centre for energy, 2007) c (NRCan, 2006a)

In Appendix 20, other assumptions regarding the end-product scenarios are stated.

[63] Assumed here is a $70 per 1000 L freight rate from Vancouver to Rotterdam.
[64] The demand in case EU complies with Kyoto targets.
[65] Assumed half of total demand as being imported from outside the EU.

# 6. Results & Analysis

This chapter addresses the outcomes derived from modelling the described scenarios for feedstock and the end-products for BC, and its five sub regions. These outcomes are presented by cost supply curves and cost breakdowns of the end-product. Feedstock volumes, as presented in the cost supply curves, should be perceived as additional available feedstock (still unutilized). Costs in the cost supply curves refer to costs for each additional delivered Odt (or GJ) of product (i.e. marginal costs).
Furthermore, the cost supply curves for BC represent an integration of the cost supply curves derived from the selected regions. Therefore, curves representing BC as a whole should not be interpreted as a representation of cost-supply situations for biomass end-products from one (central) processing plant in BC.

## 6.1 Feedstock availability BC

The current (2008) availability of feedstock in BC (Figure 25) comprises sawmill residues and roadside residues only, since MPB trees is not harvested for biomass applications yet (BC legislation). Sawmill residues are the cheapest feedstock, starting at a cost of $17.0/Odt delivered to the production plant (refer to Appendix 10). An estimated 1.3 million Odt/yr of sawmill residues is currently available, and costs increase when becoming more scarce (Appendix 10). When all sawmill residues have been used, roadside residues will be the alternative feedstock starting at much higher cost levels ($43.7/Odt). Exclusively the increase in transportation cost (due to increasing haul distances) causes the upward trend regarding roadside residues costs. Approximately 5.0 million Odt/yr roadside residues are currently available (Appendix 10).

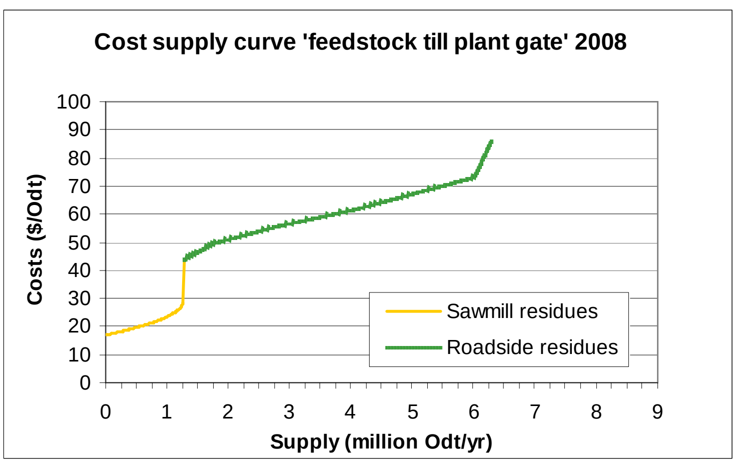


**Figure 25: cost supply curve feedstock BC, 2008**

For 2012, the four feedstock scenarios show different outcomes regarding costs and feedstock availability (Figure 26). Feedstock scenario 1 (FS 1) lacks competition for feedstock and therefore has the largest feedstock availability (Table 17). A cost breakdown is provided in Appendix 21. FS 2 shows the lowest costs for roadside residues and MPB trees due to the assumed technological improvements and cost reductions defined in this scenario.

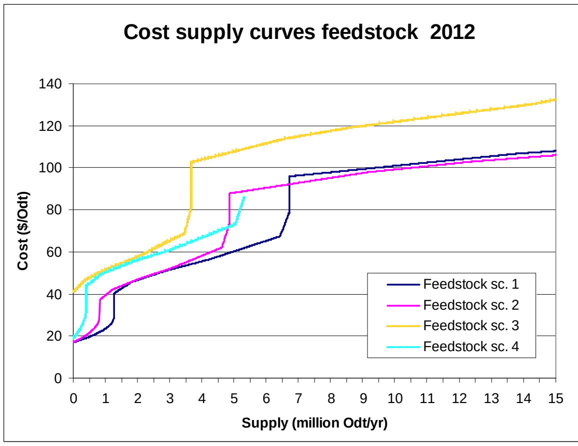


**Figure 26: cost supply curves BC, 2012**

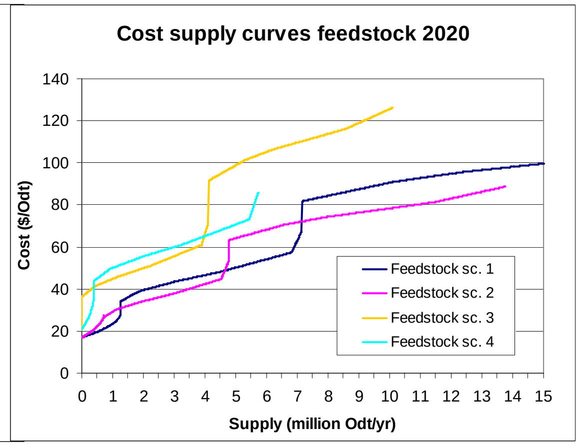


**Figure 27: cost supply curves BC, 2020**

FS 3 starts with roadside residues, since this scenario assumes that all sawmill residues are used by other industries already (Table 17). The lack of cheap feedstock and modest technological developments makes FS 3 having the highest feedstock costs of all scenarios (starting at \$41.0/Odt). FS 4 does not include MPB killed trees which limits the availability of feedstock to 5.7 million Odt/yr[1]. Feedstock scenarios concerning 2020 show larger ranges of costs projections (Figure 27)[2]. Improvements in collection efficiency increase the percentage of available roadside residues which enlarges the total roadside residue volume for FS 1, 2 and 3. FS 1 gains approximately 0.4 million Odt/yr roadside residues compared to the 2012 situation. FS 2 shows lowest roadside residues cost (starting at \$26.6/Odt) and MPB residues (starting at \$63.3/Odt) compared to the other 3 scenarios. Figure 28 depicts developments in volumes and costs for FS 1 for the years 2008, 2012 and 2020. A much stronger cost reduction trend is visible for FS 2 and the effect of feedstock competition is apparent.

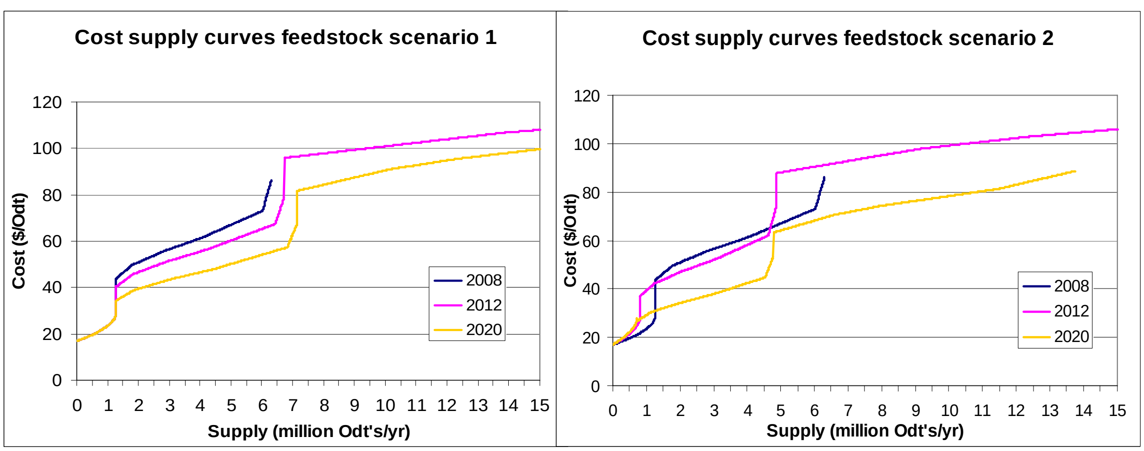


**Figure 28: cost supply curves FS 1 + FS 2 for the years 2008, 2012, 2020 for BC**

[1] The not presented maximum supply for 2012: FS 1: 42.4; FS 2: 26.3; FS 3: 17.9 (in million Odt/yr)
[2] The not presented maximum supply for 2020: FS 1: 22.1 million Odt/yr.

Table 29 shows a summary of the total availability of all feedstock surpluses in the selected areas of BC regarding FS 1, including higher and lower cost estimations. MPB killed trees are currently not available for biomass end-products but costs would start at \$99.7/Odt.

**Table 29:feedstock results for FS 1, BC**

| *Feedstock costs* | | **2008** | **2012** | **2020** |
|---|---|---|---|---|
| **Sawmill residues** | Costs (US\$/Odt)<br>Volume (Million Odt/yr) | 17.0-28.4<br>1.3 | 17.0-28.4<br>1.3 | 17.0-28.4<br>1.3 |
| **Roadside residues** | Costs (US\$/Odt)<br>Volume (Million Odt/yr) | 43.7-86.2<br>5.0 | 40.3-79.0<br>5.5 | 34.3-67.4<br>5.9 |
| **MPB trees** | Costs (US\$/Odt)<br>Volume (Million Odt/yr) | 99.7-…<br>n.a. | 95.9-109.7[3]<br>36.7 | 81.7-103.0[4]<br>15.0 |

Feedstock availabilities for each of the selected BC regions are presented in Appendix 21.

[3] Higher end value presented for a level of 10 million Odt MPB killed trees. However, the total volume of MPB killed trees is much higher (Appendix 10).
[4] Higher end value presented for a level of 10 million Odt MPB killed trees. However, the total volume of MPB killed trees is much higher (Appendix 10).

## 6.2 Pellets BC

In Figure 29, cost supply curves regarding current (2008) pellet production are presented, including an upper and lower demand line. This demand line reflects EU price levels for pellets between \$4.9 – \$6.1/GJ (FOB North Vancouver). The pellet-Max and pellet-Min scenarios form upper and lower cost levels comprising production and transportation costs to the international terminal in BC. The area in this figure enclosed by the green and red price lines refers to the probable real market price. Within this area the pellet-Max and pellet-Min scenario enclose a small area what could be considered as potential pellet volume being produced. Given the current situation, between 0-18.7 PJ/yr (Demand Min/Pellet-Min vs. Demand Max/Pellet-Max) is available for further expansion in pellet production. Current (2008) pellet production is estimated at 15.9 PJ/yr (885.000 Odt for 2008).

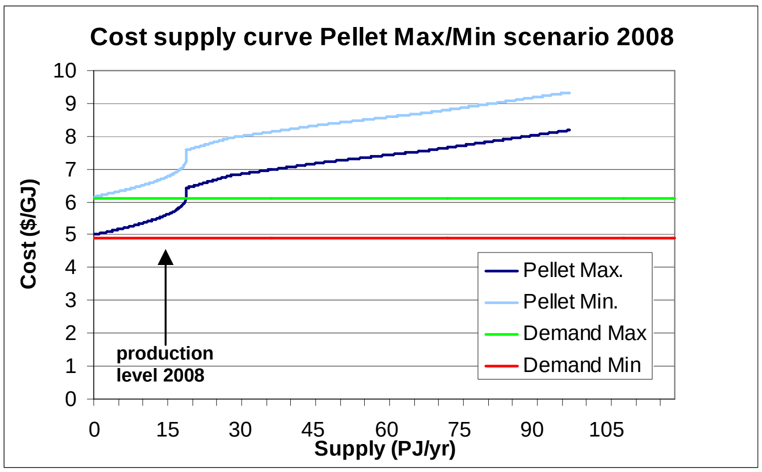


**Figure 29: cost supply curve BC, 2008**

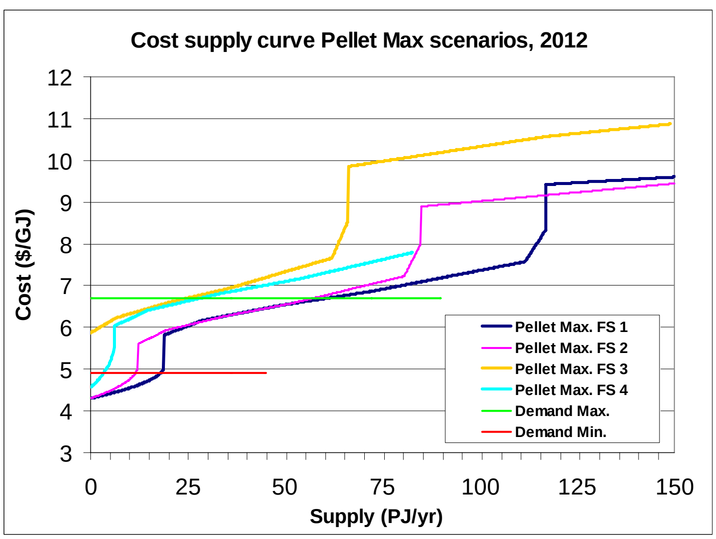


**Figure 30: cost supply curve BC, 2012**

In Figure 30, pellet-Max scenarios are presented for 2012 including prices and volumes of demand for the EU. Assuming a price level of \$6.7/GJ (demand-Max), every feedstock scenario has great potential for further expansion: highest case 60.9 PJ/yr in FS 1 lowest case 24.8 PJ/yr in FS 4.

The difference in costs between a pellet-Min and pellet-Max scenario is shown in Figure 31. Furthermore, a cost breakdown for the pellet-Max and the pellet-Min scenario is shown in which every bar represents the first Odt feedstock delivered for each feedstock. The feedstock costs are almost equivalent[1] for both scenarios whereas cost for processing and transportation to terminal differ significantly. A fixed increase in costs regarding 'production' and 'transport to terminal' is assumed for the pellet-Min scenario compared to the pellet-Max scenario. Therefore, translating Figure 30 (Max-scenarios) into pellet-Min scenarios is done by adding this difference in cost to every pellet-Max scenario.

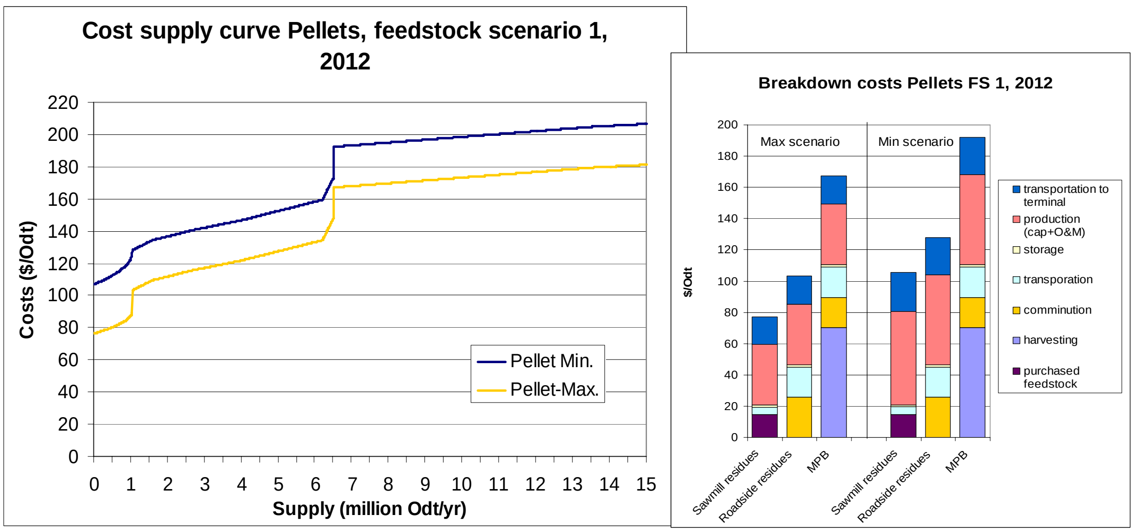

**Figure 31: cost supply curve FS 1 and cost breakdown, 2012**

Projections for the year 2020 assume further cost reductions in particularly for pellet-Max scenarios and demand lines show changes in price and volume. In Figure 32, the most extreme scenarios are presented which give upper and lower boundaries in costs, prices and volumes. The area underneath the demand-Max line implies economically feasible production volumes.

Considering the FS 1 (or FS 1)/pellet-Max scenario, the full assumed EU demand (218 PJ/yr) could be covered (Table 25). Assuming the demand-Min line as future price level, exclusively pellet-Max scenarios have potential for expansion (e.g. 49.1 PJ/yr for FS 2/pellet-Max scenario). The cost breakdown for pellet-Min/Max (FS 1) show significant differences in production costs (Figure 32).

[1] Difference in feedstock costs for pellet Max and Min scenarios are caused by the different conversion efficiency of the pellet production, since costs are expressed in \$/Odt pellets delivered.

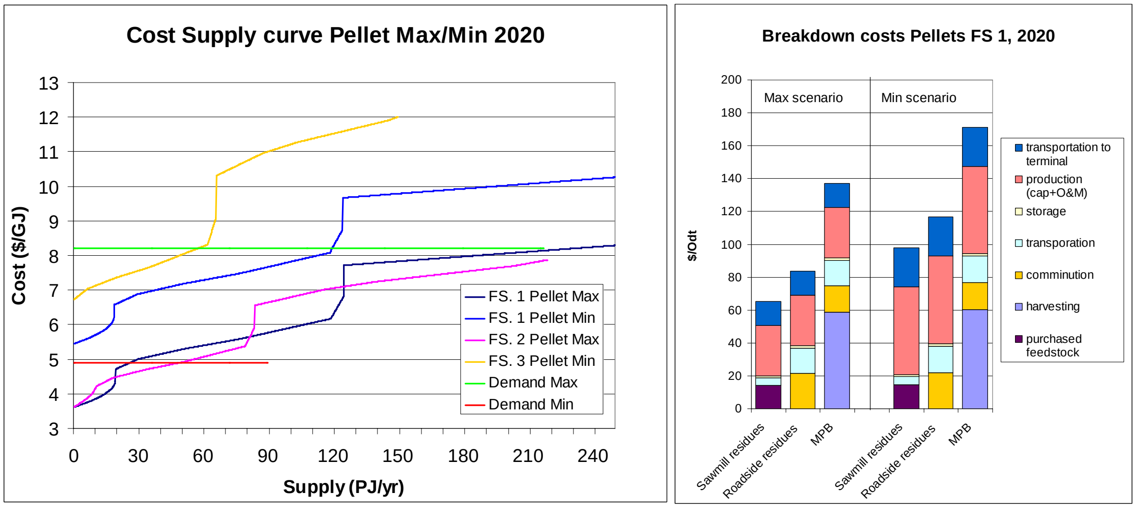


**Figure 32: cost supply curve pellets and cost breakdown, 2020**

A comprehensive overview is given in Figure 33, showing all scenarios and their potentials[2]. The final market potential for BC is dispersed over a wide range of potential pellet production volumes, depending on the selected scenario.

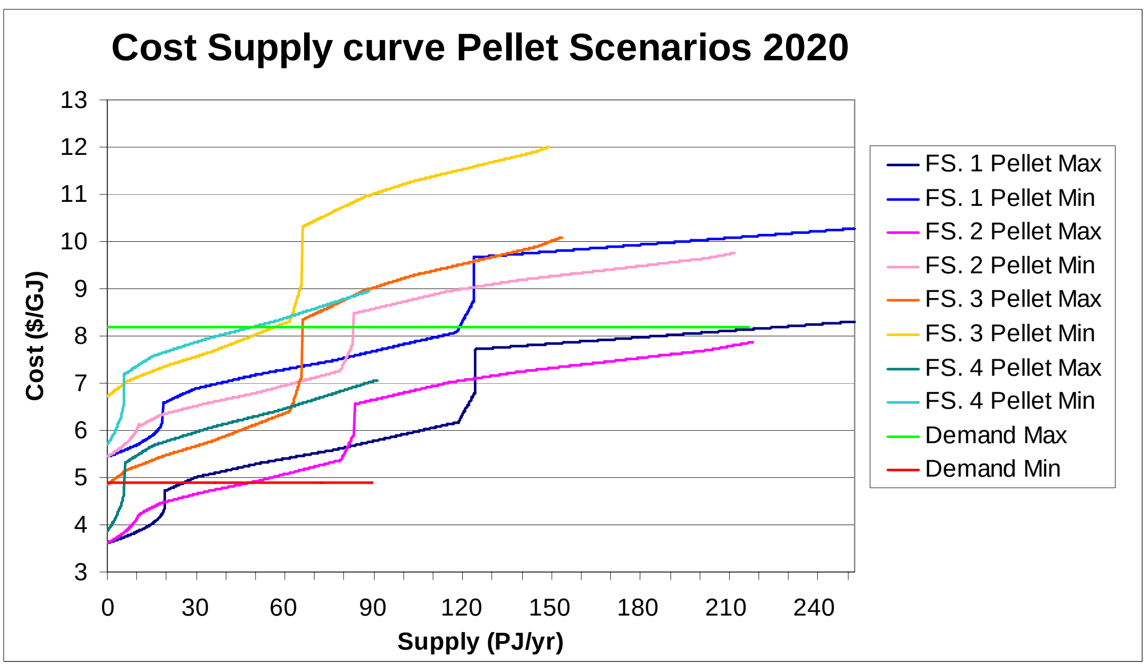


**Figure 33: cost supply curves all scenarios, 2020**

Assuming a high price of $8.2/GJ (demand-Max), all selected scenarios have future potential (50-218 PJ/yr). The implications for each scenario are will be described below.

[2] In Appendix 21, this figure is shown separately for respectively the pellet-Max and pellet-Min scenario. Furthermore, shows how cost supply curves of the pellet-Max/FS 1 scenario evolve over time.

The full availability of all feedstock sources and a moderate technological development contribute to a large quantity of relatively cheap feedstock. Where other feedstock scenarios run out of cheap feedstock supply, FS 1 continues to produce pellets from relatively cheap feedstock (roadside residues depicted in Figure 33 between 80-125 PJ/yr). A favourable pellet-Max scenario (together with FS 1) results in low costs of pellets. Even when using MPB killed trees as feedstock, results in economically feasible production capacities (depicted in Figure 33 between 125-218 PJ/yr). The pellet-Min scenario (together with FS 1) has no potential considering a lower demand line. However, assuming the higher demand line, 120 PJ/yr could be produced economically from sawmill residues and mainly roadside residues.

FS 2 is characterized by the largest technological development in the supply chain together with a moderate competition for each feedstock. This is shown in Figure 33 by reduced availability of the three feedstock sources compared to FS 1 (faster 'jump' to subsequent feedstock). Therefore, each feedstock of FS 2 has lowest costs compared to other feedstock scenarios. A pellet-Max scenario together with cheap feedstock (FS 2) results in low pellet costs and the full demand-Max volume can be produced economically (218 PJ/yr). Even in lower price ranges (demand-Min) production of pellets is economically feasible up to 49 PJ/yr (i.e. ~ 3 x current production volumes). A pellet-Min scenario (FS 2) has only potential for higher pellet prices, up to 84 PJ/yr for demand-Max price level.

Concerning FS 3, modest technological development takes place regarding the supply chain and strong competition reduces the availability of each feedstock (no sawmill residues are left for pellet production). This results in high costs levels for addition pellet production ($4.9/GJ). Furthermore, MPB killed trees as feedstock needs to be used from 66 PJ/yr on, which is most rapidly compared to other feedstock scenarios. The pellet-Max scenario has potential up to this volume whereas MPB killed trees are too expensive to utilize. A pellet-Min scenario (FS 3) shows high costs for pellet production which limits the potential to 0-53 PJ/yr (latter value regarding demand-Max price level).

This feedstock scenario assumes no technological developments at all. Moreover, MPB killed trees are excluded as feedstock, there is moderate competition for sawmill residues and harvesting residues provide the majority of feedstock. Regarding a pellet-Max scenario (FS 4), there is a maximum production of 91.6 PJ/yr at maximum price level $7.1/GJ. The least progressive scenario of all, pellet-Min (FS 4), has a range of 0-50 PJ/yr and start at cost levels of $5.7/GJ.

## 6.3 Pellets for regions BC

The current (2008) situation shows the largest pellet production potential (2.6 million Odt/yr) for the Prince George region, regarding the available feedstock (Figure 34). Due to differences in distances from pellet plants to the international terminals across BC regions, total costs differ. The related transportation costs are included in the total costs for pellets and are given for the Max and Min scenario (Figure 35). Kamloops starts at the lowest costs per Odt delivered ($77.2/Odt) whereas Prince George has the highest costs ($89.9/Odt), being furthest from an international terminal.

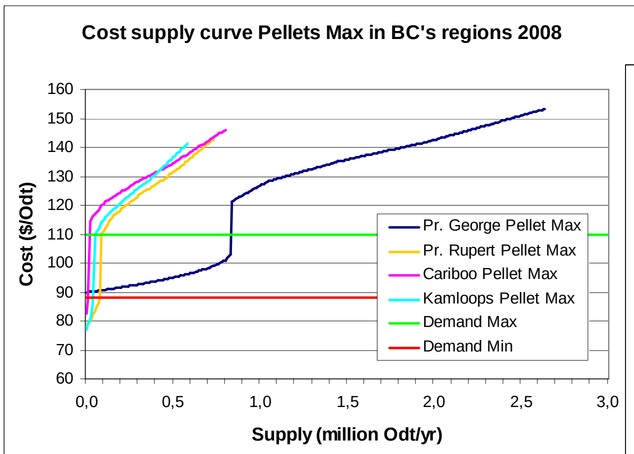


Figure 34: cost supply curve BC regions, 2008

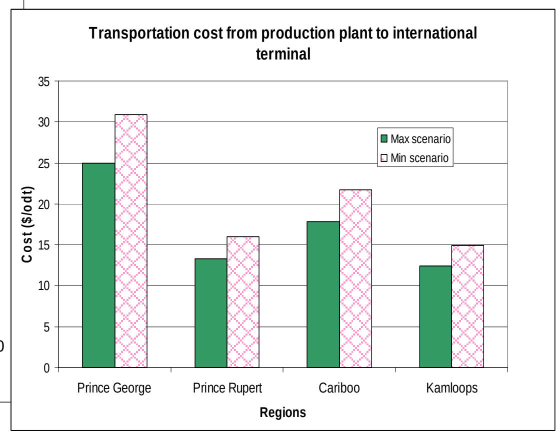


Figure 35: Transportation cost to terminal in several regions, 2008

The pellet-Max/FS 1 situation for 2012 and 2020 is shown in Figure 36. The MPB killed trees feedstock is included which enlarges the potential pellet volume considerably. Considering a pellet-Max situation and a demand-Max line for 2012, Prince George has a potential of 1.4 million Odt/yr, Prince Rupert 0.6 million Odt/yr, Cariboo 0.4 million Odt/yr and Kamloops 0.5 million Odt/yr.

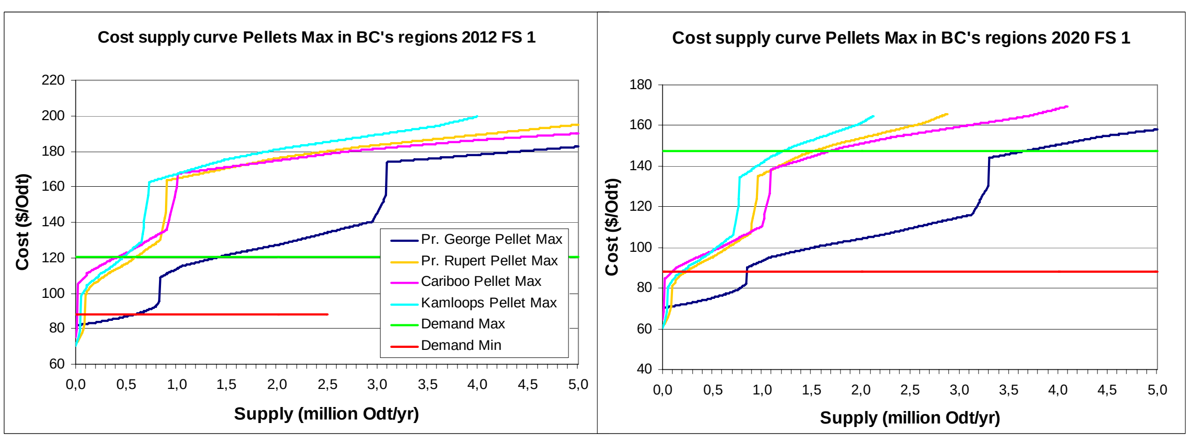


Figure 36: cost supply curve BC regions, 2012 + 2020

Regarding 2020, all regions could produce substantial volumes below the price of the demand-Max line. Therefore, an extensive pellet trade potential can be derived from this figure. More specific scenarios for the pellet production for BC regions are presented in Appendix 21.

Figure 37 presents all possible combinations of scenarios for feedstock and for pellets (Min vs Max) for the Prince George region. The majority of the cost supply curves are enclosed by the two demand lines, which implies a substantial potential for additional pellet production within this region.

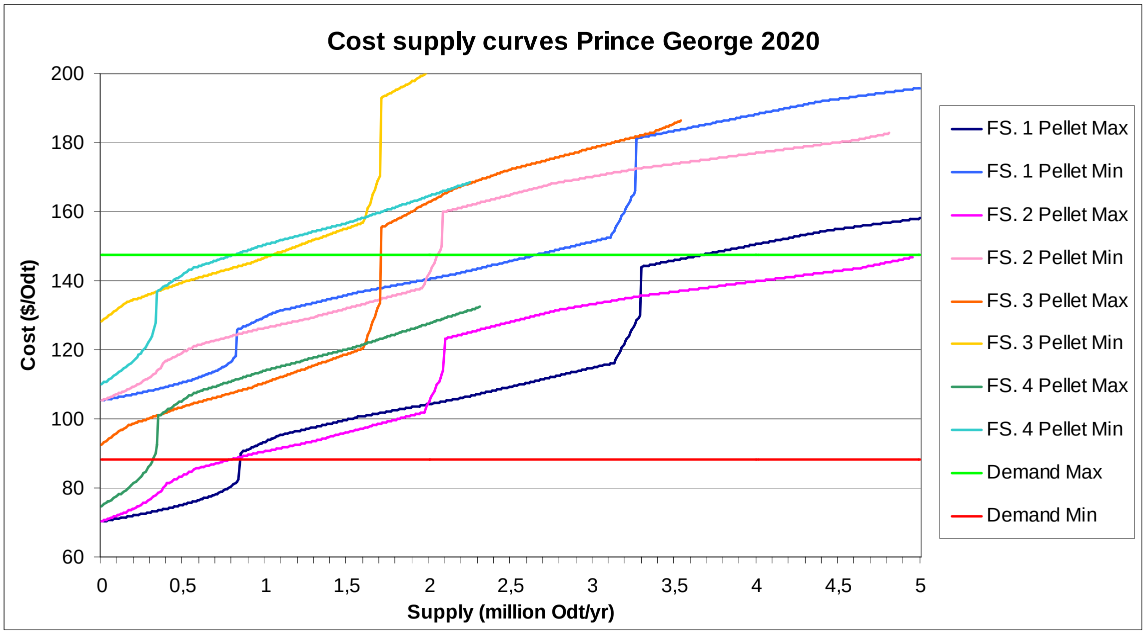


**Figure 37: cost supply curves Prince George all scenarios, 2020**

FS 1 could supply up to 3.7 million Odt/yr (66 GJ/yr), regarding the pellet-Max scenario. This includes the last 0.4 million Odt/yr of MPB killed trees based pellets.

Regarding FS 2/pellet-Max and demand-Max line, the full MPB killed tree feedstock could be used to supply economically feasible pellets.

FS 3 has less potential due to the lack of cheap feedstock (no sawmill residues). Supply could be in this case between 0-1.7 PJ/yr.

In FS 4, there is no technological development assumed in the feedstock supply chain, and therefore costs are generally high, except for the sawmill residues based part. The maximum supply in the pellet-Max scenario is constraint by total feedstock availability, due to no MPB killed trees made available in FS 4.

## 6.4 Ethanol BC

Ethanol production in BC is assumed to take off from 2012. Bark is excluded to be used as feedstock for ethanol production[1]. The situation for all feedstock scenarios is presented in Figure 38. There is a substantial difference in the total costs of ethanol-Min and ethanol-Max scenarios mostly due to the efficiency of the production process which influences feedstock costs considerable (especially when feedstock costs are high: MPB killed trees). The cost breakdown shows costs for sawmill residues and MPB killed trees based ethanol production[2]. The efficiency of the ethanol production process in the ethanol-Max scenario is 32% versus 22.5% for the ethanol-Min scenario. Production cost for the FS 1 scenario start at $18.5/GJ.

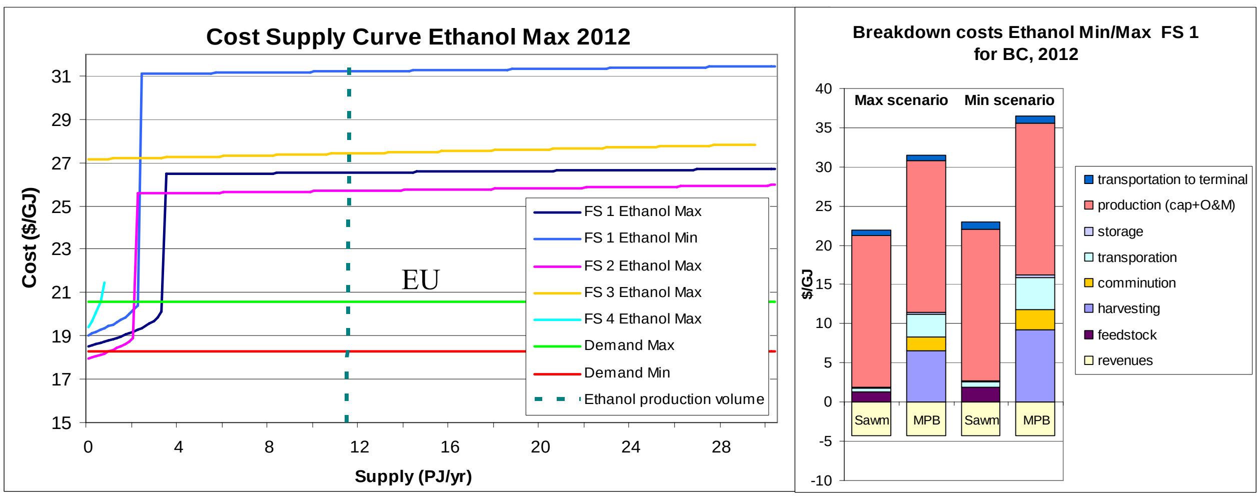


**Figure 38: cost supply curves ethanol BC + cost breakdown, 2012**

The EU demand lines enclose only (a part of) the sawmill residue based ethanol production, at a maximum production volume of 3.3 PJ/yr (ethanol-Max/FS 1). Considering the 400MW (11.52 PJ/yr) ethanol output scale for the base case (dotted vertical line), the production is for most part (MPB killed tree part) not economically feasible. Building a 400MW plant in BC would not be economically feasible regarding the most favourable scenario (ethanol-Max/FS 2), since more volume is produced with costs above market price, than profits are made from the small part made from sawmill residues (below market price).

[1] This excludes the bark share of sawmill residues and MPB killed trees. Roadside residues are excluded entirely for its high bark content.
[2] Revenues in the bar chart should be subtracted from the sum of production costs to get the actual cost.

The situation for 2020 is presented in Figure 39, excluding FS 4, since it has no significant feedstock left. The highest horizontal level in each demand line represents the demand from the EU (the EU having the highest price level). Next, the lower level till the little vertical line represents BC's demand for ethanol. From this little vertical line onwards (to the right) represents the US demand.

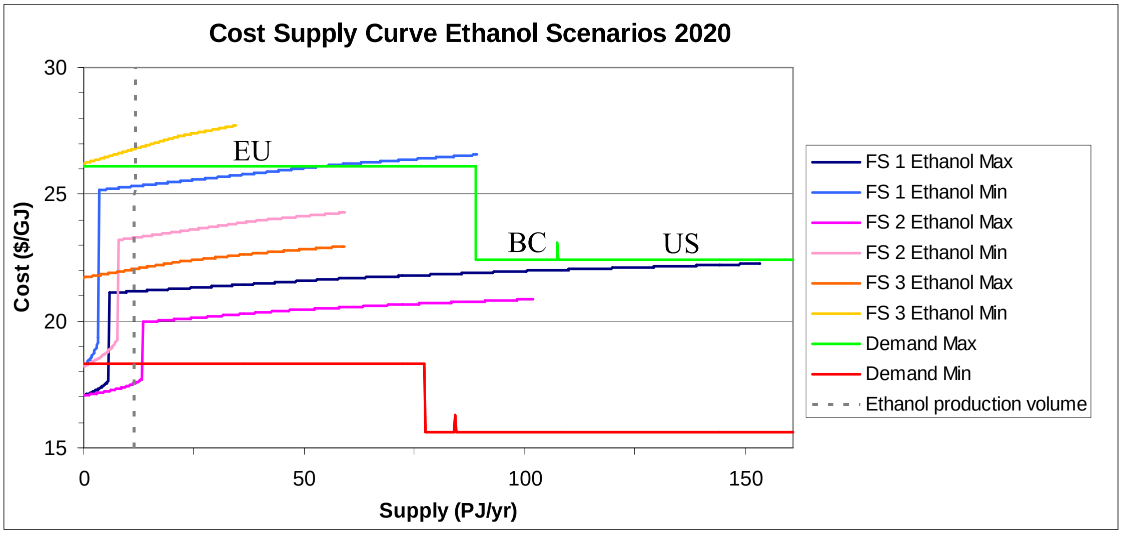


**Figure 39: cost supply curves ethanol, 2020**

In Figure 39, FS 1 has most feedstock available and could supply the full EU and BC demand regarding the ethanol-Max scenario (total of 154 PJ/yr and average total cost[3] of \$21.6/GJ). The FS 1/ethanol-Min scenario could supply 54 PJ/yr which is more than half of the total assumed EU demand for 2020.

FS 2 has lower total costs due to high technological improvements in the feedstock supply chain and could supply up to 102 PJ/yr (for ethanol-Max) at an average total cost level of \$20.0/GJ.

FS 3 has much lower feedstock volumes available, due to competition and reduced MPB killed tree allowances. Maximum supply varies between 34-59 PJ/yr (ethanol-Max vs. Min) and average total costs range between \$22.4–\$26.9/GJ.

The cost breakdown in Figure 40 shows that differences in total cost between the ethanol-Max and ethanol-Min scenario are mainly caused by feedstock costs (all segments below production). This is due to differences in efficiency in the conversion process to generate ethanol from biomass feedstock (55% in scenario-Max vs. 32% in scenario-Min).

[3] Average production costs for 400MW plants can be calculated for each scenario by calculating the surface area below the curve and divide this by produced volume.

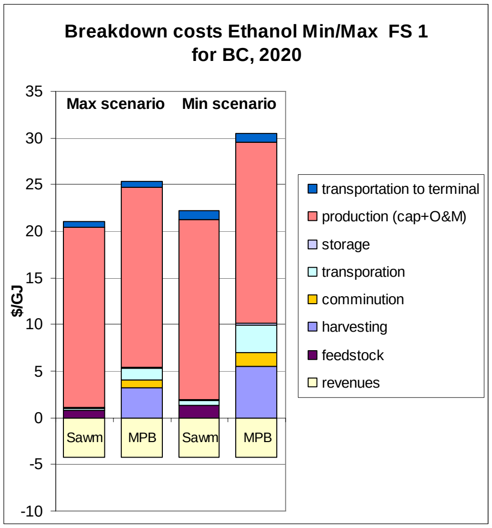


**Figure 40: cost breakdown ethanol Max scenario 2020/ ethanol Min scenario 2020, FS 1**

Figure 41 shows the outcomes for the ethanol-Max/FS 1 when the size of the ethanol plant changes. The dashed lines represent the produced ethanol volume for one ethanol plant, for each size. The 1000MW plant has the lowest costs ($/GJ), and one plant produces 28.8 PJ/yr (ethanol output). Regarding high efficiencies for the ethanol Max scenarios, even the smaller 200MW plant has much potential (5.8 PJ/yr) centred between the demand-Min and Max line.

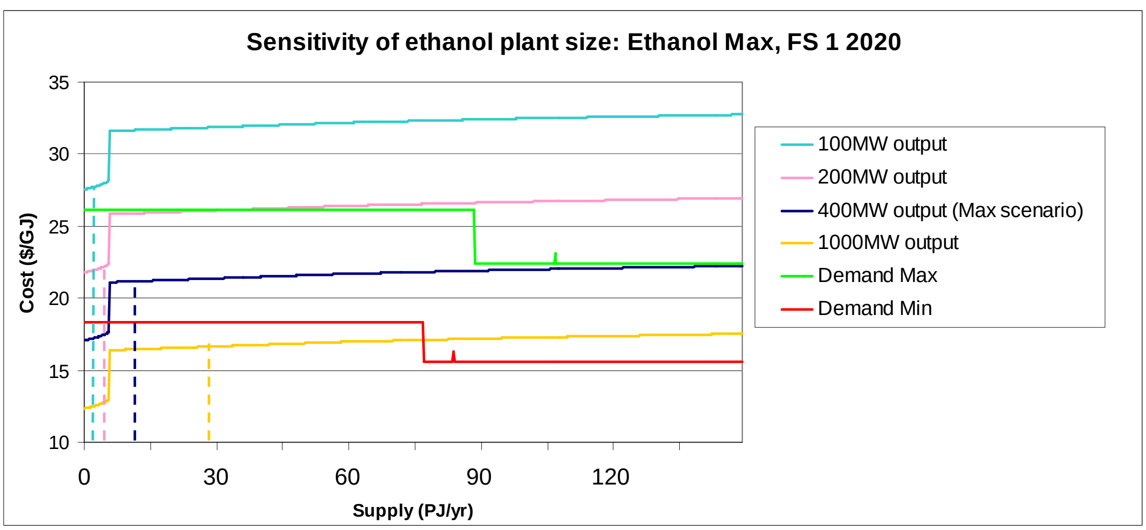


**Figure 41: cost supply curves ethanol BC, 2012 + 2020**

Concerning Figure 39, it can be stated that in most scenarios larger plant sizes could be build than a 400MW plant. However, the feedstock required for ethanol production is dispersed over the province of BC and in this study feedstock cost levels are not calculation to a central location in BC. Therefore, regarding BC as a whole, no further cost calculations are made for larger scale plants (>400MW) based on the total feedstock available in BC. When assessing regions individually, a larger scale plant can be applied since feedstock costs are assessed from closer feedstock sources.

## 6.5 Ethanol BC regions

In the assessment of the potential for ethanol trade in the BC regions, the US border region has been added for its strategic location for trade with the US. Figure 42[4] shows for the ethanol-Max scenarios that the Prince George region has the greatest market potential (2.6 PJ/yr).

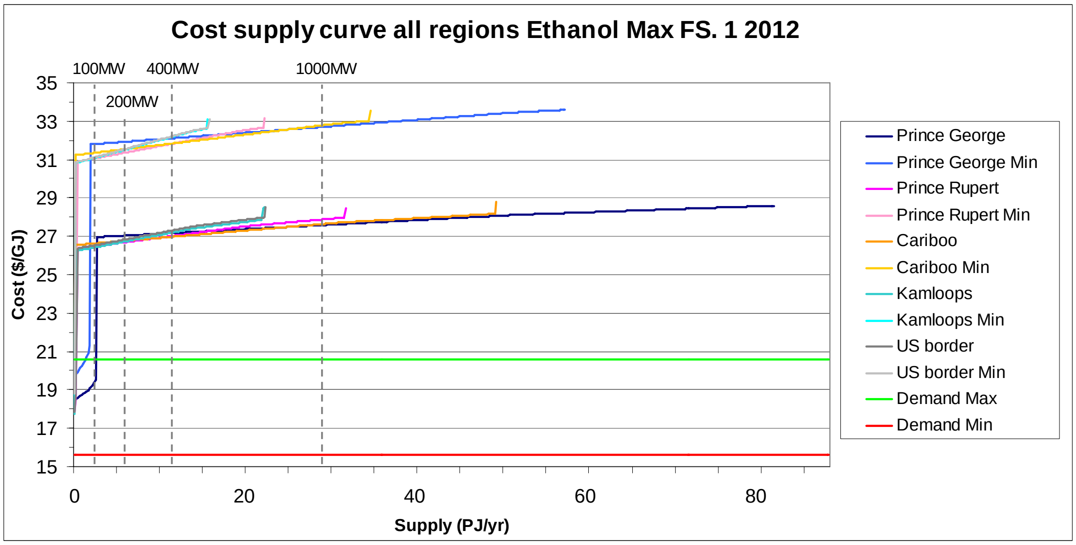


**Figure 42: cost supply curves FS 1 ethanol Min/Max BC regions, 2012**

However, a 400MW plant (base case) would be too large when using cheap sawmill residues only. Additional expensive feedstock needs to be used to run the plant at full load which makes it not economically viable in this situation. A small 100MW plant could produce ethanol from sawmill residues alone. However, smaller scale production increases ethanol production costs with regard to Figure 42 with $10.4/GJ (Figure 41).

The ethanol-Max/Min FS 1 situations for 2020 are presented in Figure 43. Regarding the ethanol-Max scenario, all regions have enough feedstock to supply a 400MW facility. Prince George and Cariboo could even supply 1000MW facilities. Furthermore, price levels above $22/GJ would make ethanol production economically feasible for every region. Regarding the ethanol-Min scenario, 400MW plants could only be build for the Prince Rupert and Cariboo region, concerning the limited availability of feedstock in the other regions (due to low efficiency plant: 32%). Price levels equal to the Demand-Max ($26.1/GJ) would be sufficient to produce economically feasible ethanol.

[4] In some parts of the figure the curves are shown close together and therefore hard to read. In order to indicate where curves end, a small upward line is added.

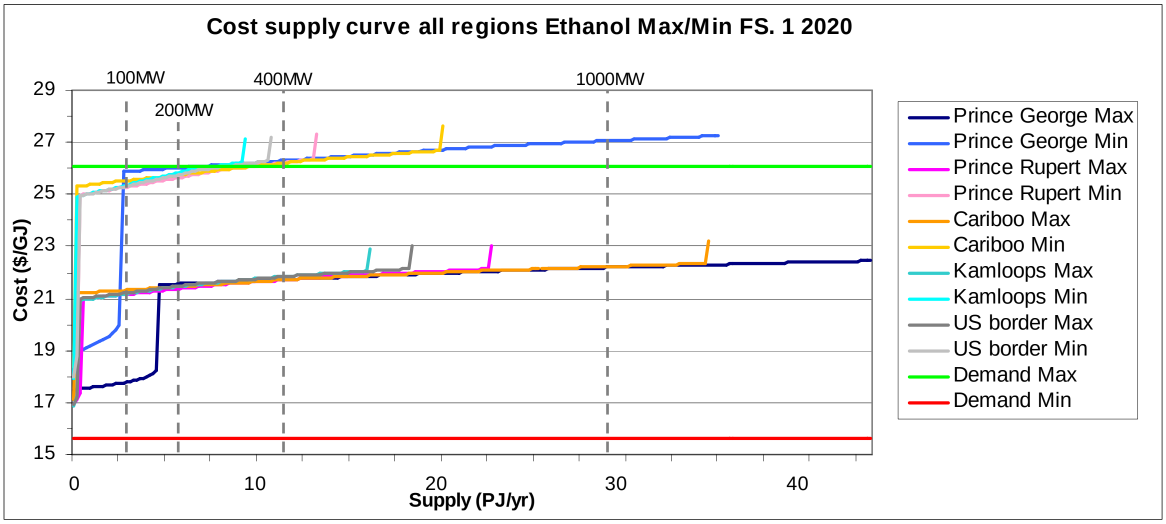


**Figure 43: cost supply curves BC regions, 2020**

Focussing at Prince George, gives the situation for the four feedstock scenarios as depicted in Figure 44. Feedstock scenario 1 could supply for 60.8 PJ/yr of ethanol production. Two 1000MW plants could be established to produce ethanol, which reduces the costs ($4.6/GJ) with regard to the curves presented in Figure 44.
Figure 44 shows that there is enough feedstock available to supply a 400MW ethanol plant for FS 1, FS 2 and FS 3 (for ethanol-Min and Max). From those 6 scenarios only one (FS 3/ethanol-Min) is not enclosed by the lower and upper demand line. This implies that five scenarios meet the requirements to be economically feasible (at 400MW).

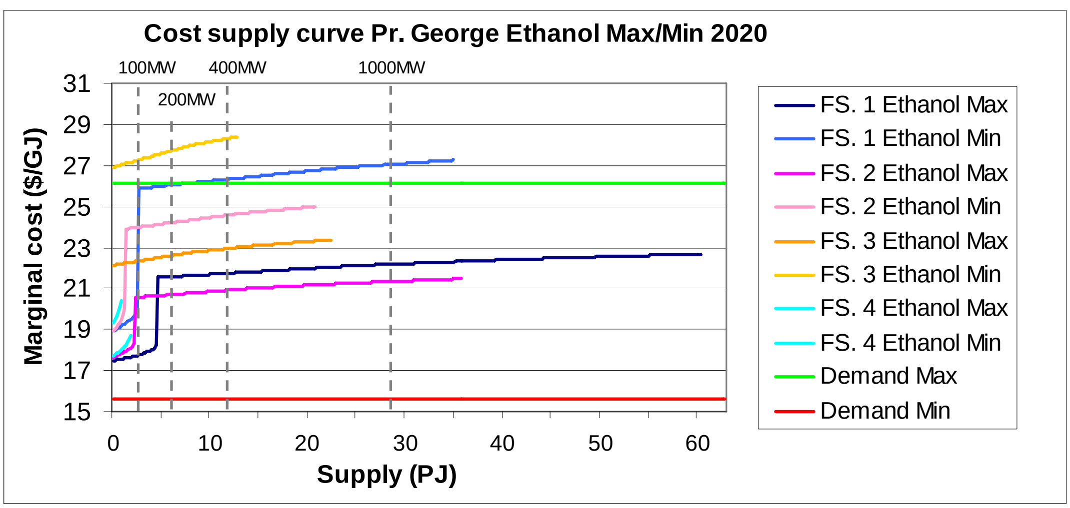


**Figure 44: cost supply curves Prince George, 2020**

Table 30 shows the results for the Prince George region. FS 4 has not enough feedstock to supply a 100MW plant, and is therefore excluded from the table. Ethanol production costs are provided in section 5.2 (and Table 21) and an efficiency of 55% is applied to each plant, except for the 400MW (ethanol-Min) scenario (32%).

**Table 30: average production costs for different plant sizes for Prince George region**[5]

| Plant size | Cost ($/GJ ethanol) | | |
|---|---|---|---|
| (Ethanol output) | **FS 1** | **FS 2** | **FS 3** |
| *100MW* | 28,13 | 29,05 | 32,75 |
| *200MW* | 23,27 | 24,28 | 27,07 |
| *400MW (Max)* | 20,08 | 20,17 | 22,56 |
| *400MW (Min)* | 24,53 | 23,63 | 27,65 |
| *1000MW* | 16,49 | 16,04 | n.a. |

[5] Average production costs for 400MW plants can be calculated for each scenario by calculating the surface area below the curve and divide this by produced volume.

# 7. Discussion

This chapter discusses the issues which must be taken into consideration when interpreting the results. Many assumptions are based upon theoretical numbers and knowledge, since accurate and up to date information is not always available. Therefore, results should be conceived with caution, and interpretation of underlying assumptions should always be taken into account.

**Method**

As being a case study, the aim was to provide a valid representation of the actual situation for BC. Geographical and logistical constraints are taken into account when assessing future possibilities regarding biomass end-products. Moreover, the focus was on existing systems (e.g. harvesting system, logistical system) which is more likely to be applied and expanded instead of a complete change in the systems. Still, radical system changes could take place but are not taken into account in this study.

Most BC data has been collected during an internship at UBC, Vancouver. Field trips formed a valuable part of acquiring recent and realistic information from the province. Experts provided significant input data for the construction of realistic scenarios. However, the extensiveness of the province of BC and the limited time available for collecting data confined the accuracy to some extent.

Chapter 2 describes the methodology for this study and results were calculated in a spreadsheet. Accuracy in results depends (regardless of data quality) upon the quality of the constructed spreadsheet (e.g. the number of influencing factors accounted for). Increasing the amount of input variables could contribute to refine outcomes but at the same time increases the complexity of the model. Especially when aiming at future projections, a more complex mode could lead to an even broader range of outcomes, which is not always preferable. To reduce complexity, the most influencing parameters derived from other studies were selected and a spreadsheet was composed for this study. However, a reduction of parameters in the spreadsheet results into less accurate outcomes.

Large scale 2$^{nd}$ generation ethanol production is not commercially available yet. Expectations regarding future breakthroughs and cost developments show a wide range of outcomes, making accurate cost calculations rather difficult. By selecting an ethanol-Max and Min scenario boundaries of costs projections were made. However, a continuous (strong) development in efficiency improvements and cost reduction is assumed until 2020, even for the ethanol-Min scenario, which is highly uncertain.

Demand lines, representing market prices and demanded volume, are constructed relatively straight forward. This results in a simplified representation of reality, however lacks precision regarding economics in commodity products and world markets.

**Critical review of input data**

For this study, most recent and accurate data was collected as far as possible. However, unavailability of data to each parameter led to assumptions being made in several cases.

Data for estimated sawmill residues was given for the year 2005, which is not likely to be an accurate reflection of the current (2008) situation given the recent developments in the province of BC. Over the last few years, the MPB infestation has caused an increase in processing lower quality logs giving rise to a higher percentage of residues.

Roadside residues volumes are based upon samples at harvesting cut blocks. Extrapolation of these estimates for BC as a whole is questionable (which is done in this study), given the different conditions in trees and harvesting practices across BC.

Due to a lack of data, this study assumes that for each region MPB killed trees can be used for biomass end-products at least until 2020. However, the varied climatic conditions across BC illustrate different decay rates of MPB trees. In dry areas the affected trees have a longer shelve life (+15 years) compared to wetter areas (3-5 years). This influences the availability of MPB feedstock in certain areas over the long run considerably. This is especially important to consider when large ethanol plants are proposed with an economic lifetime of 15 years and requiring large volumes of MPB trees.

Sawmill residues comprise several products and for this study the bark content in the residue surplus has been estimated at 55% of the total surplus volume (NRCan/CFS, 2005) . In this study bark is considered a future feedstock for pellets (Melin, 2007), which is not commercially proven yet for high bark contents. Considering ethanol, roadside residues are discarded as potential feedstock due to high bark contents and difficulties in separating this bark from the whitewood (MacDonald, 2007).

Regional specific characteristics (climate conditions, competing industries) are not taken into account in this study and therefore constrain the accuracy of outcomes in the individual regions. Most conditions, as described for the scenarios, are applied in a general way for all regions and the province as a whole.

Regarding transport by rail, congestion is likely to take place when up scaling production volume of end-products. In the current situation already train carts are queued to enter terminals sites due to under capacity of the rail tracks and terminals (Melin, 2007). To make (large volumes) future trade happen, infrastructure needs to be improved. Costs to expand infrastructure are substantial, and not likely to be covered by private companies.

Since the lumber and biomass industry in BC are currently subjected to change, due to recent developments in MPB and other contingencies, data for parameters have already been changed over the course of this research. The depreciation of the US dollar and the MPB projections are apparent examples of adjusted data. Therefore, selecting smaller time frames would benefit the consistency of data. Moreover, it would be recommendable to redo this study with more up to date data in future years.

**Scope**

Competition between pellets and ethanol is beyond the scope of this study and has therefore not been further analyzed. Therefore, after allocating a certain part of the feedstock to other industries (due to competition), this study provides the feedstock potential for biomass end-product industries as a whole. When calculated future potentials either all feedstock is destined to pellet production or ethanol production. If ethanol turns out to be economically feasible in the next decade, certainly competition between biomass end-products will occur. This will impact the availability of feedstock for other biomass end-products (e.g. pellets).

The scale of the ethanol production plant is crucial regarding cost calculations. This study assessed four different scales in the sensitivity analysis (100/200/400/1000MW ethanol output). However, depending on feedstock supply, the scale could be even much larger which reduces cost considerably and therefore the ethanol potential for BC. Most desirable would be outcomes providing a certain optimum plant size for each region but is beyond the scope of this study.

An enclosed supply area has been selected determined by geographical and logistical constraints. Within this area feedstock availability versus costs has been determined. Despite the fact that more feedstock is located beyond these predefined boundaries, this part is not taken into account in this study for the reason that the potential is very limited in terms of costs. Moreover, this requires system changes which are beyond the scope.

**Ranges in outcomes**

Outcomes of total costs of end-products differ substantially regarding individual feedstock and end-product scenarios (especially for 2020). From the before mentioned discussion points, high ranges in outcomes were expected. Instead of a detailed sensitivity analysis, this study shows ranges in outcomes by constructing lower and upper boundary scenarios (determined by the influencing parameters). Therefore, the actual outcome most likely exists in between these projected outcomes.

Regarding the feedstock scenarios, the assumed ‘rate of technological development’ determines the feedstock cost structure the most. The feedstock volume is mainly influenced by competition (e.g. from lumber industry and co-generation) and the policy stance towards MPB killed trees harvesting.

Concerning pellet scenarios, total costs are strongly influenced by technical development rates which reduces the production costs the most. Furthermore, the cost of feedstock becomes very important when all cheap feedstock (i.e. sawmill residues) has been used.

The ethanol scenarios are most influenced by the development in conversion factors which directly impacts feedstock costs since more feedstock is required when the efficiencies are low (Table 22). This is true especially when feedstock costs are relatively high (e.g. MPB killed trees). Moreover, the scale factor influences the production costs significantly (Table 21 & Figure 65) and therefore determines the economical potential of ethanol in BC to a large extent. The uncertainty of this 2$^{nd}$ generation ethanol technology makes accurate future assumptions difficult which generates a large range of outcomes and limits the viability these results to some extent.

Overall, the market price and demanded volume from several regions in the world is a significant factor determining the market potential for pellets and ethanol in the near future.

**Addition remarks**

Up scaling production capacity for biomass end-product requires additional feedstock. When sawmill residues are not available anymore, feedstock has to be gathered from the forest. This induces increasingly trucks to haul biomass feedstock to the production plants. Since in-forest roads are very narrow it becomes complicated when many trucks are using these same roads. Therefore, limits exist in the amount of trucks hauling feedstock in a certain area and still complying with safety standards and other constraints. This practical issue needs to be taken into account when planning large scale forest operations.

Transportation of woody biomass feedstock (chips) from forest to a processing plant through pipelines has been investigated by Kumar (2004). The author states that when establishing a large scale plant, requiring very large quantities of feedstock every year, chips conducting through pipelines from the forest to the plant could prevent truck congestion on roads. Therefore, instead of hauling chips for more than 300km one-way, feedstock is brought to a central gathering point in a forest area and chipped on site before it goes in the pipeline. Results from this study show that, in the case of supplying a power plant, projects are economically feasible with carbon credits ranging between $18 - $36/tonne of $CO_2$ (Kumar, 2004).

Rather than hauling chips from the forest to the processing plant, on-site processing could take place as well. In this case, mobile units (for instance, mounted on trucks) together form a small processing plant and convert wood into bio-oil. The density of bio-oil is much higher (1200 kg/m$^3$) than the density of chips (350 kg/m$^3$). Special tanker trucks transport this liquid from the forest to other plants to convert the bio-oil into a range of end-products. By applying this on-site processing system a significant reduction in transportation costs per Odt can be attained. A requirement here is that cheap transportation costs should offset the cost for small scale on-site processing, which is in principal more expensive (Badger & Fransham, 2005; Tampier et al., 2006).

In light of sustainable forestry management some other implications potentially could play a role regarding biomass end-products[6]. If this way of forest management would be applied for the rest of BC, clear cutting would not be allowed anymore and roadside residues would preferably be left at the forest floor to regenerate nutrients for the soil (Koot, 2007). Total roadside residues volumes available as feedstock would decrease

[6] At the UBC research-forest close to Williams Lake (BC), sustainable forestry is aimed for. This kind of forestry uses alternative ways of harvesting (selective harvesting rather than clear cut) and tries to attain a healthy and dynamic forest, comprising a diverse habitat of trees species and respecting wildlife.

significantly. However, opportunities exist in (previously mentioned) thinnings[7]. Implementing this in the BC's forestry would primarily result in increasing volumes of feedstock for biomass end-products and reduces the risk of forest fires considerably. The latter could potentially save money otherwise spend in preventing forest fires and furthermore in terms of maintaining capital stock (i.e. production forests) (Baxter, 2004). Governments could take this into account and support thinning activities. However, currently thinnings as feedstock for biomass end-products in BC are not economically proven yet, and requires radical system changes.

In Alberta several projects have been initiated using biomass feedstock to fuel co-generation plants. The provincial government supported this development with a substantial financial incentive for each produced $kWh_e$. As a consequence cheap feedstock is purchased from sawmills resulting in unfair competition for feedstock with regard to other industries requiring sawmill residues as feedstock. In case the BC's government was to decide to support large scale co-generation power plants, this would lead most likely to unfair competition in BC as well. Governmental policy, therefore, is crucial for the future of biomass end-products.

Depending on the end-product production process and the applied logistical supply chain differences exist in the amount of required energy input, and energy losses during conversion processes. For instance, ethanol production efficiencies in specified scenarios ranged from 22.5–55% (Table 22). This implies that in some cases 77.5% of the energy input (from biomass feedstock) is not converted into the desired end-product[8]. Pellet production efficiencies ranged from 86.5-89% efficiency (Table 18), however taking into account all other logistic steps would reduce the overall efficiency for both investigated end-products. Future BC policy could focus at most efficient products and chains to contribute most to sustainable forest management in BC.

[7] Maintaining the vitality of trees and improving future abilities for harvesting by removing side branches and underdeveloped stems. This could take place several times during the life cycle of the tree. This forms part of the forestry practices in Finland and provides additional biomass over the life-span of a forest .

[8] however, the production of co-products could offset the low efficiency to some extent

# 8. Conclusions & Recommendations

The objective of this study was to identify opportunities to develop the biomass potential for the province of British Columbia under varying scenarios projected from the present (2008) until the year 2020. By modelling specific supply chains and cost supply curves, results have been generated, presenting market potentials for international biomass trade from BC to markets in other parts of the world.

The main conclusion of this thesis is that, in most of the selected scenarios, ***BC has significant opportunities for biomass trade within the stated timeframe (2008-2020)***. A substantial share of the available feedstock in BC could be converted into profitable biomass end-products. Cost reduction throughout the supply chain and increases in market prices creates potential for extensive expansion in the biomass industry in BC. BC, therefore, could play a significant role on the global biofuels market.

**Feedstock**

Table 31 shows the total availability of all feedstock surpluses in the selected areas of BC regarding FS 1. Higher and lower cost estimations provide a range of outcomes with the lowest costs boundary estimated for the shortest transportation distance for roadside residues and MPB killed trees.

MPB killed trees are currently not available for biomass end-products but would start at $99.7/Odt. As a consequence of the relatively high volumes of MPB killed trees, transportation costs increase gradually when increasing the supply.

**Table 31: feedstock end-results for FS 1, BC. The lower case cost projection for sawmill residues indicates the first purchased Odt and the highest projected cost indicates the last available Odt sawmill residues. A cost rise for sawmill residues is assumed due to feedstock competition at sawmills**

| *Feedstock costs* | | **2008** | **2012** | **2020** |
|---|---|---|---|---|
| **Sawmill residues** | Costs (US$/Odt)<br>Volume (Million Odt/yr) | 17.0-28.4<br>1.3 | 17.0-28.4<br>1.3 | 17.0-28.4<br>1.3 |
| **Roadside residues** | Costs (US$/Odt)<br>Volume (Million Odt/yr) | 43.7-86.2<br>5.0 | 40.3-79.0<br>5.5 | 34.3-67.4<br>5.9 |
| **MPB trees** | Costs (US$/Odt)<br>Volume (Million Odt/yr) | 99.7-…<br>n.a. | 95.9-109.7[9]<br>36.7 | 81.7-103.0[10]<br>15.0 |

Most favourable feedstock scenarios show reduced costs for roadside residues and MPB trees for 2012. At 2012, FS 2 shows roadside residue of 37.2-73.5$/Odt and MPB killed trees of 87.8-105.8$/Odt (Figure 26). The expectations for 2020 show further cost reductions in feedstock and lower the marginal cost at 28.7-53.4$/Odt for roadside residues and 63.3-88.6$/Odt for MPB killed trees, in FS 2 (Figure 27).

[9] Higher end value presented for a level of 10 million Odt MPB killed trees. However, the total volume of MPB killed trees is much higher (Appendix 10).

[10] Higher end value presented for a level of 10 million Odt MPB killed trees. However, the total volume of MPB killed trees is much higher (Appendix 10).

From the selected regions in BC, Prince George has the largest forest area and ongoing lumber industry. Therefore, this region has the largest feedstock volume available (approximately 39% of total in BC).

**Pellet market potential**

Pellet production in BC has faced rapid expansion in production volume over the last decade. With reference to the availability and current costs of feedstock in the several feedstock scenarios (as stated in this study), pellet production could expand significantly. Given favourable market conditions (price level of $6.7/GJ) and cost reductions in pellet production, BC could cover a significant part of EU's assumed demand (from outside the EU) for 2012 (Figure 45). The total assumed EU's demand[11] for 2012 is 90 PJ/yr (i.e. 5 million Odt/yr) from which BC could supply in the highest case 60.9 PJ/yr (FS 1) and in the lowest case 24.8 PJ/yr (FS 4). For the year 2020, FS 1 and FS 2 show outcomes that meet the entire projected EU demand of 218 PJ (12.1 Million Odt/yr) considering favourable market conditions (price level of $8.2/GJ) (Figure 33). This produced volume is 20% more than the global wood pellets production estimated for 2007 (Swaan, 2006). However, moderate scenarios for 2020 show BC pellets export to the EU of approximately 50 PJ/yr (FS 4), even at high price levels (Figure 33).

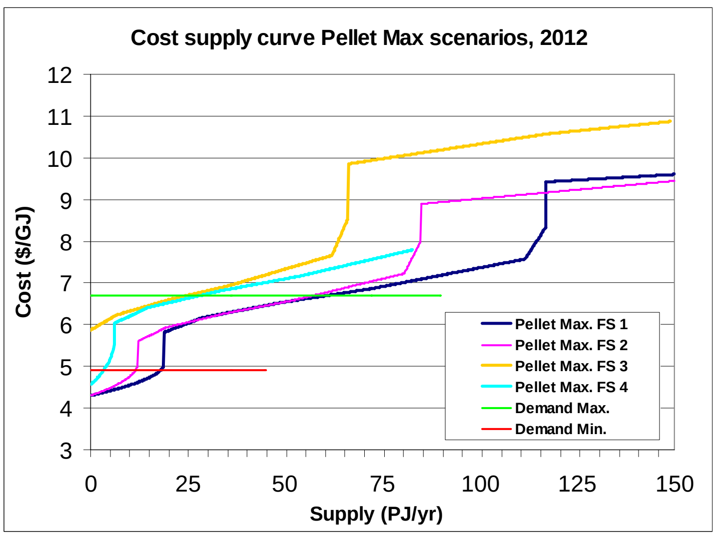


**Figure 45: pellet Max scenario 2012, BC**

**Ethanol market potential**

Ethanol production in BC from woody biomass (at present still in experimental phase) shows great possibilities for international trade in the near future (2020). Expected conversion efficiencies for the production of ethanol differ substantially among studies, which is translated into the various constructed scenarios.

For 2012, ethanol-Max scenarios show still marginal production potential (Figure 46), even regarding the higher assumed price levels (demand-Max). The results from Figure 46 are based on a 400MW (ethanol output) scale plant, described by the dotted line which represents the production volume for one plant. Therefore, when exclusively using cheap

[11] Demand from outside the EU. See also Table 25.

feedstock a smaller scale plant is required inherently having higher production costs. The ethanol market potential for 2012 could be increased by incentives, for instance subsidies per produced ethanol volume.

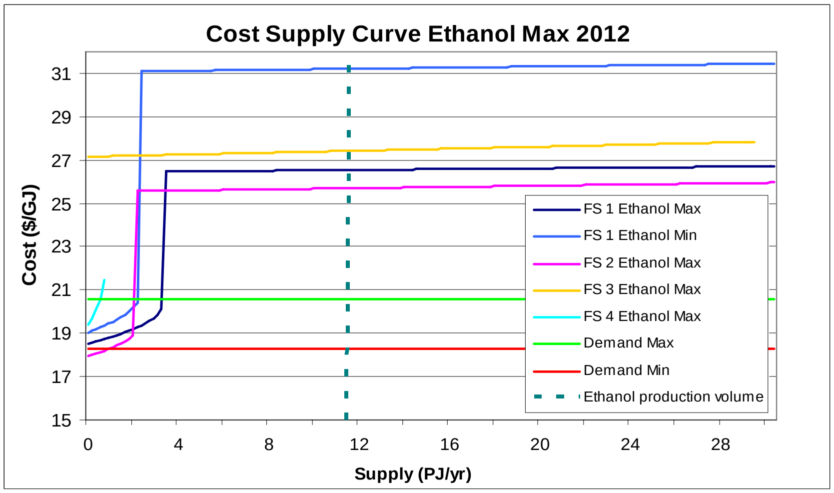


**Figure 46: cost supply curves ethanol BC, 2012**

The ambitious expectations in improvements of conversion efficiencies and cost reductions for the ethanol-Max scenarios for 2020, leads to very large ethanol trade potentials from BC to other markets in the world. Optimistic ethanol production scenarios (ethanol-Max scenarios) are economically feasible up to 154 PJ/yr[12] to meet the demand of the EU, BC, and a small part of the US demand (Figure 47). This equals approximately 21% of the global ethanol production volume for fuel use in 2005 (Walter et al., 2007). Taking the lower case (ethanol-Min scenario) the ranges of production capacity will be at 0-59 PJ/yr regarding highest price assumptions (demand-Max). Assuming ethanol market prices at the lowest price level (demand-Min) only very limited potential exists.

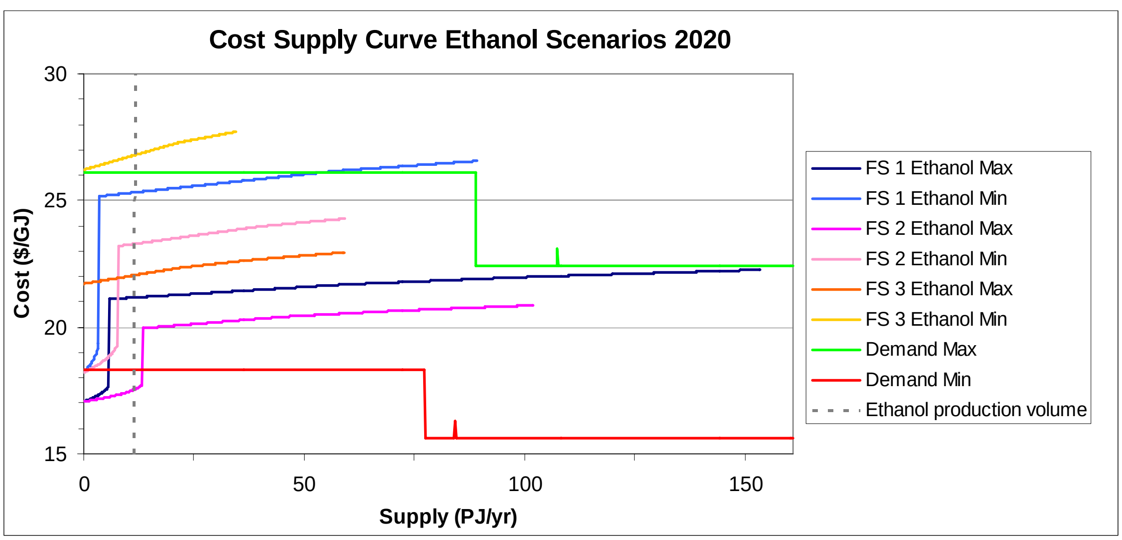


**Figure 47: cost supply curves ethanol scenarios BC, 2020**

[12] At an average total cost of $21.6/GJ regarding a 400MW ethanol output plant.

Increasing the plant scale results into significant costs reductions and increases the market potential substantially (Figure 41). For the Prince George region, 1000MW production plants could be feasible with production cost ranging from 16.0-16.5$/GJ (Table 30). However, large scale ethanol production volumes only can be achieved by using large volumes of MPB killed trees as feedstock besides sawmill residues. Since feedstock costs estimations in this study are based upon regional scale estimates (within region transportation distances), applying large scales plants in calculations do have limitations. The Prince George region has the largest share of the potential ethanol production in BC; an approximate 39% of the total.

In conclusion, BC has significant opportunities for biomass trade within the stated timeframe (2008-2020). A substantial share of the available feedstock in BC could be converted into profitable biomass end-products. Future pellet production potentials for BC (regarding 2020) exceed the global pellet production (for 2007) and future ethanol production volumes could reach 21% of global ethanol volumes (for 2005). BC, therefore, could play a major role on the global biofuels market. If costs can be reduced (regarding the feedstock supply chain and end-products production) and market prices will increase, the biomass industry in BC could develop into a highly profitable sector.

**Recommendations for policy**

The availability of cheap feedstock is essential to produce an affordable biomass end-product. Allowing MPB killed trees to be utilized as feedstock would broaden the total feedstock availability significantly. The provincial government could play a key role in supporting the biomass industry in BC to become successive. Besides granting permits to utilize MPB trees and reducing stumpage fees the biomass industry could be stimulated by research & development projects along the supply chain, to attain cost reductions.

In addition to provincial conditions, developments in foreign markets (regarding energy and climate policy) will influence the market potential as well. Stringent climate policies, in for instance the EU, could create favourable price conditions for biofuels which makes international trade a viable option. On the other hand, low prices for biofuel products from the developing world could induce severe competition for biofuels export to the EU. Therefore, BC’s policy with the aim to increase the successfulness of the bioenergy industry is to some extent deprived by the global development and market forces.

The current availability of MPB killed trees is enormous. However, when most trees cannot be used anymore for biomass end-products (due to decay after 15 years), the availability of this feedstock declines considerably. Industries which are dependent on high volumes of MPB killed trees as main feedstock then need to shift to alternative feedstock sources. This is important to take into account when establishing new plants requiring large quantities of feedstock. A possible feedstock substitute could be short-rotation crops (e.g. willow), which is already applied in Sweden.

**Suggestions for further research**

This study is based upon estimations for sawmill residues for 2005, deduced from expert knowledge and literature studies. Estimations from different sources vary considerably in particularly due to recent increases in lumber production volumes caused by MPB outbreaks. To get more detailed results for end-products produced with sawmill residues as feedstock, more investigation concerning sawmill waste streams is required. Furthermore, distinguishing those waste streams into the several products (e.g. bark, chips and shavings) provides more specific information of the availability of feedstock regarding the production of pellets and ethanol.

Volumes of roadside residues have been estimated based on a small amount of test sites in BC. Since regions in BC have different climate conditions and tree yields, it is likely that for certain areas fewer roadside residues are available than others. More samples of roadside residue across BC will increase the accuracy of expected available volume.

In this study, 5 forest regions were selected and their biomass trade potential was assessed. However, many scenario parameters (for instance competition in feedstock) were applied to the province as a whole and linearly translated to the individual regions. The quality of outcomes, for every region could be improved by taking into account the regional context. This includes the located industries (competitors for feedstock), geographical constraints which limits the accessibility of feedstock (mountains, rivers) and climate (affects MPB tree decay). GIS software might be a solution to implement these geographical constraints.

A demand figure for current and future biomass trade has been defined by using a basic approach. Straight horizontal lines represent demand lines, which is relatively easy to create and interpret. However, more realistic demand lines can be generated by using economic models, which include price elasticity in commodity products. This approach is beyond the scope of this study but would be a valuable extension to improve demand lines and therefore future expectations for biomass trade.

Only two biomass end-products have been investigated for biomass trade potentials, pellets and ethanol. Using the same feedstock, many other end-products could be produced, for instance Bio-oil, Fischer-Tropsch diesel and torrified wood pellets. Potentials of these end-products could be assessed using the feedstock potentials in BC as mentioned in this study. Moreover, alternative supply chains as described in the Discussion section could contribute to new insights regarding BC's feedstock potentials.

Considering the BC forest as a finite energy source, it would be valuable to assess differences in several supply chains in terms of energy efficiency. In order to know how energy could be extracted from the forest in the most effective and efficient way with the least overall energy losses. This could provide useful insights regarding sustainable forestry management.

Competition in forest resources between several industries is difficult to assess, especially regarding the future situation. Relationships between industries are important to take into account, since some industries provide feedstock required by others. It would be valuable to map all interactions and mass flows industries have within the forestry sector, and to address the underlying drivers. Further research could clarify these relationships more and therefore could improve future estimations concerning feedstock and end-products.

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# Appendices

# Appendix 1: Potential explained

A widely used concept in studies considering future scenarios is the concept 'potential'. To clarify how this relatively broad concept is being applied in this research, defining the concept is a useful first step. The concept potential can be distinguished into 6 different kinds as described by Blok (2006):

- *Theoretical potential*
  Describes in terms of physical limits what can be achieved. One can think of thermodynamic constraints when looking at energy conversion processes.
- *Technical potential*
  Gives the ability of technologies in a certain year to perform a certain task. This could be a percentage of the theoretical potential. It is likely that over the years this potential increases caused by technological development.
- *Economic potential*
  A certain part of the technical potential that is economically attractive taking into account the social perspective which implies the positive NPV (net present value) at a social discount rate.
- *Profitable potential*
  The part of the technical potential which is both economical attractive and also attractive for the private investor because there is a potential to make profit.
- *Market potential (*also *implementation potential)*
  The part of the technical potential which is likely to be implemented, considering all barriers and stimuli for adopting these new technologies.
- *Enhanced market potential*
  The market potential considering also the incentives and barriers which are not only derived from economics only, but also related policy.

One can see that every step downwards implicates a reduced share of the initial possibility. Therefore, the theoretical potential and enhanced market potential are the two extremes. Projecting the described potentials for this thesis will generate the following situation:

- *Theoretical potential*: Using all MPB trees, all available roadside residues and all sawmill residues available.
- *Technical potential*: Using MPB trees that can be harvested by current (or year 2020) technology, collecting all roadside residues with these technologies and using all sawmill residues.
- *Economic potential*: Same as technical potential, but as a restriction that these processes should have a positive NPV based on a social way of reasoning.
- *Profitable potential*: Same as technical potential, with the restriction that the processes are feasible for private entrepreneurs to invest in.
- *Market potential*: Part of the MPB, harvest residues and sawmill residues which is likely to be used for further processing.

- *Enhances market potential*: The amount of harvested MPB, harvest residues and sawmill residues used for further processing taking into account relevant policy stimuli and barriers (Blok, 2006).

In the same way this inventory could be made for pre-treatment technologies and transportation in the biomass supply chain to see the differences between the various potentials. Because policy will not be elaborated in great detail, this study aims at the definition of economic and market potential for the components of pre-treatment and transport, which gives the likely implementation rate of the biomass sector in Canada. However, for the potential considering harvesting biomass feedstock the technical potential will be applied since this reveals the total future feedstock perspectives given a certain price. The processing industry can always decide whether to accept this higher price or not.

# Appendix 2: The supply chain spreadsheet

An overview of the spreadsheet is presented in Figure 48. Runs in the spreadsheet have been conducted using the data as given in Appendices 10-17.

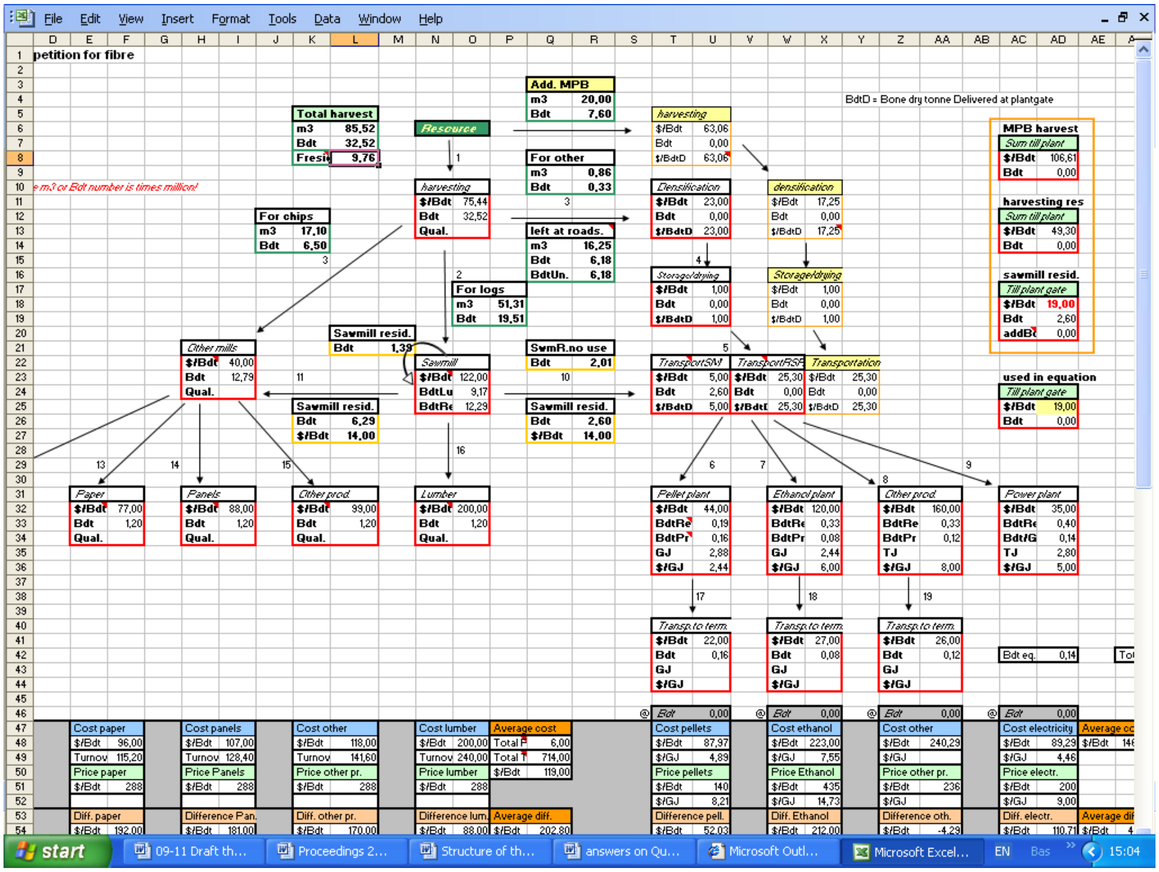


Figure 48: supply chain spreadsheet

## Appendix 3: Current AAC levels per region

| Regions and sub-regions | Coverage[13] (in %) | TSA m3 | TFL m3 | Total AAC[14] Roadside res. m3 | Total AAC[15] Sawmill res. m3 |
|---|---|---|---|---|---|
| ***-Prince George*** | | | | ***22916500*** | ***25864000*** |
| Fort Nelson | 50 | 1625000 | | 812500 | 1625000 |
| Fort St. John | 100 | 2115000 | | 2115000 | 2115000 |
| Dawson Creek | 100 | 1860000 | 900000 | 2760000 | 2760000 |
| Mackenzie | 30 | 3050000 | | 915000 | 3050000 |
| Prince George | 100 | 14944000 | 1370000 | 16314000 | 16314000 |
| ***-Prince Rupert*** | | | | ***8211559*** | ***8430001*** |
| Lakes | 100 | 3162000 | | 3162000 | 3162000 |
| Morice | 100 | 1961117 | | 1961117 | 1961117 |
| Bulkley | 100 | 882000 | | 882000 | 882000 |
| Kispiox | 100 | 977000 | | 977000 | 977000 |
| Kalum | 50 | 436884 | 1011000 | 1229442 | 1447884 |
| ***-Cariboo*** | | | | ***9979000*** | ***13920000*** |
| Quesnel | 80 | 5280000 | 870000 | 5094000 | 6150000 |
| Williams lake | 50 | 5770000 | | 2885000 | 5770000 |
| 100 mile house | 100 | 2000000 | | 2000000 | 2000000 |
| ***-Kamloops*** | | | | ***6858921*** | ***6858921*** |
| Kamloops | 100 | 4352770 | 490000 | 4842770 | 4842770 |
| Lillooet | 100 | 635900 | | 635900 | 635900 |
| Merritt | 30 | 2814171 | | 844251 | 844251 |
| Robson Valley (North int.) | 100 | 536000 | | 536000 | 536000 |
| ***-US Border*** | | | | ***7286900*** | ***9956820*** |
| **-Kamloops** | | | | **4091520** | ***6116520*** |
| Merritt | 70 | 2814171 | | 1969920 | 1969920 |
| Okanagan | 40 | 3375000 | 771600 | 2121600 | 4146600 |
| **-Nelson** | | | | **3195380** | ***3840300*** |
| Boundary | 100 | 700000 | 175000 | 875000 | 875000 |
| Arrow | 50 | 550000 | 760000 | 1035000 | 1310000 |
| Kootenay Lake | 60 | 681300 | | 408780 | 681300 |
| Cranbrook | 90 | 974000 | | 876600 | 974000 |
| Total | | 58682142 | 6347600 | ***55252880*** | ***65029742*** |

**Source: (BCMOF, 2007b)**

[13] The coverage rate describes for every sub-region the percentage of the surface area enclosed in this study. This enclosed area estimated and is situated in Figure 22 and Figure 23.
[14] Total AAC for roadside residues is calculated by adding up TSA (taking into account the coverage area) with TFL volumes.
[15] Total AAC for sawmill residues is calculated without taking into account the coverage area since it is assumed that sawmills get there feedstock from the whole forestry region, and that sawmills are located within the enclosed regions.

# Appendix 4: Sawmill residue volumes

In Table 32, the AAC levels are shown for each region. The part destined for sawmills is 75.7% of the total AAC (Melin, 2007). The LR is 48% which implies that 52% of the total mass is converted into sawmill residues. From the report of NRCan (2005) the volumes of sawmill residues (excluding chips) are acquired (NRCan/CFS, 2005). Furthermore, the consumed volume for sawmill residues is estimated as shown in Table 32 for 2004. Based on that, the total volume for ´chips and others´ is calculated (chips and others = total – consumed – surplus). This value is essential to know which volume (of chips) will likely be reserved for other industries in future years.

**Table 32: production and consumption sawmill residues 2004**

| region | AAC | part for sawmills | total sawmill residues | production excl chips | chips and others | consumed 2004 | surplus 2004 |
|---|---|---|---|---|---|---|---|
| | Mill. m3 | Mill. m3 | Mill. Odt | Mill. Odt | Mill. Odt | Mill. Odt | Mill. Odt |
| *Prince George* | 25,86 | 19,58 | 3,871 | 2,670 | 1,201 | 1,597 | 1,073 |
| *Prince Rupert* | 8,43 | 6,38 | 1,262 | 0,625 | 0,637 | 0,341 | 0,284 |
| *Cariboo* | 13,92 | 10,54 | 2,083 | 1,187 | 0,896 | 0,980 | 0,207 |
| *Kamloops* | 6,86 | 5,19 | 1,027 | 0,924 | 0,103 | 0,785 | 0,139 |
| *US border* | 9,96 | 7,54 | 1,490 | 1,146 | 0,344 | 1,034 | 0,112 |
| total | 65,03 | 49,23 | 9,733 | 6,552 | 3,181 | 4,737 | 1,815 |

After 2004, mayor changes took place in the forestry sector. The pellet industry has grown strongly together with the demand for sawmill residues[16]. In Table 33, the demanded sawmill residues volume for pellet production is shown in the first column (NRCan/CFS, 2005). In the next column, the current (2008) production volumes are given, showing a significant increase compared to 2004 (Melin, 2007). To calculate the feedstock requirements for this production volume the conversion factor of 0.865 is applied. This implies that for every Odt feedstock 0.865 Odt of pellets is produced. The difference of the pellet feedstock demand for 2004 in comparison to the 2008 situation, results in the additional feedstock use with regard to the 2004 situation. The outcome can be added to the consumed sawmill residues for 2004 (Table 32).

**Table 33: pellet production and sawmill residues consumption 2004-2008**

| region | 2004 feedst pellets | 2008 pellet production | feedstock required | additional feedstock | consumed 2008 | surplus 2008 |
|---|---|---|---|---|---|---|
| | Mill. Odt | Mill. Odt | Mill. Odt | Mill. Odt | Mill. Odt | Mill. Odt |
| *Prince George* | 0.240 | 0.260 | 0.301 | 0.061 | 1.658 | 1.013 |
| *Prince Rupert* | 0.000 | 0.160 | 0.185 | 0.185 | 0.526 | 0.099 |
| *Cariboo* | 0.120 | 0.260 | 0.301 | 0.181 | 1.161 | 0.027 |
| *Kamloops* | 0.000 | 0.075 | 0.087 | 0.087 | 0.872 | 0.052 |
| *US border* | 0.114 | 0.130 | 0.150 | 0.036 | 1.070 | 0.076 |
| total | 0.470 | 0.885 | 1.023 | 0.549 | 5.286 | 1.266 |

[16] It is likely that other industries have grown as well but due to a lack of data only the pellet production has been taken into account to calculate sawmill residues surplus adjustments.

## Appendix 5: MPB estimates per region

| Region | Pine trees (Mill.m3) | 2006 | 2010 | 2018 | 2006 | 2010 | 2018 |
|---|---|---|---|---|---|---|---|
| | | % killed trees | | | volume killed trees (Mill.m3) | | |
| ***-Prince George*** | | | | | **145.3** | **276.2** | **284.8** |
| Fort Nelson | n.a. | n.a. | n.a. | n.a. | 0 | 0 | 0 |
| Fort St. John | n.a. | n.a. | n.a. | n.a. | 0 | 0 | 0 |
| Dawson Creek | 30.9 | 1 | 75 | 81 | 0.3 | 23.2 | 25.0 |
| Mackenzie | 116.8 | 7 | 71 | 74 | 2.4 | 24.9 | 25.9 |
| Prince George | 285.2 | 50 | 80 | 82 | 142.6 | 228.1 | 233.8 |
| ***-Prince Rupert*** | | | | | **72.9** | **109.9** | **113.6** |
| Lakes | 71.0 | 72 | 81 | 82 | 51.2 | 57.6 | 58.3 |
| Morice | 57.1 | 37 | 73 | 78 | 21.1 | 41.7 | 44.5 |
| Bulkley | 13.2 | 5 | 81 | 82 | 0.6 | 10.7 | 10.8 |
| Kispiox | n.a. | n.a. | n.a. | n.a. | 0 | 0 | 0 |
| Kalum | n.a. | n.a. | n.a. | n.a. | 0 | 0 | 0 |
| ***-Cariboo*** | | | | | **147.7** | **172.2** | **175.5** |
| Quesnel | 111.0 | 80 | 82 | 82 | 71.0 | 72.8 | 72.8 |
| Williams lake | 143.6 | 53 | 75 | 78 | 38.1 | 53.9 | 56.0 |
| 100 mile house | 57.6 | 67 | 79 | 81 | 38.6 | 45.5 | 46.7 |
| ***-Kamloops*** | | | | | **33.1** | **77.4** | **81.0** |
| Kamloops | 58.8 | 44 | 76 | 77 | 25.9 | 44.7 | 45.3 |
| Lillooet | 19.5 | 16 | 80 | 81 | 3.1 | 15.6 | 15.8 |
| Merritt | 66.2 | 16 | 63 | 76 | 3.2 | 12.6 | 15.1 |
| Robson Valley | 6.2 | 15 | 74 | 77 | 0.9 | 4.6 | 4.8 |
| ***US Border*** | | | | | **15.2** | **77.6** | **92.6** |
| **-Kamloops** | | | | | 9.7 | 45.7 | 52.2 |
| Merritt | 66.2 | 16 | 63 | 76 | 7.4 | 29.2 | 35.2 |
| Okanagan | 57.3 | 10 | 72 | 74 | 2.3 | 16.5 | 17.0 |
| **-Nelson** | | | | | 5.5 | 31.9 | 40.4 |
| Boundary | 15.0 | 5 | 71 | 74 | 0.8 | 10.7 | 11.2 |
| Arrow | 7.9 | 31 | 81 | 83 | 1.2 | 3.2 | 3.3 |
| Kootenay Lake | 13.0 | 13 | 75 | 77 | 1.0 | 5.8 | 6.0 |
| Cranbrook | 30.9 | 9 | 44 | 72 | 2.5 | 12.2 | 20.0 |
| **Total** | | | | | **414.3** | **713.3** | **747.4** |

**Source: (BCMOF, 2007c; BCMOF, 2007d)**

This table shows the observed and estimated MPB killed trees volumes. The coverage rate as presented in Appendix 3 is applied to estimate MPB killed tree volumes within the selected research area.

In Figure 49, a distribution of tree destinations is shown with regard to MPB killed trees. For 2020, only 20% of the cumulative MPB killed volume (peak at 2012) is still in an acceptable condition to harvest for biomass end-products. NRL = Non Recoverable Lumber.

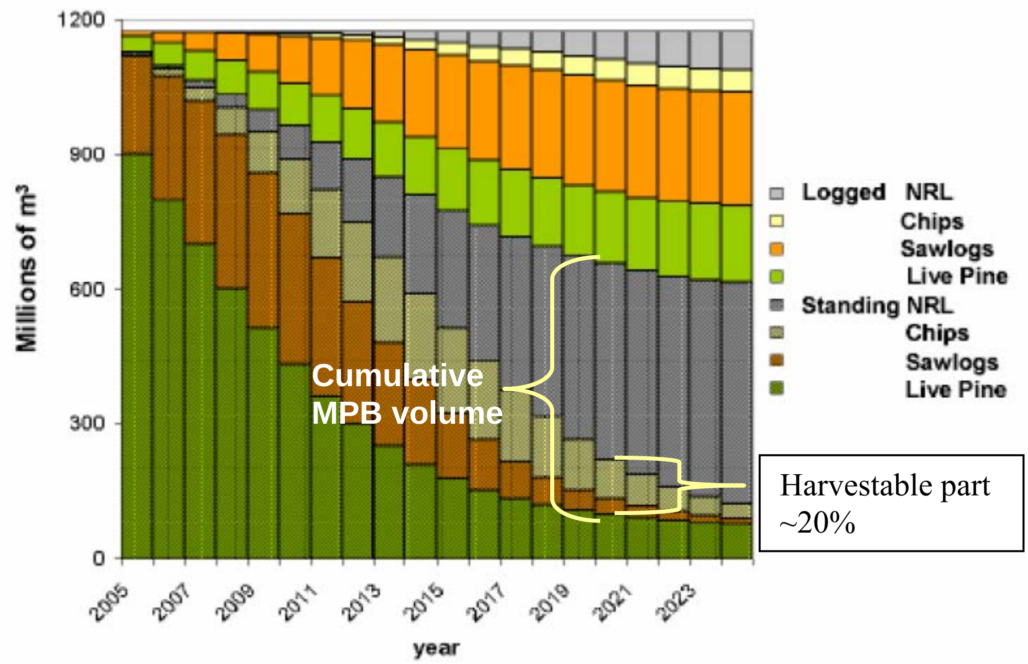



**Figure 49: MPB killed trees developments and MPB trees harvesting rates (Tampier et al., 2006)**

## Appendix 6: Transportation distances per region

| Region | Average estimated distance till terminal* | |
|---|---|---|
| | **Terminal location** | **km** |
| ***-Prince George*** | **average** | **847,9** |
| Fort Nelson | Fort nelson | 1527 |
| Fort St. John | F.st. John | 1178 |
| Dawson Creek | D.Creek | 1128 |
| Mackenzie | Mackenzie | 900 |
| Prince George | P.George | 721 |
| ***-Prince Rupert*** | **average** | **380,6** |
| Lakes | Burns Lake | 492 |
| Morice | Houston | 412 |
| Bulkley | Smithers | 348 |
| Kispiox | Hazelton | 284 |
| Kalum | Terrase | 144 |
| ***-Cariboo*** | **average** | **559,0** |
| Quesnel | Quesnel | 635 |
| Williams lake | Williams Lake | 517 |
| 100 mile house | 100 mile house | 426 |
| ***-Kamloops*** | **average** | **346,4** |
| Kamloops | Kamloops | 357 |
| Lillooet | Lillooet | 250 |
| Merritt | Merritt Clearwater | 273 |
| Robson Valley (North int.) | | 481 |
| ***-US Border*** | | **200,0** |

**Source: (Google Maps, 2007)**

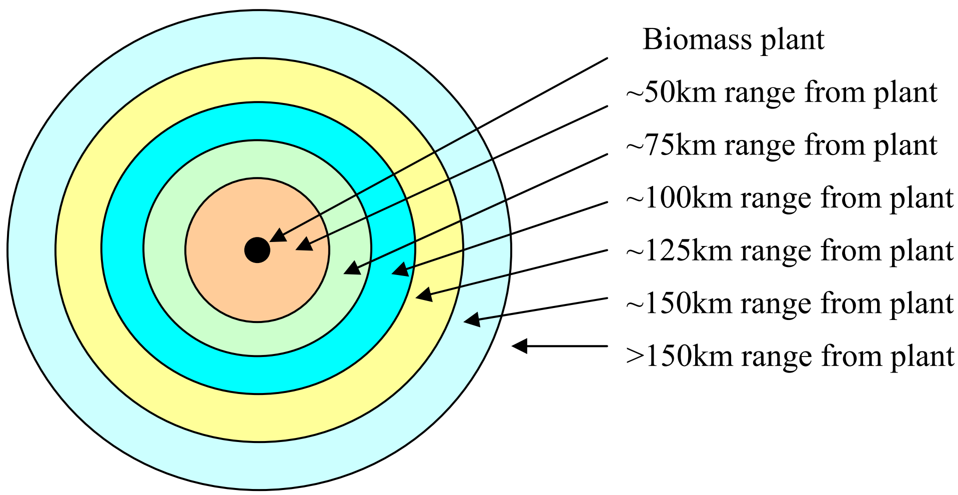
Average distances for regions are calculated based upon feedstock volume per sub region as given in formula (13).

$$d_{average} = [\ (d_{regA} * V_{regA}) + (d_{egB} * V_{egB}) + \ldots + (d_{regN} * V_{regN})\ ] / (V_{total} * N) \qquad (13)$$

Where:
$d_{average}$ = average distance
$d_{regA}$ = distance sub region A to terminal (N is Nth sub region)
$V_{regN}$ = feedstock volume for sub region N
$V_{total}$ = total feedstock volume for the selected region

## Appendix 7: Calculating transportation distance

Logically, the first roadside residues are collected in the nearby harvesting areas. An increase in demand of roadside residues forces biomass industries to collect from places further away where this feedstock is still available. The whole harvesting area could be considered a circle divided into rings. Each ring is located a certain distance from the biomass plant and encloses an area with a certain amount of residues. Collection of residues will take place first within the inner ring since it has the least average distance to the plant. When the feedstock of the smallest ring has been depleted, the subsequent ring is chosen to collect residue from.




Distances to collect roadside residues have been chosen in accordance to log hauling distances logs destined for the lumber industry. Since roadside residues inherently are found at previously harvested areas for the lumber industry, one can consider these areas to be utilized to collect roadside residues. As shown in Table 34 the highest ratio of roadside residues can be found at 100km from the plant (25% of total). Only a certain share of the harvested trees is left behind, which reduces the collection yield per ha. Hauling distances therefore increase faster (jump from small ring to a larger one) than one would notice when taking into account the whole yield of trees in the case of MPB killed trees (MacDonald, 2007).

Roadside residues supplies are allocated as presented in Table 34. An example is shown for a total 6,7 million Odt roadside residues for BC as a whole.

**Table 34: transportation distances roadside residues**

| Transportation distance vs availability | ***Roadside residues*** | | | | | | |
|---|---|---|---|---|---|---|---|
| From harvest till plant | Unit | <50 km | 75km | 100km | 125km | 150km | >150km |
| | Ratio | 0,1 | 0,2 | 0,25 | 0,2 | 0,2 | 0,05 |
| | Mill.Odt | 0,65 | 1,30 | 1,63 | 1,30 | 1,30 | 0,33 |

For the feedstock of MPB trees the same approach is applied. However, in the case of MPB trees new patches of forest will be used to harvest, rather that collecting residues.

This implies that the yield per surface area is significantly more than the roadside residues present for each supply ring0. Table 35 represents how MPB trees supplies have been allocated to the several rings, at 20 million Odt available (MacDonald, 2007).

**Table 35: transportation distances MPB trees**

| Transportation distance vs availability | ***MPB*** | | | | | | |
|---|---|---|---|---|---|---|---|
| From harvest till plant | Unit | <50 km | 75km | 100km | 125km | 150km | >150km |
| | Ratio | 0,10 | 0,10 | 0,15 | 0,20 | 0,20 | 0,25 |
| | Mill.Odt | 2,00 | 2,00 | 3,00 | 4,00 | 4,00 | 5,00 |

## Appendix 8: Ethanol production figure

In Figure 50, two pathways of ethanol production are described: The biological pathway (using enzymes) and the thermoemical pathway.

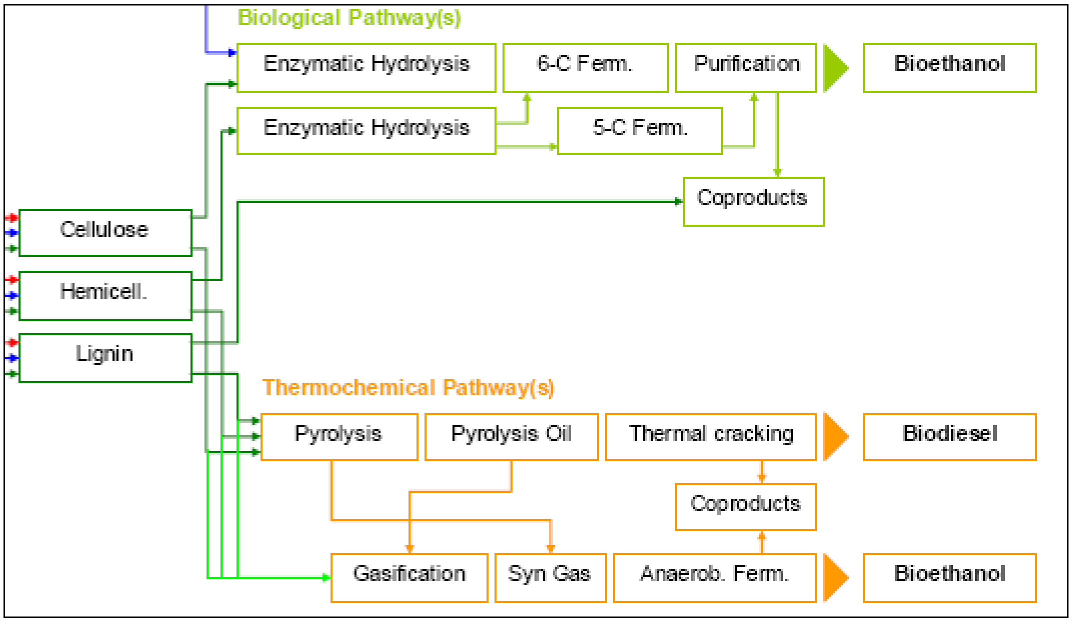



**Figure 50: pathways for ethanol production process (Mabee, 2006)**

Increasing the size of ethanol plants influences the ethanol production costs considerably. As shown in Figure 51 (especially between 100-500MW). The production costs include capital and O&M costs. Feedstock costs and revenues from co-products are not included.

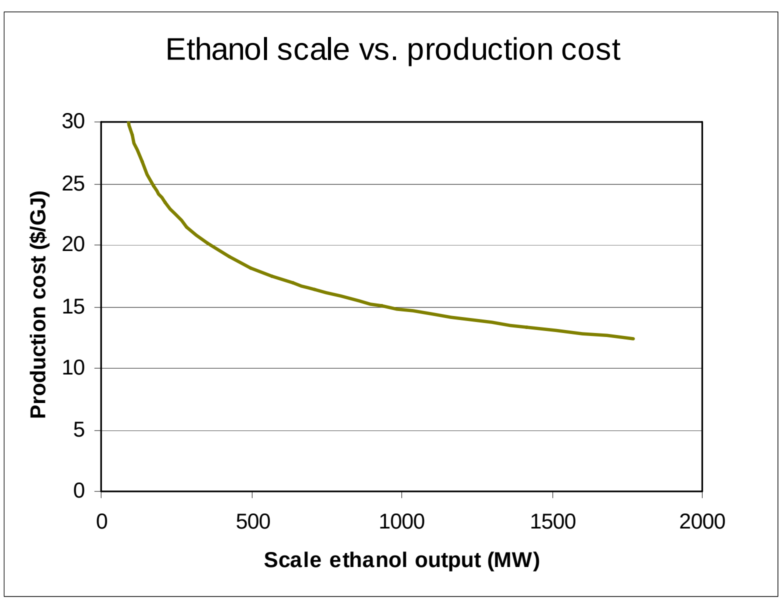



**Figure 51: ethanol scale effects reducing production costs (Hamelinck, 2004)**

## Appendix 9: Trends in lumber industry

The lumber production has grown over the part 25 years and shows fluctuations due to economic growth and corresponding demand (Figure 52).

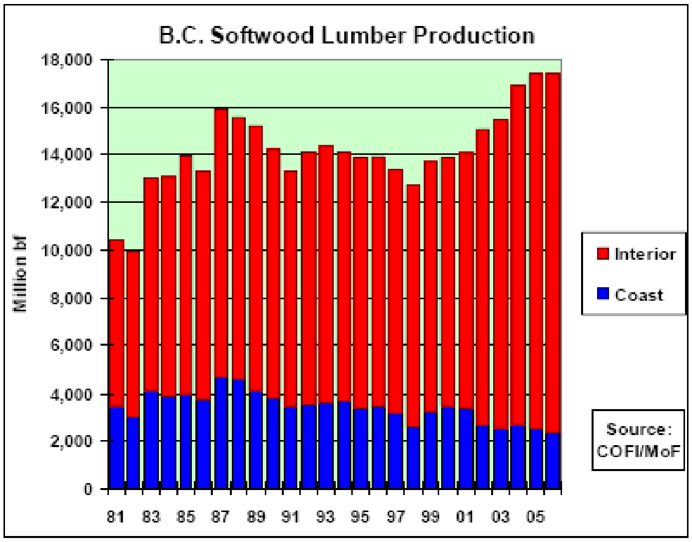
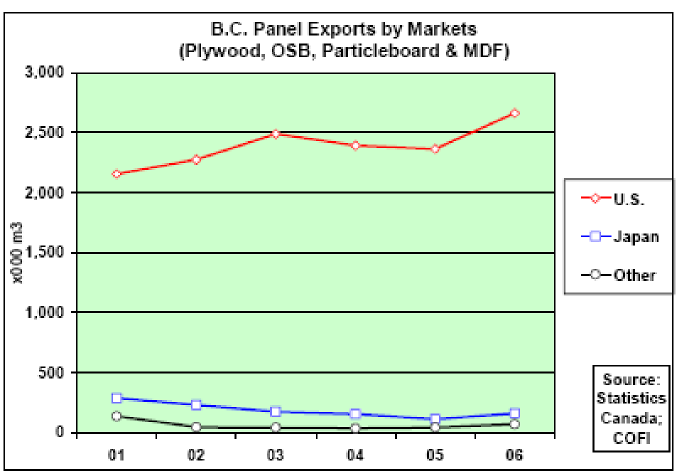



**Figure 52: BC softwood lumber production (International Wood Market Group, 2006)**

The US market is the largest buyer of BC's lumber. Not only timber but also other lumber products (e.g. OSB and particle board) have been exported mainly to the US over the last years as presented in Figure 53. According to the depicted trends an increase of export of panels to the US market is expected to take place.



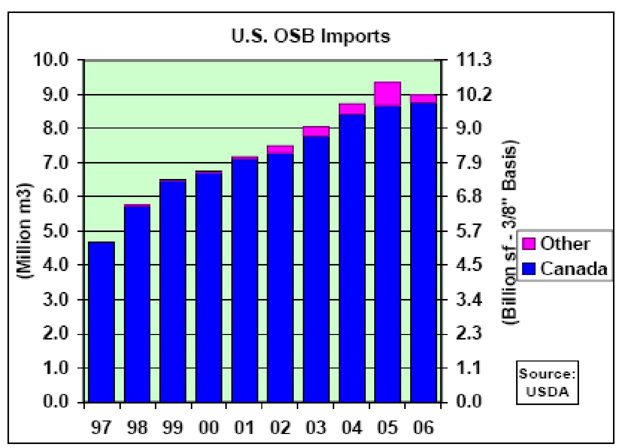




**Figure 53: panel export volumes BC (International Wood Market Group, 2006)**

# Appendix 10: Feedstock scenario 1

| | | Scenario 1 | | | | Availability-Max | |
|---|---|---|---|---|---|---|---|
| *Year* | *Unit* | ***2008*** | | ***2012*** | | ***2020*** | |
| **Feedstock availability** | | Coverage[17] | Sawmill R[18] | Coverage | Sawmill R | Coverage | Sawmill R |
| - AAC rates (total) | $Mm^3/y$ | 55,26 | 65,03 | 55,26 | 65,03 | 55,26 | 65,03 |
| Prince George | $Mm^3/y$ | 22,92 | 25,86 | 22,92 | 25,86 | 22,92 | 25,86 |
| Prince Rupert | $Mm^3/y$ | 8,21 | 8,43 | 8,21 | 8,43 | 8,21 | 8,43 |
| Cariboo | $Mm^3/y$ | 9,98 | 13,92 | 9,98 | 13,92 | 9,98 | 13,92 |
| Kamloops | $Mm^3/y$ | 6,86 | 6,86 | 6,86 | 6,86 | 6,86 | 6,86 |
| US border | $Mm^3/y$ | 7,29 | 9,96 | 7,29 | 9,96 | 7,29 | 9,96 |
| - LR[19] | % | | 48 | | 48 | | 48 |
| - **Sawmill residues surplus (total)** | MOdt[20] | | **1,27** | | **1,27** | | **1,27** |
| Prince George | MOdt | | 1,01 | | 1,01 | | 1,01 |
| Prince Rupert | MOdt | | 0,10 | | 0,10 | | 0,10 |
| Cariboo | MOdt | | 0,03 | | 0,03 | | 0,03 |
| Kamloops | MOdt | | 0,05 | | 0,05 | | 0,05 |
| US border | MOdt | | 0,08 | | 0,08 | | 0,08 |
| - **Roadside residues (total)** | MOdt | **5,05** | | **5.46** | | **5.88** | |
| Prince George | MOdt | 2,09 | | 2,27 | | 2,44 | |
| Prince Rupert | MOdt | 0,75 | | 0,81 | | 0,87 | |
| Cariboo | MOdt | 0,91 | | 0,99 | | 1,06 | |
| Kamloops | MOdt | 0,63 | | 0,68 | | 0,73 | |
| US border | MOdt | 0,67 | | 0,72 | | 0,78 | |
| - Roadside residues[21] | % | 24 | | 26 | | 28 | |
| - **MPB trees (total)** | Mm3 | **0,00** | | **35,66** | | **14,95** | |
| Prince George | Mm3 | 0,00 | | 13,81 | | 5,70 | |
| Prince Rupert | Mm3 | 0,00 | | 5,50 | | 2,27 | |
| Cariboo | Mm3 | 0,00 | | 8,61 | | 3,51 | |
| Kamloops | Mm3 | 0,00 | | 3,87 | | 1,62 | |
| US border | Mm3 | 0,00 | | 3,88 | | 1,85 | |
| - Policy figures[22] | +/- | + | | + | | + | |
| - Rate of Cut of total MPB[23] | % | 0[24] | | 50 | | 50 | |
| **Cost minus transport** | | | | | | | |
| - Techn. development (cost reductions)[25] | % | 2 | | 7.76 | | 21.53 | |
| - **Sawmill residues** | $/Odt | **17** | | **17** | | **17** | |
| - Price at sawmill | $/Odt | 12 | | 12 | | 12 | |
| - Loading/short transportation | $/Odt | 4 | | 4 | | 4 | |
| - Storage costs | $/Odt | 1 | | 1 | | 1 | |
| - **Roadside residues** | $/Odt | **23,00** | | **21,21** | | **18,05** | |
| - Comminuting costs | $/Odt | 23,00 | | 21,21 | | 18,05 | |
| - **MPB trees** | $/Odt | **80,31** | | **74,12** | | **63,14** | |
| - Harvesting costs[26] | $/Odt | 33,73 | | 31,11 | | 26,47 | |
| - Comminuting costs | $/Odt | 17,25 | | 15,91 | | 13,54 | |
| - Stumpage fee | $/Odt | 0,55 | | 0,55 | | 0,55 | |
| - Development costs[27] | $/Odt | 7,86 | | 7,25 | | 6,17 | |
| - Silviculture | $/Odt | 7,10 | | 6,55 | | 5,57 | |
| - Overhead | $/Odt | 13,82 | | 12,75 | | 10,84 | |
| **Transportation cost + loading (truck)** | $/Tkm[28] | Formula: 0,236*d+13.5 | | | | | |
| - Mean distance | km | 100 | | | | | |
| - costs of mean distance | $/Odt | 37,10 | | 34,22 | | 29,11 | |
| **Competition** (Lumber industry etc.) | | | | | | | |
| - **Sawmill residues surplus (total)**[29] | MOdt | **1.27** | | **1.27** | | **1.27** | |
| - Biomass end-products[30] | % | 100 | | 100 | | 100 | |
| - Others | % | 0 | | 0 | | 0 | |
| - **Roadside residues** | MOdt | **5.05** | | **5.46** | | **5.88** | |
| - Biomass end-products | % | 100 | | 100 | | 100 | |
| - Others | % | 0 | | 0 | | 0 | |
| - **MPB trees** | MOdt | **0.00** | | **35.66** | | **14.95** | |
| - Biomass end-products | % | 100 | | 100 | | 100 | |
| - Others | % | 0 | | 0 | | 0 | |

[17] Applying the AAC of the regions confined by the coverage rate as stated in Appendix 3
[18] Applying the AAC of the whole regions for sawmill residues since mills are located within the coverage area but haul logs from the whole region to the mills (Appendix 3).
[19] Lumber Recovery (in % of incoming log volume leaving sawmill as timber) dependent on technological development in sawmills and quality of logs.
[20] MOdt = million oven dry tones; $Mm^3$ = million cubic meters
[21] Percentage of the tree that is left behind at the roadside calculated as a percentage of the wood volume taken away to be used for the lumber industry.
[22] The standpoint of governmental policy towards utilizing MPB trees for the industry.
[23] Percentage of the total available MPB trees which is harvestable (assumed is 50% max. harvest potential due to geograph. constraints) and allowed by governmental regulations.
[24] In the current situation MPB trees are not utilized yet due to policy constraints, however, costs are calculation in case when harvesting would take place.
[25] Cost reduction in % per year as a result of technological development, numbers for 2012 and 2020 are a cumulative cost reduction with regard to 2008.
[26] This includes cutting, felling and skidding the tree to the roadside
[27] This includes road construction, lay-out costs and other capital costs
[28] $/tonne/km
[29] It is assumed that industries currently utilizing sawmill residues will continue to do this in future. Therefore, a set amount (8.47 mill. Odt for BC) is reserved for this industry and is subtracted from total sawmill residues. The surplus is the available sawmill residue after subtraction. See also Appendix 4 for amounts reserved for each region.
[30] The percentage of the stated total (surplus) destined as feedstock for biomass end-products (pellets and ethanol).

# Appendix 11: Feedstock scenario 2

| | | *Scenario 2* | | | *Pro-active* | | |
|---|---|---|---|---|---|---|---|
| *Year* | *Unit* | ***2008*** | | ***2012*** | | ***2020*** | |
| **Feedstock availability** | | Coverage[31] | Sawmill R[32] | Coverage | Sawmill R | Coverage | Sawmill R |
| - AAC rates (total) | $Mm^3$/y | 55,26 | 65,03 | 60,79 | 71,53 | 60,79 | 71,53 |
| Prince George | $Mm^3$/y | 22,92 | 25,86 | 25,21 | 28,45 | 25,21 | 28,45 |
| Prince Rupert | $Mm^3$/y | 8,21 | 8,43 | 9,03 | 9,27 | 9,03 | 9,27 |
| Cariboo | $Mm^3$/y | 9,98 | 13,92 | 10,98 | 15,31 | 10,98 | 15,31 |
| Kamloops | $Mm^3$/y | 6,86 | 6,86 | 7,55 | 7,55 | 7,55 | 7,55 |
| US border | $Mm^3$/y | 7,29 | 9,96 | 8,02 | 10,96 | 8,02 | 10,96 |
| - LR[33] | % | | 48 | | 49 | | 50 |
| - **Sawmill residues surplus (total)** | MOdt[34] | | **1,27** | | **2,03** | | **1,83** |
| Prince George | MOdt | | 1,01 | | 1,32 | | 1,24 |
| Prince Rupert | MOdt | | 0,10 | | 0,20 | | 0,17 |
| Cariboo | MOdt | | 0,03 | | 0,19 | | 0,15 |
| Kamloops | MOdt | | 0,05 | | 0,13 | | 0,11 |
| US border | MOdt | | 0,08 | | 0,19 | | 0,16 |
| - **Roadside residues (total)** | MOdt | **5,05** | | **5,78** | | **5,78** | |
| Prince George | MOdt | 2,09 | | 2,40 | | 2,40 | |
| Prince Rupert | MOdt | 0,75 | | 0,86 | | 0,86 | |
| Cariboo | MOdt | 0,91 | | 1,04 | | 1,04 | |
| Kamloops | MOdt | 0,63 | | 0,72 | | 0,72 | |
| US border | MOdt | 0,67 | | 0,76 | | 0,76 | |
| - Roadside residues[35] | % | 24 | | 25 | | 25 | |
| - **MPB trees (total)** | Mm3 | **0,00** | | **35,66** | | **14,95** | |
| Prince George | Mm3 | 0,00 | | 13,81 | | 5,70 | |
| Prince Rupert | Mm3 | 0,00 | | 5,50 | | 2,27 | |
| Cariboo | Mm3 | 0,00 | | 8,61 | | 3,51 | |
| Kamloops | Mm3 | 0,00 | | 3,87 | | 1,62 | |
| US border | Mm3 | 0,00 | | 3,88 | | 1,85 | |
| - Policy figures[36] | +/- | + | | + | | + | |
| - Rate of Cut of total MPB[37] | % | 0[38] | | 50 | | 50 | |
| **Cost minus transport** | | | | | | | |
| - Techn. development (cost reductions)[39] | % | 4 | | 15,07 | | 38,73 | |
| - **Sawmill residues** | $/Odt | **17** | | **17** | | **17** | |
| - Price at sawmill | $/Odt | 12 | | 12 | | 12 | |
| - Loading/short transportation | $/Odt | 4 | | 4 | | 4 | |
| - Storage costs | $/Odt | 1 | | 1 | | 1 | |
| - **Roadside residues** | $/Odt | **23,00** | | **19,53** | | **14,09** | |
| - Comminuting costs | $/Odt | 23,00 | | 19,53 | | 14,09 | |
| - **MPB trees** | $/Odt | **80,31** | | **67,74** | | **48,87** | |
| - Harvesting costs[40] | $/Odt | 33,73 | | 28,65 | | 20,67 | |
| - Comminuting costs | $/Odt | 17,25 | | 14,65 | | 10,57 | |
| - Stumpage fee | $/Odt | 0,55 | | 0,00 | | 0,00 | |
| - Development costs[41] | $/Odt | 7,86 | | 6,68 | | 4,82 | |
| - Silviculture | $/Odt | 7,10 | | 6,03 | | 4,35 | |
| - Overhead | $/Odt | 13,82 | | 11,74 | | 8,47 | |
| **Transportation cost + loading (truck)** | $/Tkm[42] | Formula: 0,236*d+13.5 | | | | | |
| - Mean distance | km | 100 | | | | | |
| - costs of mean distance | $/Odt | 37,10 | | 31,51 | | 22,73 | |
| **Competition** (Lumber industry etc.) | | | | | | | |
| - **Sawmill residues surplus (total)**[43] | MOdt | **1.27** | | **0.81** | | **0.73** | |
| - Biomass end-products[44] | % | 100 | | 40 | | 40 | |
| - Others | % | 0 | | 60 | | 60 | |
| - **Roadside residues** | MOdt | **5.05** | | **4.05** | | **4.05** | |
| - Biomass end-products | % | 100 | | 70 | | 70 | |
| - Others | % | 0 | | 30 | | 30 | |
| - **MPB trees** | MOdt | **0,00** | | **21.40** | | **8.97** | |
| - Biomass end-products | % | 100 | | 60 | | 60 | |
| - Others | % | 0 | | 40 | | 40 | |

31 Applying the AAC of the regions confined by the coverage rate as stated in Appendix 3
32 Applying the AAC of the whole regions for sawmill residues since mills are located within the coverage area but haul logs from the whole region to the mills (Appendix 3).
33 Lumber Recovery (in % of incoming log volume leaving sawmill as timber) dependent on technological development in sawmills and quality of logs.
34 MOdt = million oven dry tones; $Mm^3$ = million cubic meters
35 Percentage of the tree that is left behind at the roadside calculated as a percentage of the wood volume taken away to be used for the lumber industry.
36 The standpoint of governmental policy towards utilizing MPB trees for the industry.
37 Percentage of the total available MPB trees which is harvestable (assumed is 50% max. harvest potential due to geograph. constraints) and allowed by governmental regulations.
38 In the current situation MPB trees are not utilized yet due to policy constraints, however, costs are calculation in case when harvesting would take place.
39 Cost reduction in % per year as a result of technological development, numbers for 2012 and 2020 are a cumulative cost reduction with regard to 2008.
40 This includes cutting, felling and skidding the tree to the roadside
41 This includes road construction, lay-out costs and other capital costs
42 $/tonne/km
43 It is assumed that industries currently utilizing sawmill residues will continue to do this in future. Therefore, a set amount (8.47 mill. Odt for BC) is reserved for this industry and is subtracted from total sawmill residues. The surplus is the available sawmill residue after subtraction. See also Appendix 4 for amounts reserved for each region.
44 The percentage of the stated total (surplus) destined as feedstock for biomass end-products (pellets and ethanol).

# Appendix 12: Feedstock scenario 3

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | *Scenario 3* | | | *Reduced cheap feedstock* | | |
| *Year* | *Unit* | ***2008*** | | ***2012*** | | ***2020*** | |
| **Feedstock availability** | | Coverage[45] | Sawmill R[46] | Coverage | Sawmill R | Coverage | Sawmill R |
| - AAC rates (total) | $Mm^3/y$ | 55,26 | 65,03 | 55,26 | 65,03 | 55,26 | 65,03 |
| Prince George | $Mm^3/y$ | 22,92 | 25,86 | 22,92 | 25,86 | 22,92 | 25,86 |
| Prince Rupert | $Mm^3/y$ | 8,21 | 8,43 | 8,21 | 8,43 | 8,21 | 8,43 |
| Cariboo | $Mm^3/y$ | 9,98 | 13,92 | 9,98 | 13,92 | 9,98 | 13,92 |
| Kamloops | $Mm^3/y$ | 6,86 | 6,86 | 6,86 | 6,86 | 6,86 | 6,86 |
| US border | $Mm^3/y$ | 7,29 | 9,96 | 7,29 | 9,96 | 7,29 | 9,96 |
| - LR[47] | % | | 48 | | 48 | | 48 |
| - **Sawmill residues surplus (total)** | MOdt[48] | | **1,27** | | **1,27** | | **1,27** |
| Prince George | MOdt | | 1,01 | | 1,01 | | 1,01 |
| Prince Rupert | MOdt | | 0,10 | | 0,10 | | 0,10 |
| Cariboo | MOdt | | 0,03 | | 0,03 | | 0,03 |
| Kamloops | MOdt | | 0,05 | | 0,05 | | 0,05 |
| US border | MOdt | | 0,08 | | 0,08 | | 0,08 |
| - **Roadside residues (total)** | MOdt | **5,05** | | **5,25** | | **5,88** | |
| Prince George | MOdt | 2,09 | | 2,18 | | 2,44 | |
| Prince Rupert | MOdt | 0,75 | | 0,78 | | 0,87 | |
| Cariboo | MOdt | 0,91 | | 0,95 | | 1,06 | |
| Kamloops | MOdt | 0,63 | | 0,65 | | 0,73 | |
| US border | MOdt | 0,67 | | 0,69 | | 0,78 | |
| - Roadside residues[49] | % | 24 | | 25 | | 28 | |
| - **MPB trees (total)** | Mm3 | **0,00** | | **17,83** | | **7,47** | |
| Prince George | Mm3 | 0,00 | | 6,91 | | 2,85 | |
| Prince Rupert | Mm3 | 0,00 | | 2,75 | | 1,14 | |
| Cariboo | Mm3 | 0,00 | | 4,31 | | 1,76 | |
| Kamloops | Mm3 | 0,00 | | 1,94 | | 0,81 | |
| US border | Mm3 | 0,00 | | 1,94 | | 0,93 | |
| - Policy figures[50] | +/- | +- | | +- | | +- | |
| - Rate of Cut of total MPB[51] | % | 0[52] | | 25 | | 25 | |
| **Cost minus transport** | | | | | | | |
| - Techn. development (cost reductions)[53] | % | 1,5 | | 5,87 | | 16,59 | |
| - **Sawmill residues** | $/Odt | **17** | | **19** | | **21** | |
| - Price at sawmill | $/Odt | 12 | | 14 | | 16 | |
| - Loading/short transportation | $/Odt | 4 | | 4 | | 4 | |
| - Storage costs | $/Odt | 1 | | 1 | | 1 | |
| - **Roadside residues** | $/Odt | **23,00** | | **21,65** | | **19,18** | |
| - Comminuting costs | $/Odt | 23,00 | | 21,65 | | 19,18 | |
| - **MPB trees** | $/Odt | **80,31** | | **80,08** | | **71,53** | |
| - Harvesting costs[54] | $/Odt | 33,73 | | 31,75 | | 28,13 | |
| - Comminuting costs | $/Odt | 17,25 | | 16,24 | | 14,39 | |
| - Stumpage fee | $/Odt | 0,55 | | 5,00 | | 5,00 | |
| - Development costs[55] | $/Odt | 7,86 | | 7,40 | | 6,56 | |
| - Silviculture | $/Odt | 7,10 | | 6,68 | | 5,92 | |
| - Overhead | $/Odt | 13,82 | | 13,01 | | 11,53 | |
| **Transportation cost + loading (truck)** | $/Tkm[56] | Formula: 0,236*d+13.5 | | | | | |
| - Mean distance | km | 100 | | | | | |
| - costs of mean distance | $/Odt | 37,10 | | 34,92 | | 30,95 | |
| **Competition** (Lumber industry etc.) | | | | | | | |
| - **Sawmill residues surplus (total)**[57] | MOdt | **1.27** | | **0.00** | | **0.00** | |
| - Biomass end-products[58] | % | 100 | | 0 | | 0 | |
| - Others | % | 0 | | 100 | | 100 | |
| - **Roadside residues** | MOdt | **5.05** | | **3.78** | | **4.12** | |
| - Biomass end-products | % | 100 | | 70 | | 70 | |
| - Others | % | 0 | | 30 | | 30 | |
| - **MPB trees** | MOdt | **0,00** | | **14.26** | | **5.98** | |
| - Biomass end-products | % | 100 | | 80 | | 80 | |
| - Others | % | 0 | | 20 | | 20 | |

[45] Applying the AAC of the regions confined by the coverage rate as stated in Appendix 3
[46] Applying the AAC of the whole regions for sawmill residues since mills are located within the coverage area but haul logs from the whole region to the mills (Appendix 3).
[47] Lumber Recovery (in % of incoming log volume leaving sawmill as timber) dependent on technological development in sawmills and quality of logs.
[48] MOdt = million oven dry tones; $Mm^3$ = million cubic meters
[49] Percentage of the tree that is left behind at the roadside calculated as a percentage of the wood volume taken away to be used for the lumber industry.
[50] The standpoint of governmental policy towards utilizing MPB trees for the industry.
[51] Percentage of the total available MPB trees which is harvestable (assumed is 50% max. harvest potential due to geograph. constraints) and allowed by governmental regulations.
[52] In the current situation MPB trees are not utilized yet due to policy constraints, however, costs are calculation in case when harvesting would take place.
[53] Cost reduction in % per year as a result of technological development, numbers for 2012 and 2020 are a cumulative cost reduction with regard to 2008.
[54] This includes cutting, felling and skidding the tree to the roadside
[55] This includes road construction, lay-out costs and other capital costs
[56] $/tonne/km
[57] It is assumed that industries currently utilizing sawmill residues will continue to do this in future. Therefore, a set amount (8.47 mill. Odt for BC) is reserved for this industry and is subtracted from total sawmill residues. The surplus is the available sawmill residue after subtraction. See also Appendix 4 for amounts reserved for each region.
[58] The percentage of the stated total (surplus) destined as feedstock for biomass end-products (pellets and ethanol).

# Appendix 13: Feedstock scenario 4

| | | Scenario 4 | | | Limited Sources | | |
|---|---|---|---|---|---|---|---|
| *Year* | *Unit* | ***2008*** | | ***2012*** | | ***2020*** | |
| **Feedstock availability** | | Coverage[59] | Sawmill R[60] | Coverage | Sawmill R | Coverage | Sawmill R |
| - AAC rates (total) | Mm$^3$/y | 55,26 | 65,03 | 49,73 | 58,53 | 46,97 | 53,57 |
| Prince George | Mm$^3$/y | 22,92 | 25,86 | 20,63 | 23,27 | 19,48 | 20,95 |
| Prince Rupert | Mm$^3$/y | 8,21 | 8,43 | 7,39 | 7,59 | 6,98 | 6,83 |
| Cariboo | Mm$^3$/y | 9,98 | 13,92 | 8,98 | 12,53 | 8,48 | 11,28 |
| Kamloops | Mm$^3$/y | 6,86 | 6,86 | 6,17 | 6,17 | 5,83 | 5,56 |
| US border | Mm$^3$/y | 7,29 | 9,96 | 6,56 | 8,96 | 6,20 | 8,96 |
| - LR[61] | % | | 48 | | 45 | | 42 |
| - **Sawmill residues surplus (total)** | MOdt[62] | | **1,27** | | **0,80** | | **0,48** |
| Prince George | MOdt | | 1,01 | | 0,83 | | 0,64 |
| Prince Rupert | MOdt | | 0,10 | | 0,04 | | 0.00 |
| Cariboo | MOdt | | 0,03 | | 0.00 | | 0.00 |
| Kamloops | MOdt | | 0,05 | | 0,00 | | 0.00 |
| US border | MOdt | | 0,08 | | 0,00 | | 0,08 |
| - **Roadside residues (total)** | MOdt | **5,05** | | **4,92** | | **5,36** | |
| Prince George | MOdt | 2,09 | | 2,04 | | 2,22 | |
| Prince Rupert | MOdt | 0,75 | | 0,73 | | 0,80 | |
| Cariboo | MOdt | 0,91 | | 0,89 | | 0,97 | |
| Kamloops | MOdt | 0,63 | | 0,61 | | 0,67 | |
| US border | MOdt | 0,67 | | 0,65 | | 0,71 | |
| - Roadside residues[63] | % | 24 | | 26 | | 30 | |
| - **MPB trees (total)** | Mm3 | **0,00** | | **0,00** | | **0,00** | |
| Prince George | Mm3 | 0,00 | | 0,00 | | 0,00 | |
| Prince Rupert | Mm3 | 0,00 | | 0,00 | | 0,00 | |
| Cariboo | Mm3 | 0,00 | | 0,00 | | 0,00 | |
| Kamloops | Mm3 | 0,00 | | 0,00 | | 0,00 | |
| US border | Mm3 | 0,00 | | 0,00 | | 0,00 | |
| - Policy figures[64] | +/- | - | | - | | - | |
| - Rate of Cut of total MPB[65] | % | 0[66] | | 0 | | 0 | |
| **Cost minus transport** | | | | | | | |
| - Techn. development (cost reductions)[67] | % | 0 | | 0 | | 0 | |
| - **Sawmill residues** | $/Odt | **17** | | **19** | | **21** | |
| - Price at sawmill | $/Odt | 12 | | 14 | | 16 | |
| - Loading/short transportation | $/Odt | 4 | | 4 | | 4 | |
| - Storage costs | $/Odt | 1 | | 1 | | 1 | |
| - **Roadside residues** | $/Odt | **23,00** | | **23,00** | | **23,00** | |
| - Comminuting costs | $/Odt | 23,00 | | 23,00 | | 23,00 | |
| - **MPB trees** | $/Odt | **80,31** | | **80,31** | | **80,31** | |
| - Harvesting costs[68] | $/Odt | 33,73 | | 33,73 | | 33,73 | |
| - Comminuting costs | $/Odt | 17,25 | | 17,25 | | 17,25 | |
| - Stumpage fee | $/Odt | 0,55 | | 0,55 | | 0,55 | |
| - Development costs[69] | $/Odt | 7,86 | | 7,86 | | 7,86 | |
| - Silviculture | $/Odt | 7,10 | | 7,10 | | 7,10 | |
| - Overhead | $/Odt | 13,82 | | 13,82 | | 13,82 | |
| **Transportation cost + loading (truck)** | $/Tkm[70] | Formula: 0,236*d+13.5 | | | | | |
| - Mean distance | km | 100 | | | | | |
| - costs of mean distance | $/Odt | 37,10 | | 37,10 | | 37,10 | |
| **Competition** (Lumber industry etc.) | | | | | | | |
| - **Sawmill residues surplus (total)**[71] | MOdt | **1.27** | | **0.80** | | **0.48** | |
| - Biomass end-products[72] | % | 100 | | 100 | | 100 | |
| - Others | % | 0 | | 0 | | 0 | |
| - **Roadside residues** | MOdt | **5.05** | | **2.46** | | **2.68** | |
| - Biomass end-products | % | 100 | | 50 | | 50 | |
| - Others | % | 0 | | 50 | | 50 | |
| - **MPB trees** | MOdt | **0,00** | | **0.00** | | **0.00** | |
| - Biomass end-products | % | n.a. | | n.a. | | n.a. | |
| - Others | % | n.a. | | n.a. | | n.a. | |

[59] Applying the AAC of the regions confined by the coverage rate as stated in Appendix 3
[60] Applying the AAC of the whole regions for sawmill residues since mills are located within the coverage area but haul logs from the whole region to the mills (Appendix 3).
[61] Lumber Recovery (in % of incoming log volume leaving sawmill as timber) dependent on technological development in sawmills and quality of logs.
[62] MOdt = million oven dry tones; Mm$^3$ = million cubic meters
[63] Percentage of the tree that is left behind at the roadside calculated as a percentage of the wood volume taken away to be used for the lumber industry.
[64] The standpoint of governmental policy towards utilizing MPB trees for the industry.
[65] Percentage of the total available MPB trees which is harvestable (assumed is 50% max. harvest potential due to geograph. constraints) and allowed by governmental regulations.
[66] In the current situation MPB trees are not utilized yet due to policy constraints, however, costs are calculation in case when harvesting would take place.
[67] Cost reduction in % per year as a result of technological development, numbers for 2012 and 2020 are a cumulative cost reduction with regard to 2008.
[68] This includes cutting, felling and skidding the tree to the roadside
[69] This includes road construction, lay-out costs and other capital costs
[70] $/tonne/km
[71] It is assumed that industries currently utilizing sawmill residues will continue to do this in future. Therefore, a set amount (8.47 mill. Odt for BC) is reserved for this industry and is subtracted from total sawmill residues. The surplus is the available sawmill residue after subtraction. See also Appendix 4 for amounts reserved for each region.
[72] The percentage of the stated total (surplus) destined as feedstock for biomass end-products (pellets and ethanol).

## Appendix 14: Pellet-Max scenario

| | | Scenario 1 | Pellet-Max | |
|---|---|---|---|---|
| *Year* | *Unit* | *2008* | *2012* | *2020* |
| - **Production cost** | $/Odt | **43,94** | **38,90** | **30,49** |
| - O&M costs | $/Odt | 19,55 | 17,31 | 13,56 |
| - Labor cost | $/Odt | 8,16 | 7,22 | 5,66 |
| - Capital | $/Odt | 13,03 | 11,54 | 9,04 |
| - Overhead | $/Odt | 3,20 | 2,83 | 2,22 |
| - Storage (feedstock) | $/Odt | 1.65 | 1.45 | 1.15 |
| - Conversion efficiency[73] | % | 86,50 | 87,00 | 89,00 |
| - Technological development[74] | % | 3,00 | 11,47 | 30,62 |
| - **Transportation plant to terminal** | $/Tkm[75] | Formula: 0.025*d+3.8 | | |
| - Mean of transportation | - | train | train | train |
| - Average distance (average) | km | 625 | | |
| Prince George (train) | km | 850 | | |
| Prince Rupert (train) | km | 380 | | |
| Cariboo (train) | km | 560 | | |
| Kamloops (train) | km | 350 | | |
| - Cost of average distance (average) | $/Odt | 19.43 | 17.92 | 15.24 |
| Prince George (train) | $/Odt | 25.00 | 30,94 | 30,94 |
| Prince Rupert (train) | $/Odt | 13,33 | 15,99 | 15,99 |
| Cariboo (train) | $/Odt | 17,78 | 21,69 | 21,69 |
| Kamloops (train) | $/Odt | 12,45 | 14,87 | 14,87 |
| - Technological development | % | 2,00 | 7,76 | 21,53 |
| - **Demand for biomass** | | | | |
| *EU* | | | | |
| - Energy market prices (pellets) | $/GJ | 6,1 | 6.7 | 8,2 |
| - Pellet demand volume | PJ | 12,6 | 90 | 216 |

[73] Feedstock output (GJ) / feedstock input (GJ)
[74] Cost reduction in % per year as a result of technological development influencing production costs and storage costs.
[75] In $/tonne/km. In the formula the d = number of kilometers one-way haul. The fixed costs include loading and unloading.

# Appendix 15: Pellet-Min scenario

| | | Scenario 2 | Pellet-Min | |
|---|---|---|---|---|
| *Year* | *Unit* | *2008* | *2012* | *2020* |
| - **Production cost** | $/Odt | **60,00** | **57,64** | **53,18** |
| - O&M costs | $/Odt | 26,70 | 25,64 | 23,66 |
| - Labor cost | $/Odt | 11,14 | 10,70 | 9,88 |
| - Capital | $/Odt | 17,79 | 17,09 | 15,77 |
| - Overhead | $/Odt | 4,37 | 4,20 | 3,87 |
| - Storage (feedstock) | $/Odt | 1,65 | 1,59 | 1,45 |
| - Conversion efficiency[76] | % | 86,50 | 86,50 | 86,50 |
| - Technological development[77] | % | 1,00 | 3,94 | 11,36 |
| - **Transportation plant to terminal** | $/Tkm[78] | Formula: 0.032*d+3.8 | | |
| - Mean of transportation | - | train | train | train |
| - Average distance (average) | km | 625 | | |
| Prince George (train) | km | 850 | | |
| Prince Rupert (train) | km | 380 | | |
| Cariboo (train) | km | 560 | | |
| Kamloops (train) | km | 350 | | |
| - Cost of average distance (average) | $/Odt | 23.80 | 23.80 | 23.80 |
| Prince George (train) | $/Odt | 30,94 | 30,94 | 30,94 |
| Prince Rupert (train) | $/Odt | 15.99 | 15,99 | 15,99 |
| Cariboo (train) | $/Odt | 21,69 | 21,69 | 21,69 |
| Kamloops (train) | $/Odt | 14,87 | 14,87 | 14,87 |
| - Technological development | % | 0,00 | 0,00 | 0,00 |
| - **Demand for biomass** | | | | |
| *EU* | | | | |
| - Energy market prices (pellets) | $/GJ | 4,9 | 4,9 | 4,9 |
| - Pellet demand volume | PJ | 12,6 | 45 | 90 |

[76] Feedstock output (GJ) / feedstock input (GJ)
[77] Cost reduction in % per year as a result of technological development influencing production costs and storage costs.
[78] In $/tonne/km. In the formula the d = number of kilometers one-way haul. The fixed costs include loading and unloading.

# Appendix 16: Ethanol-Max scenario

| | | Scenario 3 | Ethanol-Max | |
|---|---|---|---|---|
| *Year* | *Unit* | *2008*[79] | *2012* | *2020* |
| - **Production cost** | $/GJ | | **19.4** | **19.4** |
| - O&M costs | | | 1,75 | 1,75 |
| - Labor cost | | | 0,62 | 0,62 |
| - Enzymes and chemicals | | | 3,26 | 3,26 |
| - Capital & taxes | | | 12,07 | 12,07 |
| - Overhead | | | 1,71 | 1,71 |
| - Storage (feedstock) | $/Odt | | 1,53 | 1,30 |
| - Revenues (electricity & lignin)[80] | $/GJ | | 4.27[81] | 4.27 |
| - Conversion efficiency[82] | % | | 32 | 55 |
| - **Transportation plant to terminal** | $/Tkm | Train = 0,045*d vs. Truck = 0,04*d | | |
| - Mean of transportation | - | | train/truck | train/truck |
| - Technological development[83] | % | 2,00 | 7,76 | 21,53 |
| - Mean distance (Total average) | km | 625 | | |
| Prince George (train) | km | 850 | | |
| Prince Rupert (train) | km | 380 | | |
| Cariboo (train) | km | 560 | | |
| Kamloops (train) | km | 350 | | |
| US Border (truck) | km | 200 | | |
| - Cost of mean distance (Total average) | $/L | 0,0166 | 0,0151 | 0,0128 |
| Prince George | $/L | 0,0301 | 0,0278 | 0,0237 |
| Prince Rupert | $/L | 0,0135 | 0,0125 | 0,0106 |
| Cariboo | $/L | 0,0199 | 0,0183 | 0,0156 |
| Kamloops | $/L | 0,0123 | 0,0113 | 0,0097 |
| US border | $/L | 0,0142 | 0,0131 | 0,0112 |
| - **Demand for biomass** | | | | |
| *BC* | | | | |
| - Energy market prices (petrol) | $/GJ | 15,6 | 18.1 | 22.2 |
| - Ethanol demand | PJ | 0 | 9.8 | 19.6 |
| *EU* | | | | |
| - Energy market prices (petrol) | $/GJ | 18.3 | 20.6 | 26.1 |
| - Ethanol demand | PJ | 0 | 208.3 | 88.9 |
| *US* | | | | |
| - Energy market prices (petrol) | $/GJ | 15,6 | 18.1 | 22.2 |
| - Ethanol demand | PJ | 0 | 77.2 | 294.8 |

[79] Currently there is no commercial cellulose-based ethanol facility economically running in BC. In this thesis, it is assumed that in 2012 production will take off.
[80] Co-products of ethanol production are a major part of the revenues generated.
[81] Revenues are assumed at $0,10/liter produced ethanol
[82] Feedstock output (GJ) / feedstock input (GJ)
[83] Cost reduction in % per year as a result of technological development, numbers for 2012 and 2020 are a cumulative cost reduction with regard to transportation and storage in 2008.

# Appendix 17: Ethanol-Min scenario

| | | Scenario 4 | Ethanol-Min | |
|---|---|---|---|---|
| *Year* | *Unit* | *2008*[84] | *2012* | *2020* |
| - **Production cost** | $/GJ | | **19.4** | **19.4** |
| - O&M costs | | | 1,75 | 1,75 |
| - Labor cost | | | 0,62 | 0,62 |
| - Enzymes and chemicals | | | 3,26 | 3,26 |
| - Capital & taxes | | | 12,07 | 12,07 |
| - Overhead | | | 1,71 | 1,71 |
| - Storage (feedstock) | $/Odt | | 1,53 | 1,30 |
| - Revenues (electricity & lignin)[85] | $/GJ | | 4.27[86] | 4.27 |
| - Conversion efficiency[87] | % | | 22,5 | 32,0 |
| - **Transportation plant to terminal** | $/Tkm | Train = 0,0563*d vs. Truck = 0,05*d | | |
| - Mean of transportation | - | | train/truck | train/truck |
| - Technological development[88] | % | 0,00 | 0,00 | 0,00 |
| - Mean distance (Total average) | km | 625 | | |
| Prince George (train) | km | 850 | | |
| Prince Rupert (train) | km | 380 | | |
| Cariboo (train) | km | 560 | | |
| Kamloops (train) | km | 350 | | |
| US Border (truck) | km | 200 | | |
| - Cost of mean distance (Total average) | $/L | 0,0210 | 0,0210 | 0,0210 |
| Prince George | $/L | 0,0377 | 0,0377 | 0,0377 |
| Prince Rupert | $/L | 0,0169 | 0,0169 | 0,0169 |
| Cariboo | $/L | 0.0249 | 0.0249 | 0.0249 |
| Kamloops | $/L | 0.0154 | 0.0154 | 0.0154 |
| US border | $/L | 0,0158 | 0,0158 | 0,0158 |
| - **Demand for biomass** | | | | |
| *BC* | | | | |
| - Energy market prices (petrol) | $/GJ | 15.6 | 15.6 | 15.6 |
| - Ethanol demand | PJ | 0 | 3.3 | 6.5 |
| *EU* | | | | |
| - Energy market prices (petrol) | $/GJ | 18.3 | 18.3 | 18.3 |
| - Ethanol demand | PJ | 0 | 44.5 | 77.2 |
| *US* | | | | |
| - Energy market prices (petrol) | $/GJ | 15.6 | 15.6 | 15.6 |
| - Ethanol demand | PJ | 0 | 39.8 | 147.4 |

[84] Currently there is no commercial cellulose-based ethanol facility economically running in BC. In this thesis, it is assumed that in 2012 production will take off.
[85] Co-products of ethanol production are a major part of the revenues generated.
[86] Revenues are assumed at $0,10/liter produced ethanol
[87] Feedstock output (GJ) / feedstock input (GJ)
[88] Cost reduction in % per year as a result of technological development, numbers for 2012 and 2020 are a cumulative cost reduction with regard to transportation and storage in 2008.

## Appendix 18: Fossil fuel prices

Table 36 shows, for this reference scenario, no significant price increase expectations for fossil fuel regarding the coming 20 years.

*Table 1.3:* **Fossil-Fuel Price Assumptions in the Reference Scenario** ($ per unit)

| | unit | 2000 | 2005 | 2010 | 2015 | 2030 |
|---|---|---|---|---|---|---|
| **Real terms (year-2005 prices)** | | | | | | |
| IEA crude oil imports | barrel | 31.38 | 50.62 | 51.50 | 47.80 | 55.00 |
| Natural gas | | | | | | |
| *US imports* | *MBtu* | *4.34* | *6.55* | *6.67* | *6.06* | *6.92* |
| *European imports* | *MBtu* | *3.16* | *5.78* | *5.94* | *5.55* | *6.53* |
| *Japanese LNG imports* | *MBtu* | *5.30* | *6.07* | *6.62* | *6.04* | *6.89* |
| OECD steam coal imports | tonne | 37.51 | 62.45 | 55.00 | 55.80 | 60.00 |
| **Nominal terms** | | | | | | |
| IEA crude oil imports | barrel | 28.00 | 50.62 | 57.79 | 60.16 | 97.30 |
| Natural gas | | | | | | |
| *US imports* | *MBtu* | *3.87* | *6.55* | *7.49* | *7.62* | *12.24* |
| *European imports* | *MBtu* | *2.82* | *5.78* | *6.66* | *6.98* | *11.55* |
| *Japanese LNG imports* | *MBtu* | *4.73* | *6.07* | *7.43* | *7.59* | *12.18* |
| OECD steam coal imports | tonne | 33.47 | 62.45 | 61.74 | 70.19 | 106.14 |

Note: Prices in the first two columns represent historical data. Gas prices are expressed on a gross calorific-value basis. All prices are for bulk supplies exclusive of tax. Nominal prices assume inflation of 2.3% per year from 2006.

**Table 36: Price trends fossil fuel (IEA, 2006)**

## Appendix 19: Refuel Scenario

In Figure 54, a graph is depicted giving the outlook for biofuels (light blue area) for the EU.

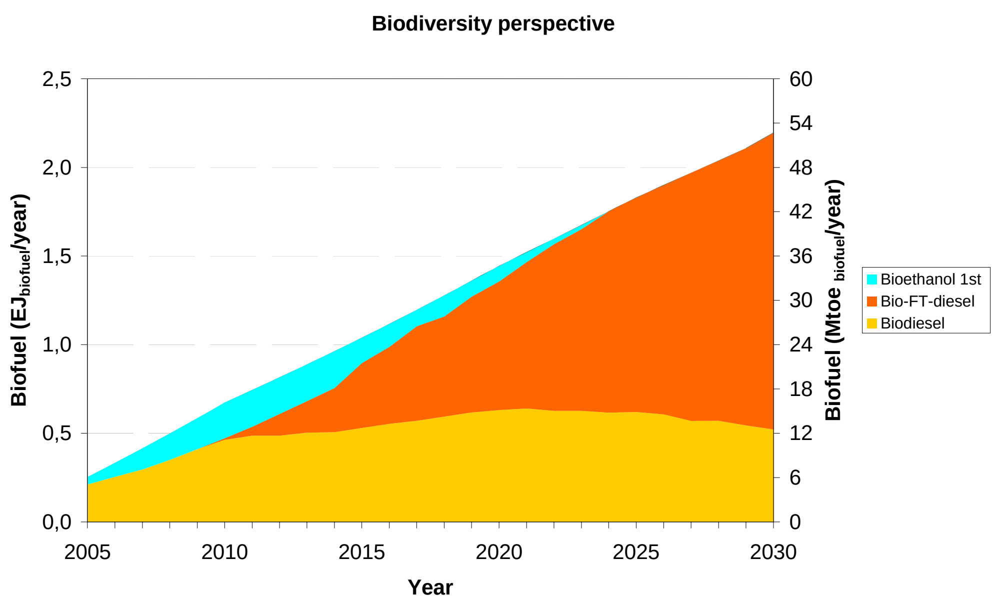



**Figure 54: Scenario ReFuel, Biodiversity (Dunham, 2004)**

Some characteristics of this particular scenario are presented in Table 37.

**Table 37: characteristics Biodiversity scenario**

| Biofuels target pathway | Moderate |
|---|---|
| Ambition levels RES-E, H | Moderate |
| GHG pricing | Yes |
| Ex-EU import levels | Limited |
| Specific targets 2nd gen. | Yes |
| Energy crop premium | No |
| Investment subsidies | No |

# Appendix 20: Assumptions and applied data

## 1. General

Assumptions

- All given data in the data sheets (Appendix 10-17) not being specified for a sub-region is applied for all specific sub-regions equally.
- The defined coverage area determines, for every selected region, the harvestable area for roadside residues and MPB killed trees. However, sawmill residues are purchased from sawmills and only require minimal transportation. In this study it is assumed that all sawmill residues generated in a sub-region can be found within the specified coverage area. Thus, sawmill residues are not distributed across a forestry region, but can be found close to the railway system, where most sawmills are located. Therefore, the AAC rates for whole regions are included (in some cases beyond the coverage boundaries) to calculate the volume of sawmill residues.
- Odt = Oven dry tonne = Bdt = Bone dry tonne = 1000 kg (0% moisture content).

Currencies:

- All monetary values are given in United States dollars (US$), unless stated differently.
- 1 Euro = 1,46 US$ (source: XE, December 10, 2007)
- 1,00 US$ = 1,00 Can$ (source: XE, December 10, 2007)

## 2. Harvesting practices

Assumptions

- Harvesting practices and logistical chains remain the same until 2020.
- Harvesting costs include all entailed costs: planning & lay-out, O&M, capital cost, stumpage fee, felling costs, skidding costs and road construction.
- Chipping costs include O&M costs, capital costs and costs to feed the chipper with roadside residues.
- Chipping operations of MPB killed trees can take place on a larger scale due to higher feedstock densities compared to chipping roadside residues. This reduces chipping costs of MPB killed trees compared to chipping roadside residues.

## 3. Bark

| | Bark content (average in %) | Source |
|---|---|---|
| Sawmill residues | 55% | (NRCan/CFS, 2005) |
| Roadside residues | 20-25% | (MacFarlane, 2007) |
| MPB killed trees | 12% | (MacFarlane, 2007) |

10% of the total bark in sawmill residues is assumed to be too contaminated with dirt and sand to use as feedstock for biomass end-products production (MacDonalds, 2007). For pellet production all feedstock can be used, except this share of contaminated bark as part of total sawmill residues (i.e. 5.5%). For ethanol production only whitewood of sawmill residues is assumed to be used (i.e. 45% of total) and whitewood of MPB killed trees (i.e. 88% of total). Roadside residues are excluded to use as feedstock for ethanol production.

## 4. Storage

| | Value | Source |
|---|---|---|
| Chips from roadside residues and MPB killed trees storing time | < 9 months | |
| Average (mean) storage of chips at the end-product plant | 5 months | (Melin, 2007) |
| Dry matter loss chips for each month stored (% of initial mass) | 1% | (Jirjis, 1995) |
| Average dry matter loss of chips | 5%. | |

For every Odt of feedstock required for production, (1/0.95) 1.053 Odt need to brought into the storage yard at the plant side. This is taken into account in the feedstock calculations. Storage of sawmill residues is limited, therefore no losses are assumed.

## 5. Sawmill residues

| | Value | source |
|---|---|---|
| Rate of projected AAC being cut | 100% | Assumed for this study |
| Rate of total AAC volume allocated to sawmills | 75.7% | (Melin, 2007) |
| Lumber recovery percentage 2008 | 48% | (McFarlane, 2007) |
| Conversion factor: 1 Odt wood | 2,63 $m^3$ wood | (Stennes & McBeath, 2006) |
| Price levels for purchased sawmill residues | 12-19 \$/Odt | (Premium Pellet, 2007) |

A substantial share of the produced sawmill residues is currently destined for other industries. In this study the volume for other industries is assumed to remains at equal levels. Furthermore, it is assumed that roadside residues and sawmill residues are regenerated every year. Thus, there is no stockpile which can be used.

## 6. Roadside residues

Assumptions

- Roadside residues are not part of the AAC volume. However, the volume of roadside residues is expressed as a percentage of the AAC volume. Increasing roadside residues rates are a result of improvements in gathering residues from cut blocks and an increase in discarded MPB infested wood (MacDonalds, 2007).

## 7. MPB killed trees

Assumptions

- Currently, no MPB killed trees are made available for biomass purposes in BC (McFarlane, 2007).
- The accessible MPB killed trees volume is assumed at 50% of the total volume due to geographic constraints (McFarlane, 2007).

Regarding MPB trees decay:

- Starting from 2012, a ten year period could serve an annual supply of 1/10 per year of the total accumulated MPB tree volume (i.e. 10%/yr of total). See also Appendix 5.
- Starting from 2020, a five year period could serve an annual supply of 1/5 (usable part by 2020) of the total accumulated MPB tree volume stated for 2012 (i.e. 4%/yr of total).

**8. Competition**

Due to competition, prices for sawmill residues gradually increase when becoming more scarce. In this research it is assumed that the price ultimately doubles along the run towards finishing all sawmill residues, with regard to the initial price of feedstock.

| Assumptions |
|---|
| The following formula is used to translate this course into an increasingly higher cost figure towards the end of the available sawmills residues. |
| $P_{sawmill} = P_{initial} * \left[\ 2 - \sqrt{\frac{Vtot - Vused}{Vtot}}\ \right]$ |
| Where $P_{sawmill}$ represents the price for one Odt sawmill residues purchased at the sawmill. This is computed by taking the initial price (current price) $P_{initial}$ and multiply this by an inclining factor, as sawmill residues become scarce. $V_{tot}$ refers to current total sawmill residues surplus volume and $V_{used}$ implies the used sawmill residues surplus volume. The 2 refers to a doubling of the initial price for the last purchased Odt of sawmill residue (Roberts et al., 2007). |

Competition given for feedstock surplus is assumed to be equal for all the investigated regions.

**9. Pellet production**

| | Value | Source |
|---|---|---|
| Production capacity | 10 Odt/hr | (Stennes & McBeath, 2006) |
| Load factor | 8000 hours/yr | (Stennes & McBeath, 2006) |
| Efficiency of pellet production ($Output_{pellet}$/ $Input_{feedst}$) | 86.5-89.0% | (Premium Pellets, 2007) |
| Pellets heating value | 18 $GJ_{hhv}$/Odt | (Melin, 2007) |

Furthermore, the required heat for the production of pellets comes from a part of the feedstock, depending on the efficiency of the production process. The efficiency for pellet production is determined by the energy content per produced Odt pellets divided by the energy content of feedstock to produce 1 Odt pellets.

**10. Ethanol production**

| | Value | Source |
|---|---|---|
| Production capacity | 400MW ethanol output | (Hamelinck, 2004) |
| Load factor | 8000 hours/yr | (Hamelinck, 2004) |
| Efficiency of pellet production (GJ $Output_{ethanol}$/ GJ $Input_{feedstock}$) | 22.5 - 55.0% | (Hamelinck, 2004; Mabee, 2006) |
| Ethanol heating value | 23,4 $MJ_{hhv}$/L | (Hamelinck, 2004) |
| Revenues from co-products | \$0.10/$L_{ethanol}$ | ($(S\&T)^2$ et al., 2004) |

The calculations are based on a 2nd generation ethanol plant with enzymatic processing.

## 11. Transportation to (international) terminal

Assumptions

- The railway system could serve increases in rail transportation when more products need to be transported from the interior of BC.
- Due to competition between railway companies, prices will stay relatively low (close to current levels).
- The total volume of end-products produced northern of Quesnel will be delivered at the Prince Rupert terminal. The total volume produced southern of Quesnel will be delivered at the terminal in North Vancouver.
- Transportation of ethanol from the US-border region is undertaken by tanker truck transport.
- Projected technological development could take place due to improvements in handling (learning) and economies of scale (Bradley, 2007).

## Appendix 21: Results

### Feedstock scenario 1 elaborated

In 2012 for FS 1, sawmill residues are still \$17/Odt whereas roadside residues start at \$40.3/Odt and MPB trees at \$95.9/Odt. The cost breakdown directly shows the significant contribution of harvesting cost to the total cost for MPB trees, presented in Figure 55. The cost breakdown represents the cost for the first gathered Odt of each feedstock. Increasing costs in the graph for roadside residues and MPB killed trees are a result of increasing transportation cost, whereas the increase in sawmill residues is a result of competition (increase in purchase price).

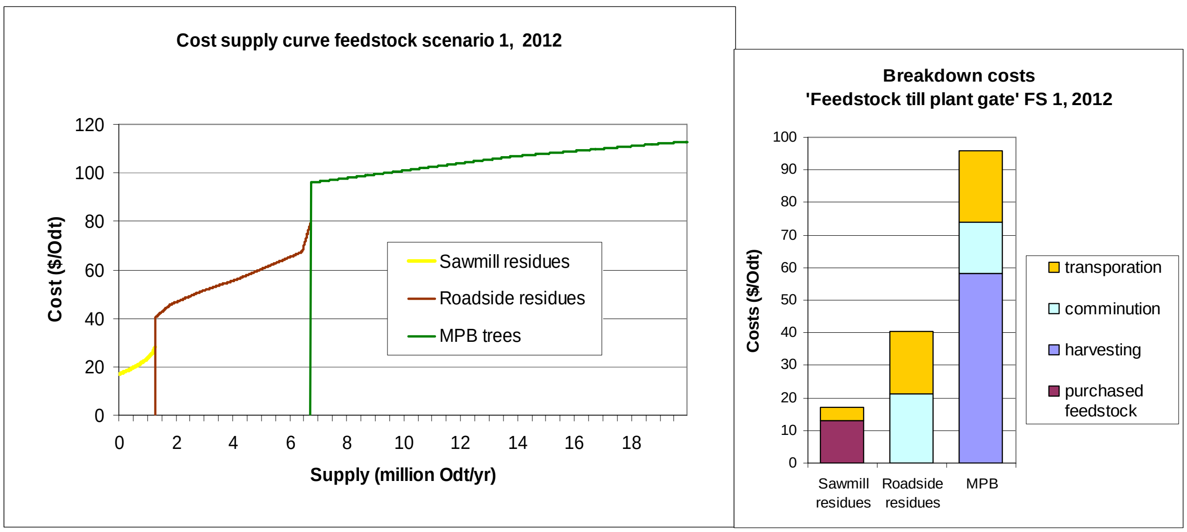



**Figure 55: cost supply curve + cost breakdown FS 1 BC, 2012**

### Feedstock for regions BC

The feedstock availability in 2008 for the 5 selected regions across BC is presented in Figure 56. MPB trees are not included in the 2008 situation.

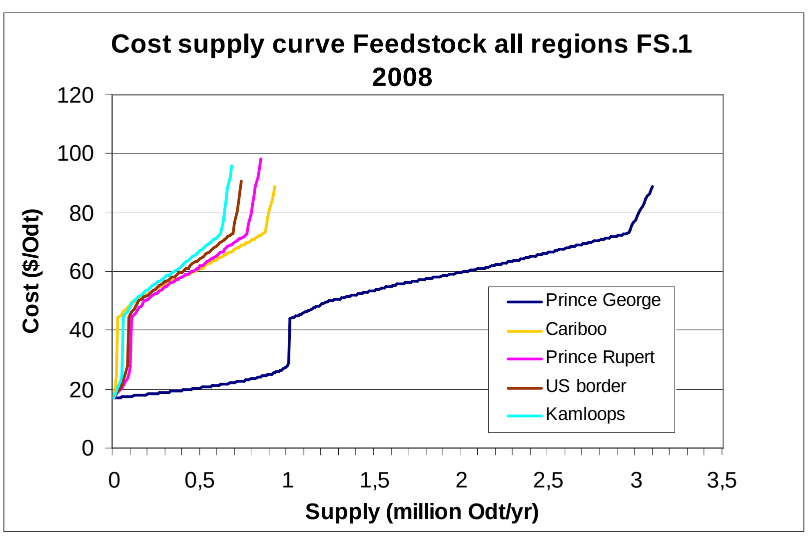



**Figure 56: cost supply curves regions BC, 2008**

Prince George has the largest feedstock availability of 3.1 million Odt/yr provided by the extensive lumber industry in the Prince George region. The much lower feedstock availability for the other four regions exist within a close range; Kamloops 0.7 million Odt/yr, Cariboo 0.9 mill Odt/yr (a closer look presented in Figure 57).

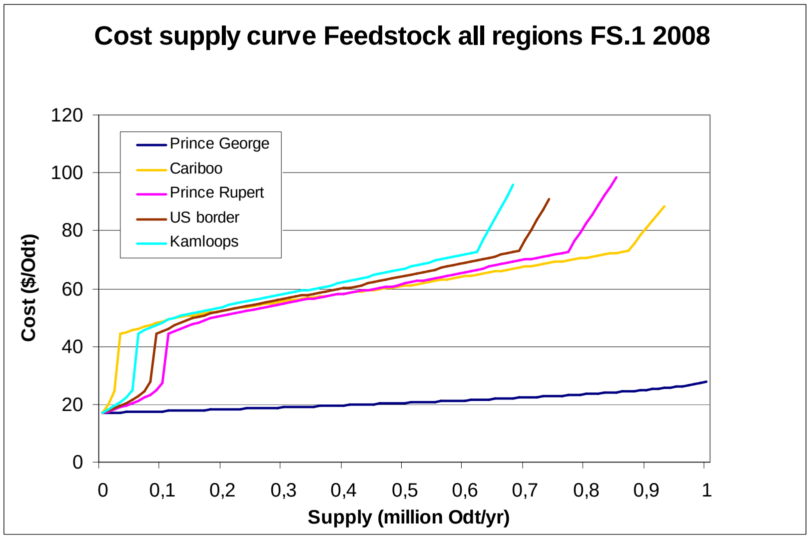



**Figure 57: cost supply curves regions BC, 2008**

The situation for the BC regions for 2012 is shown in Figure 58. The MPB killed trees availability is included in FS 1 represented by the strong bend in the curves starting at around 0.8 million Odt/yr for most regions. Prince George has a maximum feedstock availability of 17.1 million Odt/yr.

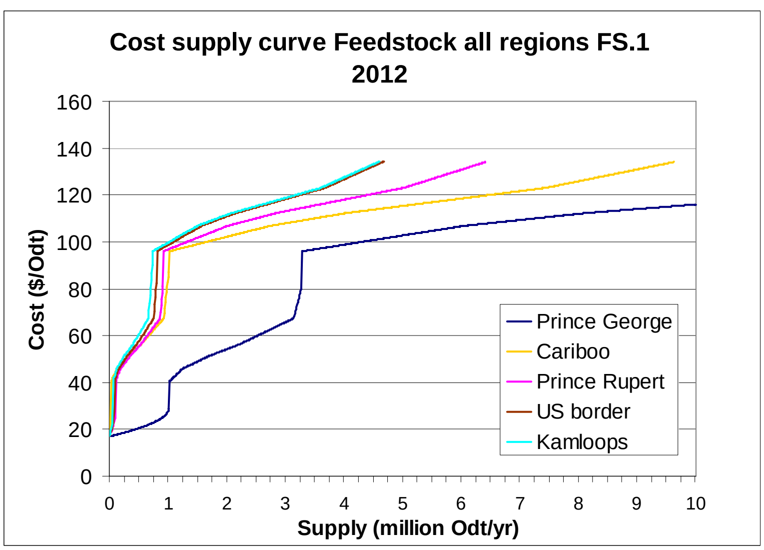



**Figure 58: cost supply curves regions BC, 2012**

In Figure 59, the cost supply curves for the regions in BC are presented for the year 2020. The main difference in comparison to the other years is the substantial cost reduction for roadside residues and MPB trees. Furthermore, MPB killed trees volumes have decreased substantially in comparison to the 2012 situation.

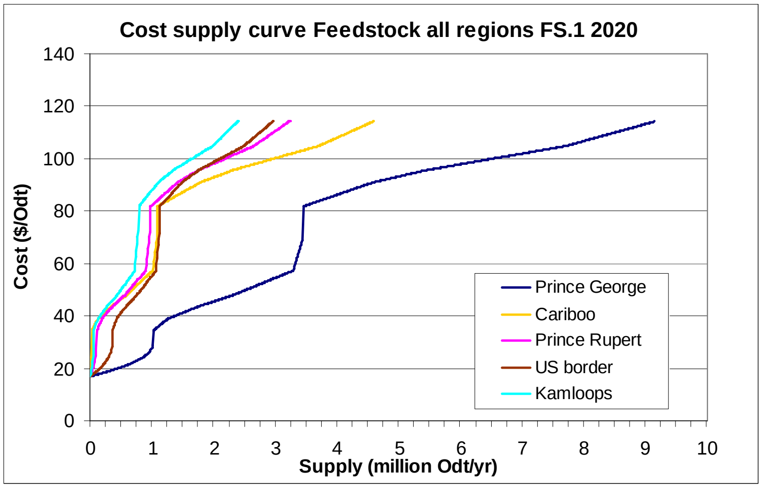



**Figure 59: cost supply curve regions BC, 2020**

As being the region with the largest feedstock availability, the Prince George region is presented in Figure 60 for the years 2008, 2012 and 2020. The cost reduction for the available feedstock is apparent. Regarding the year 2020, the costs for MPB trees feedstock increase faster compared to 2012 due to less MPB feedstock available dispersed over the same collection area.

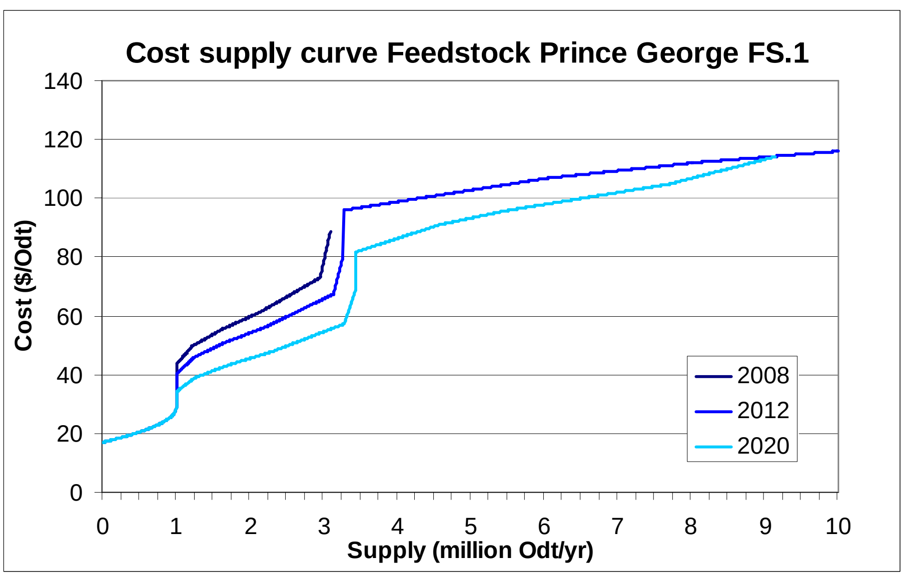



**Figure 60: cost supply curve Prince George FS. 1**

**Pellets BC**

In Figure 61 an overview is given to show how cost reductions in a pellet-Max scenario (and FS 1) evolves over time, and how the potential of pellet trade grows when production costs decrease and the market price rises.

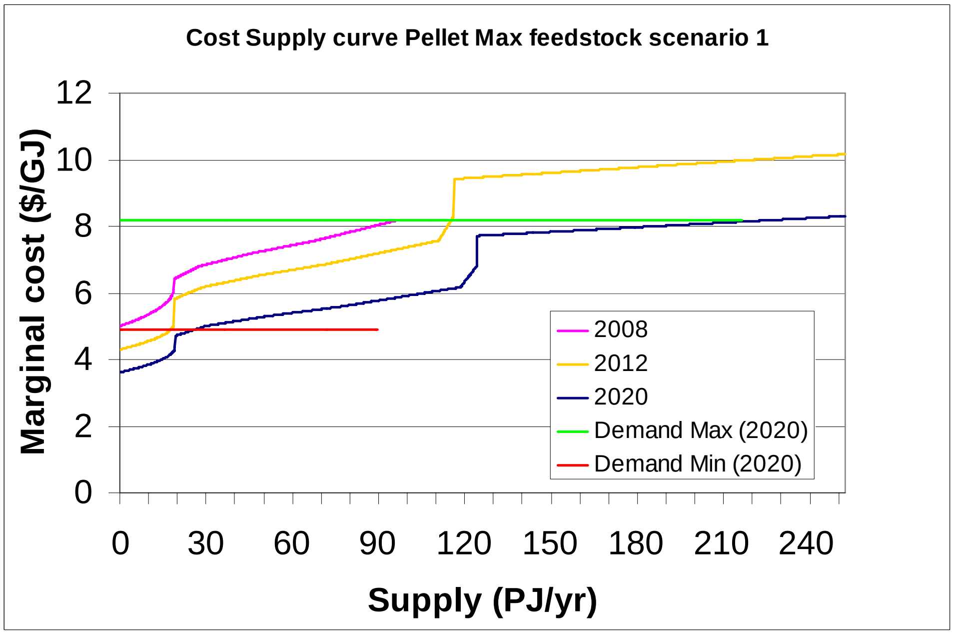



**Figure 61: cost supply curve FS 1, pellet-Max**

The pellet-Max and pellet-Min presentation for 2020 depicted in Figure 33 are distinguished into pellet-Max scenarios (Figure 62) and pellet-Min scenarios (Figure 63).

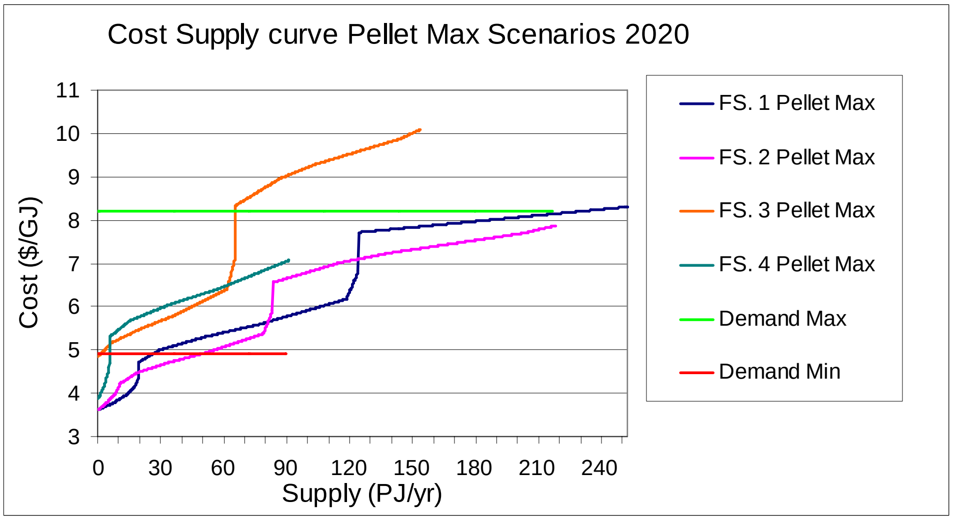



**Figure 62: cost supply curves pellet-Max BC, 2020**

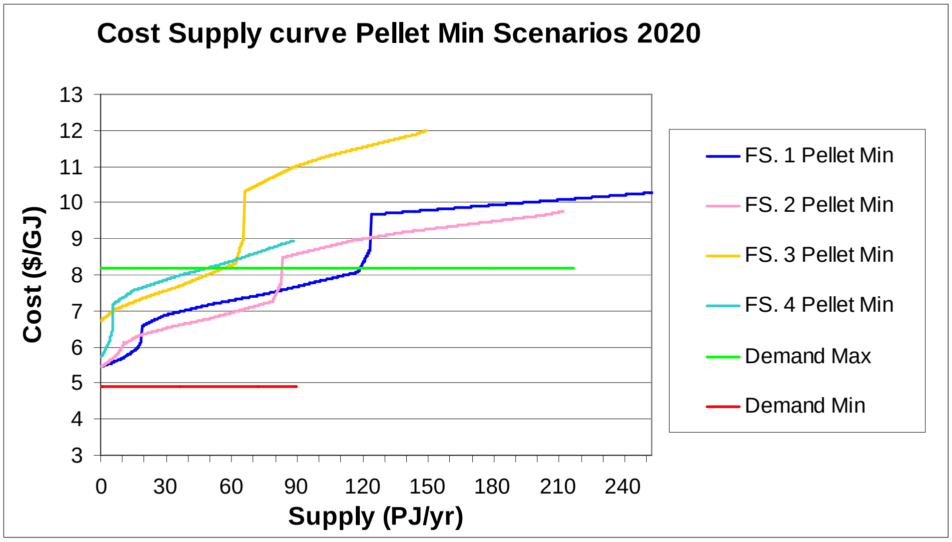



**Figure 63: cost supply curve pellet-Min BC, 2020**

## Pellets BC regions

Cost supply curves for the BC regions are presented in Figure 64. Regarding 2012, most BC regions have market potentials of approximately 10 PJ/yr (demand-Max), except for Prince George (~32 PJ/yr). By 2020, the pellet potential has increased substantially due to favourable market conditions and cost improvements in pellet production.

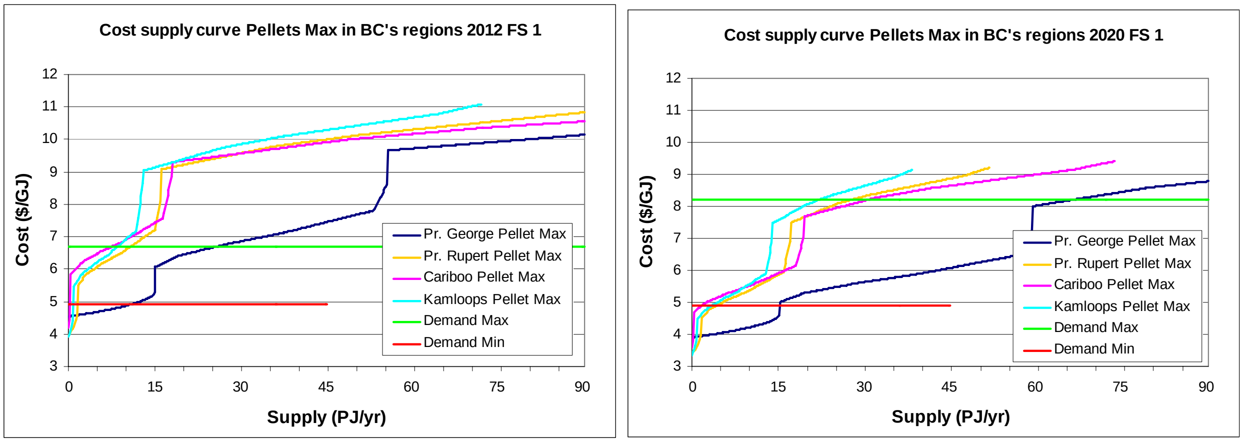



**Figure 64: cost supply curves pellet-Max BC regions, 2012 + 2020**

**Ethanol BC**

In Figure 65, the sensitivity of the ethanol plant size is shown. This sensitivity is substantial and up scaling size could contribute significantly to reduce ethanol production costs. The dotted lines show for each size plant, the ethanol production output (in PJ/yr).

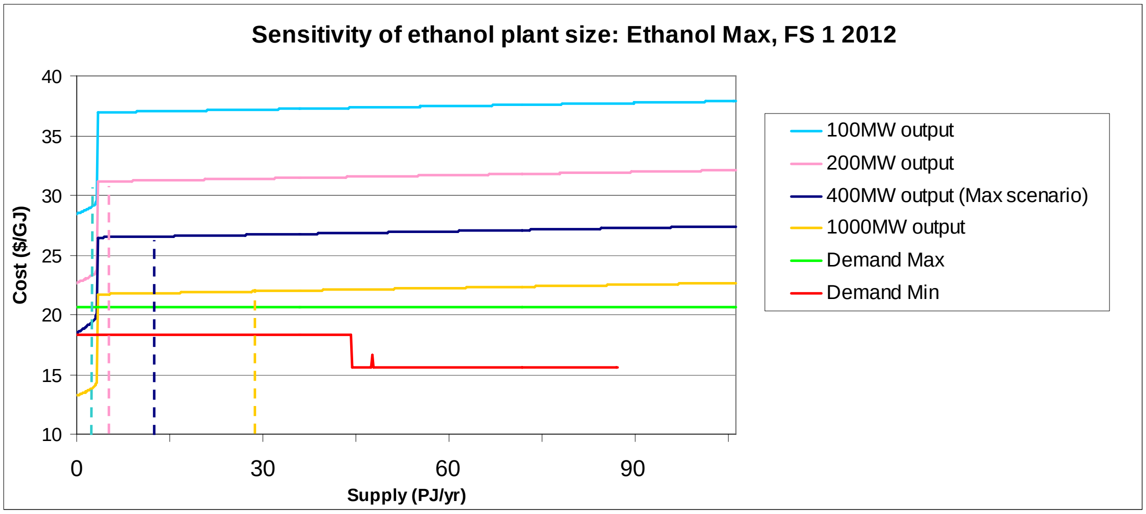



**Figure 65: sensitivity ethanol plant size ethanol-Max, FS 1 2012**

Figure 66 shows how similar scenarios change over time, from 2012 to 2020. The differences are mainly caused by efficiency improvements, which reduces feedstock costs considerably. These cost reductions result in a substantial growth of the market potential.

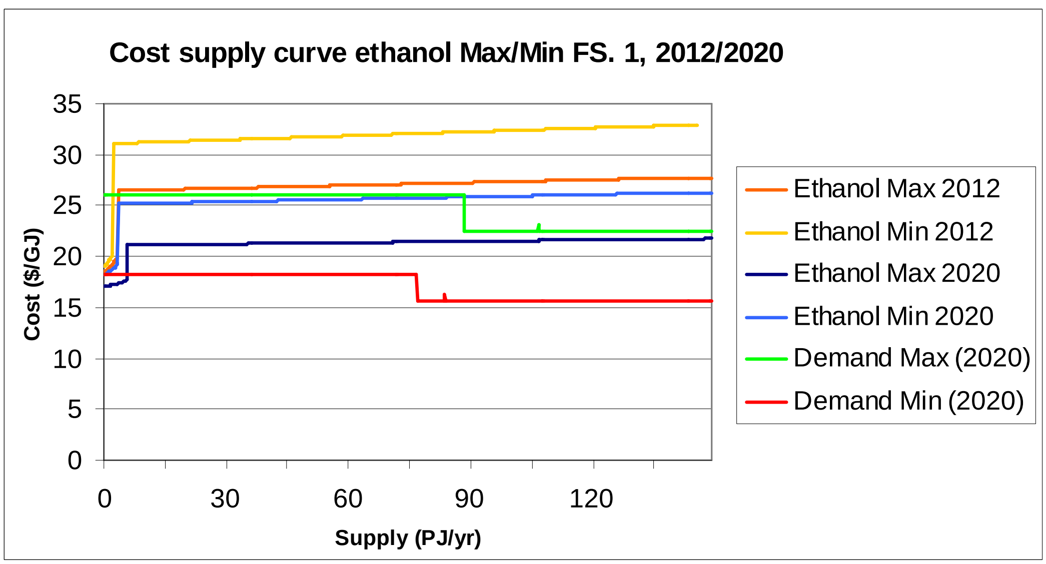



**Figure 66: cost supply curves ethanol Max/Min FS 1, 2012 + 2020**

**Ethanol BC regions**

Figure 67 shows a closer look at the potential of ethanol production for each of the BC regions.

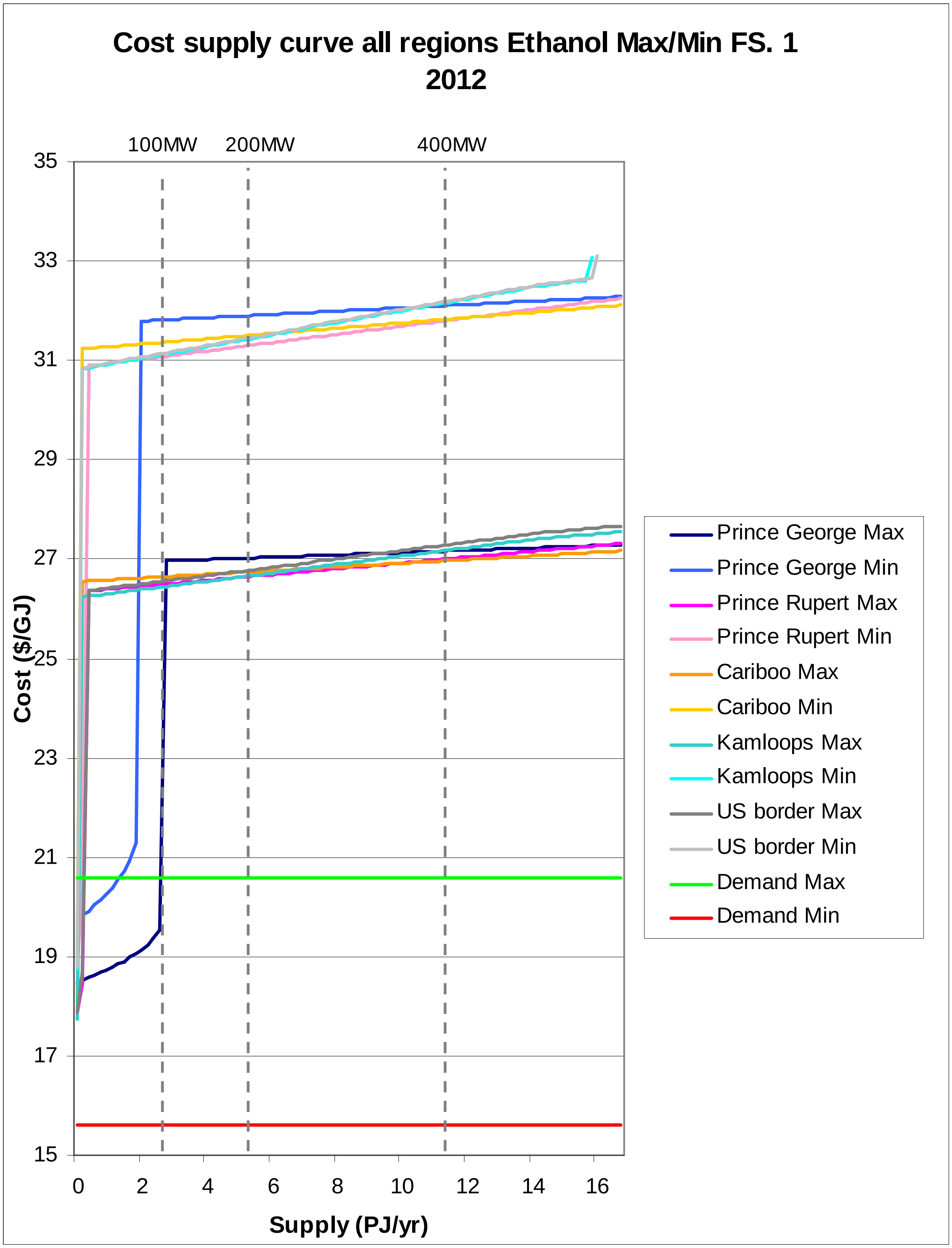



**Figure 67: cost supply curve all regions ethanol-Max FS1, 2012**