Development of a Feedstock-to-Product Chain Model for Densified Biomass Pellets

By

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A thesis submitted to the Department of Mechanical and Materials Engineering

in conformity with the requirements for

the degree of Master of Applied Science

Queen’s University

Kingston, Ontario, Canada

January, 2017

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Abstract

The Q’Pellet is a spherical, torrefied biomass pellet currently under development. It aims to improve on the shortcomings of commercially available cylindrical white and torrefied pellets. A spreadsheet-based model was developed to allow for techno-economic analysis and simplified life cycle analysis of Q’Pellets, torrefied pellets and white pellets. A case study was developed to compare the production of white, torrefied and Q’Pellet production based on their internal rates of return and life cycle greenhouse gas emissions. The case study was based on a commercial scale plant built in Williams Lake BC with product delivery in Rotterdam, Netherlands.

Q’Pellets had the highest modelled internal rate of return, at 12.7%, with white pellets at 11.1% and torrefied pellets at 8.0%. The simplified life cycle analysis showed that Q’Pellets had the lowest life cycle greenhouse gas emissions of the three products, 6.96 kgCO$_2$/GJ, compared to 21.50 kgCO$_2$/GJ for white pellets and 10.08 kgCO$_2$/GJ for torrefied pellets. At these levels of life cycle greenhouse gas emissions, white pellets are above the maximum life cycle emissions to be considered sustainable under EU regulations.

Sensitivity analysis was performed on the model by modifying input variables, and showed that white pellets are more sensitive to uncontrollable market variables, especially pellet sale prices, raw biomass prices and transportation costs. Monte Carlo analysis was also performed, which showed that white pellet production is less predictable and more likely to lead to a negative internal rate of return compared to Q’Pellet production.
Acknowledgements

I would like to acknowledge several people, without whom this thesis would never have been possible. The guidance and support from my supervisors, Prof. Pollard and Prof. Strong, was invaluable. I especially appreciated the guidance from Prof. Pollard on writing so my thesis was completed to the highest standard.

I’d like to thank Andrew Duncan and Dan Nicksy, who laid the foundation for this work through their excellent research on Q’Pellet production and characteristics. I would also like to thank my lab-mate Will Taylor, whose work proved the viability of producing Q’Pellets at scale. Furthermore, he provided much needed help to allow me to understand the methods used to create pellets.

Finally, I would like to acknowledge the support from my parents, family, Hayley and Ivy. Without their support, I would never have finished.
Publications

# Table of Contents

Abstract ........................................................................................................................................... i
Acknowledgements ......................................................................................................................... ii
Publications ....................................................................................................................................... iii
List of Figures ..................................................................................................................................... viii
List of Tables ....................................................................................................................................... ix
Nomenclature ...................................................................................................................................... xii

Chapter 1  Introduction ...................................................................................................................... 1
  1.1  Biomass ...................................................................................................................................... 1
  1.2  Biomass Fuels ........................................................................................................................... 2
  1.3  Torrefaction .............................................................................................................................. 3
  1.4  Q’Pellet ...................................................................................................................................... 3
  1.5  Thesis Goals .............................................................................................................................. 4
  1.6  Thesis Layout ............................................................................................................................ 5

Chapter 2  Review of Parameters Relevant to Building an Economic Model ......................... 7
  2.1  Overview of the Chapter ........................................................................................................... 7
  2.2  Wood Chemistry ......................................................................................................................... 7
    2.2.1  Cellulose ............................................................................................................................ 8
    2.2.2  Hemicellulose .................................................................................................................... 8
    2.2.3  Lignin ................................................................................................................................ 8
    2.2.4  Extractives and Ash .......................................................................................................... 9
    2.2.5  Bark .................................................................................................................................. 9
  2.3  Herbaceous Biomass Chemistry ............................................................................................... 10
  2.4  Torrefaction ............................................................................................................................. 10
    2.4.1  Thermal Decomposition of Biomass .................................................................................. 11
    2.4.2  Torrefaction, Pyrolysis and Gasification .......................................................................... 12
    2.4.3  Torrefaction Products ....................................................................................................... 13
    2.4.4  Benefits of Torrefaction ................................................................................................... 14
  2.5  Biomass Markets and Prices .................................................................................................... 15
    2.5.1  Wood Pellet Markets ....................................................................................................... 15
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.12.5</td>
<td>Product Combustion</td>
</tr>
<tr>
<td>2.13</td>
<td>Chapter Conclusion</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>Model Description</td>
</tr>
<tr>
<td>3.1</td>
<td>Overview of the Chapter</td>
</tr>
<tr>
<td>3.2</td>
<td>Model Overview</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Inputs</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Variable Calculations</td>
</tr>
<tr>
<td>3.3</td>
<td>Economic Analysis</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Revenue</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Costs</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Operating Cost</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Capital Cost</td>
</tr>
<tr>
<td>3.3.5</td>
<td>Income Taxes</td>
</tr>
<tr>
<td>3.3.6</td>
<td>Cash Flow Analysis</td>
</tr>
<tr>
<td>3.4</td>
<td>GHG Analysis</td>
</tr>
<tr>
<td>3.5</td>
<td>Drying and Torrefaction Model</td>
</tr>
<tr>
<td>3.6</td>
<td>Sensitivity Analysis</td>
</tr>
<tr>
<td>3.7</td>
<td>Monte Carlo Analysis</td>
</tr>
<tr>
<td>3.8</td>
<td>Case Study Description</td>
</tr>
<tr>
<td>3.8.1</td>
<td>Pellet Sale Price</td>
</tr>
<tr>
<td>3.8.2</td>
<td>Biomass Parameters</td>
</tr>
<tr>
<td>3.8.3</td>
<td>Plant Parameters</td>
</tr>
<tr>
<td>3.8.4</td>
<td>Case Study Capital Costs</td>
</tr>
<tr>
<td>3.8.5</td>
<td>Utility Requirements</td>
</tr>
<tr>
<td>3.8.6</td>
<td>Transportation</td>
</tr>
<tr>
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<tr>
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<td>Fixed Operating Costs</td>
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<tr>
<td>3.8.9</td>
<td>Dry Matter Losses</td>
</tr>
<tr>
<td>3.9</td>
<td>Model Validation and Verification</td>
</tr>
<tr>
<td>3.9.1</td>
<td>Verification</td>
</tr>
<tr>
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<tr>
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<tr>
<td>3.10</td>
<td>Chapter Conclusion</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>Results</td>
</tr>
<tr>
<td>4.1</td>
<td>Overview of the Chapter</td>
</tr>
<tr>
<td>4.2</td>
<td>Economic Results</td>
</tr>
<tr>
<td>4.3</td>
<td>GHG Results</td>
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<tr>
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</tr>
<tr>
<td>4.4.1</td>
<td>Pellet Sale Price</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Exchange Rate</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Higher Heating Value</td>
</tr>
<tr>
<td>4.4.4</td>
<td>Capital Expenditure</td>
</tr>
<tr>
<td>4.4.5</td>
<td>Transportation Cost</td>
</tr>
<tr>
<td>4.4.6</td>
<td>Raw Biomass Price</td>
</tr>
<tr>
<td>4.4.7</td>
<td>Utility Costs</td>
</tr>
<tr>
<td>4.4.8</td>
<td>Labour Cost</td>
</tr>
<tr>
<td>4.5</td>
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</tr>
<tr>
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<tr>
<td>4.6.1</td>
<td>Economic Results</td>
</tr>
<tr>
<td>4.6.2</td>
<td>GHG Emission Results</td>
</tr>
<tr>
<td>4.7</td>
<td>Customer Location</td>
</tr>
<tr>
<td>4.7.1</td>
<td>Thunder Bay Results</td>
</tr>
<tr>
<td>4.7.2</td>
<td>Japan Results</td>
</tr>
<tr>
<td>4.8</td>
<td>Plant Capacity</td>
</tr>
<tr>
<td>4.9</td>
<td>Normalized Biomass Production</td>
</tr>
<tr>
<td>4.10</td>
<td>Chapter Conclusion</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>Conclusions and Future Work</td>
</tr>
<tr>
<td>5.1</td>
<td>Conclusions</td>
</tr>
<tr>
<td>5.2</td>
<td>Future Work</td>
</tr>
<tr>
<td>References</td>
<td>116</td>
</tr>
<tr>
<td>A.</td>
<td>Appendix</td>
</tr>
</tbody>
</table>
List of Figures

Figure 2-1: The Q'Pellet .................................................................42
Figure 2-2: Pellet production process flowchart ..................................47
Figure 3-1: White pellet production flowchart ....................................56
Figure 3-2: Drying and torrefaction diagram. Solid lines indicate mass flow and
dashed lines indicate energy flow. Circles labelled ‘Q’ indicate heat
loss. ..................................................................................................68
Figure 3-3: Production processes for white, torrefied and Q'Pellets ..........72
Figure 4-1: White pellet cash flow ......................................................84
Figure 4-2: Torrefied pellet cash flow ..................................................85
Figure 4-3: Q'Pellet cash flow ................................................................85
Figure 4-4: White pellet GHG emissions ..............................................87
Figure 4-5: Torrefied pellet GHG emissions ...........................................87
Figure 4-6: Q'Pellet GHG emissions ......................................................88
Figure 4-7: Sale price sensitivity ..........................................................90
Figure 4-8: Exchange rate sensitivity ....................................................92
Figure 4-9: HHV sensitivity .................................................................93
Figure 4-10: Capex sensitivity .............................................................94
Figure 4-11: Transportation sensitivity ................................................95
Figure 4-12: Raw biomass price sensitivity ...........................................96
Figure 4-13: Natural gas cost sensitivity ...............................................97
Figure 4-14: Electricity cost sensitivity ................................................97
Figure 4-15: Labour cost sensitivity ......................................................98
Figure 4-16: Monte Carlo analysis .......................................................99
Figure 4-17: IRR for different plant capacities ......................................106
List of Tables

Table 1-1: Properties of various biomass fuels and coal; adapted from [4], [10], [23]......................................................................................................................... 4
Table 2-1: Comparison of calorific values of torrefied wood ..........................................14
Table 2-2: Annual biomass quantity available in Canada, adapted from [4]..................19
Table 2-3: Range of raw biomass costs, $/ODT.................................................................20
Table 2-4: Torrefaction plants ..............................................................................................22
Table 2-5: Torrefaction unit manufacturers (M$ - millions of dollars)..............................22
Table 2-6: Torrefier capital costs .........................................................................................23
Table 2-7: Costs of biomass truck transport .......................................................................25
Table 2-8: Cost of rail transport [70], [73]...........................................................................26
Table 2-9: Maximum load per railcar and cost per tonne to ship from Williams Lake, BC to Vancouver, BC [74], [75].........................................................26
Table 2-10: Shipping costs ..................................................................................................27
Table 2-11: Maximum weight per Panamax shipload .......................................................28
Table 2-12: Cost per tonne to ship pellets by Panamax ship ............................................29
Table 2-13: Outside battery limit capital costs ...................................................................29
Table 2-14: Seven-year modified accelerated recovery system depreciation rates [81].................................................................31
Table 2-15: Direct labour costs ............................................................................................32
Table 2-16: Indirect labour costs .........................................................................................32
Table 2-17: Maintenance costs ...........................................................................................33
Table 2-18: Electricity cost by location ...............................................................................34
Table 2-19: Storage costs ....................................................................................................35
Table 2-20: Pelletization energy required .............................................................................37
Table 2-21: Pellet mill capital costs (k$ - thousands of dollars).......................................37
Table 2-22: Capital costs of dryers .......................................................................................39
Table 2-23: Estimates of Q'Pellet pelletizer capital cost ....................................................45
Table 2-24: Maximum life cycle emissions permissible under EU regulations [103]..................................................50
Table 2-25: Combustion emission factors, adapted from [101].........................................50
Table 2-26: Emission factors for fossil fuel electricity production, adapted from [101] ..................................................................................................................51
Table 2-27: Grid electricity mix and GHG emission intensity, from [83], [104], [106] ..................................................................................................................51
Table 2-28: Transport truck fuel efficiency ..................................................................................................................52
Table 3-1: Drying and torrefaction model parameters ............................................................................................70
Table 3-2: Case study pellet parameters .................................................................................................................74
Table 3-3: Case study plant parameters ....................................................................................................................75
Table 3-4: Case study capital costs [M$] ....................................................................................................................76
Table 3-5: Case study electricity requirements .......................................................................................................76
Table 3-6: Natural gas requirements (Gj_{natgas}/Gj_{biomass}) ................................................................................77
Table 3-7: Case study transportation costs .............................................................................................................77
Table 3-8: Storage costs .............................................................................................................................................78
Table 4-1: Capital cost per GJ of annual delivered biomass .....................................................................................82
Table 4-2: Variable operating costs .......................................................................................................................82
Table 4-3: Fixed operating costs ............................................................................................................................83
Table 4-4: Modelled IRR for the three processes .................................................................................................84
Table 4-5: Modelled GHG emissions [kgCO_{2eq}/GJ] ............................................................................................86
Table 4-6: Location specific parameters for Baton Rouge, LA and Hawk Junction, ON ........................................101
Table 4-7: Logistics costs for pellet production in Hawk Junction, Thunder Bay and Baton Rouge ..................102
Table 4-8: IRR for pellet production in Williams Lake, Hawk Junction, Thunder Bay and Baton Rouge .............102
Table 4-9: GHG emissions [kgCO_{2eq}/GJ] for pellet production in Williams Lake, Hawk Junction, Thunder Bay and Baton Rouge .................................................................103
Table 4-10: IRR for production and delivery in Thunder Bay ...............................................................................104
Table 4-11: Life cycle GHG emissions for production and delivery in Thunder Bay ...........................................104
Table 4-12: IRR for customer delivery in Japan with production in Williams Lake and Baton Rouge ..................105
Table 4-13: Life cycle GHG emissions for customer delivery in Japan with production in Williams Lake and Baton Rouge .................................................................105
Table 4-14: Raw biomass requirements to supply a plant with a delivered biomass energy capacity of 1.75 TJ .................................................................107
Table 4-15: Raw biomass requirements to supply a plant with a delivered biomass capacity of 1.53 TJ .................................................................108
Table 4-16: IRR by pellet type for a plant with a delivered biomass energy capacity of 1.75 TJ .................................................................108
Table 4-17: IRR by pellet type for a plant with a delivered biomass energy capacity of 1.53 TJ .................................................................109
Table A-1: White pellet cash flow ........................................................................125
Table A-2: Torrefied pellet cash flow ..................................................................126
Table A-3: Q'Pellet cash flow ............................................................................127
Table A-4: Mass and energy yields by step for white pellet production ..............128
Table A-5: Mass and energy yields by step for torrefied pellet production ..........128
Table A-6: Mass and energy yields by step for Q'Pellet production ....................129
## Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC</td>
<td>Annual Allowable Cut</td>
</tr>
<tr>
<td>ARA</td>
<td>Amsterdam, Rotterdam, Antwerp</td>
</tr>
<tr>
<td>BC</td>
<td>British Columbia</td>
</tr>
<tr>
<td>CAD</td>
<td>Canadian Dollars</td>
</tr>
<tr>
<td>CIF</td>
<td>Cost, Insurance, Freight</td>
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<tr>
<td>DFC</td>
<td>Distance Fixed Cost</td>
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<td>DML</td>
<td>Dry Matter Loss</td>
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<td>DVC</td>
<td>Distance Variable Cost</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>FOB</td>
<td>Free on Board</td>
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<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
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<tr>
<td>GJ</td>
<td>Gigajoule</td>
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<td>GJ&lt;sub&gt;_biomass&lt;/sub&gt;</td>
<td>Gigajoule – biomass</td>
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<tr>
<td>GJ&lt;sub&gt;_el&lt;/sub&gt;</td>
<td>Gigajoule – electricity production</td>
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<tr>
<td>GS</td>
<td>Generating Station</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>HFO</td>
<td>Heavy Fuel Oil (Bunker Fuel)</td>
</tr>
<tr>
<td>HHV</td>
<td>Higher Heating Value – Dry [GJ/tonne]</td>
</tr>
<tr>
<td>HHV&lt;sub&gt;_AR&lt;/sub&gt;</td>
<td>Higher Heating Value – As Received [GJ/tonne]</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>IRR</td>
<td>Internal Rate of Return</td>
</tr>
<tr>
<td>K$</td>
<td>Thousand Dollars</td>
</tr>
<tr>
<td>ktonne</td>
<td>Thousand Metric Tonnes</td>
</tr>
<tr>
<td>LA</td>
<td>Louisiana</td>
</tr>
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<td>M$</td>
<td>Million Dollars</td>
</tr>
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<td>Description</td>
</tr>
<tr>
<td>--------------</td>
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</tr>
<tr>
<td>MACRS</td>
<td>Modified Accelerated Cost Recovery System</td>
</tr>
<tr>
<td>MC</td>
<td>Moisture Content [%, wet basis]</td>
</tr>
<tr>
<td>MPB</td>
<td>Mountain Pine Beetle</td>
</tr>
<tr>
<td>Mt</td>
<td>Million Metric Tonnes</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
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<tr>
<td>ODT</td>
<td>Oven-dry tonnes</td>
</tr>
<tr>
<td>ON</td>
<td>Ontario</td>
</tr>
<tr>
<td>OPG</td>
<td>Ontario Power Generation</td>
</tr>
<tr>
<td>tonnes/year</td>
<td>Metric Tonnes per Year</td>
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<tr>
<td>USD</td>
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Chapter 1 Introduction

In Ontario, the elimination of coal power production in 2014 was hailed as the most important climate change initiative in North American history [1]. The reduction in coal power was largely driven by increased power generation from renewable sources, which included wind, solar and biomass. In Europe, the renewable energy directive [2] requires the EU to collectively produce 20% of its energy through renewable sources, which will require increased energy production from wind, solar and biomass power. Nonetheless, 2015 was the hottest year on record [3] and pressure to prevent continued climate change through the reduction of greenhouse gas (GHG) emissions continues to increase.

1.1 Biomass

Biomass refers to any plant matter, which in general, may be split into woody biomass (from trees) and herbaceous biomass (from grasses and agricultural products). Biomass fuel is considered carbon neutral since the carbon associated with its subsequent combustion was initially sequestered in the biomass through photosynthesis. Although the carbon in fossil fuels, such as natural gas, coal and oil, was sequestered through photosynthesis, the timespan from carbon sequestration to CO$_2$ emission for fossil fuels occurred millennia ago. By comparison, the timespan from carbon sequestration to CO$_2$ emission for biomass ranges from several months to years. Biomass is also renewable, as long as the planting and growth rate of biomass equals its rate of consumption. In Canada, the biomass resources available
to be utilized renewably are significant, with 64 million tonnes of renewable biomass estimated to be available annually [4].

1.2 Biomass Fuels

Biomass occurs in several forms used for energy production. Liquid and gaseous biofuels include bio-diesel and bio-synthetic natural gas. There are several types of solid biomass that can be used as fuel, including relatively unprocessed products such as sawdust and woodchips and more processed products such as wood pellets and charcoal. Commercially available wood pellets, “white pellets,” are produced by extruding wood particles through a pellet mill, creating cylindrical pellets. Pelletization creates a more homogenous product that is easier to handle [5] and less expensive to ship as the bulk density of wood residues increases from ~250 kg/m$^3$ to ~650 kg/m$^3$ [4]. The main market for industrial wood pellets in western countries is to either co-fire with or replace coal in power plants [6].

Conversion of coal plants to use pellets is fraught with difficulties. Compared to coal, white pellets have a lower calorific value (16-18 GJ/t vs. 23-28 GJ/t [4]), so if a plant is converted to burn biomass, electrical conversion efficiency is reduced [7]. White pellets are also more difficult to grind [8] and are hygroscopic [9]. Furthermore, white pellets create fines (small wood particles) [10] and dangerous off-gases [11], and undergo self-heating which may lead to spontaneous combustion [9]. White pellets thus require silo storage, dust suppression systems and possibly new grinders [12] for coal plants to be converted to burn them, which requires significant capital costs for conversion [13].
1.3 Torrefaction

Torrefaction, or mild pyrolysis, is a process by which biomass is heated in an oxygen-free environment to 200°C-300°C. The biomass that results from torrefaction is an energy dense and hydrophobic product with greatly improved friability [14], [15]. Increased energy density lowers transportation costs while increased friability and hydrophobicity lower handling and storage costs [14]. Pelletizing torrefied biomass yields torrefied pellets, which are considered a potential improvement to white pellets due to their increased energy density, friability and hydrophobicity. Critically important is a reduction in the capital expenditure required to convert coal fired power plants to co-fire biomass because improved friability reduces the energy required to grind torrefied pellets, which permits the continued use of coal grinders [8]. Multiple techno-economic analyses have shown that torrefied pellets may have lower production costs than white pellets [5], [14], [16], [17] on an energy basis. However, pelletization technology is similar for torrefied pellets and white pellets, which leads to only marginal improvements to bulk density and material handling and storage. Torrefied wood may take more energy to pelletize than raw biomass and lead to lower quality pellets [18], [19] and despite the hydrophobicity of torrefied biomass, torrefied pellets will degrade if stored outdoors [20].

1.4 Q’Pellet

The Q’Pellet is a spherical pellet currently under development that provide increased bulk density and reduced production of fines, thereby incurring lower cost shipping and handling [10], [21]. Torrefied and Q’Pellets have bulk densities of approximately 700 kg/m³ [4] and
820 kg/m³ [10], respectively. Q’Pellets may also be stored outdoors, as they have not degraded when submersed in water in lab conditions [22, p. 211]. Table 1-1 provides a comparative list of various properties of wood chips, white pellets, torrefied pellets, Q’Pellets and coal.

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<th>Dry Wood Chips</th>
<th>White Pellets</th>
<th>Torrefied Pellets</th>
<th>Q’Pellets</th>
<th>Coal</th>
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<td>650</td>
<td>700</td>
<td>827</td>
<td>800-850</td>
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<td>Energy Density [GJ/m³]</td>
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<td>17-19</td>
<td>18-24</td>
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<td>No</td>
<td>No</td>
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1.5 Thesis Goals

Work by Duncan [22] and Nicksy [24] showed how Q’Pellets can be manufactured and also determined their properties. Work is currently underway to produce Q’Pellets in a continuous process [25]. For Q’Pellets to be viable, their production must be economically and environmentally competitive with the production methods used for white pellets and torrefied pellets.

There are many factors that need to be considered to achieve economically and environmentally competitive alternatives to white and terrified cylindrical pellets, such as the Q’Pellet. The goal of this thesis is to develop and present a techno-economic model that
analyzes the costs associated with the production of white pellets, torrefied pellets and Q’Pellets from biomass collection through to customer delivery.

1.6 Thesis Layout

To achieve this goal, the factors that need to be considered are reviewed in the next chapter, which provides a description of the background information required for the inputs into the techno-economic model. This is done by reviewing the literature to identify and assess the approaches taken and inputs used in other techno-economic papers and reports. From this, literature required to develop the thesis was identified and is described. Some of the literature described include a description of wood and torrefaction chemistry, biomass markets, wood pellet production, an overview of Q’Pellet production and a description of life cycle analysis.

Chapter 3 provides a description of the techno-economic model developed in this thesis. At each step through the production chain, the model enables mass and energy balances, economic variables, utility usage and greenhouse gas (GHG) emissions to be determined. The results from the model enable comparisons to be made between different production chains, biomass types, plant locations and levels of torrefaction. A case study of a plant built in British Columbia with product delivery to the Port of Rotterdam is considered with the production of white pellets, torrefied pellets and Q’Pellets modelled for comparison.

Chapter 4 provides results and discussion from the case study along with sensitivity analysis. Economic results are presented from cash flow analysis alongside environmental results from
life cycle analysis. Sensitivity analysis is performed on several variables in the case study.

Several modified case studies are then presented.

Chapter 5 presents conclusions and recommendations for future work.
Chapter 2 Review of Parameters Relevant to Building an Economic Model

2.1 Overview of the Chapter

This chapter reviews the literature appropriate for the development of a techno-economic model for the production and delivery of the Q’Pellet. First, the chemistry of wood and torrefaction is described, which provides the necessary background to understand biomass torrefaction. The markets for both raw biomass and wood pellets are overviewed to provide justification for the prices later used in the model and to demonstrate that there is necessary demand to support new wood pellet plant construction. Current wood pellet production techniques and the associated costs are described, which provide the bulk of the model’s inputs and structure. The last section of this chapter describes the methods used for life cycle analysis along with literature values for the inputs used in this thesis.

2.2 Wood Chemistry

The majority of wood is composed of three classes of organic polymers collectively referred to as lignocellulose: cellulose, hemicellulose and lignin. The remaining organic portions of the wood are referred to as extractives and the non-organic portions are referred to as ash. Wood is comprised of elongated cells, mainly oriented in the direction of the stem, bound together by a region called the middle lamella [26, p. 5]. The cell wall structure contains a skeleton made of cellulose, with a hemicellulose matrix and lignin acting as a binder [26, p. 5].
2.2.1 Cellulose

Cellulose is the main component of wood, accounting for 35-45% of the mass of softwoods and 40-50% of the mass of hardwoods [26, p. 208]. Cellulose is a polysaccharide composed of β-D-glucopyranose molecules, with an average chain length of 10,000 units [26, p. 51]. Cellulose is a linear molecule that readily forms hydrogen bonds. These hydrogen bonds cause bundles of cellulose molecules to join into microfibrils, which are the most basic building block of wood. Microfibrils combine to form fibrils, which in turn combine to form the cellulose skeleton of the cell walls [26, p. 5].

2.2.2 Hemicellulose

Hemicelluloses are a group of highly branched, heterogeneous polysaccharides that support cellulose in cell walls [26, p. 60]. Hemicelluloses comprise 25-30% of the mass of both softwoods and hardwoods, but with different molecules in each [26, p. 208]. The main hemicelluloses are glucomannan-based and xylan-based, with slight differences between the compounds in hardwoods and softwoods. Glucomannan-based hemicellulose accounts for 15-20% and xylan-based hemicellulose accounts for 5-10% of the mass of softwoods, while in hardwoods, xylan-based hemicellulose accounts for 15-30% and glucomannan-based hemicellulose accounts for 2-5% of the mass of the wood.

2.2.3 Lignin

Lignins are polymers with units made of variations on phenylpropane. Lignin acts as a “glue”, and is especially concentrated within the middle lamella. In softwoods, lignin accounts for
26-32% [27] and in hardwoods, lignin accounts for 20-28% of the mass of the wood [26, p. 208]. In softwoods, the primary type of lignin is guaiacyl lignin, a polymer composed of coniferyl alcohol monomers. In hardwoods, a copolymer of coniferyl and sinapyl alcohols is most prominent, with the ratio of coniferyl to sinapyl alcohol varying from 4:1 to 1:2 depending on the species and location in the cell (middle lamella vs. cell wall).

2.2.4 Extractives and Ash

Extractives form the remaining organic compounds in wood, so named as they can be extracted from the wood through the use of solvents. The main groups of extractives are fats and waxes, terpenes and terpenoids, and phenolic compounds [28]. Extractives account for 1% to 5% of the mass of the wood. Ash is made up of the non-organic components in wood, and typically accounts for less than 1% of the content of wood [27], but approximately 2% of the mass of hybrid poplar [10]. Wood extractive compounds typically have boiling points of approximately 200°C-220°C [24].

2.2.5 Bark

Bark is used as an energy source and as the main component of hog fuel, which is used onsite at wood processing facilities [29]. Bark has a complex structure that varies between species, and contains much higher percentages of both extractives and ash than wood. Extractives account for 20%-40% and ash accounts for 2-5% of the mass of bark [26, p. 102].
2.3 Herbaceous Biomass Chemistry

Herbaceous biomass that may be used for bioenergy applications include switchgrass and agricultural residues. Switchgrass is a common crop for energy production [30] due to its high growth rate, suitability to marginal land and similar higher heating value to wood [31]. Switchgrass contains higher levels of extractives and ash than wood, with extractives constituting 16%-20% [31], [32] and ash 3%-7% of mass [31]–[33]. Switchgrass's high ash content reduces its value as a fuel for co-firing with coal, as it contains too much ash to meet the lowest industrial rating for biomass pellets [34].

Agricultural residues are another potential source of biomass for energy, due to their low commercial and agricultural value. Examples of agricultural residues usable for energy include corn stover, rice husks, olive husks and grape residue. Most residues have high levels of extractives and ash, with ash ranging from 3% for olive husks to 15% for rice husks [32], [35]. Similar to switchgrass, the value of agricultural residues as a fuel for co-firing is low due to their high ash contents. Torrefaction of tomato residues was studied by Toscano et al. [36], which concluded this material was a good candidate for use as a solid biofuel. Raw tomato residues have an LHV of 26 GJ/tonne, with an ash content of 2%, rising to an LHV of 30 GJ/tonne with 3% ash after torrefaction at 282°C.

2.4 Torrefaction

Torrefaction, which is also referred to as mild pyrolysis, is a thermo-chemical process where biomass is heated to 200°C-300°C in an oxygen-free environment. Pyrolysis and gasification
are similar processes, but involve heating the biomass to higher temperatures than during torrefaction to cause further thermal decomposition of the biomass.

2.4.1 Thermal Decomposition of Biomass

Cellulose, hemicellulose, and lignin undergo depolymerisation and decomposition at different rates and temperatures, and so thermal decomposition of wood depends on the percentage of each of these components in the wood.

Hemicellulose undergoes thermal decomposition in a two stage process. The first stage takes place at temperatures below 180°C [37] and results in hemicellulose depolymerisation but little mass loss [38]. The second stage, which begins at 250°C, results in the vaporization of a large portion of the hemicellulose, with mass loss of 68% at 340°C [39], and near complete vaporization at 600°C [38]. Xylan-based hemicellulose decomposes more quickly and at lower temperatures than glucomannan-based hemicellulose, so biomass with a higher percentage of xylan-based hemicellulose decomposes faster [40].

Cellulose begins to undergo depolymerisation below 150°C [38], but with little mass loss below 280°C [37]. Unlike hemicellulose and lignin, cellulose undergoes decomposition and vaporization over a small range of temperatures, with almost all mass loss occurring between 280°C and 380°C [37].

Hemicellulose and cellulose are polysaccharides, so their decomposition largely occurs due to dehydration reactions splitting the glucosidic bonds that join the monosaccharides. This results in significant water vapour in the products from their thermal decomposition. Fourier
transform infrared spectroscopy (FTIR) was used to observe a drop in O-H bond intensity with increasing torrefaction temperature, indicating dehydration reactions occurring during torrefaction [36], [41].

Lignin begins to undergo thermal softening and a small amount of mass loss below 150°C [38]. Lignin mass loss occurs over a wide range of temperatures, beginning as low as 80°C and peaking at 350°C, but vaporisation is not complete even at 700°C [37]. In spruce at 8% moisture content (MC) lignin was shown to exhibit a glass transition temperature of 91°C, above which lignin requires less energy to extrude through a pellet mill [42].

2.4.2 Torrefaction, Pyrolysis and Gasification

Torrefaction, pyrolysis and gasification are thermal treatments of biomass, which involve heating biomass in an oxygen-free environment, with the maximum temperature distinguishing the processes. According to Beaumont and Schob [43], torrefaction occurs between 220°C and 320°C, pyrolysis between 340°C and 450°C and gasification above 500°C.

The ratio of products from the three processes depends on the processing temperature. For torrefaction, the main product is char, referred to as torrefied biomass. For pyrolysis, the main product is bio-oil with a significant amount of char. For gasification, the main product is either bio-oil or bio-gas, depending on the temperature; however, gasification always has a low char yield [43].
2.4.3 Torrefaction Products

The products that result from torrefaction can be divided into the solid yield (char or torrefied biomass), condensable gases or tars, and non-condensable gases [27]. The condensable gases and non-condensable gases are typically considered together and referred to as off-gases or torgas [8]. The solid yield is highly dependent on temperature, ranging from 95% at 230°C to 65% at 300°C [44].

The condensable off-gases largely consist of water vapour (as a product from dehydration reactions), acetic acid, methanol, lactic acid, formic acid and phenol, while the non-condensable gases are mainly carbon dioxide and carbon monoxide [44]. The calorific value of the torrefaction off-gases is given by Bergman et al. as 9.3 GJ/t for torrefaction of woodcuttings at 280°C [8].

The calorific value of both the torrefied wood and the off-gases are dependent on the temperature reached during torrefaction. Nicksy et al. reported an average HHV of 21.25 GJ/t for the Q’Pellet compared to an initial HHV of 18.61 GJ/t for raw hybrid poplar for torrefaction at 280°C [10]. Table 2-1 presents the heating values for different species of wood from several papers.
Table 2-1: Comparison of calorific values of torrefied wood

<table>
<thead>
<tr>
<th>Torrefied Wood HHV (GJ/t)</th>
<th>Raw Wood HHV (GJ/t)</th>
<th>Species</th>
<th>Torrefaction Temperature (°C)</th>
<th>Mass Loss (%)</th>
<th>Note</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.25</td>
<td>18.61</td>
<td>Hybrid Poplar</td>
<td>280</td>
<td></td>
<td></td>
<td>[10]</td>
</tr>
<tr>
<td>20.2</td>
<td>17</td>
<td>Beech</td>
<td>280</td>
<td>24</td>
<td>LHV</td>
<td>[44]</td>
</tr>
<tr>
<td>21.5</td>
<td>19.4</td>
<td>Spruce</td>
<td>280</td>
<td>29</td>
<td></td>
<td>[18]</td>
</tr>
<tr>
<td>22.1</td>
<td>20.4</td>
<td>Pine</td>
<td>280</td>
<td>27</td>
<td></td>
<td>[18]</td>
</tr>
<tr>
<td>22.3</td>
<td>19.5</td>
<td>Fir</td>
<td>280</td>
<td>13</td>
<td></td>
<td>[8]</td>
</tr>
</tbody>
</table>

2.4.4 Benefits of Torrefaction

There are multiple improvements to the energy product value of biomass from torrefaction, including increased HHV, improved hydrophobicity, reduced equilibrium moisture content, improved friability and no biological activity in the torrefied wood. Increases in HHV of 15%-30% have been described in the literature, which can be seen in Table 2-1. Torrefaction improves the hydrophobicity of the biomass due to the dehydration reactions that occur during torrefaction, which remove the hydroxyl groups where water bonds to raw biomass [42]. The improved hydrophobicity reduces the equilibrium moisture content of the biomass, with spruce torrefied at 300°C having 3.2% MC compared to 12.7% MC for raw spruce after storage at 27°C and 80% relative humidity for three weeks [45]. As the cellular structure of the biomass is destroyed during torrefaction, no biological activity can occur, preventing the possibility of rotting and biological self-heating.

Improved friability is an important result from the torrefaction of biomass. Raw biomass requires over four times the energy to grind compared to coal [8] and cannot be ground with...
typical coal grinders without “gumming” up the pulverisers. Several studies have shown that torrefaction reduces grinding energy requirements by 75% or more compared with raw wood [8], [9], [15], [46].

2.5 Biomass Markets and Prices

2.5.1 Wood Pellet Markets

Global wood pellet production volumes have increased almost 15-fold between 2000 and 2015 [47] from 2 Mt/year to 28 Mt/year. The global market is projected double in size to 54 Mt/year by 2025 [48]. Continued market growth should allow new pellet production plants to open and profitably sell pellets.

2.5.1.1 Export Markets

Currently, the main market for Canadian wood pellets is by export to the European Union (EU), which accounts for approximately 80% of sales of Canadian wood pellets [47]. Most Canadian wood pellets exported to the EU are destined for England, where wood pellets are mainly used for power production. The Drax power station in Yorkshire is the largest consumer of wood pellets, including Canadian pellets. In 2015, Drax purchased 1.16 Mt of Canadian pellets [49], out of 1.21 Mt exported to the UK [50]. Drax is expected convert additional units to operate on biomass, and will continue to increase their demand for wood pellets. One example of this continued demand growth is the ten-year, 400,000 tonne/year off-take pellet agreement signed with Rentech in Wawa, Ontario [51]. In other parts of the
EU, wood pellets are used mainly for residential or district heating and are supplied from internal EU production [52].

Asian countries are the largest emerging markets for Canadian pellets. Japan and South Korea are quickly growing biomass markets and were Canada’s fourth and fifth largest export markets, respectively, in 2015 [47]. However, South Korean imports of Canadian pellets fell significantly from 2014 to 2015 as Vietnamese pellet production took over much of the market. Due to the low cost of Vietnamese pellets and very low cost of transport to South Korea, Vietnamese pellets may maintain dominance in South Korea. In Japan, growth in pellet demand is driven by the drop in nuclear electricity production, with up to 10% of former nuclear electricity that production to be replaced by biomass [47]. According to the Wood Pellet Association of Canada, Japanese biomass plants are more likely to enter into long term contracts with North American pellet producers, making Japan a more stable market than South Korea [47]. Furthermore, as most American pellets are produced in the southeastern part of the USA, Canadian pellets exported from BC have much lower transport costs to Japan, lowering the cost of Canadian pellets compared to American pellets.

2.5.1.2 Domestic Markets

In Ontario, the main recent market developments are the conversions of the Atikokan and Thunder Bay Generating Stations to operate on biomass. Atikokan GS was converted to run on white pellets while Thunder Bay was converted to run on torrefied pellets. The costs for the Atikokan GS conversion were significant, at $170M [53] to convert the 200 MW facility to operate fully on white pellets. Major capital expenses included building new pellet silos,
modifications to the boilers, and building dust suppression systems [12]. The Thunder Bay GS was converted to operate on torrefied pellets, and was a much less expensive conversion, at $7M [53]. However, due to a lack of supply, the Thunder Bay GS has only operated using torrefied pellets for a short term trial, with pellets purchased from Arbaflame [12], [13].

2.5.2 Wood Pellet Market Prices

Wood pellets are a traded commodity, with published price indexes. Argus Media publishes a weekly biomass index, with spot and future prices for industrial and premium pellets [54]. Prices are given CIF (Cost, Insurance and Freight - including shipping to final port) ARA (Amsterdam, Rotterdam, Antwerp), FOB (Free on Board - not including shipping) Portugal, FOB Baltic, and FOB Vietnam for industrial pellets. Prices are given per tonne for pellets with an assumed as-received higher heating value (HHV$_{AR}$) of 17 GJ/tonne. The Wood Pellet Association of Canada maintains a weekly graph of CIF ARA prices from the Argus biomass index, in USD/tonne [55]. From July 2015 to April 2016, prices have fallen from ~165 USD/tonne to ~130 USD/tonne. For January 2016, prices were ~150 USD/tonne, which equals 184 CAD/tonne at an exchange rate of 1.2105 CAD/USD [56], or CAD 10.82/GJ$_{AR}$. Changes to exchange rates are analyzed and discussed in Section 4.4.

A second source of wood pellet market prices are from Statistics Canada, which publishes a database of the total weight and value of wood pellets imported to and exported from Canada [50]. The total value of Canadian pellet exports in 2015 was $284.7M and the total weight
was 1,628 Mtonnes. This equals $175/tonne, slightly lower than the value estimated from the Argus index.

2.5.3 Torrefied Pellet Market Prices

There are little data available on torrefied pellet prices, as there is very little commercial sale and no published price indexes for torrefied pellets. A conservative estimate of torrefied pellet prices would be to assume that sale prices will be the same as white pellets, on an as-received energy basis. This equals ~$220/tonne [10]. The Statistics Canada database on wood pellets imports/exports offers a second source for determining the value of torrefied pellets. As noted earlier, the Thunder Bay GS biomass conversion operates on biomass acquired from Arbaflame, based in Norway [57]. Between 2013 and 2015, 17,225 tonnes of wood pellets have been imported from Norway to Canada, at a total cost of $8,932,991 [58], which equates to $519/tonne. As there would be very little reason to import white pellets to Canada from Norway at such a high cost, it is reasonable to assume that these are all torrefied pellets imported by OPG for Thunder Bay GS. Thus, $519/tonne is an estimate of the value of torrefied pellets purchased in reasonably small quantities for commercial demonstrations/feasibility studies. Given that OPG appears to paying over double the cost per GJ for torrefied pellets than white pellets, this suggests that a large premium must be currently paid to acquire torrefied pellets in the quantities and with the lead times OPG desired.
2.5.4 Raw Biomass Markets and Prices

The cost of raw biomass is highly variable, as it is dependent on type, supply and location. The main biomass used to make pellets in Canada is mill residue [16]. In the United States, “thinnings” (small trees that cannot be sawmilled) and forest residues (branches, treetops and bark) are also used [49]. In Canada, potential sources of biomass for wood pellets include forest residues, hog fuel, unused annual allowable cut (AAC) and unmerchantable timber [4]. Table 2-2 provides the annual quantity available of certain types of biomass in thousands of oven dried tonnes (ODT).

<table>
<thead>
<tr>
<th>Biomass Type</th>
<th>Quantity Available (Thousand ODT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill Residue</td>
<td>2,900</td>
</tr>
<tr>
<td>Forest Residue</td>
<td>8,880</td>
</tr>
<tr>
<td>Hog Fuel</td>
<td>2,150</td>
</tr>
<tr>
<td>Unused AAC</td>
<td>39,400</td>
</tr>
<tr>
<td>Unmerchantable Timber</td>
<td>2,700</td>
</tr>
</tbody>
</table>

Estimated costs of each type of biomass from literature are shown in Table 2-3.
From Table 2-3, it can be seen that the price of biomass varies greatly depending on the type of biomass and can vary significantly for a single biomass type. The reported costs of mill residues range from $22-$44 per tonne, despite all reported values being from the province of British Columbia (B.C.). A major factor that affects the cost of mill residue is demand for wood products [4], as higher demand increases mill production and supply of mill residues. Hog fuel prices are similarly affected by available supply, as hog fuel is required to be burnt in some jurisdictions but stockpiled in others [4]. This leads to large supplies of hog fuel in some areas but low supplies in others.

### Table 2-3: Range of raw biomass costs, $/ODT

<table>
<thead>
<tr>
<th>Biomass Type</th>
<th>Cost ($/ODT)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill Residue</td>
<td>$21.95</td>
<td>[16]</td>
</tr>
<tr>
<td></td>
<td>$31.20-35.00</td>
<td>[4]</td>
</tr>
<tr>
<td></td>
<td>$43.76</td>
<td>[29]</td>
</tr>
<tr>
<td>Hog Fuel</td>
<td>$10.00</td>
<td>[4]</td>
</tr>
<tr>
<td></td>
<td>$18.75</td>
<td>[29]</td>
</tr>
<tr>
<td></td>
<td>$5.49</td>
<td>[16]</td>
</tr>
<tr>
<td>Forest Residue</td>
<td>$50.48</td>
<td>[16]</td>
</tr>
<tr>
<td></td>
<td>$68.77</td>
<td>[29]</td>
</tr>
<tr>
<td></td>
<td>$50.00</td>
<td>[4]</td>
</tr>
<tr>
<td>Roundwood</td>
<td>$71.22</td>
<td>[17]</td>
</tr>
<tr>
<td></td>
<td>$118.78</td>
<td>[29]</td>
</tr>
<tr>
<td></td>
<td>$80.00</td>
<td>[4]</td>
</tr>
<tr>
<td>Wood Chips</td>
<td>$70.00</td>
<td>[29]</td>
</tr>
<tr>
<td></td>
<td>$71.32</td>
<td>[16]</td>
</tr>
</tbody>
</table>

2.6 Torrefaction Technology and Commercial Status

2.6.1 Torrefaction Technology

There are several types of torrefier reactors. The most basic distinction between reactor types is direct vs. indirect heating. Indirect heating torrefiers separate the biomass from the heating
gas. Gases used for heating are typically flue gases from combustion and may have particulate matter, etc. that can foul equipment so it is advantageous to keep them separate from biomass. Direct heating torrefiers have gases flow over the biomass. This allows for much higher heat transfer rates [8]. A third type of torrefier are microwave reactors, which heat the moisture in the biomass with microwaves, instead of heating gas.

Torrefaction reactor types include screw reactors, moving bed reactors, rotating drums, the Torbed® reactor and multiple hearth reactors [8], [59]. Screw reactors are typically indirectly heated, with a helical shaped screw that moves biomass inside a chamber. Heating gases flow outside this chamber, inside an enclosing jacket. Moving bed reactors are directly heated, with biomass that flows through the reactor and the heating gases flowing against the biomass in a counter-flow type arrangement. Multiple hearth reactors are directly heated reactors that operate as a stack of rotating discs. The biomass is loaded onto the discs, and the heating gases flow over the biomass on the discs. The Torbed® reactor is a type of toroidal fluidized bed reactor. Biomass enters at the top of a toroidal reactor, where it is directly heated by high velocity swirling heating gases. The gases quickly heat the biomass and force it to exit on the sides of the reactor. This design allows for very high heat transfer rates and low residence time [59].

2.6.2 Torrefaction Commercial Status

There are several companies that currently operate pilot, demonstration or pre-commercial torrefaction facilities; these are highlighted in Table 2-4. As large white pellet plants have
capacities upwards of 100,000 tonnes/year, the only torrefaction plant at full commercial scale is the New Biomass Energy plant in Quitman, Mississippi. All other plants currently or formerly operating were commercial demonstration plants, designed to show that torrefaction technology can scale-up and to allow for short term testing in coal plants, such as the tests at Thunder Bay GS using Arbaflame pellets.

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Capacity (tonne/hour)</th>
<th>Reference</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arbaflame</td>
<td>Norway</td>
<td>6</td>
<td>[60]</td>
<td></td>
</tr>
<tr>
<td>Topell Energy</td>
<td>Netherlands</td>
<td>6</td>
<td>[61]</td>
<td>Demonstration plant; bankrupt</td>
</tr>
<tr>
<td>Andritz</td>
<td>Denmark</td>
<td>1</td>
<td>[62]</td>
<td>Moving bed reactor</td>
</tr>
<tr>
<td>Andritz</td>
<td>Austria</td>
<td>1</td>
<td>[62]</td>
<td>Rotating drum reactor</td>
</tr>
<tr>
<td>New Biomass Energy</td>
<td>Mississippi</td>
<td>30</td>
<td>[63]</td>
<td></td>
</tr>
<tr>
<td>Torr-Coal</td>
<td>Belgium</td>
<td>3.75</td>
<td>[64]</td>
<td></td>
</tr>
<tr>
<td>Airex Energy</td>
<td>Quebec</td>
<td>0.25</td>
<td>[65]</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-4: Torrefaction plants

There are several companies that advertise the manufacture and sale of torrefaction units. The only companies that appear to currently take production orders known to the author are Agri-tech Producers and Konza Renewable Fuels. Konza does not give an indication of price, but Agri-tech advertises a 5 tonne/hour torrefier for a cost of $5M [66].

<table>
<thead>
<tr>
<th>Company</th>
<th>Capacity (tonne/hour)</th>
<th>Cost (M$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Konza Renewable Fuels</td>
<td>12</td>
<td></td>
<td>[67]</td>
</tr>
<tr>
<td>Agri-Tech Producers</td>
<td>5</td>
<td>5</td>
<td>[66]</td>
</tr>
</tbody>
</table>

Table 2-5: Torrefaction unit manufacturers (M$ - millions of dollars)

The cost of torrefiers varies, partly based on the maximum initial moisture content of the biomass that can be torrefied. For torrefiers that are able to accept biomass at 40%-50% MC,
a separate dryer is not needed, which lowers capital costs. Some typical torrefier capital costs from the literature are compared to the advertised cost from Agri-tech in Table 2-6.

### Table 2-6: Torrefier capital costs

<table>
<thead>
<tr>
<th>Torrefier Capital Cost (M$)</th>
<th>Capacity (tonne/hour)</th>
<th>Torrefier Cost per tonne/hour (M$)</th>
<th>Reference</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>1</td>
<td>[66]</td>
<td></td>
</tr>
<tr>
<td>4.53-6.44</td>
<td>5</td>
<td>0.91-1.29</td>
<td>[68]</td>
<td></td>
</tr>
<tr>
<td>28.33</td>
<td>12.8</td>
<td>2.36</td>
<td>[17]</td>
<td>No separate dryer</td>
</tr>
<tr>
<td>10.73</td>
<td>15.75</td>
<td>0.68</td>
<td>[16]</td>
<td>Moving bed reactor</td>
</tr>
<tr>
<td>25.45</td>
<td>15.75</td>
<td>1.62</td>
<td>[16]</td>
<td>Screw reactor</td>
</tr>
<tr>
<td>17.58</td>
<td>15.75</td>
<td>1.12</td>
<td>[16]</td>
<td>Rotating drum reactor</td>
</tr>
</tbody>
</table>

The cost of torrefiers can be seen to vary significantly. The lowest cost per tonne/hour in Table 2-6 is $0.68M, with costs ranging up to $2.36M per tonne/hour. Typically capital costs will follow a power law, with capacity costs that decrease with increasing size [69]. However, uncertainty about reactor type and scalability means that a power law may not always be followed for torrefaction technology. The advertised cost from Agri-tech is $1M per tonne/hour, placing it in the middle of values found in the literature. Given that typical literature values fall around a commercially advertised price provides some validation of literature price estimates.

### 2.7 Biomass Transport

The most common methods to transport biomass on land are by transport truck and rail. As rail is less expensive, it is preferred when available [70]. However, trucks are required when
rail is unavailable, which is common for transportation of raw biomass to pellet plants. Ocean transport is done by ship, either packaged on a container ship or loose on bulk cargo ships.

2.7.1 Truck Transport

Transport trucks are required to transport raw biomass to pellet plants, and may also be used to ship pellets either to rail stations or to river/lake/ocean ports for export. In the case of domestic consumption of pellets, trucks may be used for delivery to final customers. If it is assumed that the trucks are owned by a contracted trucking company, there are no ownership costs [71]. The cost of truck shipping is then split between a distance fixed cost (DFC) and distance variable cost (DVC) [70], with the variable cost depending on both mass and distance transported. The fixed cost includes the cost of loading and unloading the trucks [70].

The maximum weight of a B-train double trailer transport (largest type of double-trailer transport truck) is 62.5 tonnes [72], with a maximum load weight of 42.5 tonnes and a maximum load volume of 160 m$^3$ [29]. This results in a maximum bulk density of 265 kg/m$^3$. As wet wood chips (~50% MC) have a bulk density of 300-400 kg/m$^3$, these trucks are therefore mass limited. Dried wood chips have a lower bulk density, 200-250 kg/m$^3$, and so trucks become volume limited.
Table 2-7 lists the costs of shipping weight limited biomass from the literature, split into a distance fixed cost (DFC) and distance variable cost (DVC), with values modified to have the shown units and costs into 2015 CAD.

<table>
<thead>
<tr>
<th>DFC ($/tonne)</th>
<th>DVC ($/tonne·km)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.825</td>
<td>0.112</td>
<td>[70]</td>
</tr>
<tr>
<td>3.04</td>
<td>0.037</td>
<td>[73]</td>
</tr>
<tr>
<td>15.458</td>
<td>0.08</td>
<td>[17]</td>
</tr>
</tbody>
</table>

There is a large spread in DFC and DVC in Table 2-7, which may depend on type of shipping contract in the corresponding reference. Large scale contracts will have lower costs than single shipments, but none of the papers listed describe the contract structure.

2.7.2 Rail Transport

The cost of rail transport can be split also into a DFC and DVC, with a lower DVC and higher DFC than for truck transport. Hamelinck et al. [73] gave a non-linear DVC, with a cost per kilometre that decreased with distance. Typically, rail transport will be preferred for longer distance shipping [71]. The maximum volume of a hopper car is 113 m$^3$ with a maximum load weight of 92 tonnes [74], giving a maximum bulk density of 814 kg/m$^3$. The cost of rail transport is provided in Table 2-8.
Using the CN Rail carload price tool [75], the cost of shipping a rail car between two points can be found for a number of commodities. In the case of Williams Lake, BC to Vancouver BC, for wood pellets, the cost is $2537 per carload.

Table 2-9 provides the maximum weight that can be carried per railcar and the cost per tonne to ship white pellets, torrefied pellets, and Q’Pellets from Williams Lake, BC to Vancouver, BC.

<table>
<thead>
<tr>
<th>Pellet Type</th>
<th>Bulk Density (kg/m$^3$)</th>
<th>Maximum Weight per Rail Car (tonne)</th>
<th>Cost ($/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Pellets</td>
<td>650</td>
<td>73.5</td>
<td>34.54</td>
</tr>
<tr>
<td>Torrefied</td>
<td>700</td>
<td>79.1</td>
<td>32.07</td>
</tr>
<tr>
<td>Pellets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q’Pellets</td>
<td>821</td>
<td>92</td>
<td>27.62</td>
</tr>
</tbody>
</table>

An alternative to shipping by the carload would be to lease or buy railcars and enter into long-term rail agreements. This strategy has been adopted by Rentech for delivery of pellets from Wawa to Quebec City for export to the UK [51]. They claim this reduces the cost per tonne-kilometre; unfortunately, this claim cannot be substantiated.

2.7.3 Ocean Transport

Ocean transport can be either done in fairly small quantities in packaged containers aboard container ships or loose aboard bulk cargo ships. Indeed, torrefied pellets were shipped to Thunder Bay for OPG’s trial at Thunder Bay GS using package shipping [57]. This was likely
due to the low quantity of torrefied pellets shipped, as there was not enough volume to justify the effort of bulk cargo handling.

Bulk cargo can be either shipped in a given quantity or by chartering an entire ship. Using the website http://SeaRates.com quotes were requested to ship 5000 tonnes of wood pellets from Vancouver to Rotterdam. The quotes ranged from 45 to 67 CAD/tonne, or 0.0027 to 0.0041 CAD/tonne-km [76]. Table 2-10 lists shipping costs per tonne.

<table>
<thead>
<tr>
<th>DFC ($/tonne)</th>
<th>DVC ($/tonne-km)</th>
<th>Reference</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>$17.353</td>
<td>$0.016</td>
<td>[70]</td>
<td></td>
</tr>
</tbody>
</table>

The maximum ship size to ship from Vancouver to Europe is a cargo vessel classified as the Panamax size, which is that maximum size that can pass through the Panama Canal. The cost of shipping is based on a daily charter rate and the cost of bunker fuel [29]. The daily charter rate is charged for both the number of days for shipping and for loading and unloading at port. The cost of bunker fuel depends on the cost per tonne of fuel and the amount consumed. The cost of Panamax shipping according to Stephen [29] is

\[
C_{\text{ship}} = (C_{\text{daily}} \times T) + (C_{\text{Bunker}} \times FE \times D)
\]

[2-1]

where \(C_{\text{ship}}\) is shipping cost ($/ship), \(C_{\text{daily}}\) is the daily charter cost ($/day), \(T\) is number of days required to load, ship and unload pellets (days), \(C_{\text{Bunker}}\) is the cost of bunker fuel ($/tonne), \(D\) is the distance (km), and \(FE\) is fuel efficiency (tHFO/km). Equation [2-1] can be split into the DFC and DVC (distance fixed cost and distance variable cost) as

\[
C_{\text{Ship (DFC)}} = C_{\text{Daily}} \times P
\]

[2-2]
\[ C_{Ship(DVC)} = C_{Bunker} \ast D \ast FE + C_{Daily} \ast D \ast S \]  \hspace{1cm} [2-3]

where \( C_{Ship(DFC)} \) is the distance fixed cost, \( C_{Daily} \) is the daily charter cost, \( P \) is number of days in port loading/unloading, \( C_{Ship(DVC)} \) is the distance variable cost, \( C_{Bunker} \) is the cost of bunker fuel, \( D \) is the distance, \( FE \) is fuel efficiency, and \( S \) is average speed.

Panamax ships have a maximum load of 55,000 tonnes [29] and a maximum volume of 66,500 m\(^3\) [77], which then gives a maximum bulk density of 827 kg/m\(^3\). Table 2-11 provides the bulk densities of white, torrefied and Q’Pellets and the resulting maximum weight that can carried per Panamax ship.

<table>
<thead>
<tr>
<th>Pellet Type</th>
<th>Bulk Density (kg/m(^3))</th>
<th>Maximum Weight per Panamax Shipload (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Pellets</td>
<td>650</td>
<td>43,225</td>
</tr>
<tr>
<td>Torrefied Pellets</td>
<td>700</td>
<td>46,550</td>
</tr>
<tr>
<td>Q’Pellets</td>
<td>821</td>
<td>55,000</td>
</tr>
</tbody>
</table>

Using equations [2-2] and [2-3] and Table 2-11, DFC and DVC can be determined per tonne for each of the three types of pellets. The daily charter rate is assumed to $20,000/day [29] and the cost of bunker fuel (HFO) $547.55/tonne [78]. Fuel efficiency is assumed to 20 km/tHFO at an average speed of 25.2 km/hr [29]. It is assumed that unloading and loading will each take 1.5 days [29]. Panamax shipping DFC and DVC for the three pellets are provided in Table 2-12.
Table 2-12: Cost per tonne to ship pellets by Panamax ship

<table>
<thead>
<tr>
<th>Pellet Type</th>
<th>DFC ($/tonne)</th>
<th>DVC ($/tonne-km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Pellets</td>
<td>1.388</td>
<td>0.0014</td>
</tr>
<tr>
<td>Torrefied Pellets</td>
<td>1.289</td>
<td>0.0013</td>
</tr>
<tr>
<td>Q’Pellets</td>
<td>1.110</td>
<td>0.0011</td>
</tr>
</tbody>
</table>

The values from Table 2-12 are used in the model described in chapter 3. The higher bulk density of Q’Pellets allows them to have the lowest shipping costs per tonne for both DFC and DVC.

2.8 Wood Pellet Production Costs

The economics of producing wood pellet can be split into revenue, and capital and operating costs. The revenue equals sale price multiplied by production volume.

2.8.1 Capital Costs

The capital costs can be divided into costs inside battery limits and outside battery limits. Components considered inside battery limits directly impact pellet production (e.g. pellet mills) while those components outside battery limits do not (e.g. buildings). The capital costs inside battery limits are given in sections 2.9.1 and 2.10. Literature values for outside battery components are shown in Table 2-13.

Table 2-13: Outside battery limit capital costs

<table>
<thead>
<tr>
<th>Cost (M$)</th>
<th>Plant Capacity (ktonnes/year)</th>
<th>Reference</th>
<th>Note</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5.99</td>
<td>126</td>
<td>[16]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.01</td>
<td>40</td>
<td>[9]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.77</td>
<td>100</td>
<td>[17]</td>
<td></td>
<td>Does not include indirect capital expense of $8.67M</td>
</tr>
</tbody>
</table>

The costs included in [16] are listed as storage, conveyors, separators, peripheral equipment and buildings. The costs included in [17] are conveyors, buildings and office space, paving,
fork lifts and front end loaders, and a storage warehouse. There is also an “indirect capital cost” of $8.67M, which is equal to 24% of the capital costs included in [17].

2.8.1.1 Construction Time and Capital Cost Breakdown

Pirraglia et al. [17] estimate a construction time of three years, with a capital breakdown of 20% in year one, 40% in year two and 40% in year three for a torrefied pellet plant with a capacity of 100,000 tonnes/year.

2.8.1.2 Capital Cost Depreciation

Capital costs are depreciated, which lowers taxable income. The amount depreciated is considered a loss for tax purposes, but is not an actual cash loss and should not be considered as such. Under current Canadian tax law, capital costs are depreciated using a declining balance method. With declining balance depreciation, the value of the capital is reduced annually by a percentage of the capital’s value from the previous year. Buildings are considered Class 1 property and a depreciated 4% per year, while manufacturing equipment is considered Class 43 property and is depreciated 30% per year [79]. Once capital is depreciated, its current value is determined by subtracting the depreciation amount from the previous property value. In both cases, depreciation is reduced by 50% during the first year. Manufacturing equipment purchased after 2015 may be considered Class 53 property, allowing 50% per year depreciation [80].

In the United States, the MACRS (modified cost accelerated recovery system) system is used. This method uses varying depreciation rates that are based on the initial value of the capital, with zero depreciation in the year of purchase. Commercial real property is depreciated over
a 39-year period, with depreciation rates of 2.461% in year one and 2.564% in years 2-39 [81]. Manufacturing equipment is depreciated over a 7-year period following the rates in Table 2-14.

Table 2-14: Seven-year modified accelerated recovery system depreciation rates [81]

<table>
<thead>
<tr>
<th>Year</th>
<th>MACRS 7 Depreciation Rates (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.29</td>
</tr>
<tr>
<td>2</td>
<td>24.49</td>
</tr>
<tr>
<td>3</td>
<td>17.49</td>
</tr>
<tr>
<td>4</td>
<td>12.49</td>
</tr>
<tr>
<td>5</td>
<td>8.93</td>
</tr>
<tr>
<td>6</td>
<td>8.92</td>
</tr>
<tr>
<td>7</td>
<td>8.93</td>
</tr>
</tbody>
</table>

2.8.1.3 Scaling Factor

Capital costs are determined from literature and commercial prices, which are typically only given for a single machine. To modify literature values to the desired capacity, the power law equation used is [69]

\[ C = C_b \left( \frac{P}{P_b} \right)^S \]  \hspace{1cm} [2-4]

where \( C \) is the capital cost at the desired plant capacity (ktonnes/year), \( C_b \) is base capital cost, \( P \) is desired plant capacity (ktonnes/year), \( P_b \) is base plant capacity (ktonnes/year) and \( S \) is scale factor is used. Scale factors vary from 0.6 to 0.8, with 0.7 being a typical value for wood pellet plants [17], [68], [69]. New technology that has not been built at commercial scale may have higher than average scale factors, due to unforeseen problems involved with scaling from pilot to commercial scale [82].

31
2.8.2 Operating Costs

2.8.2.1 Labour Costs

Labour costs are given in terms of direct labour, which consists of operators, supervisors and foremen, and indirect labour, which is required for administration and general management. Literature values for direct labour typically describe the number of employees required along with salaries per employee. Indirect labour costs are either given in terms of number of employees and their salaries or as a percentage of direct labour, part of which may be split into maintenance/overhead costs. Direct labour costs are shown in Table 2-15 and indirect labour costs are shown in Table 2-16.

<table>
<thead>
<tr>
<th>Direct Employees</th>
<th>Total Salary (k$/year)</th>
<th>Plant Capacity (ktonnes/year)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>705</td>
<td>126</td>
<td>[16]</td>
</tr>
<tr>
<td>26</td>
<td>1,275</td>
<td>100</td>
<td>[17]</td>
</tr>
<tr>
<td>6</td>
<td>468</td>
<td>40</td>
<td>[9]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indirect Employees</th>
<th>Total Salary (k$)</th>
<th>Plant Capacity (ktonnes/year)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% of direct labour</td>
<td>317</td>
<td>126</td>
<td>[16]</td>
</tr>
<tr>
<td>7</td>
<td>698</td>
<td>100</td>
<td>[17]</td>
</tr>
<tr>
<td>2</td>
<td>126</td>
<td>40</td>
<td>[9]</td>
</tr>
</tbody>
</table>

Commercial wood pellet plants also publish employment records; however, these numbers are often opaque and do not indicate what types of employees are included. Rentech [51] has announced the hiring of 25 employees for their 100,000 tonne/year Atikokan plant and 40 employees at their 400,000 tonne Wawa plant, but has not disclosed any salary information or the roles of the employees.
2.8.2.2 Maintenance Costs

Maintenance costs are given either as a cost per tonne or as a percentage of capital costs, provided in Table 2-17.

<table>
<thead>
<tr>
<th>Maintenance Costs</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% inside battery limit capital cost</td>
<td>[16]</td>
</tr>
<tr>
<td>$8.85/tonne</td>
<td>[17]</td>
</tr>
<tr>
<td>2.4% inside battery limit capital cost + 1.5% outside battery limit capital cost</td>
<td>[9]</td>
</tr>
</tbody>
</table>

Peng et al. [16] reported maintenance costs of 5% of inside battery limit capital cost, which was calculated to be $6.39/tonne using their capital costs. Obernberger and Thek [9] reported maintenance costs of 2.4% inside battery limit capital cost plus an additional 1.5% outside battery limit capital cost, which equals $2.91/tonne using their reported capital cost. This gives a wide range of costs per tonne, which may vary depending on what activities are included in maintenance costs. Furthermore, higher maintenance costs may be required if lower capital costs are desired, especially if equipment is bought used or is kept in service longer than designed.

2.8.2.3 Insurance and Property Tax

Insurance and property taxes are calculated as a percentage of total capital cost. Peng et al. [16] gives insurance as 0.5% and property tax as 1% of total capital cost. Property taxes are highly dependent on location, and cannot be given accurately without first determining where a facility is to be built. However, plant location can be optimized to minimize property taxes, and so, 1% is a reasonable assumption.
2.8.2.4 Overhead Costs

Overhead costs account for logistics, administration, etc., which may be partly included in indirect labour costs. Peng et al. [16] gives general overhead costs as 50% of labour and maintenance costs.

2.8.2.5 Utility Costs

The two utilities required to produce wood pellets are electricity and natural gas. The cost of electricity is dependent on location and year, shown in Table 2-18 for 2015.

<table>
<thead>
<tr>
<th>Location</th>
<th>Electricity Cost (¢/kWh)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ontario</td>
<td>9.06</td>
<td>[83]</td>
</tr>
<tr>
<td>BC</td>
<td>7.13</td>
<td>[84]</td>
</tr>
<tr>
<td>Georgia</td>
<td>11.34</td>
<td>[85]</td>
</tr>
<tr>
<td>Mississippi</td>
<td>10.41</td>
<td>[85]</td>
</tr>
<tr>
<td>Louisiana</td>
<td>8.35</td>
<td>[85]</td>
</tr>
</tbody>
</table>

The cost of natural gas is less variable by location, as long as a pipeline is close to the plant. The cost of natural gas was assumed to be $0.2612/m³ or $6.873/GJ, based on values from February 2016 [86]. Varying natural gas prices are discussed in Section 4.4.7.

2.8.2.6 Storage Costs

Storage costs depend largely on whether biomass is stored uncovered outdoors or in a silo. Hamelinck et al. [73] reported the cost of outdoor and silo storage as a cost per m³, with capital costs included. The Pellet Handbook [9] reported the capital costs of building outdoor and silo storage facilities, and gave operating costs per tonne as a percentage of capital cost. Table 2-19 shows reported storage costs.
### Table 2-19: Storage costs

<table>
<thead>
<tr>
<th>Storage Type</th>
<th>Capital Cost (M$)</th>
<th>Capacity (ktonnes/year)</th>
<th>Operating Cost ($/day/m³)</th>
<th>Operating Cost ($/day/tonne)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silo</td>
<td>0.3807</td>
<td></td>
<td></td>
<td></td>
<td>[73]</td>
</tr>
<tr>
<td>Outdoor</td>
<td>0.0048</td>
<td></td>
<td></td>
<td></td>
<td>[73]</td>
</tr>
<tr>
<td>Silo – Raw Biomass</td>
<td>1.9</td>
<td>40</td>
<td>0.0204</td>
<td>[9]</td>
<td></td>
</tr>
<tr>
<td>Silo – Pellets</td>
<td>1.28</td>
<td>40</td>
<td>0.0137</td>
<td>[9]</td>
<td></td>
</tr>
<tr>
<td>Outdoor</td>
<td>0.37</td>
<td>40</td>
<td>0.0026</td>
<td></td>
<td>[9]</td>
</tr>
</tbody>
</table>

#### 2.9 Wood Pellet Production

The steps required to produce white pellets from wood chips are biomass size reduction, drying, conditioning, pelleting, screening, and cooling. Size reduction of the wood chips is required to allow the biomass to be pelletized. Drying and conditioning are required to ensure the biomass has an ideal moisture content for pelleting. Screening is needed both for biomass after size reduction, to ensure a consistent size, and after pelleting, to remove fines from the pellets. Pellet cooling is required as the pellet temperature can be 140°C after pelleting. Production of torrefied pellets require all these steps, along with a torrefaction step.

#### 2.9.1 Biomass Densification

Raw biomass, for example wood chips, has very low bulk density that makes it expensive to ship, so densification is required. The most common methods to densify biomass are briquetting and pelleting.
2.9.1.1 Briquetting

Briquetting produces large volume masses of compressed biomass obtained through the use of either a screw or piston press. Screw presses operate by forcing biomass forward in a tapered tube (called the barrel) utilising a rotating screw. The constriction is the die, which forces the biomass to compress. This process creates significant heat from the combination of wall friction and internal friction in the material [87], which leads to the outside of the briquette being partially torrefied.

Piston presses operate by having a piston, either hydraulic or electric powered, which push biomass through a conical die to create the briquettes. Piston presses require more energy than screw presses and produce lower quality briquettes than screw presses, but require less maintenance and have longer lifespans [87]. The energy required to operate a piston press is estimated to be 30-53 kWh/tonne [88].

2.9.1.2 Pelletization

Traditional pelletization creates cylindrical pellets, typically with a diameter of 6-8 mm and length of 3-50 mm [42]. Although pelletization requires higher capital expenditures and requires more power than briquetting, it is preferred if transportation of the biomass is required due to higher bulk densities [87].

Pellet mills operate by using rollers to force biomass through dies with cylindrical press channels [42]. There are two standard designs for pellet mills dies: either ring or flat. Ring mills have rollers inside a ring shaped die while flat dies have a roller that moves over a flat disk shaped die. As the rollers pass over the press channels in the die the biomass is forced
into the channels. This creates densified pellets in the channels that exhibit a layered structure, with a layer built up for every roller pass.

The power required to operate pellet mills varies significantly. Changes to biomass particle size, wood species and moisture and die temperature will cause large variations in energy required to produce pellets [89]. For example, the pressure in the die channels was shown to be reduced from 60-90 MPa to under 15 MPa when temperature was increased from 20°C to 140°C [90]. Furthermore, laboratory studies underestimate the required energy as they do not account for electrical requirements of auxiliary components (conveyors, etc.) found on industrial pellet mills [87]. Table 2-20 provides examples of values for pellet mill energy requirements from various sources.

<table>
<thead>
<tr>
<th>Energy Requirement (kWh/tonne)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>74</td>
<td>[68]</td>
</tr>
<tr>
<td>51</td>
<td>[9]</td>
</tr>
<tr>
<td>16.4–74.5</td>
<td>[87]</td>
</tr>
<tr>
<td>16–49</td>
<td>[42]</td>
</tr>
<tr>
<td>72</td>
<td>[91]</td>
</tr>
</tbody>
</table>

Furthermore, the capital costs and capacities of pellet mills are provided in Table 2-21.

<table>
<thead>
<tr>
<th>Capital Cost (M$)</th>
<th>Capacity (tonne/hour)</th>
<th>Cost per tonne/hour (k$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.79</td>
<td>15.75</td>
<td>50.2</td>
<td>[16]</td>
</tr>
<tr>
<td>1.27</td>
<td>8.93</td>
<td>142.2</td>
<td>[91]</td>
</tr>
<tr>
<td>1.50</td>
<td>5</td>
<td>300</td>
<td>[68]</td>
</tr>
<tr>
<td>0.80</td>
<td>5</td>
<td>160</td>
<td>[9]</td>
</tr>
</tbody>
</table>

The cost per unit of capacity is quite variable, but does generally decrease with increasing capacity as would be expected for capital costs that follow a power law. The values provided in Obernberger and Thek [9] and Pirraglia et al. [91] are what would be expected for cost
following a power law, although the values from Peng et al. [16] and Batidizirai [68] are lower and higher than expected, respectively. All four references suggest that the cost provided is the full installed cost, so the difference may depend on technology type or assumed delivery location.

2.9.2 Pelletizing Torrefied Biomass

Torrefied pellets have been produced using wood pellet mills normally employed for the production of white, un-torrefied pellets. The pelletization of torrefied biomass may take more energy and lead to lower quality pellets than pelletization of raw biomass [17]–[19], [45], [92]. Increased die temperature has been shown to improve pellet quality and reduce friction in the dies [18], [19]. Torrefied pellets pressed when the die temperature is maintained at 260°C require a similar amount of energy to pelletize and had similar density as white pellets [93]. All results reviewed have used torrefied biomass that had been cooled before being conditioned and torrefied [17]–[19], [45], [92]. Based on literature that state that torrefied biomass may take the same amount of pelletization energy as raw biomass [93], it is assumed that pelletization in a commercial scale torrefied pellet plant would take the same amount of energy as pelletization of raw biomass.

2.9.3 Dryers

Biomass in its raw form may contain up to 50% water; thus, some form of dryer is necessary to remove this moisture prior to pelletization. These dryers can be powered by electricity, natural gas, solar power or by the combustion of raw biomass. Biomass can also be air dried,
but the equilibrium moisture content depends on location, and is rarely below 15% for
Canadian locations [94]. The energy required to dry biomass using electricity or natural gas,
according to Batidzirai [68], is

\[ E_{\text{dryer}} = \frac{(MC_i - MC_f) \times M_{\text{biomass}} \times BE}{\eta_{\text{dryer}}} \]  \hspace{1cm} [2-5]

where \( E_{\text{dryer}} \) is the energy required to dry to the biomass, \( MC_i \) is initial moisture content
(percent wet basis), \( MC_f \) is final moisture content, \( M_{\text{biomass}} \) is initial wet mass, \( BE \) is energy
to heat and boil one tonne of water (2.6 GJ) and \( \eta_{\text{dryer}} \) is dryer thermal efficiency.

Along with the energy required to directly dry the biomass, the electrical energy is needed
to operate auxiliary components of the dryer is 23.8 kWh/tonne [9].

The capital costs of dryers vary depending on the technology employed. Examples are provided in Table 2-22.

<table>
<thead>
<tr>
<th>Capital Cost (M$)</th>
<th>Capacity (tonne/year)</th>
<th>Cost per tonne/hour (k$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.16</td>
<td>15.75</td>
<td>264.1</td>
<td>[16]</td>
</tr>
<tr>
<td>1.88</td>
<td>8.93</td>
<td>210.5</td>
<td>[91]</td>
</tr>
<tr>
<td>1.58</td>
<td>9</td>
<td>175.6</td>
<td>[95]</td>
</tr>
<tr>
<td>0.064</td>
<td>9</td>
<td>7.1</td>
<td>[95]</td>
</tr>
<tr>
<td>1.63</td>
<td>5</td>
<td>326</td>
<td>[9]</td>
</tr>
</tbody>
</table>

The costs per tonne/hour vary hugely for dryers. Namely, Lamers et al. [95] reported a capital
cost of only $64,000 for a vertical grain dryer. However, this was under the assumption that
biomass could be pelletized at ~35% MC, and then subsequently dried at low temperature.
Nonetheless, the values provided in Table 2-22 do not show a reduction in cost per capacity
with increasing scale as would be expected if costs followed a power law. This may be due
to differing technology or changes to what is included in the capital costs. Neither Peng et al. [16] nor Pirraglia et al. [91] describe the dryer technology they used, although both imply the costs are the full installed costs, including auxiliary components.

2.9.4 Conditioners and Binders

Steam conditioning is required to soften lignin and to ensure that the wood has the correct moisture content [95]. Stelte et al. [90] found that biomass should have a moisture content between 5%-15%, as pellets were poor quality when moisture content was outside this range. Pirraglia et al. [17] recommends steam conditioning at 25% w/w, and gives a capital cost of $168,000 for a steam boiler capable of producing the 25,000 tonnes/year of steam required for a 100,000 tonne/year pellet plant.

The natural gas required to produce 1.56 tonnes of steam per hour in a steam boiler is 158.01 m$^3$/hr of natural gas [96]. Given a natural gas price of $6.87/GJ in February 2016 [86], the cost of producing steam is estimated to be $21.47/tonne of steam. If 25% weight to weight of steam is required, the cost to produce steam is $5.37/tonne of biomass.

Binders include soy, corn, dried distiller’s grain [17], and castor bean [97]. Binders reduce the energy require for pelletization, but are an extra cost and may not be desirable in pellets [24, p. 36] as such binders may cause grinder “gumming”. Q’Pellets do not require any binders, which is an additional benefit.
2.9.5 Screeners

Biomass screening is required both before and after pelleting. Screening is required before pelleting to ensure particle sizes are small enough for the pellet mill to operate efficiently and after pelleting to filter out fines which can then be recycled back into the pellet mill [17]. The capital cost of a screener is estimated at $112,000 for a unit with a capacity of 100,000 tonne/year, with electricity usage of 23.5 kWh/tonne [17].

2.9.6 Coolers

Coolers are required to lower the temperature of biomass which often emerges from pelletizers at over 140°C. Capital costs are between $30,000 and $570,000 [9], [16], [17], [68] with electricity usage between 2 and 4 kWh/tonne.

Coolers also help provide process heat by recycling heat collected from biomass back into drying or torrefaction.

2.10 The Q’Pellet

2.10.1 Q’Pellet Production

Q’Pellets are different from any previously reviewed pellets due to their spherical, as opposed to cylindrical, shape. Q’Pellets are also unique as their formation combines torrefaction and pelletization in one step. The process to produce Q’Pellets is patent pending under US patent application number US 13/984,131 [98]. Duncan described the first
iteration of Q'Pellet design [22]. Q'Pellets have been produced from hybrid poplar, a popular short rotation crop. A Q'Pellet has a diameter of 12.7 mm and a mass of 1.6 g [10].

![Figure 2-1: The Q'Pellet](image)

Q'Pellet were first produced by compressing two hemispherical dies together to create spherical pellets. However, Duncan found that using hemispherical dies led to a fracture plane where the dies met, leading to pellets that split into hemispheres. To solve this issue, a new die featuring an offset punch was created. This die forces the wood particles to roll, analogous to an ice cream scoop rolling up a portion of ice cream. Duncan showed that Q'Pellets produced with this die are stronger than known pellets and created no fines [21].

To create Q'Pellets, biomass was torrefied in situ, and then immediately pelletized so that the biomass remained hot. This improves the strength of the pellets as the binding properties of lignin are reduced if it is allowed to cool. Q'Pellets produced from hot biomass that was not allowed to cool had hard, polymerized shells that allowed the pellets to be highly durable.

Nicksy [24] attempted to create a continuous Q'Pellet production method based on sets of two rolling dies. The concept was to replace the “ice cream scoop” method with a method
based on multiple compressions from different directions to prevent the hemispherical splitting observed by Duncan, referred to as the “snowball” method. The attempts to create the “snowball” method failed. The material was never able to stay together through the first compression, and so the “ice cream scoop” method was resurrected in attempts to create a workable continuous production method.

Nicksy also attempted to create Q’Pellets from partially torrefied biomass, which was more successful than the snowball method. A batch torrefier was used to partially torrefy biomass to ~260°C. This biomass was cooled, followed by pelletization at ~280°C. The process of pelletizing torrefied biomass at higher temperatures than pre-torrefaction lead to pellets of similar quality to those created from in-situ torrefied biomass [10].

Taylor [25] has demonstrated a continuous method for the production of Q’Pellets. The offset die was inverted, with biomass compressed upwards into the die. The die action was made repeatable using a spring and ejector pin. Furthermore, biomass was partially torrefied and compressed prior to entering the die. This partially torrefied biomass went directly into the die without cooling. Taylor showed that Q’Pellets produced in this manner had properties similar or slightly superior to those produced by Nicksy [25]. Taylor also suggested a design for a multi-cavity die that provides a framework to begin work on larger scale Q’Pellet production.
2.10.2 Q’Pellet Capital Costs

The capital cost of building a Q’Pellet system is based on the combination of the cost of a torrefier and the scaled cost of a laboratory scale pelletizer. Scaling the laboratory scale unit to production volumes requires an estimate of the number of pellets than can be produced from a single die with pre-torrefied material. Based on typical compression time to produce a good pellet in lab conditions, it was conservatively estimated that one to two seconds would be needed to produce a pellet [25]. The cost to build the laboratory unit was between two and three thousand dollars. The cost of a production scale unit utilizing a power law is

\[ C_{\text{prod}} = C_{\text{bench}} \left( \frac{P_{\text{prod}}}{T_{\text{cycle}} M_{\text{Q'Pellet}}} \right)^S \]  \hspace{1cm} [2-6]

where \( C_{\text{prod}} \) is the cost of the production scale unit, \( C_{\text{bench}} \) is the cost of the bench scale unit, \( P_{\text{prod}} \) is the capacity of the production scale unit, \( T_{\text{cycle}} \) is the time to produce one Q’Pellet in the bench unit, \( M_{\text{Q'Pellet}} \) is the mass of a Q’Pellet, and \( S \) is the scale factor. This cost is added to the cost of a torrefaction unit, discussed in Section 2.6.2.

Estimates for the capital cost of a Q’Pellet pelletizer are given for a plant capacity (ktonnes/year) of 100,000 tonnes/year are given in Table 2-23.
Table 2-23: Estimates of Q’Pellet pelletizer capital cost

<table>
<thead>
<tr>
<th>Cycle Time (s)</th>
<th>Bench Scale Cost ($)</th>
<th>Scale Factor</th>
<th>Production Scale Cost (M$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000</td>
<td>0.7</td>
<td>0.44</td>
</tr>
<tr>
<td>1</td>
<td>2000</td>
<td>0.8</td>
<td>0.94</td>
</tr>
<tr>
<td>1</td>
<td>3000</td>
<td>0.7</td>
<td>0.66</td>
</tr>
<tr>
<td>1</td>
<td>3000</td>
<td>0.8</td>
<td>1.14</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
<td>0.7</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
<td>0.8</td>
<td>1.64</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td>0.7</td>
<td>1.06</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td>0.8</td>
<td>2.46</td>
</tr>
</tbody>
</table>

The estimates in capital cost vary from $0.44M to $2.46M. The most sensitive variable in Table 2-23 is scale factor. Scale factor is very difficult to predict for untested technology, and so a conservative value should be used. Typically, single components will have scale factors between 0.6 and 0.8, so 0.8 should be a conservative value. If a pilot plant is built and it is shown that the technology is capable of scaling from bench scale at a scale factor of 0.7, the model should be reflected to update this. Without any data on how well the Q’Pellet system will scale, a scale factor of 0.8 will be used to ensure that the capital cost is a conservative estimate.

2.10.3 Q’Pellet Production Energy Requirements

The amount of energy required to create Q’Pellets is uncertain. Peng et al. [93] showed that the energy required to pelletize torrefied wood decreased if die temperatures increased from 230°C to 260°C. At a die temperature of 260°C, it took a similar amount of energy to pelletize torrefied wood as white wood at a standard die temperature of approximately 140°C. Nicksy heated dies to 280°C, so it is assumed that it will not take more energy to produce Q’Pellets from torrefied biomass than from raw biomass. Piston briquette presses require less energy
than pellet mills [87], [88], and as this technology is similar to the Q’Pellet system, it may be assumed to provide a reasonable estimate of the required energy. Given that smaller pellets require more energy per pellet than briquettes, it is estimated that the Q’Pellet will require a similar amount of pelletization energy as standard white pellet mills.

2.11 Wood Pellet Production and Logistics Steps

The steps required to produce wood pellets depend the pellet type desired and the logistics required for raw biomass and finished product delivery. Figure 2-2 shows a flowchart to determine the required steps to produce pellets. In the flowchart, diamonds indicate decisions (i.e. choose biomass) with arrows leading to the options available (i.e. mill residue/hog fuel or forest residue/roundwood). Rectangles indicate processes and ovals indicate outputs. Although the cost and GHG emissions may not be the same for equivalent process flowcharts, the required steps will be the same. For example, although both white pellets and Q’Pellets may both require bulk shipping, the cost and GHG emissions will be different for the two products.
Figure 2-2: Pellet production process flowchart
2.12 Life Cycle Analysis

Life cycle analysis (LCA) is a systemic approach to determine the environmental effects over the life cycle of a product [99]. There are three components to creating a life cycle analysis – defining the scope of the analysis, creating a life cycle inventory (LCI) of the inputs and outputs at each step of production, and creating a life cycle impact assessment. The most common type of life cycle analysis is attributional life cycle analysis, which accounts for all inputs and outputs during a process in a static manner. Consequential life cycle analysis, on the other hand, estimates how potential decisions would change the process [100].

2.12.1 LCA Scope and Methodology

The LCA scope and methodology followed in this thesis are from Giuntoli et al. [101], to comply with European Commission legislation laid out in two reports, COM(2010) 11 [102] and SWD(2014) 259 [103]. The methodology used is a simplified attributional life cycle analysis, which considers the global warming effects of three GHGs: CO$_2$, CH$_4$ and N$_2$O. Sulfur hexafluoride, SF$_6$, is also considered for grid electricity usage for Canadian provinces [104]. Other environmental effects, e.g. acid rain, are not considered. The global warming potentials (GWP) of CO$_2$, CH$_4$, N$_2$O and SF$_6$ are from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [105], with CO$_2$ defined as having a GWP of 1. CH$_4$, N$_2$O and SF$_6$ have GWPs of 25, 298 and 22,800, respectively.

The system boundary of the life cycle analysis is from collection of biomass through to customer delivery. Transportation of raw biomass to the plant is in the scope of the LCA, but
all earlier activities are not. Key assumptions made in the methodology are CO\textsubscript{2} emissions from combusting biomass are zero (although other GHGs are accounted for), and GHG emissions from land use changes and biomass cultivation are zero [101]. The functional unit considered is energy in GJ of delivered biomass.

Non-binding EU requirements for solid biomass life cycle emissions call for a 35% reduction in GHG emissions compared to a fossil fuel comparator (FFC), increasing to a 50% reduction on January 1, 2017, and then a 60% reduction on January 1, 2018 for new installations beginning operations after January 1, 2017 [103]. The FFC for electricity production is assumed to be 50% natural gas, 25% high efficiency coal and 25% standard coal, with GHG emissions of 186 kgCO\textsubscript{2}eq/GJ\textsubscript{el} [103]. For biomass electricity production, there is assumed to be a 25% electrical production efficiency. GHG savings are

\[ \text{GHG Savings (\%)} = \frac{\text{FFC} - \text{GHG}_{\text{biomass-\text{el}}}}{\text{FFC}} \]  

where \text{FFC} is the fossil fuel comparator GHG emissions, and \text{GHG}_{\text{biomass-\text{el}}} is life cycle GHG emissions from biomass production and combustion. Equation [2-7] is in terms of GHG emissions for electrical production, but this thesis gives life cycle emissions for pellet production. Table 2-24 gives the maximum life cycle emissions permissible to achieve the GHG savings for the three savings levels to meet EU requirements.
Table 2-24: Maximum life cycle emissions permissible under EU regulations [103]

<table>
<thead>
<tr>
<th>Savings Level (%)</th>
<th>Maximum Wood Pellet Production Life Cycle Emissions (kg CO₂ eq/GJ biomass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>30.2</td>
</tr>
<tr>
<td>50</td>
<td>23.3</td>
</tr>
<tr>
<td>60</td>
<td>18.6</td>
</tr>
</tbody>
</table>

2.12.2 LCI Inputs

The three components considered for the LCI are raw material acquisition, processing and manufacturing, and final combustion. Input values for GHG of combustion of various fuel, including processing and supply emissions, are given in Table 2-25.

Table 2-25: Combustion emission factors, adapted from [101]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>71.78</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>93.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFO</td>
<td>93.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td>0</td>
<td>0.003</td>
<td>0.0006</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Giuntoli et al. [101] provide the combustion emission factors as CO₂eq values for natural gas, diesel and HFO, while for biomass, the emissions of CH₄ and N₂O are provided. The combustion emission factors for the three fossil fuels are based on life cycle analyses and account for the production, delivery and combustion of the fuels. The biomass emission factor only accounts for combustion.

The emission factors to produce electricity from natural gas, coal and diesel vary from those in Table 2-25 due to the low efficiency of thermal power plants. Emission factors are assumed to be zero for nuclear, wind, hydro and other renewables [104]. Emission factors for electricity production are shown in Table 2-26.
Table 2-26: Emission factors for fossil fuel electricity production, adapted from [101]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>GHG Emission Intensity [gCO2eq/kWh]</th>
<th>Power Station Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>487.6</td>
<td>0.53</td>
</tr>
<tr>
<td>Coal</td>
<td>1045.1</td>
<td>0.35</td>
</tr>
<tr>
<td>Diesel</td>
<td>776.6</td>
<td>0.35</td>
</tr>
</tbody>
</table>

GHG emission intensity from grid electricity depends on the production mix which varies by location. The production mix and GHG intensity for the electricity grids for BC, Ontario, Georgia, Mississippi and Louisiana are shown in Table 2-27.

Table 2-27: Grid electricity mix and GHG emission intensity, from [83], [104], [106]

<table>
<thead>
<tr>
<th>Electricity Production Type</th>
<th>Ontario</th>
<th>BC</th>
<th>Georgia</th>
<th>Mississippi</th>
<th>Louisiana</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Electricity Production (TWh)</td>
<td>154.02</td>
<td>52.53</td>
<td>121.38</td>
<td>52.81</td>
<td>102.01</td>
</tr>
<tr>
<td>Natural Gas (TWh)</td>
<td>14.80</td>
<td>0.89</td>
<td>40.33</td>
<td>31.78</td>
<td>52.51</td>
</tr>
<tr>
<td>Coal (TWh)</td>
<td>0.10</td>
<td>0</td>
<td>40.23</td>
<td>8.70</td>
<td>20.84</td>
</tr>
<tr>
<td>Diesel or Other Fuels (TWh)</td>
<td>0.00</td>
<td>0.99</td>
<td>0.36</td>
<td>0.03</td>
<td>7.87</td>
</tr>
<tr>
<td>Biomass (TWh)</td>
<td>0.30</td>
<td>0</td>
<td>3.82</td>
<td>1.43</td>
<td>2.79</td>
</tr>
<tr>
<td>Nuclear (TWh)</td>
<td>94.90</td>
<td>0</td>
<td>32.90</td>
<td>10.86</td>
<td>16.95</td>
</tr>
<tr>
<td>Hydro (TWh)</td>
<td>37.10</td>
<td>50.50</td>
<td>3.71</td>
<td>0</td>
<td>1.04</td>
</tr>
<tr>
<td>Wind (TWh)</td>
<td>6.80</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other Renewables (TWh)</td>
<td>0.02</td>
<td>0.15</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GHG Intensity (gCO2eq/kWh)</td>
<td>47.53</td>
<td>22.86</td>
<td>510.72</td>
<td>466.08</td>
<td>524.44</td>
</tr>
</tbody>
</table>

The GHG emissions from transportation depend on the emission intensity of the three transportation modes considered: transport truck, train, and Panamax ship. The GHG emission intensity depends on the fuel efficiency of the vehicle, the emission intensity of the combustion fuel and vehicle specific emissions of CH₄ and N₂O. To allow for direct comparison and to maintain consistency with economic values, transportation GHG emissions are given in units of g/tonne-km. Literature values for the average fuel efficiency of transport trucks are shown in Table 2-28.
The variability in three transport truck fuel efficiencies listed in Table 2-28 is partly based on location and year. The estimate of 30.5 L/100 km is provided by Giuntoli et al. [101] for European trucks in 2015. The value from Davis et al. [107] is based on the fleet average from North American trucks in 2014. The value from Zhang et al. [7] is also for North American trucks, but is based on values from 2010 and includes assumed fuel consumption from truck idling. The GHG emission intensity for trucks is given from the diesel GHG emission factor in Table 2-25, along with CH\(_4\) and N\(_2\)O emissions factors of 0.0034 g/tonne-km and 0.0015 g/tonne-km, maximum load of 27 tonnes and diesel volumetric LHV of 36 MJ/L from [101]. The GHG emissions for a transport truck are

\[
I_{CO_{2eq}} \left[ \frac{g}{\text{tonne} \cdot \text{km}} \right] = 2 \times \frac{F E \times I_{\text{diesel}}}{100 \times M L \times LHV_{\text{diesel}}} + GWP_{\text{CH}_4} \times I_{\text{CH}_4} + GWP_{\text{N}_2\text{O}} \times I_{\text{N}_2\text{O}} \tag{2-8}
\]

where \(I_{CO_{2eq}}\) is CO\(_{2eq}\) intensity, \(F E\) is fuel efficiency (L/100 km), \(I_{\text{diesel}}\) is diesel GHG intensity (g/MJ), \(M L\) is maximum load (tonnes), \(LHV_{\text{diesel}}\) is diesel volumetric LHV (MJ/L), \(GWP_{\text{CH}_4}\) is CH\(_4\) global warming potential, \(I_{\text{CH}_4}\) is CH\(_4\) emissions intensity, \(GWP_{\text{N}_2\text{O}}\) is N\(_2\)O global warming potential and \(I_{\text{N}_2\text{O}}\) is N\(_2\)O emission intensity. The emissions are doubled to account for the return trip [101].

The fuel consumption for rail is given as 0.252 MJ/tonne-km [101], with CH\(_4\) and N\(_2\)O emissions factors of 0.005 g/tonne-km and 0.001 g/tonne-km. The GHG emissions for rail are

\[
I_{\text{CO}_{2eq}} \left[ \frac{g}{\text{tonne} \cdot \text{km}} \right] = 0.252 \times \frac{F E \times I_{\text{diesel}}}{100 \times M L \times LHV_{\text{diesel}}} + GWP_{\text{CH}_4} \times I_{\text{CH}_4} + GWP_{\text{N}_2\text{O}} \times I_{\text{N}_2\text{O}} \tag{2-9}
\]

### Table 2-28: Transport truck fuel efficiency

<table>
<thead>
<tr>
<th>Fuel Efficiency (L/100 km)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.5</td>
<td>[101]</td>
</tr>
<tr>
<td>61.3</td>
<td>[107]</td>
</tr>
<tr>
<td>183.1</td>
<td>[7]</td>
</tr>
</tbody>
</table>
\[ I_{CO2eq} \left[ \frac{g}{\text{tonne} \cdot \text{km}} \right] = FE \times I_{\text{diesel}} + GWP_{CH4} \times I_{CH4} + GWP_{N2O} \times I_{N2O} \]  \hspace{1cm} [2-9]  

where \( FE \) is fuel efficiency (MJ/tonne·km) and \( I_{\text{diesel}} \) is diesel GHG intensity (g/MJ), \( GWP_{CH4} \) is CH\(_4\) global warming potential, \( I_{CH4} \) is CH\(_4\) emissions intensity, \( GWP_{N2O} \) is N\(_2\)O global warming potential and \( I_{N2O} \) is N\(_2\)O emission intensity.

The fuel efficiency for a Panamax is 1.62 gHFO/tonne-km, the LHV of HFO is 40.5 GJ/tonne [101] and the emission intensity of HFO is given in Table 2-25 as 93.3 CO\(_2eq\) (kg/GJ). The GHG emissions for a Panamax ship are

\[ I_{CO2eq} = \frac{(FE \times I_{HFO} \times LHV_{HFO})}{1000} \]  \hspace{1cm} [2-10]  

where \( FE \) is fuel efficiency [g/tonne-km], \( I_{HFO} \) is the GHG intensity of HFO [kg/GJ] and \( LHV_{HFO} \) is the lower heating value of HFO [GJ/tonne].

2.12.3 Raw Material Acquisition

As noted in section 2.12.1, it is assumed that emissions from cultivation and land use changes are zero. Hence, the only GHG emissions are from transportation to the plant.

2.12.4 Processing and Manufacturing

The GHG emissions from processing and manufacturing are from burning natural gas for process heat and steam production, the use of grid electricity, and from product transport to the customer.
2.12.5 Product Combustion

The CO$_2$ emissions are set to be zero for biomass combustion [101], [104]. Thus, the only emissions from biomass combustion are CH$_4$ and N$_2$O emissions, given in Table 2-25.

2.13 Chapter Conclusion

This chapter has outlined relevant literature that is required to develop the model built for this thesis. Literature was reviewed regarding wood chemistry, wood pellet markets and production, Q'Pellet production and life cycle analysis. The literature data gathered and presented are necessary to the model described.

Chapter 3 outlines the model developed for this thesis, including all equations used. The second part of Chapter 3 describes a case study and the values used in it. These values are from literature, all of which have been presented in the preceding chapter.
Chapter 3 Model Description

3.1 Overview of the Chapter

This chapter presents a feedstock-to-product chain model and a case study that was undertaken using this model. The model inputs and operation are first described. A flowchart that describes the steps required to produce various types of wood pellets is presented. The equations that drive the model for both economic and life cycle analysis are then explained. A model that determines energy and mass yields for drying and torrefaction is then described.

The second part of this chapter describes a case study to compare white, torrefied and Q’Pellet production. The inputs for the model are given along with all relevant parameters. Model verification and validation are discussed at the end of the chapter.

3.2 Model Overview

The model described in this thesis allow for techno-economic and life cycle analyses of pellet production and delivery. Using data and process ideas described in 0, the model compares different wood pellet production processes. At each step in the process, the model determines biomass, economic and GHG emission values. Using these variables, cash flow analysis and life cycle analysis are performed on the given process to determine economic value and environmental impact.
3.2.1 Inputs

To operate the model, a process flowchart must be completed from biomass acquisition through product delivery. The flowchart provided in Figure 2-2 can be followed to determine the required production steps needed for the model. An example of a production process for white pellets created following Figure 2-2 is shown in Figure 3-1.

![White Pellet Production Flowchart](image)

*Figure 3-1: White pellet production flowchart*

The flowchart in Figure 3-1 would be appropriate for white pellets produced from mill residue with a rail line nearby the pellet plant and trans-Atlantic product delivery. If the raw biomass was changed to forest residue or roundwood, an initial chipping step would be required before drying the biomass. Without rail access, product shipping would need to be
done by trucks and oceanic shipping would not be required for product delivery to a North American customer.

3.2.2 Variable Calculations

At each step in the process, the model enables the determination of biomass, economic and GHG emission variables.

3.2.2.1 Dry Mass at Step k [tonne]

Dry mass is tracked to account for all dry matter losses. Each step has a certain dry matter loss (DML), caused by, among other reasons, biomass degradation, losses during shipping and handling, and mass loss during torrefaction. The dry matter remaining in the process after an arbitrary number of steps (step number k) according to Hamlinck et al. [73] is

\[
M_k = M_{k-1} \times (1 - DML_k)
\]

[3-1]

where \(M_k\) is dry mass [tonne] after step k, \(M_{k-1}\) is dry matter after step k-1 and \(DML_k\) is dry matter loss at step k [%]. Dry mass may also be determined from wet mass and water content. Dry mass at step k is [8]

\[
M_k = WM_k - W_k
\]

[3-2]

where \(WM_k\) is wet mass [tonne] and \(W_k\) is water mass [tonne] at step k.

3.2.2.2 Wet Mass at Step k [tonne]

Wet mass is determined from the dry mass and the biomass moisture content (MC). Moisture content is determined at step k experimentally and is an input in the model. The moisture content at step k is [8]
$$MC_k = \frac{W_k}{WM_k} \quad [3-3]$$

After rearranging equation [3-3], the wet mass after step \( k \) is

$$WM_k = \frac{M_k}{1 - MC_k} \quad [3-4]$$

where \( WM_k \) is wet mass [tonnes] at step \( k \), \( M_k \) is dry mass at step \( k \) [tonnes] and \( MC_k \) is moisture content (% wb) at step \( k \).

### 3.2.2.3 Energy at Step \( k \) [GJ]

The energy remaining in the process is determined from the dry mass and the higher heating value (HHV) of the biomass (dry basis). The dry mass is determined by equation [3-1] and the HHV is provided from experimental or literature results. The energy after step \( k \) is [108]

$$E_k = M_k \times HHV_k \quad [3-5]$$

where \( E_k \) is energy remaining at step \( k \) [GJ], \( M_k \) is dry mass at step \( k \) [tonne] and \( HHV_k \) is higher heating value [GJ/tonne, dry] at step \( k \).

### 3.2.2.4 Operating Cost at Step \( k \) [$/GJ]

Costs are all considered on an energy basis with units of $/GJ to allow for a fair comparison between pellets with different heating values. If the process step is not a transportation or storage step, costs are given in terms of dry mass. For transportation and storage, costs are given in terms of wet mass. The step cost per GJ for steps other than transportation and storage is [14]

$$C_k = \frac{c_k \times M_k}{E_n} \quad [3-6]$$
where $C_k$ is cost at step k [$/GJ], $c_k$ is cost at step k [$/tonne], $E_n$ is energy at the end of the production chain [GJ] and $M_k$ is dry mass at step k [tonnes].

For a transportation step, the cost is split between a distance fixed cost (DFC) [$/tonne] and a distance variable cost (DVC) [$/tonne·km]. The total transportation cost an energy basis is [29]

$$C_k = \frac{(DFC_k + DVC_k \times D) \times WM_k}{E_n} \quad [3-7]$$

where $C_k$ is cost at step k [$/GJ], DFC$_k$ is distance fixed cost at step k [$/tonne], DVC$_k$ is distance variable cost at step k [$/tonne·km], D is distance (km), $E_n$ is energy at the end of the production chain [GJ] and $WM_k$ is wet mass at step k [tonnes].

Literature storage costs from Hamelinck et al. [73] are in units of [$/tonne·day], and need to be converted into [$/GJ] for consistency with other values in the model. Storage cost on an energy basis is [73]

$$C_k = \frac{(SC_k \times T) \times WM_k}{E_n} \quad [3-8]$$

where $C_k$ is cost at step k [$/GJ], SC$_k$ is storage cost at step k [$/tonne·day], T is storage days, $E_n$ is energy at the end of the production chain [GJ] and $WM_k$ is wet mass at step k [tonnes].

3.3 Economic Analysis

Variables required for cash flow analysis are annual revenues, costs and taxes. All values are adjusted for inflation, so production year is a required variable.
3.3.1 Revenue

Revenue in year $m$ is [16]

$$R_m = S_m \times P_m \times (1 + i)^m \quad [3-9]$$

where $R_m$ is revenue in year $m$, $S_m$ is sale price in year $m$ [$/tonne], $P_m$ is plant production in year $m$ [tonne], $i$ is inflation rate and $m$ is year.

3.3.2 Costs

Total annual costs can be split into operating and capital costs as [91]

$$C_m = Opex_m + Capex_m \quad [3-10]$$

where $C_m$ is total annual cost in year $m$, $Opex_m$ is annual operating cost in year $m$ and $Capex_m$ is annual capital cost in year $m$. Alternately, costs could be split between fixed and variable costs, but dividing into operating and capital costs gives a clearer description of the advantages and disadvantages of the different pellet types.

3.3.3 Operating Cost

Operating cost in year $m$ can split into fixed and variable operating costs as [16]

$$Opex_m = (V_m + F_m) \times (1 + i)^m \quad [3-11]$$

where $Opex_m$ is annual operating cost, $V_m$ is annual variable operating cost and $F_m$ is annual fixed operating cost.

Variable operating cost is [16]

$$V_m = \Sigma C_k + U_m \quad [3-12]$$
where $\sum C_k$ is the sum of the $k$th-step operating costs given in equations [3-6] to [3-8], and $U_m$ is the annual cost for utilities.

The annual utilities cost is [17]

$$U_m = EL_m + NG_m$$  \hspace{1cm} [3-13]

where $U_m$ is annual utilities cost [$/GJ]$, $EL_m$ is annual electricity cost [$/GJ]$ and $NG_m$ is annual natural gas cost [$/GJ]$. Annual electricity cost is [17]

$$EL_m = \frac{EL \times P_m \times ER}{E_n}$$  \hspace{1cm} [3-14]

where $EL_m$ is annual electricity cost [$/GJ]$, $EL$ is electricity requirement to produce a tonne of pellets [kWh/tonne], $P_m$ is annual pellet production [tonne], $ER$ is electricity price [$/kWh]$ and $E_n$ is energy at the end of the production chain [GJ]. Annual natural gas cost is [17]

$$NG_m = \frac{(NG \times NGR + CD) \times P_m}{E_n}$$  \hspace{1cm} [3-15]

where $NG_m$ is annual natural gas cost [$]$, $NG$ is natural gas requirement to produce a tonne of pellets [GJ/tonne], $NGR$ is natural gas price [$/GJ]$, $CD$ is conditioner cost per tonne [$/tonne]$, $E_n$ is energy at the end of the production chain [GJ] and $P_m$ is annual pellet production.

Annual fixed costs are [16]

$$F_m = L_m + INS_m + PT_m + M_m$$  \hspace{1cm} [3-16]
where $F_m$ is annual fixed cost [$/GJ], $L_M$ is annual labour cost [$/GJ] and $INS_m$ is annual insurance cost [$/GJ], $PT_m$ is annual property tax [$/GJ] and $M_m$ is annual maintenance cost [$/GJ].

Labour is a fixed cost once production has begun and zero beforehand. Labour costs are

$$L_m = \begin{cases} \frac{L}{E_n}, & \text{if } m > \text{Startup} \\ 0, & \text{if } m < \text{Startup} \end{cases} \tag{3-17}$$

where $L_m$ is annual labour cost [$/GJ], $L$ is labour cost [$], $m$ is year, and $\text{Startup}$ is the number of year to build plant and start construction.

Maintenance, insurance, property tax and costs are given in sections 2.8.2.2 and 2.8.2.3, and are calculated as a percentage of capital costs. It is assumed that these costs are constant, and paid during construction.

3.3.4 Capital Cost

Capital costs are split between inside battery limit costs and outside battery limit costs, with annual costs dependent on the capital cost breakdown. Capital costs during year $m$ are [16]

$$Capex_m = (Capex_{ibl} + Capex_{obl}) \times CB_m \times (1 + i)^m \tag{3-18}$$

where $Capex_m$ is capital cost during year $m$, $Capex_{ibl}$ is inside battery limit capital cost, $Capex_{obl}$ is outside battery limit capital cost, $CB_m$ is capital cost breakdown during year $m$, $i$ is inflation rate and $m$ is year.
Inside battery limit costs are determined from the production steps in the model, from base capital costs after scaling using a power law. Inside battery limit costs are [16]

$$\text{Capex}_{\text{ibl}} = \sum \left[ \text{Capex}_{\text{base} - k} \left( \frac{P}{P_{\text{base}}} \right)^{S} \right]$$ [3-19]

where \( \text{Capex}_{\text{ibl}} \) is inside battery limits capital costs and \( \text{Capex}_{\text{base} - k} \) is capital cost for model step \( k \) at base pellet capacity [\$], \( P \) is pellet production [tonne] and \( P_{\text{base}} \) is base pellet production capacity [tonne].

Outside battery limit costs are shown in 2.8.1, for base capacities. Outside battery limit costs are [16]

$$\text{Capex}_{\text{obl}} = \sum \left[ \text{Capex}_{\text{base} - \text{obl}} \left( \frac{P}{P_{\text{base}}} \right)^{S} \right]$$ [3-20]

where \( \text{Capex}_{\text{obl}} \) is outside battery limit capital cost and \( \text{Capex}_{\text{base} - \text{obl}} \) is outside battery limit capital cost at base capacity.

### 3.3.5 Income Taxes

Annual income taxes depend on net revenue, losses carried forward from previous years and income tax rate. Net revenue is

$$NR_{m} = R_{m} - C_{m} - DN_{m}$$ [3-21]

where \( NR_{m} \) is net revenue during year \( m \), \( R_{m} \) is revenue during year \( m \), \( C_{m} \) is cost during year \( m \), and \( DN_{m} \) is depreciation during year \( m \). Depreciation during year \( m \) using the declining balance method used in Canada is [79]
\[
DN_m = \begin{cases} 
DN_{\text{buildings}m} + DN_{\text{equipment}m}, & \text{if } m > 0 \\
\frac{DN_{\text{buildings}m} + DN_{\text{equipment}m}}{2}, & \text{if } m = 0 
\end{cases} \quad [3-22]
\]

\[
DN_{\text{buildings}m} = \text{Capex_{obl}} \times CCA_{\text{Class } 1} \quad [3-23]
\]

\[
DN_{\text{equipment}m} = \text{Capex_{ibl}} \times CCA_{\text{Class } 43} \quad [3-24]
\]

where \( DN \) is depreciation during year \( m \), \( DN_{\text{buildings}m} \) is building depreciation during year \( m \), \( DN_{\text{equipment}m} \) is equipment depreciation during year \( m \), \( \text{Capex_{obl}} \) is outside battery limit capital cost and \( \text{Capex_{ibl}} \) is inside battery limit cost. Depreciation following the modified accelerated cost recovery system (MACRS) used in the United States similarly splits equipment and buildings. Annual depreciation rates are given in section 2.8.1.2. MACRS depreciation is [81]

\[
DN_m = \begin{cases} 
DN_{\text{buildings}m} + DN_{\text{equipment}m}, & \text{if } m > 0 \\
0, & \text{if } m = 0 
\end{cases} \quad [3-25]
\]

\[
DN_{\text{buildings}m} = \text{Capex_{obl}} \times MACRS - 39_m \quad [3-26]
\]

\[
DN_{\text{equipment}m} = \text{Capex_{ibl}} \times MACRS - 7_m \quad [3-27]
\]

Taxable income is [109]

\[
TI_m = \begin{cases} 
NR_m, & \text{if } LF_m \leq 0 \\
NR_m + LF_m, & \text{if } LF_m > 0 
\end{cases} \quad [3-28]
\]

where \( TI_m \) is taxable income, \( NR_m \) is net revenue and \( LF_m \) are losses forward. Losses forward in year \( m \) are [109]

\[
LF_m = \begin{cases} 
NR_{m-1}, & \text{if } NR_{m-1} < 0 \\
0, & \text{if } NR_{m-1} \geq 0 
\end{cases} \quad [3-29]
\]

Annual income taxes are [110]

\[
IT_m = TI_m \times ITR \quad [3-30]
\]
where $IT_m$ is income tax paid in year $m$, $TI_m$ is taxable income in year $m$, and $ITR$ is income tax rate. Income tax rate is dependent on the jurisdiction the plant is built in.

3.3.6 Cash Flow Analysis

Annual cash flow is [109]

$$CF_m = R_m - C_m - IT_m$$  \[3-31\]

where $CF_m$ is cash flow in year $m$, $R_m$ is revenue in year $m$, $C_m$ is total cost in year $m$, and $IT_m$ is income tax paid in year $m$.

The net present value (NPV) of a series of cash flows is determined by discounting future cash by some rate and summing the resulting values. NPV is calculated by [111]

$$NPV = \sum_{m=0}^{M} \frac{CF_m}{(1 + r)^m}$$  \[3-32\]

where $NPV$ is net present value, $CF_m$ is cash flow in year $m$, $r$ is discount rate and $m$ is year.

The internal rate of return (IRR) is the discount rate that will set the net present value of a series of cash flows to zero. The IRR is determined by solving [111]

$$\sum_{m=0}^{M} \frac{CF_m}{(1 + IRR)^m} = 0$$  \[3-33\]

Equation [3-33] can be solved numerically using the Excel function “=IRR”, which automatically solves for the IRR of a series of cash flows given an initial guess. A downside to using the IRR to determine the economic value of a project is that if cash flow is sufficiently negative, the discount rate cannot be brought low enough to allow the NPV to become zero.
In these cases, the IRR is incalculably negative, and the exact economic value cannot be found from the IRR. However, this is not a major problem when determining if a project is economically viable, as any project with a negative IRR is not viable.

3.4 GHG Analysis

GHG emissions are from transportation, natural gas combustion, grid electricity usage and biomass combustion. Transportation emission factors for trucks, trains and ships are given by equations [2-8] to [2-10], in units of g/tonne-km. Transportation emissions at model step k are [101]

\[ GHG_k = \frac{I_{CO2eq-k} \times D}{1000} \]

where \( GHG_k \) is GHG emissions at step k [kg/tonne], \( I_{CO2eq-k} \) is CO\(_{2eq}\) intensity at step k [g/tonne-km] and \( D \) is distance transported [km].

Natural gas and biomass combustion emission intensities are given in Table 2-25. Combustion is required for process heat, steam production and final pellet combustion. Process heat emissions during step k are [101]

\[ GHG_k = I_{CO2eq-k} \times E_{in-k} \]

where \( GHG_k \) is GHG emissions from step k [kg/tonne], \( I_{CO2eq-k} \) is combustion GHG intensity [kg/GJ] and \( E_{in-k} \) is energy required at step k [GJ/tonne]. From section 2.9.4, 3.85 GJ of natural gas is required to produce one tonne of steam. GHG emissions from steam production are [101]
\[ GHG_k = I_{\text{CO}_2eq}^k * S_\% * NG_{\text{steam}} \]  
where \( GHG_k \) is GHG emissions from step k \([\text{kg/tonne}]\), \( I_{\text{CO}_2eq}^k \) is natural gas combustion GHG intensity \([\text{kg/GJ}]\), \( S_\% \) is steam per tonne of biomass and \( NG_{\text{steam}} \) is natural gas required to produce one tonne of steam \([\text{GJ}]\).

Grid electricity GHG emissions depend on the location specific grid GHG intensity, given in Table 2-26. The GHG emissions from electricity consumption is [104]

\[ GHG_k = I_{\text{CO}_2eq}^k * EL_k \]  
where \( GHG_k \) is GHG emissions from step k \([\text{kg/tonne}]\), \( I_{\text{CO}_2eq}^k \) is grid electricity GHG intensity and \( EL_k \) is electricity requirements for step k.

On an energy basis, GHG emissions are [101]

\[ GHG_m = \frac{\sum GHG_k}{HHV_{ar}} \]  
where \( GHG_m \) is GHG emissions in year m \([\text{kg/GJ}]\), \( GHG_k \) is GHG emissions from step k \([\text{kg/tonne}]\), and \( HHV_{ar} \) is pellet HHV \([\text{GJ/tonne, as received}]\).

### 3.5 Drying and Torrefaction Model

To determine the mass and energy balances during drying and torrefaction, a model was built using a spreadsheet (Excel) based on the work of Batidzirai [68]. The model requires biomass, torrefied biomass, torrefaction off-gas and machine efficiency variables as inputs and the outputs include mass and energy balances and efficiencies. As the model has multiple feedback loops, it is solved as a non-linear optimization problem using a built in
genetic algorithm solver embedded in Excel. The model was set to maximize energy yield.

Figure 3-2 shows the diagram of the modelled mass and energy flows.

\[ E_{\text{torr}} = \frac{[M_{\text{torrbio}} \times HHV_{\text{torrbio}} \times (1 - M_{\text{torrbio}}) - M_{\text{drybio}} \times HHV_{\text{drybio}} \times (1 - M_{\text{drybio}})]}{\eta_{\text{torr}}} + M_{\text{torgas}} \times HHV_{\text{torgas}} \]  \[ \text{[3-39]} \]

where \( M_{\text{torrbio}} \) is the mass of torrefied biomass, \( HHV_{\text{torrbio}} \) is the HHV of torrefied biomass, \( M_{\text{torrbio}} \) is the moisture content of torrefied biomass, \( M_{\text{drybio}} \) is the mass of dried biomass, \( HHV_{\text{drybio}} \) is the HHV of dried biomass, \( M_{\text{drybio}} \) is the moisture content of dried biomass,
\( M_{\text{tor gas}} \) is the mass of torrefaction off gases and \( HHV_{\text{torrbio}} \) is the HHV of torrefaction off gases.

The energy required to dry biomass, modified from equation [2-5], is

\[
E_{\text{dryer}} = \frac{(MC_{\text{rawbio}} - MC_{\text{drybio}}) \cdot M_{\text{rawbio}} \cdot BE}{\eta_{\text{dryer}}} \tag{3-40}
\]

where \( E_{\text{dryer}} \) is energy required to dry to the biomass, \( MC_{\text{rawbio}} \) is initial moisture content (percent wet basis), \( MC_{\text{drybio}} \) is final moisture content, \( M_{\text{rawbio}} \) is initial wet mass, \( BE \) is energy to heat and boil one tonne of water (2.6 GJ) and \( \eta_{\text{dryer}} \) is dryer thermal efficiency.

To allow for accurate modelling, mass and energy must be conserved. At each step in the model, mass and energy balances are maintained and act as constraints on the optimization. Furthermore, mass and energy yields must be less than one at each step, which creates another constraint on the model. Along with these constraints, there are constraints regarding process conditions that are modifiable to allow the model to accurately portray the desired process.

Modelled input conditions are shown in Table 3-1.
Using these input values, the mass yield is 76.3% and the energy yield is 91.6%, with 0.091 GJ of natural gas required per dry tonne of raw biomass.

### 3.6 Sensitivity Analysis

Sensitivity analysis can be performed by modifying input values. The model employs macros that allow changes to the variables that have been found to have the highest sensitivity – labour cost, capital expenditure, electricity cost, pellet sale price, natural gas cost, transportation cost, biomass cost and pellet HHV. To perform sensitivity analysis in the model, a percentage modification to variables is chosen, then the macro for each respective variable varies the results. The results are then graphed automatically.

### 3.7 Monte Carlo Analysis

Monte Carlo analysis is a sensitivity analysis technique based on stochastically varying multiple inputs to determine the effect of variations to multiple variables. Each variable considered for Monte Carlo analysis is required to have a probability distribution, ideally
determined experimentally or from historical data. However, when the variable’s true
distribution is uncertain, typically a uniform, normal or triangular distribution is assigned to
the variable based on analyst experience [95]. A random number generator is then used with
the inverse cumulative distribution function of the probability distribution to create random
numbers weighted by the probability distribution. The cumulative distribution function of a
probability distribution has outputs between zero and one; these values are the zero-
percentile and hundred-percentile of the distribution. Correspondingly, the inverse
cumulative distribution takes inputs from zero to one, and if given a uniform distribution for
an input, will output numbers weighted by the probability distribution.

The model assumes that all variables considered have a triangular distribution, as suggested
by Lamers et al. [95]. A triangular distribution can be determined from a minimum,
maximum and a most likely value. The inverse cumulative distribution for the triangular
distribution is [112]

\[
y = \begin{cases} 
a + \sqrt{(x \times (b - a) \times (c - a))}, & \text{if } x \leq \frac{c - a}{b - a} \\
 b - \sqrt{(1 - x) \times (b - a) \times (-c + b)}, & \text{if } x > \frac{c - a}{b - a}
\end{cases}
\]

where \( y \) is output value, \( x \) is input value, \( a \) is minimum value, \( b \) is maximum value and \( c \) is
most likely value.

The Monte Carlo process is repeated by generating new sets of random number over many
iterations to provide results from a range of varied input conditions. The model has a macro
to run this process automatically for a user defined number of iterations. For the eight
variables listed, several thousand iterations are required to have the Monte Carlo results stay consistent, with ten-thousand found to be a reliable number.

3.8 Case Study Description

A case study was designed to compare white pellet, torrefied pellet and Q'Pellet production. The case study has the plant built in Williams Lake, BC with product delivery to Rotterdam. Using the flowchart in Figure 2-2, production processes for white, torrefied and Q'Pellets were created, shown in Figure 3-3.

![Flowchart](image-url)

**Figure 3-3:** Production processes for white, torrefied and Q'Pellets
The three processes have common steps up to the point the biomass is screened. The steps that vary between the processes are shaded in Figure 3-3. The case study plant has an intake capacity of 100,000 dry tonnes of biomass, so that the three processes are identical until screening.

Q’Pellets require the fewest production steps, as the Q’Pellet process combines torrefaction with pelletization and does not require biomass conditioning or pellet screening [10], [21]. Torrefied pellets and white pellets both require biomass to be conditioned and the pellets to be screened. Additionally, they both require covered storage, whereas Q’Pellets do not. Torrefied pellets also require the torrefied biomass to be cooled before pelletization [17].

3.8.1 Pellet Sale Price

The sale price for white pellets was assumed to be $184/tonne (as received) [55], which equals $10.82/GJ. The sale price of torrefied and Q’Pellets was assumed to be equal to white pellets on an energy basis, so a sale price of $221/tonne was used. These prices are CIF ARA, so shipping and insurance to Rotterdam are included in the price.

3.8.2 Biomass Parameters

Raw biomass is assumed to be sourced from mill residue, at a cost of $35/ODT. Parameters of the three types of pellets are shown in Table 3-2.
Table 3-2: Case study pellet parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>White Pellets</th>
<th>Torrefied Pellets</th>
<th>Q’Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>7%</td>
<td>3%</td>
<td>2.68%</td>
</tr>
<tr>
<td>Bulk Density [kg/m$^3$]</td>
<td>650</td>
<td>700</td>
<td>821</td>
</tr>
</tbody>
</table>

It is assumed that white pellets and torrefied pellets require silo storage, while Q’Pellets do not. The mass loss during torrefaction is assumed to be 22.1% for torrefied pellets and 23.7% for Q’Pellets.

3.8.3 Plant Parameters

All prices have been converted to 2015 Canadian dollars, using the consumer price index [113] and Bank of Canada exchange rates [56]. Financing was assumed to be 100% equity. A plant with an annual intake capacity of 100 ktonnes/year of raw biomass is used for the case study to permit the three different plants to be identical until after the biomass is dried. The plant location is Williams Lake, BC, chosen due to its proximity to biomass supplies and current biomass plants [114]. Product delivery is to the Port of Rotterdam. Inflation is assumed to 3% per year, the long term Canadian average [115]. The plant capacity and operating factors are both assumed to be 95% and the plant is assumed to have a 20-year life. A declining balance depreciation method is used [79], with equipment depreciated at 30% per year and buildings at 4% per year. The income tax rate is assumed to be 26% [110]. The parameters used for the case study are shown in Table 3-3.
Table 3-3: Case study plant parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Capacity</td>
<td>100</td>
<td>ktonnes/year</td>
</tr>
<tr>
<td></td>
<td>12.6</td>
<td>tonnes/hour</td>
</tr>
<tr>
<td>Shifts</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Operating Hours</td>
<td>7906</td>
<td>hours/year</td>
</tr>
<tr>
<td>Plant Operating Factor</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>Plant Capacity Factor</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>Plant Life</td>
<td>20</td>
<td>year</td>
</tr>
<tr>
<td>Inflation Rate</td>
<td>3%</td>
<td>year⁻¹</td>
</tr>
<tr>
<td>Tax Rate</td>
<td>26%</td>
<td></td>
</tr>
<tr>
<td>Depreciation Rate</td>
<td>30% year⁻¹ (Manufacturing equipment)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4% year⁻¹ (Buildings)</td>
<td></td>
</tr>
<tr>
<td>Electricity Rate</td>
<td>7.13</td>
<td>¢/kWh electricity</td>
</tr>
<tr>
<td>Natural Gas Price</td>
<td>26.12</td>
<td>¢/m³ natural gas</td>
</tr>
</tbody>
</table>

3.8.4 Case Study Capital Costs

Capital costs were based on literature values described in Chapter 2, scaled to a plant capacity of 100,000 tonnes/year using the power law equation described in equation [2-4] with a scaling factor of 0.7. The capital cost of the Q’Pellet system was based on the capital cost of a torrefier added to the estimated cost of the Q’Pellet pelletizer, given in Table 2-23. The Q’Pellet pelletizer was assumed to cost $1.64M.
Table 3-4: Case study capital costs [M$]

<table>
<thead>
<tr>
<th>Item</th>
<th>White Pellet</th>
<th>Torrefied Pellet</th>
<th>Q'Pellet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peripheral Equipment</td>
<td>3.12</td>
<td>3.12</td>
<td>3.12</td>
</tr>
<tr>
<td>Buildings</td>
<td>2.46</td>
<td>2.46</td>
<td>2.46</td>
</tr>
<tr>
<td>Outdoor Biomass Storage</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Dryer</td>
<td>3.54</td>
<td>3.54</td>
<td>3.54</td>
</tr>
<tr>
<td>Hammermill</td>
<td>1.04</td>
<td>1.04</td>
<td>1.04</td>
</tr>
<tr>
<td>Cooler</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Biomass Screens</td>
<td>0.22</td>
<td>0.22</td>
<td>0.11</td>
</tr>
<tr>
<td>Steam Conditioner</td>
<td>0.17</td>
<td>0.17</td>
<td>-</td>
</tr>
<tr>
<td>Pellet Mill</td>
<td>0.67</td>
<td>0.67</td>
<td>-</td>
</tr>
<tr>
<td>Pellet Silo</td>
<td>1.28</td>
<td>1.28</td>
<td>-</td>
</tr>
<tr>
<td>Torrefier</td>
<td>-</td>
<td>8.68</td>
<td>-</td>
</tr>
<tr>
<td>Q'Pellet System</td>
<td>-</td>
<td>-</td>
<td>10.32</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12.91</strong></td>
<td><strong>21.62</strong></td>
<td><strong>21.00</strong></td>
</tr>
</tbody>
</table>

3.8.5 Utility Requirements

Required utilities are electricity and natural gas. Electricity requirements are from literature, with ranges shown in section 2.9. The electricity requirements used for the case study are shown in Table 3-5.

Table 3-5: Case study electricity requirements

<table>
<thead>
<tr>
<th>Operation</th>
<th>Electricity Usage (kWh/GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>White Pellets</td>
</tr>
<tr>
<td>Dryer</td>
<td>1.38</td>
</tr>
<tr>
<td>Hammermilling</td>
<td>6.44</td>
</tr>
<tr>
<td>Screening</td>
<td>2.73</td>
</tr>
<tr>
<td>Torrefying</td>
<td>4.29</td>
</tr>
<tr>
<td>Pelletizing</td>
<td>1.38</td>
</tr>
<tr>
<td>Cooling</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Energy requirements for drying and torrefying are given in section 3.5. It is assumed that 0.09 GJ of natural gas is required to dry and torrefy Q'Pellets. Following [68], it is assumed no natural gas is needed to dry and torrefy for torrefied pellets. The natural gas requirements for steam conditioning are from [96]. The natural gas requirements are shown in Table 3-6.
Table 3-6: Natural gas requirements ($G_{\text{natGas}}/G_{\text{biomass}}$)

<table>
<thead>
<tr>
<th>Operation</th>
<th>White Pellets</th>
<th>Torrefied Pellets</th>
<th>Q’Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying and Torrefying</td>
<td>0.12</td>
<td>-</td>
<td>0.005</td>
</tr>
<tr>
<td>Steam Conditioning</td>
<td>0.055</td>
<td>0.046</td>
<td>-</td>
</tr>
</tbody>
</table>

3.8.6 Transportation

The required transportation modes are transport trucks to bring raw biomass to the plant, trains to bring pellets to port and Panamax ships to transport to Rotterdam. The distance from Williams Lake to Vancouver is 540 km [116] and from Vancouver to Rotterdam it is 16,500 km [117]. It is assumed that the average distance required to bring raw biomass to the plant is 129 km [29]. Literature transportation costs are given in section 2.7, and the costs used for the case study are given in Table 3-7.

Table 3-7: Case study transportation costs

<table>
<thead>
<tr>
<th>Transportation Mode</th>
<th>Pellet Type</th>
<th>DFC [$/GJ]</th>
<th>DVC [$/GJ\cdot100km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td>White Pellets</td>
<td>0.28</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Torrefied Pellets</td>
<td>0.23</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Q’Pellets</td>
<td>0.23</td>
<td>0.54</td>
</tr>
<tr>
<td>Rail</td>
<td>White Pellets</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Torrefied Pellets</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Q’Pellets</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td>Panamax Ship</td>
<td>White Pellets</td>
<td>0.080</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>Torrefied Pellets</td>
<td>0.063</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>Q’Pellets</td>
<td>0.053</td>
<td>0.005</td>
</tr>
</tbody>
</table>

3.8.7 Storage

Storage is assumed to be outdoors for raw biomass and Q’Pellets and in silos for white and torrefied pellets. Storage costs used in the case study are shown in Table 3-8.
### Table 3-8: Storage costs

<table>
<thead>
<tr>
<th>Biomass Type</th>
<th>Storage Type</th>
<th>Capital Cost (M$)</th>
<th>Operating Cost ($/tonne·day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Biomass</td>
<td>Outdoor</td>
<td></td>
<td>0.0026</td>
</tr>
<tr>
<td>White Pellets</td>
<td>Silo</td>
<td>1.28</td>
<td>0.0137</td>
</tr>
<tr>
<td>Torrefied Pellets</td>
<td>Silo</td>
<td>1.28</td>
<td>0.0137</td>
</tr>
<tr>
<td>Q’Pellets</td>
<td>Outdoor</td>
<td></td>
<td>0.0059</td>
</tr>
</tbody>
</table>

#### 3.8.8 Fixed Operating Costs

Fixed operating costs are for labour, overhead, insurance, property tax and maintenance.

Labour is assumed to consist of 14 labourers, 2 foremen and 1 supervisor, for a total labour cost of $1.56M per year. Direct overhead is assumed to cost 45% of labour and general overhead is 50% of labour and maintenance. Insurance and property tax assumed to be equal to 1% and 0.5% of capital costs, and maintenance is assumed to equal 5% of equipment capital costs [16].

#### 3.8.9 Dry Matter Losses

Several steps are assumed to incur dry matter losses (DML). Drying and cooling are assumed to have a 1% DML, hammermilling is assumed to have a 2% DML and oceanic transportation is assumed to have a 0.3% DML. Outdoor raw biomass storage is assumed to have a DML of 3% per month [73].

#### 3.9 Model Validation and Verification

#### 3.9.1 Verification

All equations and inputs used in the model have been reported and are based on values from literature. There is a wide amount of uncertainty in many variables, especially regarding to
the capital costs and energy requirements of the Q'Pellet system. To account for these uncertainties, a sensitivity analysis was performed.

Model verification was performed by providing literature results to the model. Pirraglia et al. found an IRR of 12% [17] for the production of torrefied wood pellets. The operating costs, capital costs and biomass and pellet sale prices were used in the model, which resulted in an IRR of 11.56%. Although the result is not identical, a difference in IRR of less than 0.5% is deemed quite small. Potential differences include tax rates, inflation rates and other financial information not given by Pirraglia et al.

3.9.2 Validation

Currently the model is not validated, as validation would require industrial results for energy consumption and capital costs produce Q’Pellets. Lab scale results would not fully confirm energy requirements, as noted by Tumuluru et al. [87]. To validate capital costs, detailed engineering would be required to determine so that the costs of peripheral equipment could be estimated. Additionally, without a site selected, construction costs remain quite variable.

3.10 Chapter Conclusion

This chapter outlined the techno-economic model created and the case study developed for use in the model. The model was described along with all the equations that drive it. The model allows for both economic and life cycle analysis for any user defined wood pellet production chain. Economic analysis is based on cash flow analysis, with internal rate of
return used to determine economic value. Costs are divided into capital and operating costs. Environmental value is determined by life cycle GHG emissions.

A case study of a plant built in Williams Lake BC with product delivery in Rotterdam was then described. Parameters required for the study were described, along with capital expenditures required to build plants for each of white, torrefied and Q'Pellets. Using this case study, Chapter 4 will present results. Results will be presented and discussed from the base values in the case study, followed by sensitivity analyses of several parameters and Monte Carlo analysis.
Chapter 4 Results

4.1 Overview of the Chapter

This chapter presents results of the case study with sensitivity analyses. Economic results are described for white, torrefied and Q’Pellets for the case study. Costs for each pellet type are described, broken into the various components that combine to form operating and capital costs. Internal rate of return is the metric used to determine economic value for pellet production. Cash flows are given for each of the pellet types, with full cash flow descriptions provided in the appendix. Life cycle analysis results are presented as waterfall charts for each of the pellet types. Sensitivity analysis results are presented for several variables along with results of Monte Carlo modelling. Several modified case studies are presented to determine the effects of changes to production plant location and size along with customer location.

4.2 Economic Results

Following the case study outlined in section 3.8, cash flow was determined for each of the three pellet production methods. To allow comparison between the three types of pellets, the costs are determined on an energy basis, from the equations provided in Chapter 3. Capital costs from Table 3-4 were used with case study values to determine the capital cost per GJ of annual delivered biomass, provided in Table 4-1.
Table 4-1: Capital cost per GJ of annual delivered biomass

<table>
<thead>
<tr>
<th>Pellet Type</th>
<th>Capital Cost [$/GJ-year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Pellets</td>
<td>7.37</td>
</tr>
<tr>
<td>Torrefied Pellets</td>
<td>13.98</td>
</tr>
<tr>
<td>Q'Pellets</td>
<td>13.71</td>
</tr>
</tbody>
</table>

Variable operating costs are shown on an energy basis in Table 4-2. For the case study, biomass is assumed to cost $35/ODT and cost per GJ is found using equation [3-6]. Transportation costs used in the case study in terms of distance fixed cost and distance variable cost are provided in Table 3-7, transportation distances are described in Section 3.8.6, and costs per GJ were found from equation [3-7]. Utility requirements to produce a tonne of pellets for each of the pellet types are provided in Table 3-5 and Table 3-6, utility rates are provided in Table 3-3 and utility costs per GJ were found using equations [3-14] and [3-15].

Table 4-2: Variable operating costs

<table>
<thead>
<tr>
<th>Item</th>
<th>White Pellet</th>
<th>Torrefied pellet</th>
<th>Q'Pellet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Biomass</td>
<td>2.00</td>
<td>2.26</td>
<td>2.28</td>
</tr>
<tr>
<td>Truck Transportation</td>
<td>1.07</td>
<td>1.18</td>
<td>1.19</td>
</tr>
<tr>
<td>Rail Transportation</td>
<td>1.86</td>
<td>1.51</td>
<td>1.30</td>
</tr>
<tr>
<td>Ship Transportation</td>
<td>1.32</td>
<td>1.07</td>
<td>0.92</td>
</tr>
<tr>
<td>Electricity</td>
<td>1.07</td>
<td>1.01</td>
<td>0.92</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1.14</td>
<td>0.26</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>8.46</td>
<td>7.29</td>
<td>6.64</td>
</tr>
</tbody>
</table>

From Table 4-2, it is noted that the costs for raw biomass and truck transportation are higher per GJ for Q'Pellets and torrefied pellets than for white pellets due to the reduction in total energy caused by torrefaction. During torrefaction, approximately 10% of the initial energy in the biomass is converted into off gases and is not available in the final product. The mass and energy yields for each of the three processes are provided in the Appendix in Table A-4.
to Table A-6. The purchased quantity of biomass is the same in all cases, so the reduction in total energy available increases the cost per GJ for the torrefied pellets. The cost increase from lowered total energy also increases the operating expenses for rail and ship transportation and utilities, but the overall cost is lowered due the cost savings provided by torrefaction.

Fixed operating costs are shown in Table 4-3, with input values described in Section 3.8.8.

\[\text{Table 4-3: Fixed operating costs}\]

<table>
<thead>
<tr>
<th>Item</th>
<th>White Pellet</th>
<th>Torrefied pellet</th>
<th>Q'Pellet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour</td>
<td>0.45</td>
<td>0.51</td>
<td>0.46</td>
</tr>
<tr>
<td>Direct Overhead</td>
<td>0.20</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td>General Overhead</td>
<td>0.34</td>
<td>0.38</td>
<td>0.35</td>
</tr>
<tr>
<td>Insurance</td>
<td>0.04</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Property Tax</td>
<td>0.08</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Maintenance</td>
<td>0.23</td>
<td>0.48</td>
<td>0.52</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.34</strong></td>
<td><strong>1.81</strong></td>
<td><strong>1.75</strong></td>
</tr>
</tbody>
</table>

Insurance, property tax and maintenance are all based on capital costs [16], which are higher for both Q'Pellets and torrefied pellets than for white pellets. Labour costs are assumed to be equal for the three pellets types [16] while direct and general overhead are determined as a percentage of labour costs, so the reduction in energy after torrefaction increases the cost per GJ for torrefied pellets and Q'Pellets.

Using the operating costs from Table 4-2 and Table 4-3, capital costs from Table 3-4 and plant parameters from Table 3-3, cash flow analysis was performed to determine the economic performance of the three production methods and IRR was calculated using equation [3-33]. The IRR of three pellet production processes are given in Table 4-4.
Table 4-4: Modelled IRR for the three processes

<table>
<thead>
<tr>
<th>White Pellet</th>
<th>Torrefied pellet</th>
<th>Q'Pellet</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1%</td>
<td>8.0%</td>
<td>12.7%</td>
</tr>
</tbody>
</table>

The highest IRR is from Q'Pellet production at 12.7%, followed by white pellet production.

Although white pellets require the least capital expenditure, they have the highest operating cost. Specifically, white pellets have much higher transportation costs and natural gas costs from drying and steam conditioning. Full cash flow results from the three processes can be found in the appendix in Table A-1 to Table A-3. Figure 4-1 to Figure 4-3 give cash flows and internal rates of return for white, torrefied and Q'Pellet production.

![Figure 4-1: White pellet cash flow](image)

84
Figure 4-2: Torrefied pellet cash flow

Figure 4-3: Q'Pellet cash flow
In all three production scenarios, the cash flow charts show similar features. For the first three years, the plant is under construction with no pellet production and no revenue. 20% of total capital spending occurs in the first year and 40% of capital spent in each of the second and third year. Beginning at the start of the fourth year, pellets are produced. Revenue and costs increase exponentially due to the assumption of annual 3% inflation, based on the long term Canadian average [115]. All assumptions have undergone sensitivity analysis to determine their effect on overall process IRR, as described in the sensitivity analysis. There is a dip in cash income that is apparent from the cash flow charts around the 13th year of production caused by the plant becoming fully depreciated. Once the plant is fully depreciated, depreciation is no longer available as a tax deduction and income tax is paid from that point moving forward, which causes the reduction in cash income.

4.3 GHG Results

Using the LCI inputs from section 2.12 and equations from section 3.4, life cycle GHG emissions were calculated for each of the production processes. Table 4-5 gives the life cycle GHG emissions for the three production processes.

<table>
<thead>
<tr>
<th>Table 4-5: Modelled GHG emissions [kgCO₂eq/GJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Pellet</td>
</tr>
<tr>
<td>21.50</td>
</tr>
</tbody>
</table>

Figure 4-4 to Figure 4-6 are waterfall charts that give GHG emission breakdowns into four categories – transportation, natural gas combustion, electricity, and biomass combustion. White pellets have the highest emissions due to transportation and natural gas combustion emissions.
Figure 4-4: White pellet GHG emissions

Figure 4-5: Torrefied pellet GHG emissions
In all three cases, electricity emissions are very low. This is due to the low grid electricity GHG emission intensity in BC, as described in Section 2.12.2. Compared to Louisiana, electricity generated in BC produces 96% less GHG emissions per GJ [104], [106]. The effect of higher grid GHG emissions on life cycle emissions is discussed in Section 4.6.2.

Section 2.12.1 gives the requirements for solid biomass to be considered sustainable by the European Union. All three pellet production methods achieve the requirement to reduce GHG life cycle emissions by 50% over the fossil fuel comparator (maximum life cycle emissions of 23.3 kgCO2eq/GJ). White pellet production does not meet the required 18.6 kgCO2eq/GJ to achieve GHG emission reductions of 60%. Hence, if a white pellet plant were to be built after January 1, 2017 given the case study parameters, it would not meet EU
requirements to be considered a sustainable energy source [103]. Given the assumption of 3 years to build the plant, white pellet production could not begin until 2019 at the earliest.

4.4 Sensitivity Analysis

Sensitivity analysis may be performed by modifying a single variable to determine how overall output is impacted. The variables described for sensitivity analysis are labour cost, capital cost, electricity cost, pellet sale price, exchange rate, natural gas cost, transportation cost, raw biomass price, and pellet HHV. Other variables considered had much lower sensitivity, including plant life, depreciation rate, and capital breakdown. In Sections 4.6, 4.7 and 4.8, the effects of modifying plant location, customer location and plant capacity are considered, respectively. The default range for sensitivity analysis is +/- 20% of base cost, a level which is adjustable in the model. This level was chosen to be near the lowest calculable IRR for the more sensitive values to allow for clear graphical presentation of results. In the Monte Carlo analysis presented in Section 4.5, values are allowed wider ranges of variance.

4.4.1 Pellet Sale Price

For all three processes, the most sensitive variable is pellet sale price. The white pellet process has the highest sensitivity: if the pellet sale price is reduced by 8%, white pellet IRR falls to -7.3%. If pellet sale price drops more than 8%, the IRR becomes incalculably negative for white pellets. To allow for a graphical comparison, +/- 8% of base price was chosen to show sale price sensitivity. Between November 2015 and February 2016, pellet prices in
USD fell by approximately 13% [55], showing that an 8% drop is not an unreasonably large change in price. Thus, the lower sensitivity to pellet sale price of Q'Pellets is highly valuable. Nonetheless, obtaining long term sale contracts at prices that allow profitable sale is key to the long term viability of any wood pellet plant. White pellets have a higher sensitivity to sale price as the difference between sale price and variable cost is lower for white pellets than for Q'Pellets or torrefied pellets, so a change in pellet price causes a relatively larger change to the difference. Figure 4-7 shows sensitivity to pellet sale price, with Q'Pellets represented by the solid line, torrefied pellets by the dashed line and white pellets by the dashed and dotted line.

![Sale Price](image)

**Figure 4-7:** Sale price sensitivity

4.4.2 Exchange Rate

The three pellets show a similar sensitivity to USD to CAD exchange rate as they do to sale price. The model assumes that operating costs and raw biomass costs are in CAD while pellet sale price is converted from USD to CAD, causing the sensitivity to exchange rate to be
similar to sale price. However, the true sensitivity to exchange rate is difficult to determine, as many input costs may be sensitive to exchange rates but are not considered to be in the model. For instance, many of the capital costs for equipment are given in terms of CAD, but they would likely be sensitive to exchange rates as they would require imported parts, etc. even if they are priced in CAD.

White pellets show a higher sensitivity to exchange rate than torrefied or Q'Pellets in a similar manner to sale price sensitivities. At an exchange rate of 1.40 CAD/USD, white pellets have an IRR of 27.3%, compared to 21.7% for Q'Pellets. However, at an exchange rate of 1.10 CAD/USD, Q'Pellet production maintains a positive IRR of 5.7% while the IRR of white pellet production falls to -16.8%. The high sensitivity to exchange rate underpins the importance of ensuring that any pellet production plant has long term pellet sale contracts to reduce the influence of fluctuations in uncontrollable market conditions. The sensitivity to USD to CAD exchange rate is shown in Figure 4-8.
4.4.3 Higher Heating Value

HHV was increased and decreased by 2.25 GJ/tonne for the torrefied pellet and the Q’Pellet to 19 and 23.5 GJ/tonne. 19 GJ/tonne corresponds to an increase of 0.5 GJ/tonne over the white pellets, and is assumed to be a worst case for torrefied pellets. An HHV of 23.5 GJ/tonne corresponds to a LHV of approximately 22 GJ/tonne, which is the highest value HHV of torrefied biomass known to the author, reported by Bergman [14]. Higher HHV values are possible, but the energy yield and process efficiency drops quickly above this point [38]. Both Q’Pellet and torrefied pellet production showed a similar sensitivity to heating value. Q’Pellet production has an IRR close to 20% for pellets with a heating value of 23.5 GJ/tonne and maintains a positive IRR for pellets with an HHV of 19 GJ/tonne. As the HHV for the white pellets only depends on the biomass used, it was not considered for this sensitivity. Figure 4-9 shows HHV sensitivity.

Figure 4-8: Exchange rate sensitivity
Figure 4-9: HHV sensitivity

4.4.4 Capital Expenditure

All three processes show a similar sensitivity to capital expenditure. If capex is reduced by 20%, the Q’Pellet IRR is increased to above 15%. Additionally, Q’Pellet IRR will only be reduced to below 11.1% (base white pellet IRR) if capex is increased by over 14%, or $2.94 M. As the only component of the Q’Pellet process that is not also in a component in white pellet production is the Q’Pellet system, the Q’Pellet process will only have an IRR lower than the white process if the Q’Pellet system is $2.94 M (28.5%) more expensive than predicted. Figure 4-10 shows capex sensitivity.
4.4.5 Transportation Cost

The sensitivity to transportation costs was similar to the sensitivity to capex for torrefied pellets and Q’Pellets, but white pellets were more sensitive to transportation costs than to capex. Combined with white pellets high sensitivity to sale price, white pellets are more sensitive to uncontrollable market-based factors than Q’Pellets or torrefied pellets. The higher sensitivity of white pellets to transportation costs are because transportation costs account for a higher percentage of overall costs for white pellets than for Q’Pellets so white pellets are more affected by changes. Figure 4-11 shows transportation sensitivity.
4.4.6 Raw Biomass Price

White pellets are the most sensitive to raw biomass cost, and the IRR of a white pellet plant will exceed that of a Q’Pellet plant if the biomass costs $30/tonne or less. However, white pellet production will have a negative IRR if the cost of raw biomass is increased to $50/tonne, while Q’Pellet production will still have an IRR over 5%. The reason for the higher sensitivity to raw biomass for white pellets is the same as for pellet sale price, a lower difference between variable cost and pellet sale price. Thus, the same change in raw biomass price causes a larger proportional decrease in the profitability of white pellet production compared to Q’Pellet and torrefied pellet production. Figure 4-12 shows raw biomass price sensitivity.
4.4.7 Utility Costs

White pellets were far more sensitive to both electricity and natural gas costs than either torrefied or Q’Pellets. As natural gas usage is much higher for white pellet production than either torrefied pellet or Q’Pellets, it leads to a much higher sensitivity for white pellets. Specifically, as very little natural gas is required to create Q’Pellets, their production shows essentially no sensitivity to changes in natural gas costs.

White pellets also have a higher sensitivity to electricity costs. As mentioned above, the smaller difference between sale price and variable cost causes white pellet production to have a higher proportional change in IRR from the same change to variable cost. Beyond this, more electricity is required to create white pellets than Q’Pellets or torrefied pellets on an energy basis, as seen in Table 3-5. Higher electricity requirements for white pellet production means that the same percentage change leads to a larger absolute change and a
larger change in IRR. Figure 4-13 and Figure 4-14 show natural gas cost and electricity cost sensitivities.

**Figure 4-13: Natural gas cost sensitivity**

**Figure 4-14: Electricity cost sensitivity**
4.4.8 Labour Cost

The final variable considered for sensitivity analysis was labour cost. All three processes show a similar, low sensitivity to labour cost. Production of all three pellet types was assumed to require the same amount of direct labour, and so all three processes show a similar level of sensitivity. White pellet production has a higher sensitivity due the lower difference between sale price and costs, but the lower sensitivity of labour cost makes this difference less noticeable. Figure 4-15 shows labour cost sensitivity.

Figure 4-15: Labour cost sensitivity

4.5 Monte Carlo Analysis

Monte Carlo analysis was performed to determine the ranges of outcomes possible given uncertainty in multiple variables. The eight variables considered for sensitivity analysis in section 4.4 were considered for Monte Carlo analysis. All variables were assumed to have a triangular distribution, as described in section 3.7, so a minimum, maximum and most likely value are required for each. In all cases, the most likely value was assumed to be the base
case value. The minimum and maximum was assumed to ±50% of the base case for electricity cost, natural gas cost, capital cost, labour cost, and transportation cost. For sale price, the minimum and maximum were assumed to be ±25% of base cost. Raw biomass cost was assumed to have a minimum of $18.75/ODT and maximum of $80.00/ODT. HHV was assumed to have a minimum of 19 GJ/tonne and a maximum of 23.5 GJ/tonne for torrefied and Q’Pellets, and was assumed not to vary for white pellets. Ten-thousand iterations were run for each process. The results of the Monte Carlo are given as a histogram and plotted in Figure 4-16:

![Histogram of IRR results for different types of pellets.](image)

**Figure 4-16: Monte Carlo analysis**

It is clear from Figure 4-16 that white pellet production has a wider range in IRR results modelling than Q’Pellets. For white pellets, there is a 28% chance that the modelled IRR is below -10%, compared to a 21% chance for Q’Pellets. However, white pellets are much more likely to achieve an IRR above 25% than Q’Pellets. These results show a similar pattern to the sensitivity analyses, as white pellet production was more sensitive than Q’Pellet
production for most variables. Lower sensitivity to changes allows Q'Pellet production to have a positive modelled IRR more often than for white pellet production.

4.6 Plant Location

The case study presented in section 4.2 is based on a plant built in Williams Lake BC. In this section, plants built in Hawk Junction, ON, Thunder Bay, ON and Baton Rouge, LA are considered. These locations were chosen due to current biomass pellet plants and access to rail and ports. Hawk Junction is near the Rentech Wawa plant [51] and has rail access. Rentech’s logistics involves rail shipping to the Port of Quebec City. Thunder Bay is close to Rentech’s Atikokan Plant [51] and Atikokan GS and Thunder Bay GS, which have been converted to operate on biomass. Furthermore, Thunder Bay has access to lake port with the potential to export pellets. Baton Rouge was chosen due to current pellet mills operating nearby [118] and the Port of Baton Rouge is currently exporting pellets [119]. Additionally, Louisiana offers lower electricity rates than either Mississippi or Georgia [85].

Logistics involved in production in Hawk Junction include truck transportation to the plant, rail shipping to Quebec City (1395 km [120]), and then Panamax shipping to Rotterdam (5836 km [121]). Logistics from Thunder Bay involve truck shipping to the plant, shipping on a packaged lake ship to Quebec City from the Port of Thunder Bay (then transfer to a Panamax for shipping to Rotterdam (5836 km [121]). Baton Rouge logistics require truck transport to the plant followed by truck transport to port and Panamax shipping to Rotterdam (9197 km [122]). The distance from the Baton Rouge plant to port is assumed to be 15 km.
At this distance, the main cost is the distance fixed cost associated with loading and unloading the trucks.

Table 4-6 shows the parameters that are modified from the base case study for the three new locations. The parameters that change from the base case study are for finished product logistics, electricity rates, income tax rates and depreciation method.

<table>
<thead>
<tr>
<th>Item</th>
<th>Baton Rouge</th>
<th>Ref</th>
<th>Hawk Junction</th>
<th>Ref</th>
<th>Thunder Bay</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport to port (km)</td>
<td>15</td>
<td></td>
<td>1395</td>
<td>[120]</td>
<td>2206</td>
<td>[123]</td>
</tr>
<tr>
<td>Panamax Transport (km)</td>
<td>9197 [122]</td>
<td></td>
<td>5836</td>
<td>[121]</td>
<td>5836</td>
<td>[121]</td>
</tr>
<tr>
<td>Electricity Rate (¢/kWh)</td>
<td>8.35 [85]</td>
<td></td>
<td>11.04</td>
<td>[83]</td>
<td>11.04</td>
<td>[83]</td>
</tr>
<tr>
<td>Income Tax Rate</td>
<td>42% [124]</td>
<td></td>
<td>25%</td>
<td>[110]</td>
<td>25%</td>
<td>[110]</td>
</tr>
</tbody>
</table>

4.6.1 Economic Results

The costs for logistics in the three locations were calculated using the same methods as for Table 4-2 and are provided in Table 4-7.
Table 4-7: Logistics costs for pellet production in Hawk Junction, Thunder Bay and Baton Rouge

<table>
<thead>
<tr>
<th>Item</th>
<th>Hawk Junction</th>
<th>Thunder Bay</th>
<th>Baton Rouge</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Pellet</td>
<td>$8.24</td>
<td>$2.79</td>
<td>$0.35</td>
</tr>
<tr>
<td>Panamax Shipping</td>
<td>$0.51</td>
<td>$0.51</td>
<td>$0.77</td>
</tr>
<tr>
<td>Torrefied Pellet</td>
<td>$6.68</td>
<td>$2.43</td>
<td>$0.31</td>
</tr>
<tr>
<td>Panamax Shipping</td>
<td>$0.42</td>
<td>$0.42</td>
<td>$0.62</td>
</tr>
<tr>
<td>Q’Pellet</td>
<td>$5.75</td>
<td>$2.43</td>
<td>$0.31</td>
</tr>
<tr>
<td>Panamax Shipping</td>
<td>$0.36</td>
<td>$0.36</td>
<td>$0.54</td>
</tr>
</tbody>
</table>

From Table 4-7, it is clear that rail transport from Hawk Junction to Quebec is the most expensive logistics component. The IRR that results from production in the three locations compared to the base case of Williams Lake is shown in Table 4-8.

Table 4-8: IRR for pellet production in Williams Lake, Hawk Junction, Thunder Bay and Baton Rouge

<table>
<thead>
<tr>
<th>Location</th>
<th>White Pellets</th>
<th>Torrefied Pellets</th>
<th>Q’Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Williams Lake, BC</td>
<td>11.1%</td>
<td>8.0%</td>
<td>12.7%</td>
</tr>
<tr>
<td>Hawk Junction, ON</td>
<td>Incalculable</td>
<td>Incalculable</td>
<td>Incalculable</td>
</tr>
<tr>
<td>Thunder Bay, ON</td>
<td>-2.4%</td>
<td>-0.9%</td>
<td>4.4%</td>
</tr>
<tr>
<td>Baton Rouge, LA</td>
<td>27.3%</td>
<td>16.2%</td>
<td>18.5%</td>
</tr>
</tbody>
</table>

For all types of pellet production, Baton Rouge has the highest IRR. Baton Rouge has favourable logistics due to it being a tidewater port, which leads to low shipping costs. The low shipping costs are most favourable for white pellet production; white pellet production is the most sensitive to shipping costs as noted in Section 4.4.5.

Thunder Bay is the superior option for production in Ontario, but only the IRR of Q’Pellet production is positive. In all cases, the IRR of production in Hawk Junction was incalculably negative due the high cost of rail transport to Quebec City. Rentech claims lower rail transportation costs by leasing rail cars as opposed to shipping by the carload. To achieve
an IRR of 10% with production of Q’Pellets in Hawk Junction, the cost per tonne to ship to Quebec City would need to be reduced from $122/tonne to $29/tonne.

4.6.2 GHG Emission Results

Life cycle GHG emissions were calculated in the same way as Table 4-5, but with updated values for transportation distances and grid electricity GHG intensity. Life cycle GHG emissions are shown in Table 4-9.

Table 4-9: GHG emissions [kgCO$_2$/GJ] for pellet production in Williams Lake, Hawk Junction, Thunder Bay and Baton Rouge

<table>
<thead>
<tr>
<th>Location</th>
<th>White Pellets</th>
<th>Torrefied Pellets</th>
<th>Q’Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Williams Lake, BC</td>
<td>21.50</td>
<td>10.08</td>
<td>6.96</td>
</tr>
<tr>
<td>Hawk Junction, ON</td>
<td>17.29</td>
<td>8.30</td>
<td>5.29</td>
</tr>
<tr>
<td>Thunder Bay, ON</td>
<td>19.24</td>
<td>7.32</td>
<td>4.32</td>
</tr>
<tr>
<td>Baton Rouge, LA</td>
<td>25.41</td>
<td>12.67</td>
<td>9.11</td>
</tr>
</tbody>
</table>

Pellet production in Baton Rouge has the highest life cycle emissions for all type of pellets, despite having the lowest emissions from transportation. This is caused by high emission factor of grid electricity produced in Louisiana. Both Ontario and BC have a large percentage of electricity produced by hydroelectric, wind or nuclear while Louisiana produces power mainly from fossil fuels.

Q’Pellet and torrefied pellet production meet the 60% reduction in CO$_2$ emissions required to be considered sustainable by the EU in all cases, but white pellet production only meets the requirement for production in Hawk Junction.
4.7 Customer Location

Growth markets for Canadian wood pellets include Japan and OPG. With OPG as the customer, it is assumed that production would take place in Thunder Bay. It is assumed that the distance from a plant built in Thunder Bay to Thunder Bay GS would be 15 km. For customer delivery to Japan, it is assumed that production would take place in Williams Lake or Baton Rouge. The distance from Vancouver to Japan is 8000 km [117] compared to 17,000 km from Baton Rouge to Japan [122].

4.7.1 Thunder Bay Results

The IRR that results from production in Thunder Bay with OPG as the customer is shown in Table 4-10.

<table>
<thead>
<tr>
<th></th>
<th>White Pellets</th>
<th>Torrefied Pellets</th>
<th>Q’Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRR</td>
<td>31.2%</td>
<td>18.5%</td>
<td>20.7%</td>
</tr>
</tbody>
</table>

White pellet production has the highest IRR, due to the low transportation costs, as only a short truck trip is required for product delivery. The life cycle GHG emissions are shown in Table 4-11.

<table>
<thead>
<tr>
<th></th>
<th>White Pellets</th>
<th>Torrefied Pellets</th>
<th>Q’Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG emissions</td>
<td>15.32</td>
<td>5.13</td>
<td>2.20</td>
</tr>
</tbody>
</table>

Torrefied and Q’Pellets have very low emissions from natural gas combustion, and given the low emission factor for electricity produced in Ontario, the main emission source for these pellets is typically transportation. However, for pellets produced and consumed in Thunder
Bay, transportation emissions are very low. Thus, the life cycle emissions are extremely low for torrefied and Q’Pellet production in this scenario. White pellet production is low enough to meet the EU requirements for a 60% reduction over a fossil fuel comparator, but are nearly seven times higher than Q’Pellet life cycle emissions.

4.7.2 Japan Results

Table 4-12 gives the IRR for pellet production for pellets delivered to Japan with production in Williams Lake and Baton Rouge.

<table>
<thead>
<tr>
<th>Production Location</th>
<th>White Pellets</th>
<th>Torrefied Pellets</th>
<th>Q’Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Williams Lake</td>
<td>18.2%</td>
<td>11.5%</td>
<td>15.4%</td>
</tr>
<tr>
<td>Baton Rouge</td>
<td>21.7%</td>
<td>16.1%</td>
<td>18.0%</td>
</tr>
</tbody>
</table>

The highest IRR’s are for white pellet production in Baton Rouge and then Williams Lake. As Baton Rouge only requires a short truck trip before Panamax shipping, transportation costs are low. Similarly, the reduced distance from Vancouver to Japan compared to Europe reduces transportation costs. White pellets have the highest sensitivity to transportation cost, and the reduced transportation costs cause the IRR of white pellets to increase above Q’Pellets. The life cycle emissions for delivery to Japan are shown in Table 4-13.

<table>
<thead>
<tr>
<th>Production Location</th>
<th>White Pellets</th>
<th>Torrefied Pellets</th>
<th>Q’Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Williams Lake</td>
<td>18.47</td>
<td>7.67</td>
<td>4.67</td>
</tr>
<tr>
<td>Baton Rouge</td>
<td>28.18</td>
<td>14.89</td>
<td>11.22</td>
</tr>
</tbody>
</table>

The lowest life cycle emissions are from Q’Pellet production in Williams Lake, which are 83% less than the worst case of white pellet production in Baton Rouge. White pellet
production in Baton Rouge does not meet the current standard to be considered sustainable by the EU, which requires maximum life cycle emissions of 23.3 kgCO2eq/GJ.

4.8 Plant Capacity

The case study assumed a plant capacity of 100 ktonnes/year of dry biomass. Figure 4-17 shows IRR for the three pellets for plant capacities of 60 ktonnes/year, 100 ktonnes/year, 200 ktonnes/year and 500 ktonnes/year.

At the base capacity of 100 ktonnes/year, the Q’Pellet has the highest IRR. The Q’Pellet also has the highest IRR at 60 ktonnes/year, but is slightly lower than for white pellets at a capacity of 200 ktonnes/year and 500 ktonnes/year.

At a plant capacity of 60 ktonnes/year, no pellet production method had an IRR over 10%. Q’Pellet production had the highest IRR, but only 5.9%. For a Q’Pellet plant to be reach a 10% IRR, given the case study parameters, the capacity must be at least 80 ktonnes/year.
4.9 Normalized Biomass Production

The case studies considered up to this point are all based on the amount of biomass entering the plant being constant for the three pellet types. In this section, the amount of delivered biomass energy is set to be constant amongst the three pellet types with the quantity of raw biomass varying between the pellet types. The two plant sizes considered are based on an output of 1.75 TJ of delivered biomass (the output of the base case white pellet mill) and 1.53 TJ (the output of the base case Q'Pellet mill). Thus, to have 1.75 TJ of delivered energy, 100 ktonnes of raw dry biomass is required for white pellet production and for 1.53 TJ, 100 ktonnes of raw dry biomass is required for Q'Pellet production. Table 4-14 shows the plant capacities in terms of ktonnes of dry, raw biomass required for a delivered biomass energy output of 1.75 TJ.

Table 4-14: Raw biomass requirements to supply a plant with a delivered biomass energy capacity of 1.75 TJ

<table>
<thead>
<tr>
<th>Pellet Type</th>
<th>Plant Capacity [ktonnes/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Pellet</td>
<td>100</td>
</tr>
<tr>
<td>Torrefied Pellet</td>
<td>113</td>
</tr>
<tr>
<td>Q'Pellet</td>
<td>114</td>
</tr>
</tbody>
</table>

Due to the higher biomass energy yield of white pellet production, less raw biomass is required to have the same quantity of energy delivered than for torrefied or Q'Pellets. Table 4-15 shows the required biomass to allow for 1.53 TJ of delivered biomass.
Table 4-15: Raw biomass requirements to supply a plant with a delivered biomass capacity of 1.53 TJ

<table>
<thead>
<tr>
<th>Pellet Type</th>
<th>Plant Capacity [kt/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Pellet</td>
<td>88</td>
</tr>
<tr>
<td>Torrefied Pellet</td>
<td>99</td>
</tr>
<tr>
<td>Q’Pellet</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4-15 shows that less raw biomass is required to produce the same quantity of delivered biomass, as would be expected from the results in Table 4-14.

From the plant capacities provided by Table 4-14, the IRR was determined for the three pellet types. The IRR results are provided in Table 4-16.

Table 4-16: IRR by pellet type for a plant with a delivered biomass energy capacity of 1.75 TJ

<table>
<thead>
<tr>
<th>Pellet Type</th>
<th>Plant Capacity [kt/yr]</th>
<th>IRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Pellet</td>
<td>11.1%</td>
<td></td>
</tr>
<tr>
<td>Torrefied Pellet</td>
<td>9.4%</td>
<td></td>
</tr>
<tr>
<td>Q’Pellet</td>
<td>14.2%</td>
<td></td>
</tr>
</tbody>
</table>

From Table 4-16, it can be seen that the IRR of torrefied pellet and Q’Pellet production is increased from their base values of 8.0% and 12.7% to 9.4% and 14.2%, respectively. The IRR of white pellet remains 11.1%.

However, there is a concern that increased capacity would cause an increase to raw biomass cost. If the average cost of biomass increases to $43/ODT, the IRR of Q’Pellet production would fall below white pellet production. As it is assumed that the first 100 kt of biomass would still be acquired at $35/ODT, the marginal cost of the next 14 kt would need to be $99/ODT to bring the average biomass cost to $43/ODT.
Table 4-17: IRR by pellet type for a plant with a delivered biomass energy capacity of 1.53 TJ

<table>
<thead>
<tr>
<th>Pellet Type</th>
<th>Plant Capacity [ktonnes/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Pellet</td>
<td>8.9%</td>
</tr>
<tr>
<td>Torrefied Pellet</td>
<td>7.8%</td>
</tr>
<tr>
<td>Q'Pellet</td>
<td>12.7%</td>
</tr>
</tbody>
</table>

If the desired plant capacity is 1.53 TJ of delivered energy, the IRR of white pellet production falls to 8.9% while the IRR of Q'Pellet production remains at 12.7%. Thus, if raw biomass is acquired for $35/ODT, the IRR for white pellet production falls below minimum investment grade. For the IRR of white pellet production to rise to 10%, raw biomass must average $33/ODT and for the IRR to increase above the IRR for Q'Pellet production, the average biomass price must be $29/ODT. For the average price to increase from $29/ODT to buy 88 ktonnes to $35/ODT to buy 100 ktonnes, the marginal biomass price must be $79/ODT.

4.10 Chapter Conclusion

In this chapter, results were presented. The highest case study pellet production IRR was from Q'Pellets, at 12.7%, compared to white pellet production at 11.1%. Q'Pellet production also had the lowest life cycle emissions at 6.96 kgCO$_2$/GJ, compared to 21.50 kgCO$_2$/GJ for white pellet production. White pellets do not meet the maximum life cycle emissions to be considered sustainable under EU regulations.

Sensitivity analysis showed that white pellet production was more sensitive to several market based variables, including sale price, exchange rate, biomass price and utility costs. Monte Carlo analysis also showed that white pellet production IRR is more variable than Q'Pellet
production. White pellet production has a 28% chance of an IRR below -10% compared to 21% for Q’Pellets.

Different production locations were considered for delivery to Rotterdam. The highest IRR was for production in Baton Rouge, which also had the highest life cycle emissions. The lowest life cycle emissions were from Q’Pellet production in Thunder Bay. Different customer locations were also considered with delivery to Thunder Bay and to Japan. White pellet production had the highest IRR for delivery to Thunder Bay and Q’Pellet production had the lowest life cycle IRR. White pellet production in Baton Rouge had the highest IRR for delivery to Japan while Q’Pellet production in Williams Lake had the lowest life emissions.

The Q’Pellet had the highest IRR for plant capacities below 200 ktonnes/year, but white pellets had a slightly higher IRR at a capacity of 200 ktonnes/year. At 200 ktonnes/year, the difference between white pellet and Q’Pellet production IRR is less than 0.5%. The minimum Q’Pellet plant capacity to have an IRR of 10% is 80 ktonnes/year.

For plant sizes based on producing 1.75 TJ of delivered biomass energy, the IRR of Q’Pellet production is increased to 14.2% while white pellet production remains 11.1%. For the IRR of Q’Pellet production to fall below white pellet production, the marginal cost of the excess biomass required to produce the same quantity of delivered energy must be $99/ODT. If the plants are sized to produce 1.53 TJ of delivered energy, the IRR of white pellet production falls to 8.9% while the IRR of Q’Pellet production remains at 12.7%. For the IRR of Q’Pellet
production to fall below white pellet production, the marginal of the excess biomass must be $79/ODT.

Chapter 5 will present conclusions derived from the work presented in this thesis, along with recommendations for future work.
Chapter 5  Conclusions and Future Work

To be competitive with current wood pellet production, Q’Pellets must be both economically and environmentally competitive. A techno-economic model was developed to determine the economic and environmental viability of producing Q’Pellets at commercial volumes. The model evaluated white, torrefied and Q’Pellets for their internal rates of return (IRR) and lifecycle GHG emissions. A case study of a wood pellet plant built in Williams Lake, BC with pellet delivery to Rotterdam, Netherlands was modelled to compare the three types of pellet production.

The results of the case study showed that Q’Pellets are economically superior while producing less life cycle emissions than white and torrefied pellets. The IRR of Q’Pellet production was 12.7%, compared to 11.1% for white pellets and 8.0% for torrefied pellets. The life cycle emissions from Q’Pellet production were 6.96 kgCO$_{2eq}$/GJ, compared to 21.50 kgCO$_{2eq}$/GJ for white pellets and 10.08 kgCO$_{2eq}$/GJ for torrefied pellets. Q’Pellets had a higher modelled IRR than white pellets, despite higher capital costs, due to the reduced costs for transportation, storage, and natural gas. The capital cost of building a 100,000 tonne/year Q’Pellet plant is $21.0 M compared to $12.9 M to build an equal capacity white pellet plant and $21.6 M to build a torrefied pellet plant.

The base case study had the input capacities of the plant set to be equal. A modified case study where the quantity of delivered energy was set to be equal was also considered. For a
Q’Pellet plant with the capacity to supply 1.75 TJ of energy, the IRR was 14.2% compared to 11.1% for a white pellet plant and 9.4% for a torrefied pellet plant.

Q’Pellet life cycle emissions were lower than white pellets due to reduced emissions from transportation and natural gas combustion. Emissions from transportation are lowered because an increased amount of energy is transported per shipload due to the increased bulk density of Q’Pellets. Natural gas combustion is required for white pellet production to provide process heat to dry the biomass. Q’Pellet production utilizes torrefaction off-gases for process heat, which allows the drying process to be nearly carbon neutral.

Two types of sensitivity analyses were performed. The first type of sensitivity analysis involved modifying a single variable at a time to determine its effect on overall output. The results of the sensitivity analysis showed that white pellet production is more sensitive to market-based variables, including pellet sale price, exchange rate, raw biomass price, transportation cost, natural gas price and electricity price. Sensitivity analysis on capital expenditure showed that Q’Pellet production will only have a lower IRR than white pellet production if the Q’Pellet system is $2.94 M (28.5%) more expensive than predicted. The second type of sensitivity analysis performed was Monte Carlo analysis. The result of the Monte Carlo analysis was that Q’Pellet production has a more predictable IRR than white pellet production.
5.1 Conclusions

A model that allows for techno-economic and life cycle analysis of wood pellet production was developed and demonstrated to be viable based on case study assessment. The model allows for variable inputs to reflect changing market conditions and production methods. Both the techno-economic model and life cycle model were validated by comparison with a literature case study.

The work in this thesis demonstrated that Q’Pellet production are economically and environmentally superior to current wood pellet production methods. The modelled internal rate of return for Q’Pellet production is 12.7% compared to 11.1% for white pellet production and 8.0% for torrefied pellet production. The life cycle GHG emissions are 67% lower for Q’Pellet production than white pellet production. It is recommended that a pilot plant be built to determine more accurate estimates for capital expenditure, energy requirements and pellet and torrefaction off-gas values for a commercial scale facility.

5.2 Future Work

The model was based on literature reviews combined with input from a laboratory scale process. To determine more accurate estimates for energy requirements and capital expenditures required to build a commercial scale facility, it is recommended a pilot scale facility be built. A pilot scale facility will demonstrate that the technology can be viably scaled, which is a necessary step in the journey towards a full scale plant. Taylor [25] has demonstrated a continuous process to create Q’Pellets and suggested a design for a multi-
cavity die that may form the heart of a pilot plant. Key data that would need to be collected from the pilot plant to would be capital expenditure required to build the plant, the energy required to create the pellets, the mass loss from torrefaction and the heating values of the Q’Pellets and the torrefaction off-gases. The collection of this data will allow the techno-economic model to more accurately predict the economic performance of a commercial scale facility.

Another key piece of future work will be to ensure that sufficient quantities of raw biomass are available at prices low enough for the plant to maintain economic viability. It will also be necessary to ensure that there is customer demand for the pellets. Although the pellet market is rapidly growing and would appear to provide plenty of demand for torrefied pellets, there is very little commercial supply of torrefied pellets and so demand is uncertain.
References


116


[34] European Committee and for Standardization, “Solid biofuels — fuel specifications and classes,” EN 14961-2.


[66] Agri-Tech Producers, LLC, “Torre-Tech 5.0 Specifications.”


A. Appendix

<table>
<thead>
<tr>
<th>Year</th>
<th>Inflation</th>
<th>Production (tonnes)</th>
<th>Revenue (M$)</th>
<th>Transportation Costs (M$)</th>
<th>Other Opex (M$)</th>
<th>Operating Costs (M$)</th>
<th>Capital Costs (M$)</th>
<th>Labour (M$)</th>
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### Table A-3: Q'Pellet cash flow (continued)

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### Table A-4: Mass and energy yields by step for white pellet production

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### Table A-5: Mass and energy yields by step for torrefied pellet production

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Table A-6: Mass and energy yields by step for Pellet production