University of Alberta

Utilization of Triticale Straw for Power Generation

By

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ABSTRACT

The concept of producing electricity by using a dedicated energy crop has initiated many research projects in the recent past. Triticale, a hybrid between wheat and rye, has gained the attention of researchers as a feasible future energy crop for Canada. The study focuses on the techno-economic assessment of triticale straw based electricity generation and its GHG abatement potential at larger plant capacities. The research for this study involved the development of techno-economic models to estimate the cost of power generation and the optimum size of the power plant. In the base case, the size of the triticale straw based power plant is 300 MW. It is assumed that enough straw is available to fuel the plant. Direct combustion is the conversion technology considered due to its reliability and large-scale commercial availability. The cost of power production via direct combustion is in the range of \$76.33 ± 4.76 /MWh, at a boiler unit size of 300 MW. The estimated carbon credit required for triticale straw based power plant to be competitive with coal based power is \$16.4 /tCO_{2e}. In a scenario in which the unit size is unlimited, the optimum power plant size of triticale straw based power plant and the cost of power are 595 MW and \$75.02 /MWh, respectively.

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Table of Contents

1 Introduction 1
1.1 Background 1
1.2 Purpose of the Research 3
1.3 Methodology 4
1.4 Organization of the Thesis 5
References 7

2 Triticale as an Energy Crop 8
2.1 Background 8
2.2 Triticale Varieties 9
2.3 Present and Future of Canadian Triticale 11
2.4 Triticale Farming and Harvesting 11
2.5 Straw Collection and Harvesting 18
2.6 Transportation 18
2.7 Straw Combustion 19
2.8 Conclusions 20
References 21

3 Cost of Power from Direct Combustion 23
3.1 Introduction 23
3.2 Goal and Scope 24
3.3 Direct Combustion Technology 25
3.4 Input Data and Assumptions 27
3.5 Economic Analysis 28

3.6 Results and Discussion 38
3.7 Sensitivity Analysis 41
3.8 Uncertainty Analysis 55
3.9 Conclusions 58
References 60

4 Life Cycle Assessment of Direct Combustion of Triticale Straw for Power Generation 65
4.1 Introduction 65
4.2 Goal and Scope 66
4.3 Life Cycle Energy and Emissions Inventory 68
4.4 Impact Assessment 79
4.5 Discussion 82
4.6 CO_2 Abatement cost 83
4.7 Sensitivity Analysis 84
4.8 Uncertainty Analysis 89
4.9 Conclusions 91
References 92

5 Conclusions and Recommendations for Future Work 96
5.1 Conclusions 96
5.2 Recommendations for Future Research 98
Appendix 100

List of tables

Table 2-1: Triticale Crop Yield for Alberta..11

Table 2-2: Nutrients requirement for triticale 13

Table 2-3: Straw to grain ratios in earlier studies..15

Table 2-4: Estimation of triticale straw's present power generation capacity 16

Table 2-5: Estimation of net straw availability per hectare..17

Table 2-6: Straw availability at different stages 19

Table 3-1: Input data and assumptions for techno-economic model...27

Table 3-2: Cost of the nutrients 29

Table 3-3: Unit cost coefficients 30

Table 3-4: Unit transportation cost for straw..31

Table 3-5: Literature review on biomass direct combustion plant capital cost...........................32

Table 3-6: Variation of PCCI since year 2000 33

Table 3-7: Employee wages for base case...35

Table 3-8: Employee numbers for different plant sizes...36

Table 3-9: Investment cost breakdown..39

Table 3-10: Direct combustion component costs...40

Table 3-11: Sensitivity scenarios..42

Table 3-12: Influence of capital cost at different plant sizes 43

Table 3-13: Maintenance cost change at different plant sizes 44

Table 3-14: Plant efficiency sensitivity results for direct combustion base case.........................45

Table 3-15: Yield sensitivity results for its direct combustion in the base case 47

Table 3-16: Power cost variation with SGR for base case..50

Table 3-17: Straw moisture content effect on base case power cost..51

Table 3-18: Impact of change of triticale grown land fraction on base case power cost............53

Table 3-19: Feasible direct combustion cost sensitivity ranges 54

Table 3-20: Change in optimum plant size for sensitivities 55

Table 3-21: Uncertainty estimation methodology....56

Table 3-22: Assigned unit process uncertainty values....57

Table 3-23: Monte-Carlo results for direct combustion power cost 58

Table 3-24: Power cost summary....58

Table 4-1: Farming Operations 70

Table 4-2: Literature review on fertilizer production energy and emissions....72

Table 4-3: Literature review on chemical production energy and emissions 73

Table 4-4: Machinery used for straw collection and transportation 74

Table 4-5: Energy and GHG emissions benefit of recycling 78

Table 4-6: Input data and assumptions 78

Table 4-7: Life cycle energy consumption for base case 79

Table 4-8: Energy ratios....80

Table 4-9: CO_{2e} Emission for base case 80

Table 4-10: Comparative CO_2 Mitigation Potential 81

Table 4-11: CO_2 Abatement Potential for Different Plant Sizes 81

Table 4-12: Assumptions for sensitivity analysis scenarios 84

Table 4-13: Impact of plant efficiency on base case energy and emissions....85

Table 4-14: Straw yield sensitivity results for base case....85

Table 4-15: Straw to grain ratio sensitivity results for base case 86

Table 4-16: Straw moisture content sensitivity results for base case....87

Table 4-17: Land devoted to triticale sensitivity results for base case 88

Table 4-18: Uncertainty in LCA Unit Processes....89

Table 4-19: Results with low and high estimates....90

Table 5-1: Summary of two technologies 97

Table A - 1: Discounted cash flow of the base case 102
Table A - 2: Direct combustion life cycle data analysis 106

List of Figures

Figure 2-1: Collection process flow diagram....18

Figure 2-2: Field to plant process flow....19

Figure 3-1: Operations in direct combustion pathway....24

Figure 3-2: Flow diagram of direct combustion power generation....25

Figure 3-3: Circulating fluidized bed (CFB) boiler....26

Figure 3-4: Bubbling fluidized bed (BFB) boiler....27

Figure 3-5: Variation of average haul distance with plant size....31

Figure 3-6: Capital cost variation with plant size....34

Figure 3-7: Unit Capital cost variation with plant size....34

Figure 3-8: Direct combustion power cost curve....38

Figure 3-9: Power cost variation without the limitation on maximum boiler unit size....40

Figure 3-10: Effect of different unit sizes on power cost....41

Figure 3-11: Sensitivity analysis for capital cost....42

Figure 3-12: Different maintenance cost assumptions....44

Figure 3-13: Power cost variation for low, average and high plant efficiency cases....46

Figure 3-14: Power cost variation with plant efficiency for selected plant sizes....46

Figure 3-15: Power cost variation for low, average and high straw yield cases....48

Figure 3-16: Power cost variation with straw yield for selected plant sizes....48

Figure 3-17: Power cost variation for low, average and high straw to grain ratio cases....49

Figure 3-18: Power Cost Variation with Straw to Grain Ratio for Selected Plant Sizes....50

Figure 3-19: Power cost variation with straw moisture content for selected plant sizes....52

Figure 3-20: Power cost variation for low, average and high triticale land fraction....52

Figure 3-21: Power cost variation with triticale land fraction for selected plant sizes....53

Figure 3-22: Relative influence of power cost sensitivities....54

Figure 3-23: Graphical representation of Monte-carlo results..57

Figure 4-1: Life Cycle Boundary of the Study 68

Figure 4-2: Carbon credit for triticale straw based power at different electricity prices...............83

Figure 4-3: Carbon credit requirement for different plant sizes 84

Figure 4-4: Relative influence of emission sensitivities..88

Figure 4-5: Monte Carlo simulation results for CO_{2e} emissions 90

Figure 4-6: Monte Carlo simulation results for energy 90

Abbreviations

CTBI	Canadian Triticale Bio-refinery Initiative
DC	Direct Combustion
DFC	Distance fixed cost
DVC	Distance variable cost
GHG	Greenhouse Gas Emissions
PCCI	Power Plant Capital Cost Index
SGR	Straw to Grain Ratio
TCI	Total Capital Investment

1 Introduction

1.1 Background

Global warming is defined in simple terms as the gradual heat build-up near the surface of earth due to the sun's heat trapped by the atmosphere. The earth's heat trapping capability is increased by the emissions of greenhouse gases (GHG), which absorb the long-wave infrared solar radiation re-emitted from the earth's surface. The phenomenon is called the greenhouse effect (New Generation Power, 2010). Although the resulting temperature increments are small, they have increased rapidly during the last few decades compared to the past million years. It has been estimated that these increases could impact the melting of glaciers and potentially increase the sea levels within the next 50 to 100 years (Example Essays, 2010). An increasing consensus appears to exist among the nations on the negative effects that global warming could have for all living things on the planet, and appropriate actions are needed to address this issue.

The debate on the causes of global warming has been continuing for decades. However, it is now widely attributed to the indiscriminate use of fossil fuels for generating heat and power, and also to industrial and agricultural processes which produce GHGs such as carbon dioxide, methane, and many types of chlorofluorocarbons. Researchers claim that the present GHG emissions must be reduced by 60% to avoid catastrophic climate changes by the year 2050 (Yeatman, 2009). However, with an 80% energy and a 70% GHG emissions increase forecasted for the mid 21st century, reducing GHG emissions quickly will be difficult (Yeatman, 2009). The main GHG emission sources are the fossil fuels such as coal, oil and natural gas. With 86% of the world's primary energy being generated from fossil fuels, the increased release of carbon into the atmosphere is a continuing problem (ClimateAvenue, 2010). The reduction of fossil fuel usage is a challenging task. The three broad categories of reducing GHG emissions are increasing energy efficiency, sequestering released carbon, and substituting renewable energy sources for fossil fuel sources.

Canada is one of the largest per capita GHG emitters in the world and contributes to 2% of the global emissions. With a 21.7% increase in its GHG emissions from 1990-2006, Canada ranks first in terms of increased GHG emissions among G8 countries (Environment Canada, 2009). Canada was one of the first nations to sign the Kyoto protocol and committed to reduce GHG emissions by 6% of the 1990 level by 2012, but still lags behind its GHG mitigation commitments. However, while keeping pace with the climate change initiatives around the globe, Canada has implemented many programs to reduce potential global warming and to reduce emissions to 572 million tonnes of CO_2. by the year 2012 (CBC, 2007). Canada's economic planning includes green investments to change technologies and protect the environment, including investments in the development of clean energy. Some of these initiatives include the development of carbon capture and storage options (CCS), the development and implementation of renewable energy technologies, and the improvement of energy efficiency in energy utilization (FMC Law, 2010).

The Province of Alberta's economy is basically fossil energy driven. However, with the increased awareness of global warming and climate change, attention to renewable energies has become prominent in recent years. Biomass energy technology, which is one of the renewable energy options, has a large potential in Alberta. Alberta is wealthy in biomass feedstocks such as forest residues (mainly branches and tops produced during logging operations) and agricultural residues (i.e., straw), which could produce a considerable amount of low carbon transportation fuel and power. Alberta has already taken initiatives to create an energy mix in the province's energy profile that will reduce GHG emissions by implementing renewable energy technologies. Bio-energy is an important part of these initiatives, as Alberta's 2006 six point bio-energy plan indicates (Alberta Energy, 2010). The focus of this thesis on biomass utilization is on electricity production in the Province of Alberta. The details are given in the following sections.

1.2 Purpose of the Research

In Canada, the main focus of biomass energy researchers in the recent past has been on identifying the most biologically equipped biomass sources to produce energy, bio-polymers and bio-chemicals. Although many studies have been published on the utilization of agricultural residues for power production, the concept of using a dedicated energy crop to provide sustainable biomass feedstock is still in the conceptual stage. However, a man made crop called triticale has managed to gain considerable attention as a possible future energy crop for Canada (Gormely, 2008). An ideal energy crop should require low agricultural inputs and water requirements, be tolerant to the harsh weather conditions in Canada, and be a non-food platform so that food versus energy competition would not arise. Interestingly, triticale has all these characteristics, and researchers have already gained the support of the federal and provincial governments for research programs on triticale based bio-refineries. The main purpose of this study is to investigate the economic and environmental aspects of triticale straw based electricity production. The relative appeal of a particular bioenergy project depends not only on the power cost, but also on the GHG mitigation potential, as biomass is considered to be nearly carbon neutral.

In this research, the main focus is on estimating the cost of power generation from triticale straw and also estimating the GHG abatement cost required to make it competitive with coal power in Alberta. This study will assist in identifying the most favourable and feasible conditions for any future triticale straw based power plant establishment. The study also assesses the power generation at various scales. It differs from many other biomass power generation studies because it focuses on a dedicated energy crop, a concept which specially has a considerable effect on the life cycle GHG emissions. However, it can also be useful as an extension to any other straw types such as wheat, barley and rye, although triticale differs in agronomical, technical and logistical aspects. Nevertheless, some of the sensitivity analysis in this thesis could be used to identify the patterns of agricultural biomass behaviour to certain variables.

1.3 Methodology

1.3.1 Development of techno-economic models

Since the economics of biomass energy options are still generally unfavourable (Levelton Consultants and Envirochem Services Inc, 2008), conceptual studies of energy projects, on power generation cost and the influencing factors are needed. The methodologies employed in this thesis are generic to biomass techno-economic assessment, but the interpretation of results is greatly influenced by the fact that triticale straw power generation is still a developing concept in Alberta.

The triticale power cost for direct combustion is determined by developing techno-economic models using data obtained from published articles, databases, consultations with experts, and publicly available modeling tools. Wherever data were not available, appropriate assumptions were made. Costs are calculated for five main unit processes: farming and harvesting, collection, transportation, plant operations and plant construction, maintenance and decommissioning.

1.3.2 Life Cycle Analysis

A quantifiable estimate of GHGs is critical in determining the impact and environmental benefits of a renewable energy project. The life cycle analysis in this thesis is based on a cradle-to-grave investigation of the use of triticale farming for electricity production in Alberta. As explained earlier, GHG emissions and energy consumption for the base case scenario is calculated by using data relevant to wheat straw and other biomass types wherever triticale straw specific data are not available. GHG emissions and energy requirements are calculated for five key unit processes, and these components include all activities in the unit processes, material production, manufacturing & construction, use, repair & maintenance, decommissioning, and material recovery and disposal.

1.3.3 Key Objectives

The overall objective of this study is to determine the unit cost of electricity production using triticale straw as the feedstock. The conversion technology considered is direct combustion which is the most common and proven technology used around the globe.

The key specific objectives of this study are the following:

- Development of a data intensive techno-economic model for estimating the cost of power production from triticale straw.
- Development of the cost curve as a function of capacity.
- Determination of optimum plant size by using the techno-economic model.
- Assessment of life cycle energy and emissions.
- Estimation of the abatement cost ($/tonne of CO2).

1.3.4 Limitations

This entire study is based on a scenario which assumes that enough triticale straw is available to support a medium to large scale power plant in Alberta. The details on new triticale farming areas are not specified, and the location of the plant is based on the potential for triticale production in the Province of Alberta. The lack of a specific geographical location for the plant limits the investigation in terms of the availability and construction needs of roads, rail ways and power grid infrastructure. Some important facts and agricultural data are not yet available for triticale and have been approximated from the best alternative sources available.

1.4 Organization of the Thesis

Chapter 1 details the background, reasons for and objectives of the research. The key objectives of the study and the methodology of techno-economic models are described.

Chapter 2 provides a brief history of Canadian triticale, its agronomy, and the properties which make it a potential future energy crop. Additionally, the future triticale expansion plan in Canada, the amount of collectable straw, and its logistics are discussed.

Chapter 3 discusses the development of techno-economic models for assessing the production of electricity via the direct combustion of triticale straw. This chapter also explains the sensitivity and uncertainty analysis.

Chapter 4 assesses the GHG emissions from direct combustion based power production over its life cycle. This chapter also estimates the possible GHG mitigation potential and carbon credits required for triticale straw based power to be competitive with a coal based power plant in Alberta.

Chapter 5 gives details on the key results of the research and the recommendations for future research.

References

Alberta Energy. "Bioenergy." Energy. 2010. http://www.energy.alberta.ca/OurBusiness/bioenergy.asp (accessed 12 20, 2010).

CBC. "Canada-Kyoto timeline." CBC News. 2007. http://www.cbc.ca/news/background/kyoto/timeline.html (accessed 09 02, 2010).

ClimateAvenue. "Coal fuels." Energy. 2010. http://climateavenue.com/en.fossil.index.htm. (accessed 10 02, 2011)

Environment Canada. "National Inventory Report-Green House Gas Sources and Sinks in Canada, 1990-2007." 2009.

Example Essays. "Global Warming." 2010. http://www.exampleessays.com/viewpaper/76199.html (accessed 09 02, 2010).

FMC-Law. "Programs Supporting Renewable and Clean Energy Development in Canada." Edited by Toronto Forum For Global Cities The International Economic Forum of the Americas. 2010.

Gormely, I. "Planting the Seed." Progress Research & Discovery, 2008: 16-17.

Levelton Consultants, and Envirochem Services Inc. Feasibility Study: Identifying Economic Opprtunities for Bugwoood and Other Biomass Resources in Alberta and BC. Alberta Energy Research Institute, 2008.

New Generation Power. Renewable Energy Glossary. 2010. http://www.newgenerationpower.org/about-solar/renewable-glossary/ (accessed 12 20, 2010).

Yeatman, W. "Global Warming 101: Costs." GlobalWarming.org. 2009. http://www.globalwarming.org/2009/02/04/global-warming-101-costs/ (accessed 09 02, 2010).

2 Triticale as an Energy Crop

2.1 Background

After many years of research, triticale, a hybrid man-made from wheat and rye, is now believed to be an ideal energy crop for Canada. Triticale can be grown in almost every region of Canada and is tolerant to drought and has lesser nutrient requirements and higher disease tolerance than other cereal crops (Alberta Agriculture, 2005). Moreover, its yield is higher than that of wheat (Gormely, 2008). These qualities make triticale the best option for the dry and marginal lands in Canadian prairies. In the food versus fuel debate about whether most cereal crops have energy production potential, triticale seems to be an attractive option. The other important aspect of triticale is that almost the whole crop can be utilized in a bio-refinery to produce a range of by products such as building materials, animal feed, plastics and chemicals and heat and power (Gormely, 2008). This versatility makes triticale an economical energy crop in the long term.

2.1.1 Brief History of Canadian Triticale

Triticale originated in Scotland, when the first wheat and rye hybrid was made in 1876 (Gormely, 2008). The techniques to produce fertile hybrids were developed for the first time in the 1930s. In Canada, the research on triticale started at the University of Manitoba in 1953. In 1969, its research program introduced Rosner, the first triticale variety in North America (Salmon et al., 2001). After the Manitoba program had ended, longer term triticale research programs were initiated at Lacombe, Alberta and Swift Current with the aid of Agriculture and Agri-Food Canada (AAFC) (Briggs, 2001). The initial varieties like Rosner, Carman and Welsh had agronomic and grain quality issues which made these hybrids unsuitable for the commercial grain market. These varieties suffered from late maturing, low test weight, and weak straw and had more frequent sterile florets than other cereals (Alberta Agriculture, 2005).

In the early 1980’s, many breeding programs were discontinued due to the slow progress in improving the yield. However, in the late 1980’s, the triticale grain quality was significantly improved. By the 1990’s, triticale’s agronomical limitations had been overcome and the new findings were incorporated into Canadian breeding programs (Alberta Agriculture, 2005). During this decades, new applications of triticale started appearing, such as soil erosion control, crop rotation for sustainable cropping systems, and the use of triticale for forage applications (Briggs, 2001). Since then, numerous triticale varieties have been developed and made commercially available for farmers.

2.1.2 Current Research Initiatives on Triticale

2.1.2.1 Canadian Triticale Bio-refinery Initiative

The Canadian triticale bio-refinery initiative (CTBI) is a 10 year research and development program initiated to develop triticale as an industrial bio-refining crop for Canada. CTBI's 10 year vision focuses on growing enough triticale in Western Canada by 2015 to establish a world-scale bio-refinery which will produce energy, chemicals, biomaterials and bio-composites based on triticale. Currently, 130 researchers are involved in the CTBI, and 30 research projects are in progress to make the CTBI's vision a reality (CTBI, 2010). The CTBI is currently working on Alberta-driven 10 year triticale project launched in 2004 (Agricultural Policy Framework, 2008). Although only 85,000 acres were seeded in 2008 across Canada, the CTBI hopes to expand it to 3 million acres by 2015 (Agricultural Policy Framework, 2008).

2.2 Triticale Varieties

The agronomic attributes such as higher grain and biomass yield, advantageous net energy balance, and adjustability to different climatic conditions make triticale a better energy crop than the other cereals grown in Canada (Gormely, 2008). Some of the advantages of triticale in general as the future energy crop of Canada are the following (Alberta Agriculture, 2005):

- It is a crop for all seasons. Triticale can be used in combination with other crops to spread the workload of seeding and harvesting more evenly throughout the year.

- Triticale possesses superior disease, insect and drought resistance compared to other crops. Therefore, triticale is useful for breaking disease cycles in cereal crop rotations. This capability results in an improved yield.
- Triticale has a non-food base, unlike crops like wheat, barley and rye. Triticale is a man-made species that does not naturally hybridize with other crops or wild native species.

Triticale has two main varieties based on seasonality: spring triticale and winter triticale.

2.2.1 Spring Triticale

Spring triticale is generally planted in early May and matures in about 120 days. For example, Pronghorn spring triticale seeded in May matures around early September (Salmon et al., 2001). Spring triticale is best suited for brown soil zones in Alberta and its adjacent provinces. The farming practices and techniques specific to triticale are similar to those for wheat in general. Some of the advantages of spring triticale are listed below (Alberta Agriculture, 2005).

- Superior drought tolerance compared to other spring cereals.
- An alternative to barley and oats under dry land conditions, so that triticale is an excellent silage alternative for livestock producers.
- About 5 -19% yield advantage over Canada prairie spring wheat (CPS) and 30% over Canada western red spring wheat (CWRS).

2.2.2 Winter Triticale

The key difference between spring and winter triticale is that winter triticale needs a period with cold conditions to initiate heading. This variety is seeded during the end of August to early September and adapts best to the brown-soil zone of southern Alberta and higher snowfall areas (Alberta Agriculture, 2005). Winter triticale matures 2-3 weeks earlier than spring triticale (Salmon et al., 2001). The agronomic practices for winter triticale are similar to those for winter wheat. Some of the advantages of growing winter triticale are

- About 10-20% yield over winter wheat.
- Disease resistance.
- Forage potential.

2.3 Present and Future of Canadian Triticale

The total triticale seeded area for Alberta in 2006 was 76,299 acres (30,877 ha). This amount dropped to 14,200 ha by 2008 (Stat Canada, 2009). The calculated average triticale yield in Alberta is 2,544 kg/ha, as shown in Table 2-1, which lists the yield values for the last 9 years. However, the present yield of triticale is greatly influenced by its animal feeding applications. For example, in order to maintain high yield potential, cattle grazing needs to be controlled. If the main focus of triticale farming is achieving high yields, then the timing of grazing should be planned so that the grain has sufficient time to recover after the grazing period. If in the future, triticale is grown as an energy crop, then animal feeding activities will have a minimal effect on the grain yield.

Table 2-1: Triticale Crop Yield for Alberta[1]

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	Average
Yield (kg/ha)	2,600	2,300	2,100	2,100	2,800	2,700	2,500	2,400	3,400	2,544
Seeded Area (1000 ha)	36.4	28.3	48.6	40.5	40.5	26.3	30.9	16.2	14.2	31.322

The area of cultivation for triticale is very small compared to the cultivated areas for other cereal grains like wheat and barley. However, according to the CTBI's 10 year triticale expansion plan (Brett, 2008), triticale will become a major crop in Canada. Hence, this study has assumed that enough straw will be available in Alberta to support a straw combustion power plant within the next five years. In 2008, the total triticale grain production[1] in Alberta was only 19,400 tonnes. This amount has to be significantly increased to meet the CTBI's growth forecast.

2.4 Triticale Farming and Harvesting

2.4.1 Fertilizer Requirement

The fertilizer requirement for triticale is generally similar to that for wheat. The actual fertilizer usage should be based on the results from soil tests. However, the growers' experiences with cereal crops have shown that fertilizer rates vary widely across the province. The general fertilizer requirements for spring and

[1]Data extracted from Stat Canada, CANSIM Table 001-0010 (2009).

winter triticale are given in both the Alberta Agriculture Triticale Production Manual (Alberta Agriculture, 2005) and Alberta Fertilizer Guide (Alberta Fertilizer Guide, 2004). According to these documents, nitrogen and phosphorous are the most important nutrients for crop yield in Alberta.

2.4.1.1 Nitrogen

For continuous cropping systems, the rate of nitrogen application is crucial. The actual application rate is decided after determining the soil nitrogen amount, soil moisture content, precipitation during the growing period, weed competition, and seeding time period (Alberta Agriculture, 2005). However, triticale farming on fallow would require less fertilizer, ranging from 5-35 lb/ac, where as stubble land needs a higher application rate of between 20-80 lb/ac, based on the soil type (Alberta Agriculture, 2005). In this study, the nitrogen application is assumed to be 25 lb/ac for all the soil types. Urea, anhydrous ammonia and ammonium nitrate are common sources of nitrogen for farmers (Nagy, 1999). The air seeders enhance the seed bed utilization of nitrogen. Here, anhydrous ammonia (82-0-0) delivered by air seeders is considered as the source of nitrogen fertilizer.

2.4.1.2 Phosphorous

The phosphorous level in Alberta’s soil varies greatly and is generally at a moderate level (Alberta Agriculture, 2005). Since the soil phosphorus does not change with the cropping system, the application rate should be based on the present phosphorous level, crop requirement, and growing conditions (Alberta Agriculture, 2004). Phosphorous application rates tend to change between 0-40 lb/ac in Alberta. An application rate of about 10-15 lb/ac is regarded as the minimum to produce any crop response (Alberta Agriculture, 2004). This study assumes an average phosphorous application rate of 25 lb/ac for all the triticale fields across Alberta. In reality, this rate would vary depending on soil test results. Since phosphate fertilizer is known as a slow mover in the soil, Banding is the popular choice for fertilizer application. Mono-ammonium phosphate (MAP, 12-51-0) is the most available phosphate fertilizer in Alberta and, in this study, is assumed to be the phosphorous fertilizer source (Alberta Fertilizer Guide, 2004).

2.4.1.3 *Potassium, Sulphur and Micronutrients*

Generally, these nutrients are not deficient in Alberta farm lands, so potassium, sulphur, and micronutrients are not required by most crops (Alberta Agriculture, 2008). If the soil test level of potassium is 300 lb/ac, fertilizer application should be considered, while the test level for sulphur is 10 lb/ac (Alberta Agriculture, 2008). Moreover, Alberta Agriculture (2008) also reports that sufficient sulphur is present in irrigation water to meet the crop demand. Hence, in this study, potassium and sulphur are not considered as external nutrient requirements for triticale plant growth. However, potassium needs to be added to replace the amount lost from the soil due to straw removal, which reduces the sustainable potassium level in the soil (Hartman, 2008).

Table 2-2: Nutrients requirement for triticale

Nutrient	Nutrient requirement[2] (lb/acre)	Nutrient removal by straw[3] (lb/acre)	Total nutrient replacement (lb/acre)
Phosphorus (P_2O_5)	25	4	29
Potassium (K_2O)	0	36	36
Nitrogen	25	14	39
Sulphur[4]	0	3	0

2.4.2 Disease Control

Triticale has been reported to have a low incidence of disease (Alberta Agriculture, 2005). However, triticale can get infected with the common diseases of other cereal crops. The only seed treatment approved for triticale is vita flo 280 (Alberta Agriculture, 2005). Due to triticale's proven leaf and head disease tolerance property, fungicides are not recommended for Western Canadian triticale growers. According to Alberta Agriculture's triticale production manual, the only noticeable disease threat to triticale is fusarium head blight (FHB), and all seeds have to be tested for FHB before seeding. FHB is not a serious problem

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[2]These values are assumed based on the Alberta Agriculture and Rural Development Fertilizer Guide (Alberta Agriculture, 2004).
[3] (Hartman, 2008); Values are converted from lb/t.
[4] Sulphur is not added; see section 2.4.1.3 for the explanation.

in Alberta, but is serious in Manitoba and Saskatchewan (Alberta Agriculture, 2005).

2.4.2.1 Herbicides and Pesticides

The risk for triticale from insects is similar to that for wheat. Management practices need to be applied only when the problem has reached economically threatening proportions (Alberta Agriculture, 2005). Triticale has a better ability to compete with weeds than both winter and spring wheat. Triticale has more leaves and is taller, so that it is more weed-competitive agronomically. Although Canadian growers believe that triticale can be potentially used as an herbicide substitute in crop rotation, few published studies support this perception as yet (Alberta Agriculture, 2005).

Pardner, Koril, Bromotril and Brotex are recommended as herbicides for triticale (Manitoba Agriculture, 2010). Other chemicals suitable for triticale are Cruiser 350FS, Dividend XL RTA, Rancona Apex and Vitaflo 280 (Manitoba Agriculture, 2010). Since Pardner and Vitaflo 280 are mentioned by both Alberta and Manitoba Agriculture for triticale, these are considered as the chemicals for the energy and emission calculations in the study. The application rates considered in this study are 0.44 L/ha for Pardner and 200 ml/100 kg of seed for Vitaflo 280.

2.4.3 Straw Yield

2.4.3.1 Crop Yield

Many new triticale varieties are being developed at institutes such as the Agriculture and Agri-Food Canada Research Centre and the Alberta Agriculture, Field Crop Development Centre and have shown very high yield potential. Most test sites at Alberta Agriculture have had an average yield of over 4,500 kg/ha (Sieusahai, 2010). Phelps et al. (2009) reported a 6,529 kg/ha triticale straw yield for Western Canada. Since the future triticale expansion will be based on these new varieties, the yield in this study is approximated to the average test yield of these test fields.

2.4.3.2 *Straw to Grain Ratio*

Generally, yield data are reported for the grains but rarely for the straw in particular. Hence, to obtain the straw yield, the straw to grain ratio (SGR) is used. This ratio usually depends on many factors such as geographical location, soil conditions, weather conditions and moisture content. However, considering the nature of this study and the data availability, using the different regional straw to grain ratios relevant to each agricultural zone in Alberta is not feasible. Instead, a single SGR is used for all of Alberta. The data on the straw to grain ratios proposed in several earlier studies were reviewed. Again, in this study, the data for wheat are regarded as a reasonable approximation.

Table **2-3** lists some of the straw to grain ratios reported in previous studies.

Table 2-3: Straw to grain ratios in earlier studies

Source	Value	Remarks
Sokhansanj et al. (2008)	1.1	Estimation for wheat
Prairie Practitioners Group (2008)	1.3	For wheat and winter wheat
Prairie Practitioners Group (2008)	1.1	Crops other than wheat
Stephen (2008)	0.75 – 1.5	Using Conventional Combine type
Patterson et al. (1995)	1.33 – 1.88	For winter wheat
Patterson et al. (1995)	1.17 – 1.67	For spring wheat. Higher value for irrigated wheat and lower value for dry land

In this study, the straw to grain ratio assigned for the base case is 1.1, and the sensitivity analysis of this parameter is included in next three chapters.

2.4.4 Collectable Straw Amount

Because a surface residual cover is required for erosion control, all the straw left in fields after grain harvesting cannot be removed. Stumborg et al. (1996) stated that 0.75 t/ha straw amount should be left in fields when there's no tillage. Sokhansanj et al. (2006) assumed 1 t/ha as a reasonable estimate. Many researchers expect the future expansion of triticale cultivation to be in the marginal and dry lands of the Canadian prairies. This study assumes that the sufficient residual cover for these less fertile triticale lands as 0.75 t/ha. It is considered that 75% of the straw is harvestable by existing machines (Graham et al., 2007). Other field losses considered include 5% as field losses, 3% as handling loses and 10% for uncovered storage facilities (Prairie Practitioners Group, 2008).

2.4.5 Yield Calculation

2.4.5.1 Existing Scenario

The currently available triticale straw amount based power generation capacity is estimated below in Table 2-4, which uses the parameters discussed so far.

Table 2-4: Estimation of triticale straw's present power generation capacity

Description	Alberta	Canada	Remarks
Average harvested area (ha)	9,311	21,078	(Stat Canada, 2009), Year 2000-2008
Triticale yield (kg/ha)	2,544	2,333	(Stat Canada, 2009), Year 2000-2008
Straw to grain ratio	1.1	1.1	Assumed.
Harvestable straw percentage by machines	75%	75%	(Graham et al., 2007)
Straw available from grain (kg/ha)	2,099	1,925	
Straw retained for soil conservation (kg/ha)	750	750	(Stumborg et al., 1996)
Straw used for livestock (kg/ha)	660	660	(Sultana et al., 2010)
Straw remaining after allocations	689	515	
Straw losses from field to plant	18%	18%	(Prairie Practitioners Group, 2008)
Net yield of straw (kg/ha)	565	422	
Energy (PJ)	90	152	Using 17.1 MJ/kg calorific value of straw. (Food and Agriculture Organization, 2004).
Power (MW) (with 34% efficiency)	1.0	1.6	

2.4.5.2 Hypothetical futuristic Scenario

This study has developed a future base case scenario with the hypothesis that abundant triticale straw will be available to sustain a large scale power plant in Alberta. Based on the data described in sections 2.4.3.2 and 2.4.4, the net available straw amount per hectare for the base case scenario is developed in Table 2-5.

Table 2-5: Estimation of net straw availability per hectare

Parameter	Value	Source
Average grain yield (t/ha)	4.5	Assumed.
Straw to grain ratio	1.1	Assumed.
Straw yield (t/ha)	4.95	
Harvestable straw by machines	75%	(Graham et al., 2007)
Straw availability (t/ha)	3.71	
Straw retained for soil conservation (t/ha)	0.75	(Stumborg et al., 1996)
Field losses	3%	(Prairie Practitioners Group, 2008)
Handling losses	5%	(Prairie Practitioners Group, 2008)
Storage losses	10%	(Prairie Practitioners Group, 2008)
Net straw yield (t/ha)	2.43	

According to above assessment, the net straw yield available for power production is 2.43 t/ha, which represents 49% of the original biomass amount other than grain.

2.4.6 Harvesting

Grain harvesting schedules in Alberta are understandably driven by the influence of climatic conditions. Harvesting operations are always planned for termination before the start of cold, snowy conditions. Generally, the harvesting begins around the second week of August and ends by the end of September (Sokhansanj et al., 2008). As per conventional practice, straw collection starts almost just after the grain harvesting begins. Normally, straw harvesting lasts for about one month after the grain harvest, so that the total harvesting period ranges from 90 -110 days (Sokhansanj et al., 2008). However, the exact harvesting time depends on the number of machines employed for straw collection. In this study, the straw harvesting and collecting window is assumed to be 75 days, and the machinery requirements are planned accordingly.

2.5 Straw Collection and Harvesting

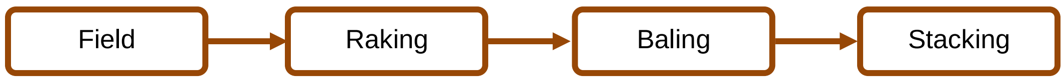


Figure 2-1: Collection process flow diagram

The collection process starts with raking the straw into windrows after the grain has been harvested, and the straw has been spread in the field for drying. The straw is kept on the fields until a suitable moisture level is reached for bailing. The safe storage moisture content to avoid spontaneous heating is below 20% (Sokhansanj et al., 2008). In this study, the assumed moisture content is 15% (wet basis). Once this moisture content is reached, the baler picks up the straw and produces rectangular bales sized 1.2 m x 1.2 m x 2.4 m. The automatic baler collects the bales and brings them to end of the field or to the roadside. These bales are stacked and tarped. Stacked bales are kept in the field until they are required by the power plant.

2.6 Transportation

According to the base case scenario, 1.4 million green tonnes of triticale straw would be transported annually to the direct combustion power plant (See Table 2-6). Several transportation modes are available depending on the locations and the infrastructure near the farms and power plant. Trucks, trains, barges, and pipelines can be considered as feasible options for the Canadian prairies. However, truck transportation is the most frequently used mode and is also the only transportation method considered in this study.

2.6.1.1 Hauling Distance

A geometrically rectangular road grid over the flat terrain of Alberta is assumed as the transportation infrastructure for the estimation purposes. The formulae and assumptions are detailed in the Appendix. According to the harvesting area requirement based on the straw yield, the maximum straw transportation distance is 119 km. The average transportation distance is calculated to be 101 km for the base case. The loading, the transfer from field storage to the power plant, and unloading are considered as the transportation unit process.

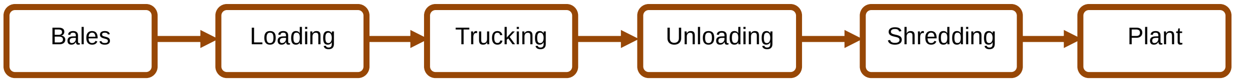


Figure 2-2: Field to plant process flow

Table 2-6: Straw availability at different stages

Straw collection stage	Associated loss[5]	Total biomass[6] (green tonnes)
Raking	5.0%	1,686,778
Baling	10.0%	1,589,837
Stinger	0.5%	1,425,936
Stacking	0.5%	1,418,623
Truck loading	0.5%	1,411,386
Transportation	0.5%	1,404,221
Truck unloading	0.5%	1,397,129
Shredder	0.5%	1,390,108
Straw input to plant	-	1,383,158

2.7 Straw Combustion

When the straw bales reach the power plant, the trucks are weighed and then unloaded. A truck is typically unloaded by using large cranes with bale grabbers (Sokhansanj et al., 2006). The bales are then shredded before being feed to the boiler. In this study, a bubbling fluidized bed boiler is considered for the straw combustion. The calorific value of Alberta's triticale straw is not available in the literature. Therefore, the calorific value provided by the Food and Agriculture Organization is used for the calculation purposes. This value is 17.1 MJ/kg at 15% moisture content (Food and Agriculture Organization, 2004).

[5] Straw losses are from (Sokhansanj, 2008) and (Prairie Practitioners Group, 2008).
[6] At 15% moisture content.

2.8 Conclusions

Triticale is currently a minor crop in Alberta. However, with the prospect of triticale becoming a dedicated energy crop for Canada, triticale farming is expected to expand rapidly on a large scale in the coming years to feed bio-refineries and power plants. The study is based on a hypothetical power plant scenario, which assumes abundant triticale straw availability for sustainable power production. In the base case, the triticale grain yield is assumed to be 4.5 t/ha, which produces a net straw yield of 2.43 t/ha. The total annual straw requirement for the base case 300 MW direct combustion plant is 1.4 million green tonnes. However, in reality, some key issues remain, such as developing successful initiatives for farming higher yield triticale varieties and convincing farmers to grow triticale as a major crop in the future.

References

Alberta Agriculture. "Alberta Fertilizer Guide." Agri-Facts, June 2004.

Alberta Agriculture. "Irrigated Crop Recommendations." Agri-Facts, July 2008.

Alberta Agriculture. "Triticale Production and Utilization Manual." Alberta Agriculture, Food and Rural Development, 2005.

Brett, K. "Triticale: a crop for all reasons." Renewal Now, 2008 : 1.

Briggs, K. G. "The Growth Potential of Triticale in Western Canada." Alberta Agriculture, Food and Rural Development, Government of Alberta, 2001.

CTBI. Canaditan Triticale Biorefinery Initiative. 2010. http://www.ctbi.ca/ (accessed 5 5, 2010).

Food and Agriculture Organization. UBET Unified Bioenergy Terminology. Edited by FAO Forestry Department. Food And Agriculure Organization of the United Nations. 2004. http://www.fao.org/docrep/007/j4504e/j4504e00.htm (accessed 4 10, 2010).

Gormely, I. "Planting the Seed." Progress Research & Discovery, 2008: 16-17.

Graham, R. L., R. Nelson, J. Sheehan, R. D. Perlack, and L. L. Wright. "Current and Potential U.S. Corn Stover Supplies." Biofuels (American Society of Agronomy) 99 (2007):1-11 .

Hartman, M. "Direct Seeding - Estimating the value of crop residues." Alberta Agriculture and Rural Development, 2008.

Manitoba Agriculture, Food and Rural Initiatives. "Guide to Field Crop Protection." 2010.

Nagy, C. N. "Energy Coefficients for Agriculture Inputs in Western Canada." Canadian Agricultural Energy End-Use Data Analysis Centre, 1999.

Phelps, S.M., B. Beres, E. Johnson, C. Pozniak, and S. Chant. 2008 Western Canadian Ethanol Feedstock Trial Interim Report. Western Applied Research Corporation, 2009.

Prairie Practitioners Group. "Straw Procurement Business Case." 2008.

Salmon, D.F., M. McLelland, T. Schoff, P.E. Juskiw, and V.S. Baron. "Triticale." Agri-Facts, April 2001.

Sieusahai, G. "Personal Communication." Agriculture Research Division , Alberta Agriculture & Rural Development , 2010.

Sokhansanj S., M.S., Stumborg M., Samson R., Fenton J. ,. "Production and Distribution of Cereal Straw on the Canadian Prairies." Canadian Biosystems Engineering 48 (2006): 3.39-4.46.

Sokhansanj, S., A. Kumar, and A.F. Turhollow. "Development and implementation of intergrated biomass supply analysis and logistics model (IBSAL)." Biomass & Bioenergy 30, 10 (2006): 838-847.

Sokhansanj, S., A.F. Turholow, J. Stephen, M. Stumborg, J. Fenton, and S. Mani. "Analysis of five simulated straw harvest scenarios." Canadian Biosystems Engineering 50 (2008): 2.27-2.35.

Stat Canada. 2006 Census of Agriculture. Statistics Canada, Available from: http://www.statcan.gc.ca.login.ezproxy.library.ualberta.ca/ca-ra2006/index-eng.htm, 2009.

Stat Canada. CANSIM Table 001-0010. Available from: www.statcan.gc.ca, 2009.

Stumborg, M., E. Coxworth, and L. Townley-Smith. "Sustainability and economic issues for cereal crop residue export." Canadian Journal of Plant Science 76, 4 (1996): 669-673.

Sultana, A., A. Kumar, and D. Harfield. "Development of agri-pellet production cost and optimum size." Bioresource Technology 101, 14 (2010): 5609-5621.

3 Cost of Power from Direct Combustion

3.1 Introduction

Direct combustion is an established and proven technology for biomass electricity production. In this study, direct combustion is investigated as the main conversion pathway for triticale straw–based power production in Alberta. This chapter assesses the detailed economics of producing electricity by direct combustion of triticale straw. Triticale straw is the focus of study as this would be one of the main interests in future triticale developments in Canada due to triticale's significant advantages compared to spring wheat. The cost of power is estimated by developing detailed data-intensive techno-economic models. These models include the characteristics and costs of the different unit operations involved in producing power, starting from harvesting straw to decommissioning the power plant. Several studies have been published on biomass electricity generation in Canada (Kumar et al., 2008; Kumar et al., 2003; Levelton Consultants & Envirochem Services Inc, 2008; Allnorth Consultants, 2010), but the use of triticale straw as the only feedstock is has not been studied.

In the USA and Canada, many small-scale biomass direct combustion power plants are operating successfully. These plants are based mainly on mill residues. The largest plant in North America is in Williams Lake, Canada (Capital Power Income, 2011). Most of these plants in North America are in the range of 20-25 MW (Bain et al., 2003; IEA, 2007). The largest in the world is the 240 MW power plant in Pietarsaari, Finland (OPET, 2001). This plant was designed to use 100% biomass but is currently operating as a co-fired power plant. Wood chips of forest residues are fired with coal and peat (Kumar and Flynn, 2005). Europe also has some straw fired power plants (The Centre for Biomass Technology, 1998).

The main challenge in developing a techno-economic model to determine the cost of power from biomass is in estimating the different parameters for the various unit operations involved in producing power. These parameters include the characteristics and cost determination of the supply and logistics of the biomass from the field to the plant, construction, operation, maintenance and decommission. Once all these parameters are developed, the cost of power is developed through discounted cash flow analysis, which is explained in this chapter. Previous studies on different biomass feed stocks have shown that the power cost benefits from the economy of scale at larger plant sizes (Kumar et al., 2003).

3.2 Goal and Scope

The study considers all the processes involved in using triticale straw to produce energy, from biomass harvesting to electricity production. Figure 3-1 shows the unit operations considered in this study, which focuses mainly on estimating the power cost and cost curve and showing the variation of cost with plant size. The study also calculates the optimum size for a triticale straw-based power plant.

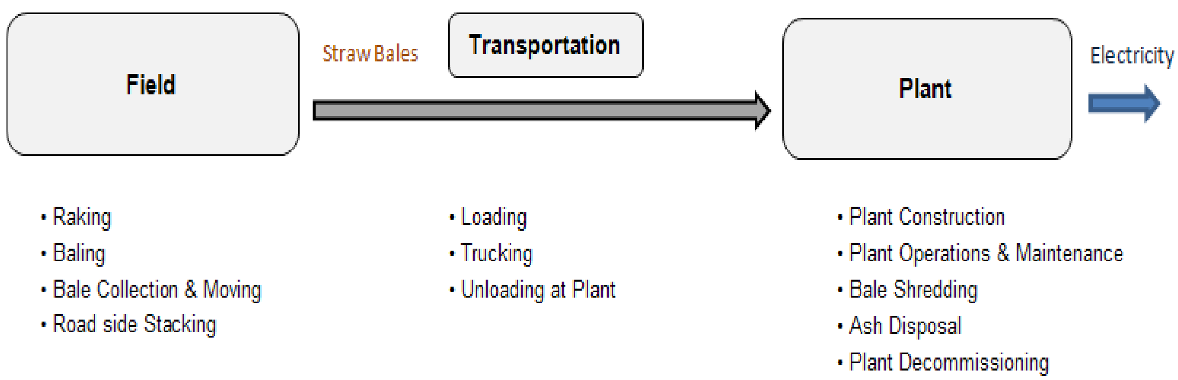


Figure 3-1: Operations in direct combustion pathway

3.2.1 Objectives

The main objectives of this part of the study are,

- Estimation of the cost of power production through the direct combustion of triticale straw
- Estimation of the optimum size of a power plant
- Study of the impact of the key parameters on power cost and optimum size through sensitivity and uncertainty analysis.

3.3 Direct Combustion Technology

The most widely used power generation technique utilizing biomass is direct combustion. It provides about 90% of the energy globally produced by biomass (Fleuren et al., 2005). The basic flow of the direct combustion technology is illustrated in Figure 3-2. Straw is combusted and heat is transferred to the working fluid in a boiler to produce steam. Steam is directed through the steam turbine coupled with a generator to produce electricity.

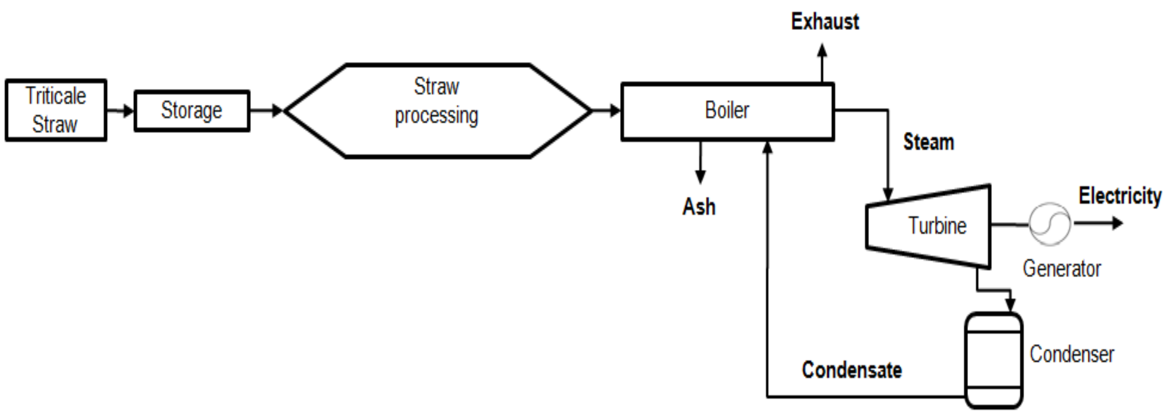


Figure 3-2: Flow diagram of direct combustion power generation[7]

The main direct combustion technologies are fixed bed, traveling bed, and fluidized bed combustion (Bastiaans, 2010). In fixed bed systems, biomass is burnt on a grate and ash is discharged. Although this technology is reliable and less costly than the other technologies, variation in fuel is limited (Brown et al., 2006). In fluidized bed boilers, biomass is burnt in a hot combustion air flow on an inert granular bed material. The inert granular bed material is in a fluidized condition (Brown et al., 2006). Although capital cost is higher compared to fixed bed boilers, this type of boiler can handle a variety of fuels and fluidized bed combustion and is becoming the preferred combustion technology for larger scale biomass combustion, especially over 100 MW (Brown et al., 2006).

[7] Figure is adopted from U.S. Department of Energy web site. http://www1.eere.energy.gov/tribalenergy/guide/biomass_biopower.html

Fluidized bed boilers have been developed in two forms which are bubbling fluidized bed (BFB) boilers and circulating fluidized bed (CFB) boilers (Khan et al., 2009). In bubbling fluidized bed technology, air is introduced through a grate at the bottom thus forming a free flowing granular material bed (Bain et al., 2003). In a circulating fluidized bed, the bed materials circulate between the vessel and a cyclone separator (McKendry, 2002). The type of bed formed during the operation is called as a turbulent fluid bed (Bain et al., 2003). The CFB boilers are manufactured in utility sizes and 250 MW units are in operation (Lundqvist, 1999). BFB boilers are mostly developed for outputs mainly between 15 and 100 MW (DeFusco et al., 2007). The largest biomass boiler in Finland is 240 MW in size and is a circulating fluidized bed type (Kumar and Flynn, 2005).

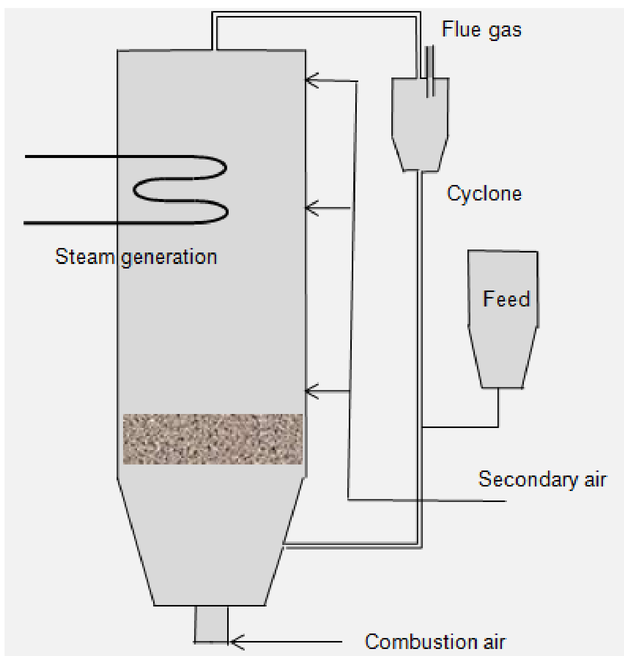


Figure 3-3: Circulating fluidized bed (CFB) boiler[8]

[8] Figure is adopted from (Khan et al., 2009).

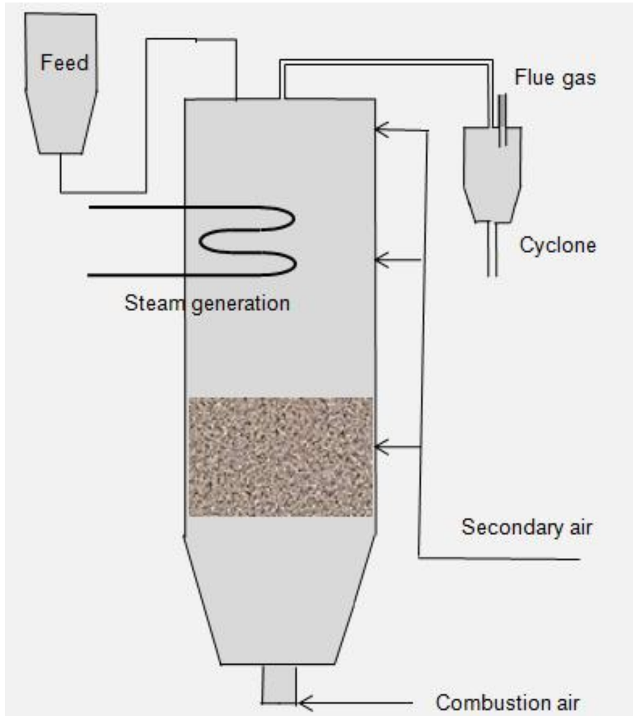


Figure 3-4: Bubbling fluidized bed (BFB) boiler[8]

3.4 Input Data and Assumptions

The base case scenario is a 300 MW triticale straw fired power plant which generates electricity as the end product. All key data and assumptions relevant to the base case techno-economic model are shown in Table 3-1.

Table 3-1: Input data and assumptions for techno-economic model

Items	Values	Comments/Remarks
Grain yield	4500 kg/ha	Based on the 2006-2009 average triticale yield data of Alberta Agriculture (Sieusahai, 2010).
Fraction of area planted to triticale	0.2	Study considers a rectangular transportation area consisting of 20% triticale lands (Overend, 1982).
Tortuosity factor	1.27	Overend (1982).
Straw to grain ratio	1.1	Prairie Practitioners Group (2008); Sokhansanj et al. (2008).
Harvestable straw	75%	This percentage is assumed based on the

Items	Values	Comments/Remarks
percentage		highest amount of collectable agricultural residue such as corn stover and wheat straw by machines (Graham et al., 2007; Sultana et al., 2010)
Straw retained for soil conservation	750 kg/ha	Coxworth et al. (1996); Prairie Practitioners Group (2008).
Truck capacity	25 tons	Mann and Spath (1997).
Moisture content	15 dry basis%	Food and Agriculture Organization (2004).
Ash percentage	5.90 dry basis%	Food and Agriculture Organization (2004).
Calorific value of triticale straw	17.1 MJ/kg	Food and Agriculture Organization (2004).
Bale density	10 lb/ft^3	IBSAL model (Sokhansanj, 2008).
Plant capacity	300 MW_e	This size is assumed for the base case. The largest power plant based on biomass is operating in Finalnd and has a capacity of 240 MW. Based on the discussion with Kaverner Power Inc. and Kvaerner Power, manufacturer of the Finland boiler, identifies no technical barriers in scaling up the boiler size from 240 MW_e to 300 MW_e (Kumar and Flynn, 2005).
Plant life	30 years	Based on earlier study (Kumar, et al. 2003).
Plant capacity factor	Year 1: 0.7 Year 2: 0.8 Year 3 and onwards: 0.85	Kumar et al. (2003); Sarkar and Kumar (2009)

3.5 Economic Analysis

3.5.1 Field Cost

3.5.1.1 Nutrient Replacement Cost

Nutrients are applied as fertilizers to provide consistent crop growth and yield potential. Generally, when straw is left in the field for decomposition, some of the nutrients are returned back to the soil. As explained in Section 2.4.1, straw removal increases the rate of fertilizer application (Hartman, 2008). Fertilizer prices have recently been fluctuating considerably (Pauly, 2008). The cost of fertilizer is given below in Table 3-2, which lists the average estimated fertilizer costs for summer 2008.

Table 3-2: Cost of the nutrients[9]

Nutrient	Cost ($/t)
Phosphorus (P_2O_5)	1500
Potassium (K_2O)	575
Nitrogen	1100
Sulphur	550

3.5.1.2 Farmer Premium

A key issue in developing a sustainable biomass production for power generation is that the revenue generation is not attractive enough to induce most farmers. It has been found that paying the energy equivalent monetary value would not encourage farmers to commit to a long term straw supply (Larson et al., 2007). In Europe, payments up to 45 €/ha are paid under the EU Energy Crop Aid Scheme to make the growing of energy crop more appealing to the farmers (Sherrington et al., 2008). Sherrington et al. (2008) also suggest that similar incentives be provided for triticale farmers to motivate them to grow and collect straw so that a sustainable straw supply chain will be established within a few years. The authors suggest that an additional $10 /dt be paid to farmers as a premium above the production cost of straw bales. Premium payments are in place for most biomass supply chains around the globe, and previous studies have considered them (Kumar et al., 2003; EPA, 2007; Haq, 2002).

3.5.2 Collection Cost

The collection of straw commences with raking, which is started following the grain harvest and distribution of straw in the field. A wheel rake with 85 hp is used to leave behind rows of straw for baling (Sokhansanj, 2008). Generally,

[9]Cost values are taken from ``The Blade`` publication. (Pauly 2008)

large square or round bales are produced by balers. Round bales are not suitable for large scale biomass handling, because of their tendency to deform under the application of static loads during stacking, and also because of the de-baling issues due to the density variation (Sokhansanj et al., 2009). Furthermore, rectangular bales utilize truck space more efficiently, enhancing the economics of transportation (Sokhansanj et al., 2009). The produced square bales are collected by Stingers, which have self-loading, unloading and stacking capability (Stinger Inc., 2009). Once the bales are moved to edge of the field by the stinger, a bale wrapper wraps them with the help of a bale loader. These bales are then left on the roadside, awaiting transportation to the plant. The cost data for all collecting operations and other straw-related processes were extracted from IBSAL model (Sokhansanj, 2008). Since the types of machinery, operations, fuel usage and costs are similar across North America; these cost data are considered as reasonable approximations for this study. The inherent uncertainty of the mentioned assumption is studied under the uncertainty analysis.

Table 3-3: Unit cost coefficients (Sokhansanj, 2008)

Cost	Value ($/dt)
Raking	1.73
Baling	7.34
Roadside stacking	1.26
Wrapping	6.83
Stacking	1.15
Storage cost	8.82
Shredding	4.08

3.5.3 Transportation Cost

Straw transportation involves two stages. In the first stage, straw bales are moved from the field to the roadside and in the second phase, from the roadside to the power plant. Once in the power plant, these bales are stacked for storage. In the field, bale transport can be performed either by an automatic bale collector or a flatbed truck accompanied by a front-end bale grabber (Sokhansanj, 2008). As stated in Section 3.5.2, this study has considered Stinger automatic bale collector since it is more efficient than trucks for large scale field operations and level terrains because of its stacking feature (Sokhansanj et al., 2009). The field transportation cost is included in the total straw collection cost. From the field to the power plant, transportation is carried out by large trucks. The cost of biomass transportation by truck consists of two components. The distance fixed cost (DFC) includes the loading and unloading costs of the biomass, and the distance variable cost (DVC) includes of the costs of wages, fuel, depreciation, and maintenance. The unit cost coefficients of these two components are given in Table 3-4.

Table 3-4: Unit transportation cost for straw[10]

Cost Year	DFC ($/dt)	DVC ($/dt-km)
2004	4.76	0.1309
2008[11]	5.16	0.1419

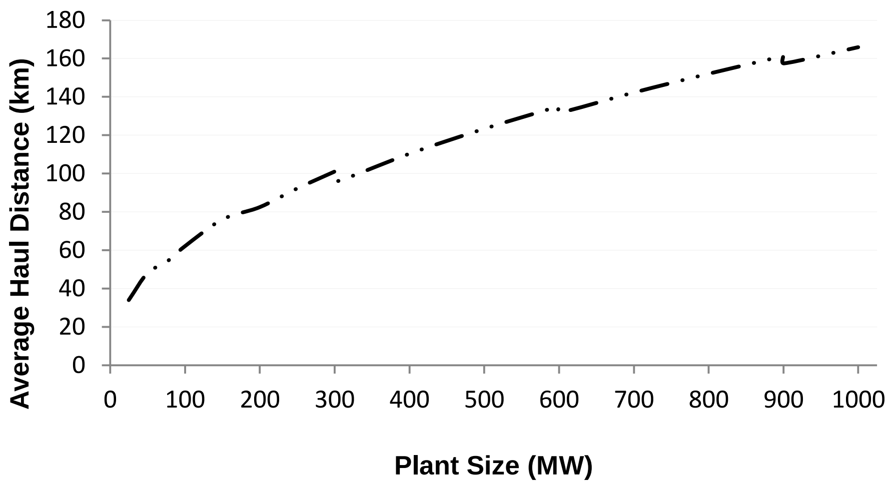


Figure 3-5: Variation of average haul distance with plant size

The transportation cost increases with an expanding collection area, which is denoted by the average haul distance. The haul distance is continuously increased with incremental plant capacity as plotted in Figure 3-5.

[10] Mahmudi and Flynn 2006
[11] The cost of inflation is taken from, http://cost.jsc.nasa.gov/inflation/nasa/inflateNASA.html

3.5.4 Capital Cost

Capital cost data for straw fired biomass power plants are scarce for Canada. As a result, the capital costs of direct combustion plants were drawn from an extensive literature review. The details are given in Table 3-5, and the cost values are for the base year 2008. These unit cost data were used to calculate the total capital cost function of the plant capacity.

Table 3-5: Literature review on biomass direct combustion plant capital cost

Power (MW)	Capital Cost ($/kW)	Source
5	3,000	(IEA, 2007)
10	2,350	(Uddin, 2004)
20	2,602	(Fleuren et al., 2005)[12]
30	1,790	(Uddin, 2004)
36	1,805	(Barreto and Uddin, 2007)
50	1,970	(Bain et al., 2003)
50	1,870	(Barreto and Uddin, 2007)
75	1,747	(Bain et al., 2003)
100	1,605	(Bain et al., 2003)
100	1,730	(Barreto and Uddin, 2007)
200	1,400	(Gustavsson and Madlener, 2003)
250	1,407	(Cameron et al., 2007)
383	1,431	(Searcy 2009)
450	1,300	(Cameron et al., 2007)
500	1,532	(Cameron et al., 2007)
500	1,493	(Kampman et al., 2005)[13]

3.5.4.1 Power Plant Capital Cost Index (PCCI)

The PCCI is an indicator representing the construction cost of power generation projects in North America. The index follows the cost variations in equipment capital costs, facilities, materials and man-power (IHS, 2009). It is maintained by Information Handling Systems (IHS) and its values since year the 2000 is given

[12] The original cost value is €2,300 /kW_e
[13] The value is derived from the original €1,200 /kW_e

in Table 3-6. The PCCI index is used in our study to adjust the historical capital cost data. For example, if a power plant had a capital cost of $100 million in the year 2000, based on this index, it would cost $182 million if built in year 2008.

Table 3-6: Variation of PCCI since year 2000

Year	Power Plant Capital Cost Index (PCCI)[14]	PCCI Difference from Year 2008	Inflation Based to Year 2008
2000	100	82	19.4
2001	106	76	15.6
2002	111	71	12.8
2003	116	66	10.6
2004	124	58	8.4
2005	135	47	6.3
2006	155	27	4.3
2007 Q1	171	11	2.1
2007 Q3	178	4	2.1
2008 Q1	182	-	-

3.5.4.2 Capital Cost Adjustment

As indicated by the PCCI variation in the last 9 years compared to inflation, adjusting the cost values in Table 3-5 only for inflation will not be sufficient. The capital cost also increases due to various other factors such as increases in the price of steel, cement, and construction material and also changes in labour costs. In order to incorporate all these factors, the capital cost data were adjusted by using the PCCI and plotted as shown in Figure 3-6. For example, the year 2000 capital cost value needs to be increased by 19.4% to correct only for inflation to represent the year 2008 value, but the real capital cost increase as indicated by the PCCI is 82%.

[14] Source - (IHS, 2009)

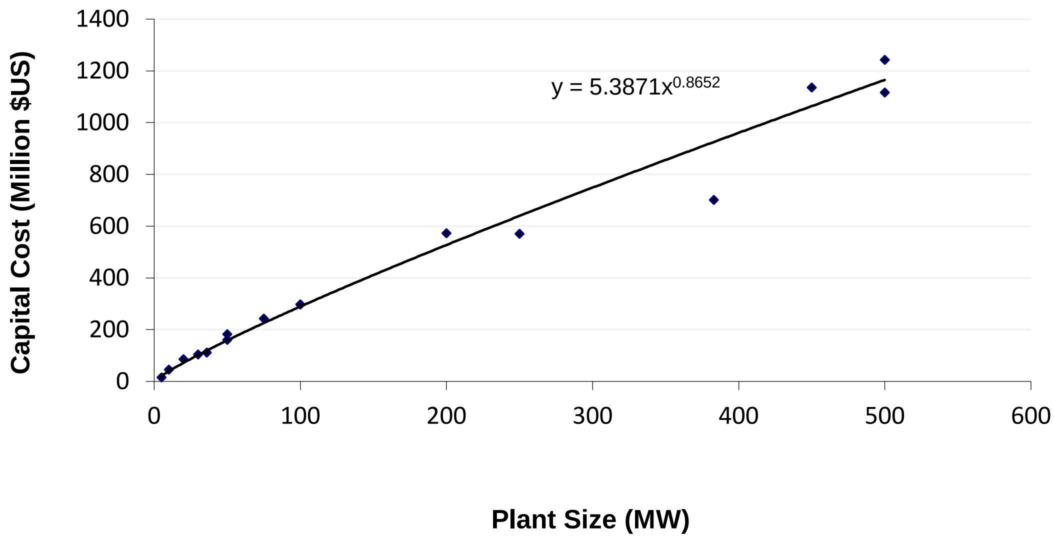


Figure 3-6: Capital cost variation with plant size

Given the capital cost function derived in the above graph, the unit capital cost is calculated and plotted against the plant capacity. The resulting plot is shown in Figure 3-7 where the unit capital cost at 300 MW is $2497 /kW.

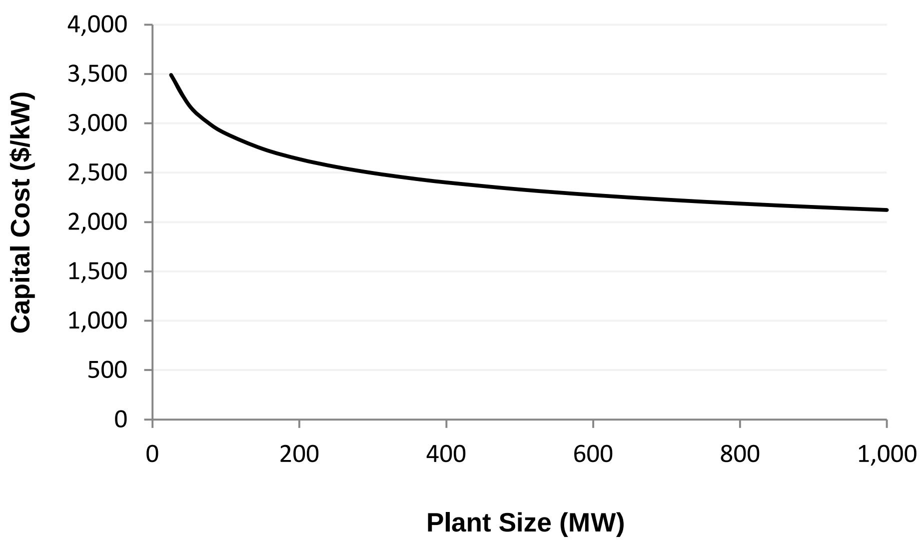


Figure 3-7: Unit Capital cost variation with plant size

3.5.4.3 Maximum boiler unit size

The maximum boiler unit size is presumed to be 300 MW and is based on the existing 250 MW biomass fired boiler in Alholmens, Finland. The boiler manufacturer, Kaverner Power Inc. believes that no technical barriers exist in manufacturing a 300 MW boiler unit (Kumar and Flynn, 2005). For plant capacities over 300 MW, multiple boiler units were considered. For example, if the plant size is 400 MW, the plant would consist of two units of 200 MW capacity each.

3.5.5 Operating Costs

3.5.5.1 Employee cost

For the base case, the number of employee was estimated based on an earlier study by Spath et al. (2005) for a 2000 dry tonne/day biomass plant. The details are given in Table 3-7. The number of yard employees increases with the increasing plant size to handle the increased volume of feedstock. It is considered that when the feedstock requirement is increased by 1000 dry tonne/day, the number of operating staff needed increases by five (Sarkar and Kumar, 2007). The change in the number of employees with plant size is shown in Table 3-8. The employees' salaries are calculated based on the 2008 wage rate of Canadian Salary Calculator (Canada Visa, 2009). All salaries were rounded off in Canadian dollars and converted to US dollars as given in Table 3-7.

Table 3-7: Employee wages for base case

Position	Annual salary [15] (CAD)	Personnel #	Annual cost ($US)
Plant manager	100,000	1	102,470
Plant engineer	75,000	1	76,853
Lab manager	70,000	1	71,729
Maintenance supervisor	65,000	1	66,606
Shift supervisor	60,000	6	368,892
Lab technician	50,000	3	153,705

[15] Source (Canada Visa, 2009).

Position	Annual salary [15] (CAD)	Personnel #	Annual cost ($US)
Maintenance technician	40,000	12	491,856
Shift operators	35,000	25	896,613
Yard employees	35,000	16	573,832
Clerks & secretaries	35,000	3	107,594
Total salaries		69	2,910,149

Table 3-8: Employee numbers for different plant sizes

Plant capacity (MW)	Total number of employees	Annual cost ($US)
25	34	1,496,063
50	39	1,680,509
75	44	1,864,955
100	49	2,075,018
150	54	2,310,699
200	59	2,490,022
250	64	2,679,592
300	69	2,910,149
350	74	3,115,089
400	80	3,381,511
500	84	3,586,452
600	89	3,811,886
700	94	4,037,320
800	99	4,252,507
900	104	4,436,953
1000	110	4,693,128

3.5.5.2 Maintenance Cost

The maintenance cost generally includes material, labour and replacement part costs. Accurate maintenance cost data on biomass power plants are difficult to obtain from the literature, and most studies have considered approximations rather than the actual cost data. The electric Power Research Institute (EPRI) has recommended that 5% of the original capital equipment expenditure be used as the annual maintenance cost (Hughes et al., 2003). In another study, for a biomass gasification plant, the maintenance cost is considered as 2% of the total project investment (Spath et al., 2005). Kumar et al. (2003) estimated that the maintenace cost is approximately equal to 3% of the total capital cost investment of the biomass power plant. In this study it is considered that the anuual maintenance cost is 2% of the total capital investment and that this cost can be regarded as one of the uncertainities in the input data. The effect of changing the maintenance cost is discussed in sensitivity analysis (Section 3.7).

3.5.5.3 General Overheads

Other fixed costs such as the cost of plant utilities, office supplies, safety equipment, plant security, engineering expenses and all miscellaneous costs are included under general overheads. The annual general overheads are assumed to be about 95% of the annual wages (Spath, et al. 2005).

3.5.5.4 Ash Disposal Cost

The bottom ash disposal cost is also considered in this study as a cost component. This ash can be used in several ways including cement-concrete production, returning ash to farming lands, landfilling, and using it as a building material (Prairie Practitioners Group, 2008). In this study, it is assumed that the ash is spread on farm fields. The average transportation distance for ash disposal is assumed to be 50 km, and the transportation expense is considered as the only cost involved since the ash will be spread at the farmers cost. The direct fixed cost of ash transportation is (DFC) $27 dry tonne/ha, and the direct variable cost (DVC) is $0.19 dry tonne/km, based on a previous study (Zundel et al., 1996).

3.5.6 Decommissioning Cost

The site recovery cost is assumed to be 20% of the total capital investment and considered to be incurred in the last year of operation (Kumar, 2003).

3.5.7 Return on Investment

The triticale straw base case power cost model is developed with a 10% pre-tax return.

3.6 Results and Discussion

The techno-economic model was used to estimate the cost of the power from triticale straw at different plant sizes. The optimum size of the plant is also investigated. However, the cost model hasn't considered taxes, insurance payments and any government subsidiaries that could be available for certain plant capacities.

3.6.1 Cost Analysis

3.6.1.1 Power Cost Curve

The power cost versus the plant capacity plot is given in Figure 3-8. Here, all base case assumptions were kept constant and the only variable is plant capacity.

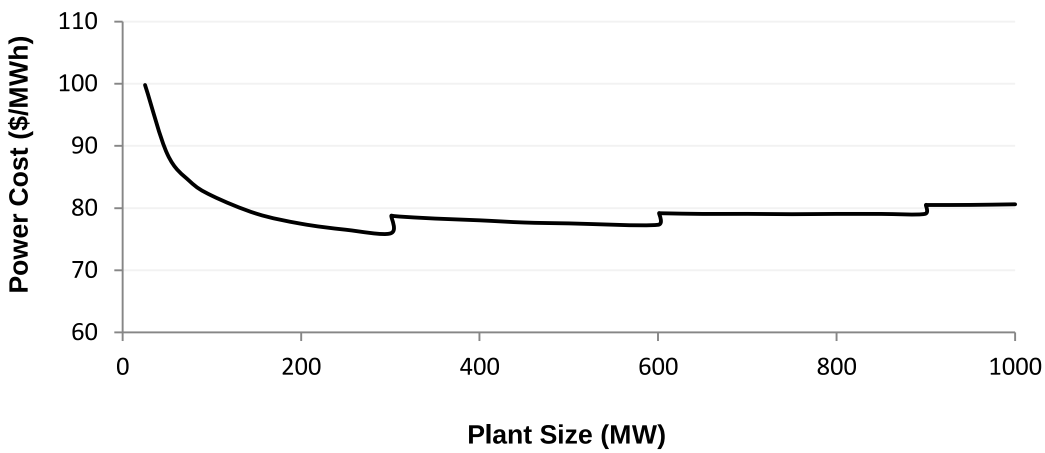


Figure 3-8: Direct combustion power cost curve

The assumption of a largest unit size of 300 MW creates discontinuity in the cost versus electricity production capacity curve. At multiple plant sizes of 300 MW, the power cost shows a higher cost for electricity production because of the increased transportation cost and the minimal benefits from the economy of scale in the capital cost. Up to 300 MW, the power cost drops sharply from $100.16 /MWh at 25 MW plant capacity to $76.33 /MWh at 300 MW, which is about a 24% power cost reduction. In this range, the economy of scale benefits in the capital cost are more than the increase in the transportation cost due to the plant capacity increase. After 300 MW, the power cost keeps increasing in smaller increments because the increase in the transportation cost of the biomass is higher than the capital cost benefits due to economy of scale. The increase between 300 MW to 1000 MW is \$4.7 /MWh which is about a 6% increase. It is evident that the power cost from 130 to 900 MW is within 5% of the lowest power cost at 300 MW unit size. Hence the optimum size is 300 MW, at which the cost of power production is minimal.

3.6.1.2 Capital Cost Breakdown

The investment in the biomass boiler is understandably high and is generally estimated to be about three times that of the investment in a coal-driven boiler of the same size (Cameron et al., 2004). The basis of the cost allocation is actual investment data from the Enkoping plant (24 MW_e) in Sweden (Van den Broek et al., 1995). The capital investment in the Enkoping plant was \$1947 /kW in year 1992, which can be approximated to \$2862 /kW after adjusting for inflation.[16] The capital cost breakdown is shown in Table 3-9.

Table 3-9: Investment cost breakdown

Item	Percentage (%)	Cost (million $)
Boiler	38	285
Turbine	19	142
Civil Work	9	67
Fuel Preparation	9	67
Control System	5	37
Others	6	45
Administration	14	105
Total		749

3.6.1.3 Cost Components

In the Power production cost breakdown given below, the main component of the power cost is the capital cost recovery (41.7%). Costs for harvesting and collection, transportation and maintenance together contribute to 38.7% of the total power cost.

[16] Source - Nasa inflator (NASA, 2007)

Table 3-10: Direct combustion component costs

Cost Component	Cost ($/MWh)	Percentage
Capital Cost Recovery	31.8	41.7%
Harvesting & Collection cost	10.8	14.1%
Transportation cost	10.2	13.3%
Ash disposal cost	1.4	1.9%
Shredding Cost	2.2	2.9%
Nutrient Cost	2.1	2.7%
Storage cost	0.5	0.7%
Premium for the Farmers	5.6	7.3%
Fixed Operating Cost	1.6	2.1%
Maintenance cost	8.6	11.3%
General Overhead	1.5	2.0%
Total cost	76.3	-

3.6.1.4 Optimum Unit Size

Determining the size of the power plant at which the power cost will be minimal is critical. The optimum size of a power plant based on triticale straw with a boiler unit size of 300 MW is the same. The cost of power at 300 MW is $76.30 /MWh. The cost of power production is higher than $76.30 /MWh at any other size of the power plant. The optimum size of the plant is influenced by the unit size of the boiler. A cost versus capacity curve for the triticale straw based power plant was developed with an unlimited unit size of the boiler and is shown in Figure 3-9.

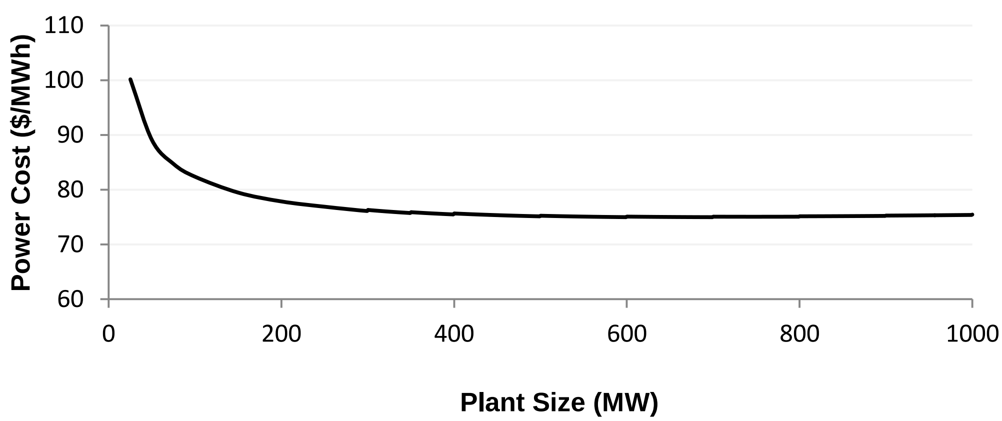


Figure 3-9: Power cost variation without the limitation on maximum boiler unit size

The curve is flat after 400 MW, and a minimal change in power cost occurs up to 1000 MW. The minimum power cost of $75.02 /MWh occurs at plant size 595 MW. However, this cost is only 1.31 $/MWh or 1.7% lower than power cost at 300 MW size. Given the flatness of the curve, it is estimated that a triticale straw power plant can be built in the range of 150 MW to 1000 MW with a cost variation of 6%, compared to the power cost at the optimum plant size.

3.6.1.5 Different Unit Sizes

The effect on the power cost curve when the boiler unit size is reduced from that in the base case is illustrated in Figure 3-10. As the unit size decreases, discontinuity in the power cost occurs more frequently with the application of multiple units. From the different unit size plots shown, it is evident that the power cost increases with a decrease in the unit size of the boiler. This result occurs because of the comparatively decreasing benefit of economy of scale in the capital cost.

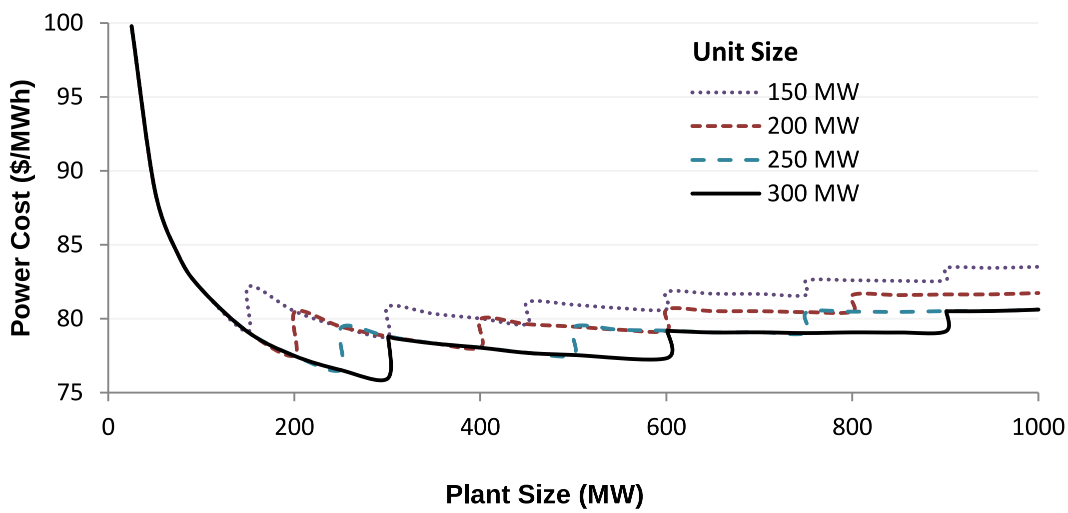


Figure 3-10: Effect of different unit sizes on power cost

3.7 Sensitivity Analysis

The sensitivity of key cost factors and other major assumptions were studied by varying these parameters in the most probable range. The sensitivity factors are listed below, and the influence of these parameters on the power cost has been investigated in the sensitivity analysis. The power cost variation for different plant sizes for each of these parameters is important as the input parameters can change with continuous development and more commercial scale development of the technology.

Table 3-11: Sensitivity scenarios

Scenarios	Considered range
1. Capital Cost	-25% to 25% change
2. Maintenance Cost	1 - 5% of TCI
3. Plant Efficiency	30% to 40%
4. Straw Yield	1.08 t/ha - 4.80 t/ha (Grain yield : 2.0 t/ha - 8.0 t/ha)
5. Straw to Grain Ratio	0.75 to 1.80
6. Moisture Content	10% to 20% (Calorific value change also considered)
7. Fraction of the land devoted to Triticale	0.1 to 0.9

3.7.1 Capital Cost

Capital cost is a key parameter in this study. Hence, the effect of capital cost variation on the output power cost must be analyzed.

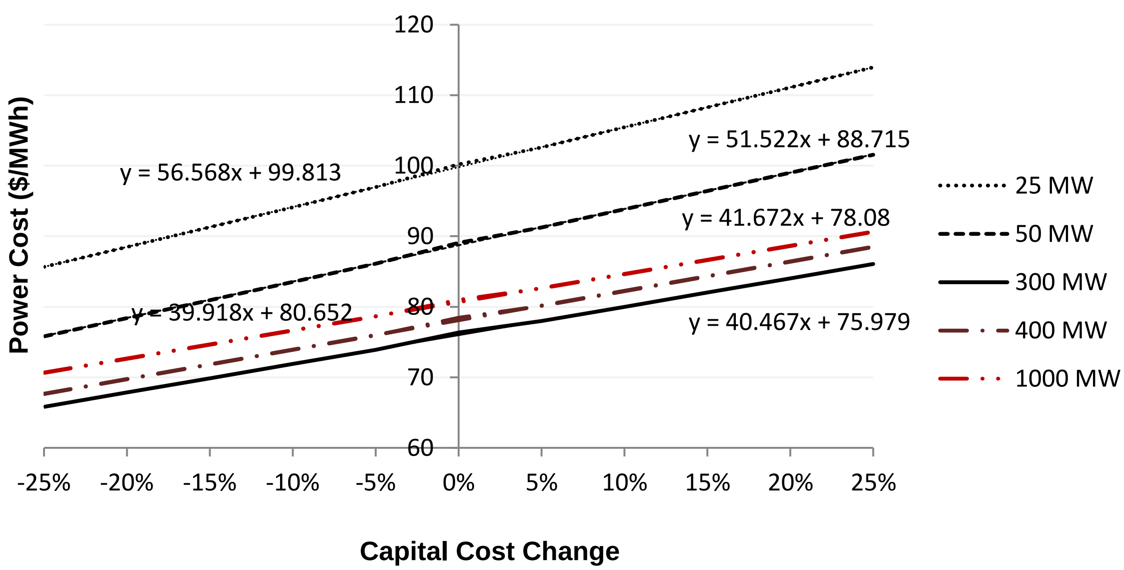


Figure 3-11: Sensitivity analysis for capital cost

Figure 3-11 illustrates the power cost plots for a few selected plant sizes with ± 25% capital cost variation. The power cost values for the capital cost change from -25% to 25%, at 300 MW plant size, and can be approximated accurately with a linear trend line equation of the form,

New Power Cost (y) = 40.467 * Capital Cost Changed % (x) + Original Power Cost

Here, the intercept gives the original power cost, and the gradient is the power cost increment in cents for a 1% change in the capital cost. At 300 MW, the power cost change for a one percentage change in the capital cost is 0.405 $/MWh.

Table 3-12: Influence of capital cost at different plant sizes

Plant capacity (MW)	Power cost change for 1% capital cost increment (cents/MWh)
25	56.57
50	51.52
100	46.93
200	42.74
300	40.47
400	41.67
600	39.46
1000	39.92

At lower plant sizes such as 25 MW or 50 MW, the power cost change is over 50 cents/MWh for a 1% capital cost difference. As the plant capacity increases, the effect of the capital cost change decreases. From 200 to 1000 MW, the difference in the power cost change per unit percentage capital cost variation is about 3 cents/MWh.

3.7.2 Maintenance Cost

The study has assumed the annual maintenance cost is 2% of the total capital investment. However, as discussed in section 3.5.5.2, other studies have considered the maintenance cost to be 2 to 5% of the capital cost. The maintenance cost appears to be a significant sensitivity parameter.

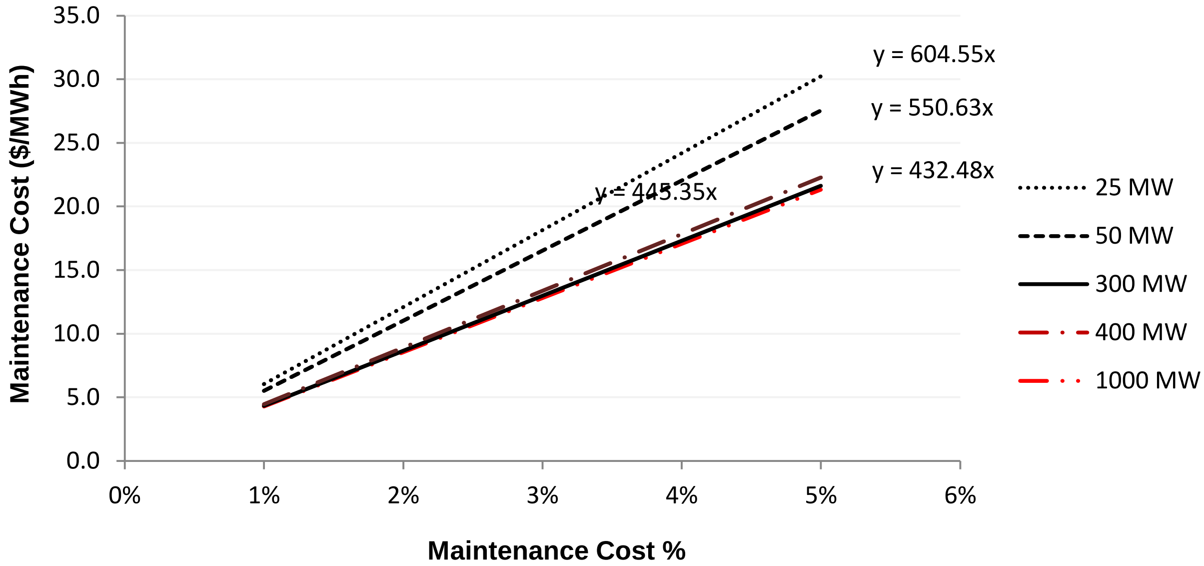


Figure 3-12: Different maintenance cost assumptions

Figure 3-12 shows that, for a specific plant size, the maintenance cost variation is linear with the changing maintenance cost percentage assumption. The gradient of each graph is the cents/MWh increase in the maintenance cost with a changing annual maintenance cost assumption. At 300 MW, the maintenance cost will increase by $4.3 /MWh for each 1% increment in the maintenance cost assumption. If we assume 1 to 5% of the total capital cost to be the annual maintenance expenditure, relevant increase in unit maintenance cost values are as listed in Table 3-13.

Table 3-13: Maintenance cost change at different plant sizes

Plant capacity (MW)	Maintenance cost change for 1% increment ($/MWh)
25	6.05
50	5.51
300	4.45
400	4.32
1000	4.23

It is evident that for higher plant capacities, the magnitude of the maintenance cost sensitivity is lower, as is illustrated by the data given in the above table.

3.7.3 Plant Efficiency

The Alholmens plant in Pietarsaari, Finland runs at about 38-39% gross efficiency when operating without heat extraction (Kumar and Flynn, 2005). In order to accommodate the plant efficiency variations, the model was run for different efficiencies ranging from 30% - 40%. The results are shown below.

Table 3-14: Plant efficiency sensitivity results for direct combustion base case

Plant Efficiency	Power Cost ($/MWh)	Variation
30%	81.35	6.6%
31%	79.96	4.8%
32%	78.67	3.1%
33%	77.46	1.5%
34%	76.33	0.0%
35%	75.27	-1.4%
36%	74.27	-2.7%
37%	73.33	-3.9%
38%	72.44	-5.1%
39%	71.60	-6.2%
40%	70.81	-7.2%

It is evident that a 1% incremental efficiency improvement always decrease the power cost by at least 1%. When the base case efficiency is increased to 35% (by 1%), the power cost is reduced by $1.05 /MWh (-1.4%). If the base case plant could consistently achieve the maximum efficiency of the Finnish plant, the cost would decrease by 6.2% ($4.70 /MWh). The power cost curve for the probable lowest and highest plant efficiencies is given in Figure 3-13.

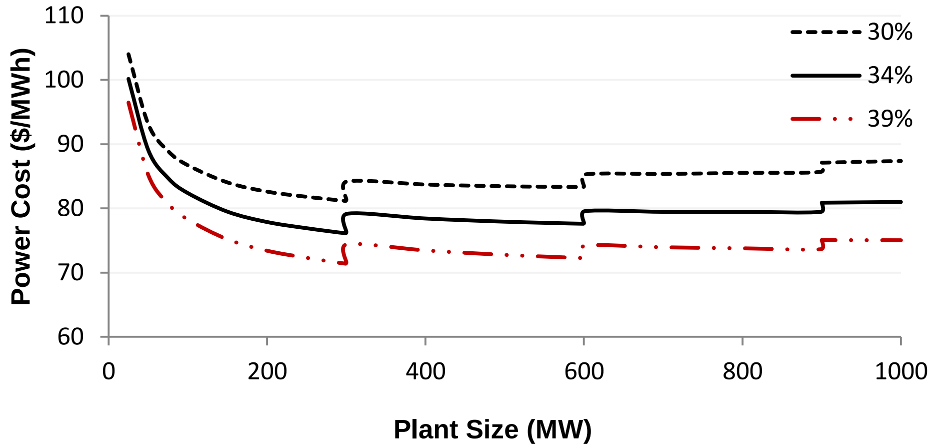


Figure 3-13: Power cost variation for low, average and high plant efficiency cases

The effect of plant efficiency tends to be more influential as the plant size increases, mainly because an increase in efficiency decreases the feedstock requirement and hence reduces the transportation cost, thereby decreasing the overall feedstock cost. Figure 3-14 presents a plot of the power cost curves for different plant sizes with varying plant efficiency. As the plant capacity increases, the steepness of curves increases indicating that the gradient or power cost change per unit efficiency is improved.

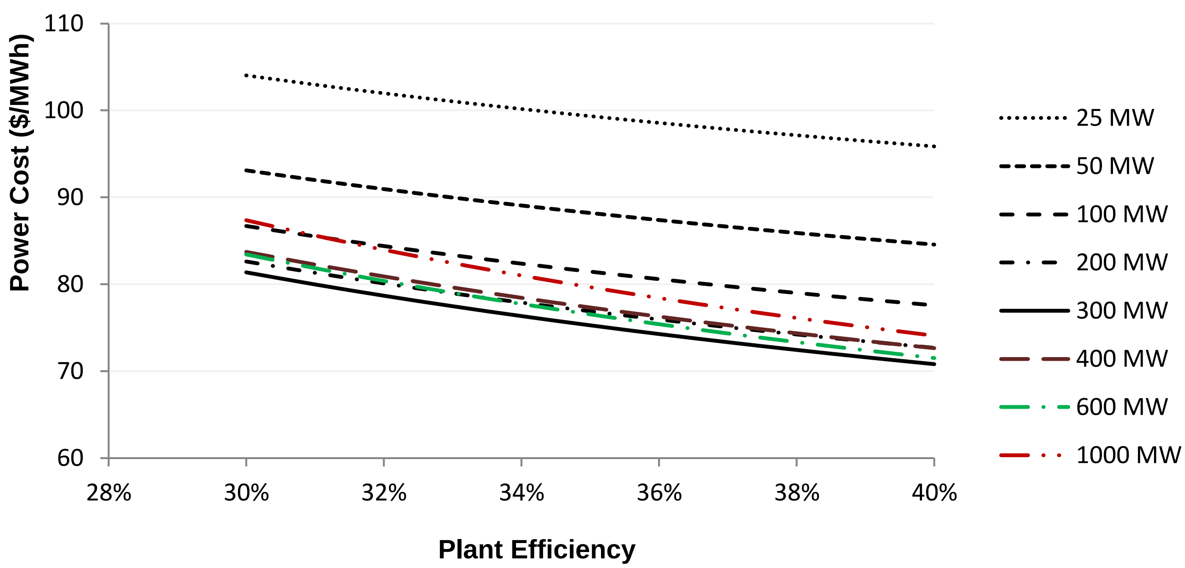


Figure 3-14: Power cost variation with plant efficiency for selected plant sizes

3.7.4 Yield

Triticale has not yet been grown as a dedicated energy crop with the purpose of generating power and bio-refined products. The energy crop concept is expected to increase the focus on reaching higher crop yields. As mentioned in section 2.4.3, the straw yield in the coming years could significantly increase compared to the yield values reported in the past. In order to investigate the yield influence as a sensitivity scenario, a wide range of yield values was considered as given in Table 3-15. Most of the triticale yield data were obtained through personal communications (Sieusahai, 2010). However the Western Applied Research Corporation has published new variety test report on cereal grain yields, which gives the triticale trials yields for three new varieties as 6,386 kg/ha (Phelps et al., 2009).

Table 3-15: Yield sensitivity results for its direct combustion in the base case

Grain Yield	Straw Yield (t/ha)	Power Cost ($/MWh)	Cost Change
2.50	1.08	81.82	7.2%
3.00	1.41	79.65	4.4%
3.50	1.75	78.20	2.4%
4.00	2.09	77.14	1.1%
4.50	2.43	76.33	0.0%
5.00	2.77	75.68	-0.8%
5.50	3.11	75.15	-1.5%
6.00	3.44	74.71	-2.1%
6.50	3.78	74.33	-2.6%
7.00	4.12	74.00	-3.1%
7.50	4.46	73.71	-3.4%
8.00	4.80	73.45	-3.8%

Table 3-15 presents the calculated percentage effect of yield variation on the power cost. If the straw yield is increased from 2.43 t/ha (4.5 t/ha grain yield) to 4.8 t/ha, the resulting 78% increase, will reduce the power cost by only 3.8%. Figure 3-15 provides the variation of power cost with respect to four yield values including low, medium and high yield cases.

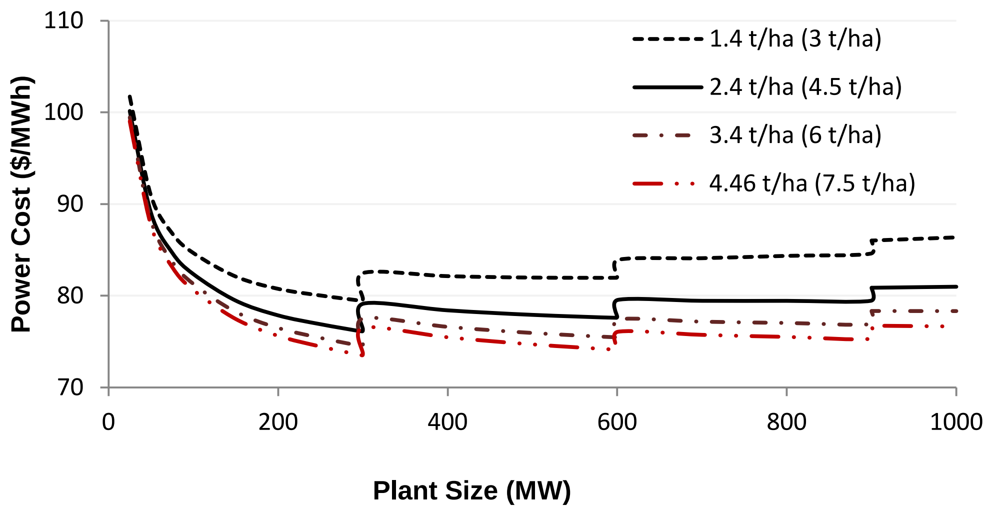


Figure 3-15: Power cost variation for low, average and high straw yield cases

Figure 3-16, predicts that the effect of the yield on the power cost will be magnified as the plant size increases. This figure shows a sharp cost reduction for power plants over 200 MW, up to an average yield of the study (2.43 t/ha) starting from the lowest yield. For this reason, when feeding larger scale power plants, especially those over 200 MW, more attention should be paid to improving the straw yield.

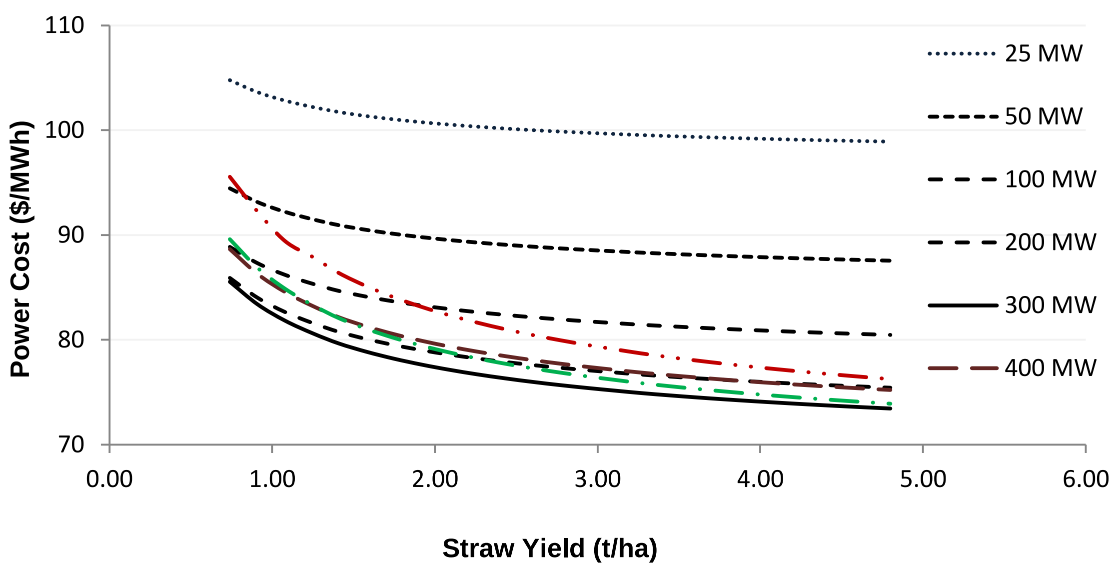


Figure 3-16: Power cost variation with straw yield for selected plant sizes

3.7.5 Straw to Grain Ratio (SGR)

When the straw yield is calculated based on grain yield, considerable sensitivity is always assigned because of the challenging nature of selecting a suitable straw to grain ratio (SGR). This ratio greatly varies by location, weather patterns, harvesting machinery and soil characteristics (Prairie Practitioners Group, 2008). Nevertheless, we inevitably still have to use a single straw to grain ratio across all of Alberta, including the prairies. Although this study has assumed a SGR of1.1, there are other studies that have stated different ranges. Stephen (2008) has analysed the straw to grain ratio variation for different soil types and harvesting techniques in Alberta for cereal crops and found that the straw to grain ratio varied from 0.75 to 1.5 for wheat. It is reasonable to conclude that the same variation may apply for triticale as well.

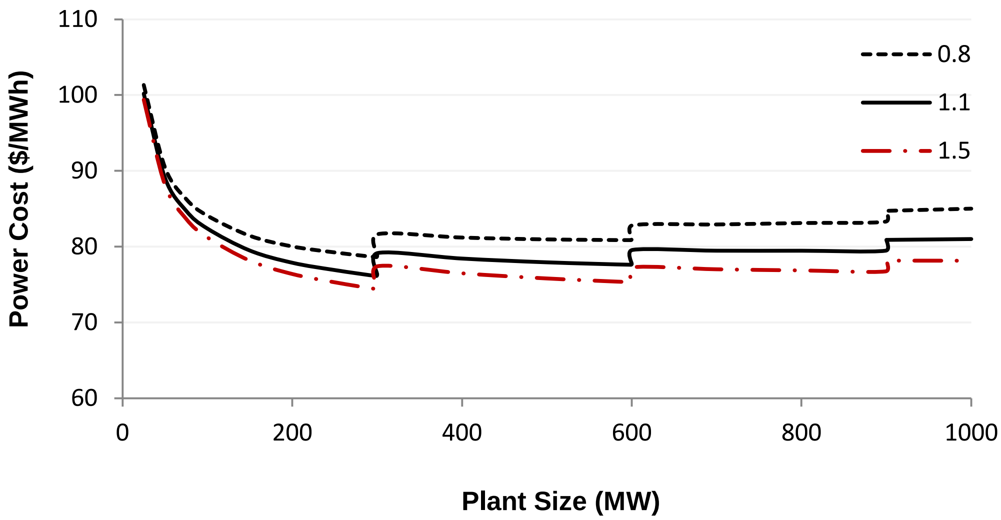


Figure 3-17: Power cost variation for low, average and high straw to grain ratio cases

The maximum effect on the power cost by changing the SGR is -3.3%, at 1.8 SGR. However, such a higher SGR is not found in most of the prairie areas in Alberta for any cereal crops. Hence, with better machinery for harvesting, the SGR could be improved by up to 1.5, and the relevant power cost reduction would be 2.3%.

At lower plant capacities, the influence of the SGR on power cost is insignificant as exemplified in Figure 3-18. At larger plant sizes over 300 MW, SGR could be a significant factor for variations in the 0.8-1.5 range. At 1000 MW, the power cost increases by 7% if SGR is 0.8.

Table 3-16: Power cost variation with SGR for base case

Straw to Grain Ratio	Power Cost ($/MWh)	Cost Change
0.80	78.80	3.2%
0.90	77.78	1.9%
1.00	76.98	0.8%
1.10	76.33	0.0%
1.20	75.79	-0.7%
1.30	75.33	-1.3%
1.40	74.94	-1.8%
1.50	74.60	-2.3%
1.60	74.29	-2.7%
1.70	74.02	-3.0%
1.75	73.90	-3.2%
1.80	73.78	-3.3%

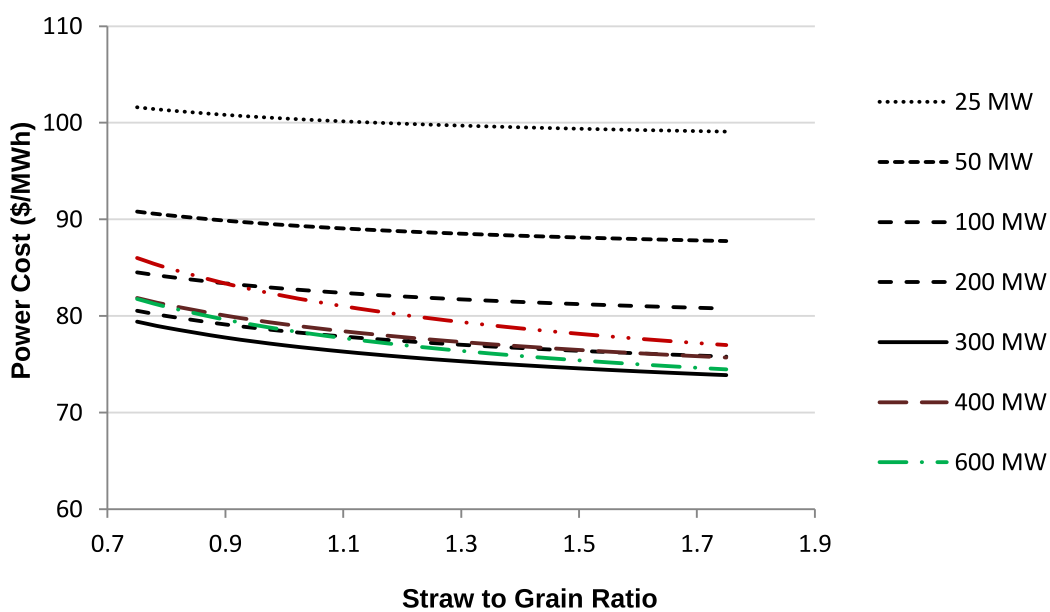


Figure 3-18: Power Cost Variation with Straw to Grain Ratio for Selected Plant Sizes

3.7.6 Moisture Content

As explained in section 2.5, the maximum moisture content for the baling is 20%. If the moisture content in straw influences the power cost considerably, then the straw collection operations should be planned to attain the minimum moisture content level. Another important factor is that the net calorific value of the straw also changes with moisture content. In this study, a set of test results for wheat straw's moisture content and calorific value co-relation published by Biomass Energy Center (UK) (Biomass Energy Center, 2008) were considered, and it was assumed that the variation would be similar for triticale straw as well. After analysing the above mentioned test data on moisture content versus net calorific value, it was found that a change of 1% in the moisture amount in straw results in approximately 0.19 MJ/kg change in the calorific value. The sign of the change is opposite to the sign of moisture content change, which means the calorific value is highest at the least possible moisture content.

As calculated in Table 3-17, the effect of a moisture content ±5% change, results in about a ± 0.5% difference in base case power cost. This result is common for all plant sizes as shown in Figure 3-19. All the curves are flat and have hardly any noticeable effect on the power cost for ±5% change in the straw moisture content.

Table 3-17: Straw moisture content effect on base case power cost

Moisture Content	Power Cost ($/MWh)	Cost Change
10%	75.99	-0.4%
11%	76.05	-0.4%
12%	76.12	-0.3%
13%	76.19	-0.2%
14%	76.26	-0.1%
15%	76.33	0.0%
16%	76.40	0.1%
17%	76.48	0.2%
18%	76.55	0.3%
19%	76.63	0.4%
20%	76.71	0.5%

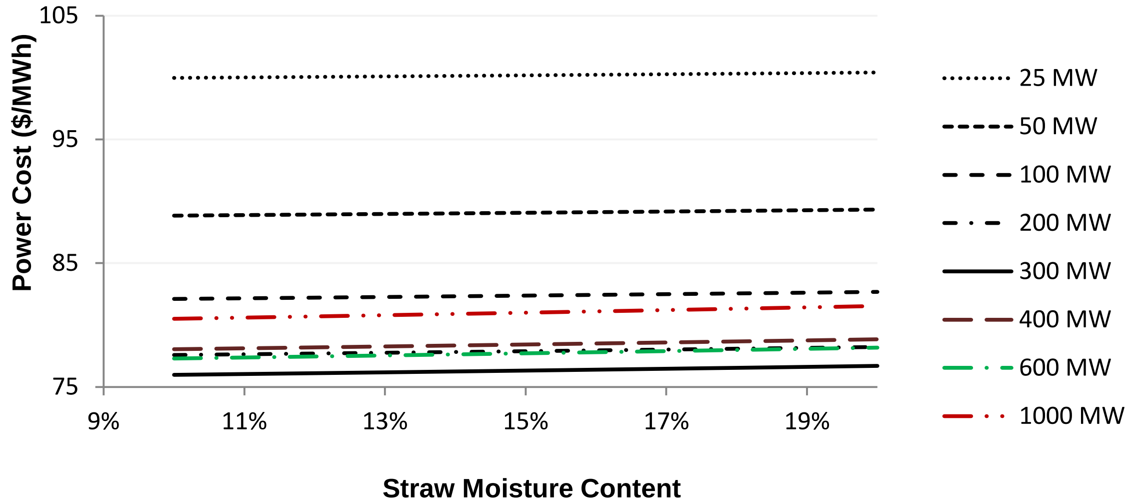


Figure 3-19: Power cost variation with straw moisture content for selected plant sizes

3.7.7 Fraction of the Land Devoted to Triticale (Ø)

Presently, triticale farms are scattered across Alberta, and due to their small acreage, the fraction of the triticale land compared to the total land area in Alberta is way below 0.01 (Stat Canada, Census of Agriculture 2006)[17].

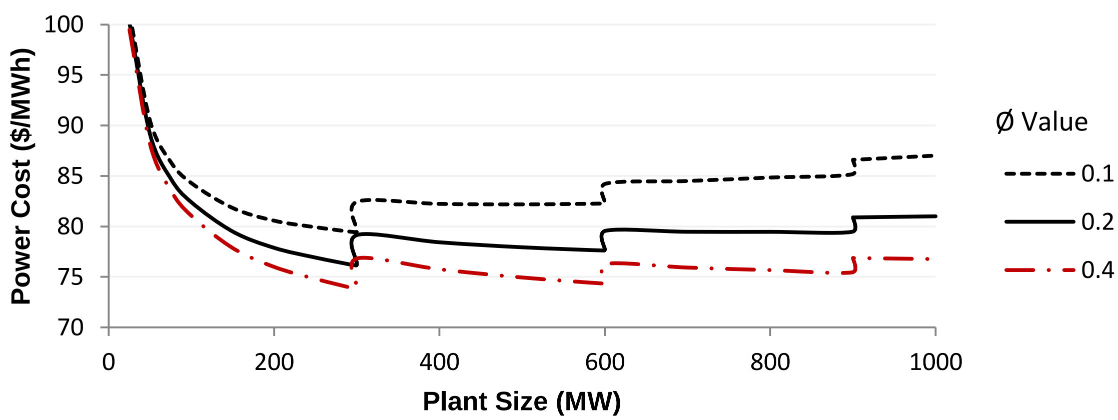


Figure 3-20: Power cost variation for low, average and high triticale land fraction

The base case assumption is Ø = 0.2, and if this value is 0.1, the power cost is increased by 4.3%. If the land portion occupied by triticale increased two folds, or

[17] This value was calculated by using the data given in Statistics Canada's web site (Stat Canada, 2006).

Ø = 0.4, the cost reduction would be 3%. It is evident that power cost of plant sizes above 200 MW is significantly influenced by a variation in Ø. As is illustrated in Figure 3-21, the power cost drops sharply as the Ø varies in the range of 0.4-0.5.

Table 3-18: Impact of change of triticale grown land fraction on base case power cost

Fraction of the land devoted to Triticale (Ø)	Power Cost ($/MWh)	Cost Change
0.10	79.62	4.3%
0.15	77.56	1.6%
0.20	76.33	0.0%
0.25	75.49	-1.1%
0.30	74.87	-1.9%
0.35	74.39	-2.5%
0.40	74.00	-3.0%
0.45	73.68	-3.5%
0.50	73.41	-3.8%
0.60	72.97	-4.4%
0.70	72.63	-4.8%
0.80	72.36	-5.2%
0.90	72.13	-5.5%

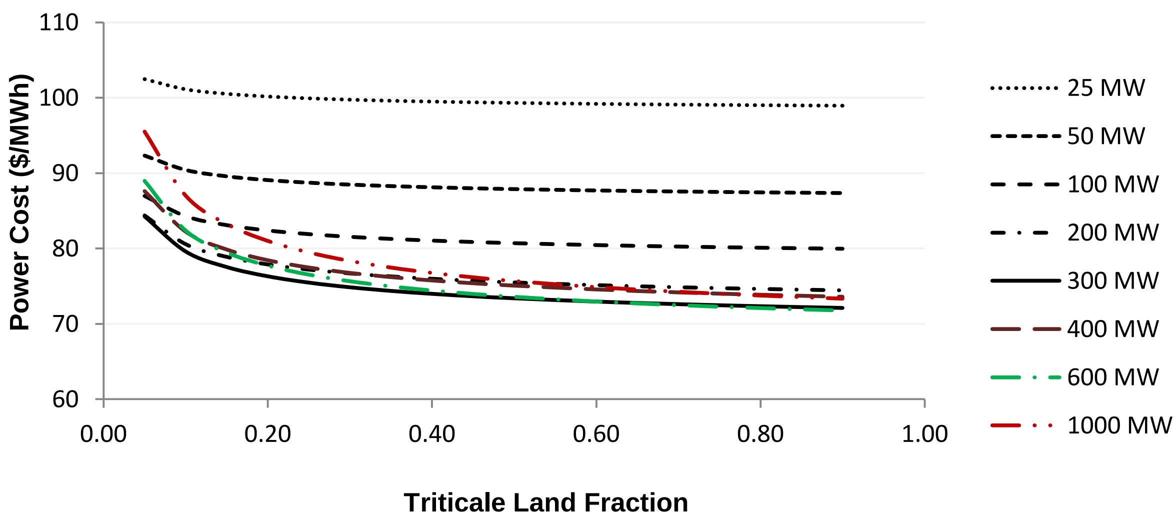


Figure 3-21: Power cost variation with triticale land fraction for selected plant sizes

3.7.8 Summary of Sensitivities

3.7.8.1 Feasible ranges of cost sensitivities

From the broad ranges studied for all sensitivities, the feasible minimum and maximum values were identified and are summarised in Table 3-19.

Table 3-19: Feasible direct combustion cost sensitivity ranges

Sensitivity	Range		Cost ($/MWh)		Change	
	Min	Max	Min	Max	Min	Max
Capital Cost	-20%	20%	67.85	84.04	-11.1%	10.1%
Maintenance Cost	1%	4%	72.70	83.59	-4.8%	9.5%
Plant Efficiency	30%	39%	81.35	71.60	6.6%	-6.2%
Grain Yield (t/ha)	2.5	7.5	81.82	73.71	7.2%	-3.4%
Straw to Grain Ratio	0.8	1.5	78.80	74.60	3.2%	-2.3%
Moisture Content	10%	20%	75.99	76.71	-0.4%	0.5%
Fraction of Triticale Land	0.1	0.4	79.62	74.00	4.3%	-3.0%

According to the above results, a variation in the capital cost is the most advantageous variation. If capital cost can be reduced by 20%, a power cost reduction of 11% is possible, and will result in a power cost of 67.85 $/MWh. If the plant efficiency is increased by 5%, power cost can be decreased by 6%.

3.7.8.2 Relative influence of cost sensitivities

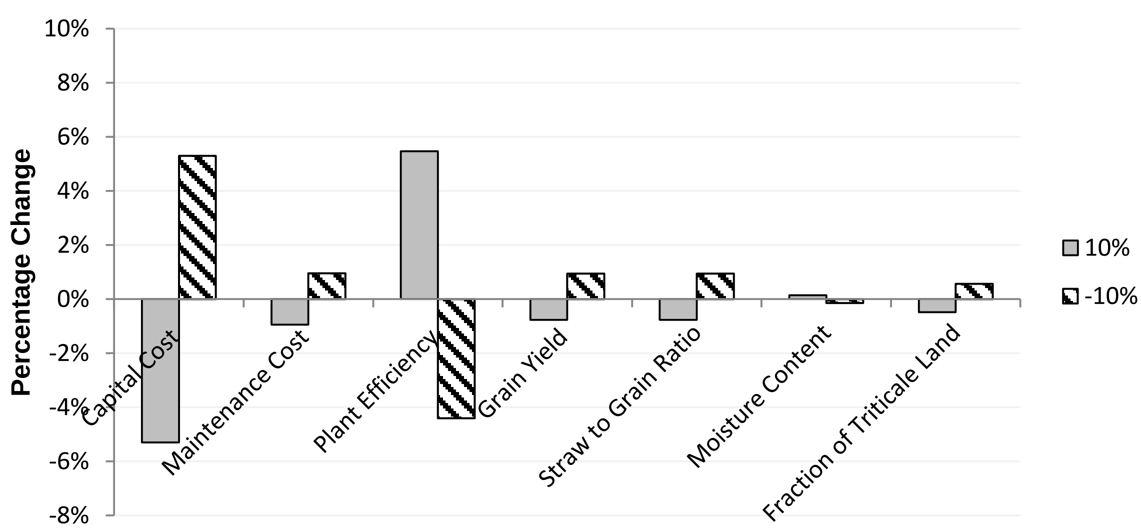


Figure 3-22: Relative influence of power cost sensitivities

Figure 3-22 represents the relative influence of these parameters by analysing the influence shown on the power cost per unit percentile variation. If all sensitivities are changed by the same percentage value (±10%), capital cost shows the highest sensitivity, followed by the plant efficiency.

3.7.9 Effect of the sensitivities on optimum plant size

Because of the ranges of the sensitivity parameters given in Table 3-19, the effects on the base case optimum plant size and the optimum power cost analysed are as given in Table 3-20. The lowest optimum plant is achieved by reducing the capital cost by 20%. The optimum plant size for this scenario is 497 MW, and the relevant power cost is $67.61 /MWh.

Table 3-20: Change in optimum plant size for sensitivities

Sensitivity	Range		Optimum size (MW)		Optimum cost ($/MWh)	
	Min	Max	At Min	At Max	At Min	At Max
Capital Cost	-20%	20%	497	799	67.61	82.19
Maintenance Cost	1%	4%	595	797	71.71	81.46
Plant Efficiency	30%	39%	496	798	80.66	69.44
Grain Yield (t/ha)	2.5	7.5	998	998	71.17	71.17
Straw to Grain Ratio	0.8	1.5	495	795	78.17	72.51
Moisture Content	10%	20%	698	595	74.57	75.48
Fraction of Triticale Land	0.1	0.4	397	998	79.31	71.17

3.8 Uncertainty Analysis

3.8.1 Estimation of Uncertainty for Unit Processes

The lack of exact representative data for the production system studied is a major concern for cost and life cycle analysis. In such a situation the researcher has to use the most appropriate data source for completing the study. Inevitably, such a practice creates an uncertainty in the modeling results. Moreover, quantifying the uncertainty of a data source is often very difficult, but a quantitative scoring matrix can be quite useful for estimating the uncertainty. Table 3-21 was developed by using the methodology described by Weidema (Huijbregets et al., 2001). This methodology has been discussed in many uncertainty studies (Meier, 1997; Weidema, 1998; Van der Berg et al., 1999). Since the reliability and completeness of the data sources used in this study are more defined, only three uncertainty factors illustrated by Weidema have been considered.

Table 3-21: Uncertainty estimation methodology

Assumed Uncertainty	5%	10%	20%	30%	50%
Temporal Correlation	Less than 3 years of difference to year of study	Less than 6 years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years of difference
Geographical Correlation	Data from Alberta	Average data from Canada	Data from USA	Data from outside North America for similar conditions	Data from outside North America with very different production conditions
Technological Correlation	Data from Farms, processes and materials related to Triticale or Wheat	Data from processes and materials under study but for other Canadian straw types	Data from processes and materials under study but from different Cereal Crops	Data on related processes or materials but from same technology	Data on related processes or materials but from different technology

Table 3-22 shows the uncertainty values assigned for each unit process based on the above uncertainty quantifying matrix.

Table 3-22: Assigned unit process uncertainty values

Unit Process	Cost
Farming and Harvesting	5%
Collecting	5%
Transportation	5%
Plant Operations	10%
Plant Con., Maint. & Decommissioning	10%

3.8.2 Monte-Carlo Analysis

By using the available uncertainty analysis methods and simulation techniques, one can obtain a better understanding of the effect of uncertainty on the system as a whole. Monte Carlo analysis is a well known simulation application for uncertainty analysis. It has the ability to use large number of random values for inputs and to obtain an accurate result without propagating an error (Checkel et al., 1999). When using Monte Carlo analysis, the model must be run through a sufficient number of iterations to converge on a mean value (Checkel et al., 1999). Many Monte Carlo models are available online and in this analysis, excel based Montercarlito 1.10 application is used as the simulation source (Available from: http://www.montecarlito.com). Monte Carlo simulation was used with 10,000 iterations to identify the total system uncertainty. The Monte-Carlo analysis results for the direct combustion power cost are shown graphically in Figure 3-23. The results distribution is bit flatter than the normal distribution.

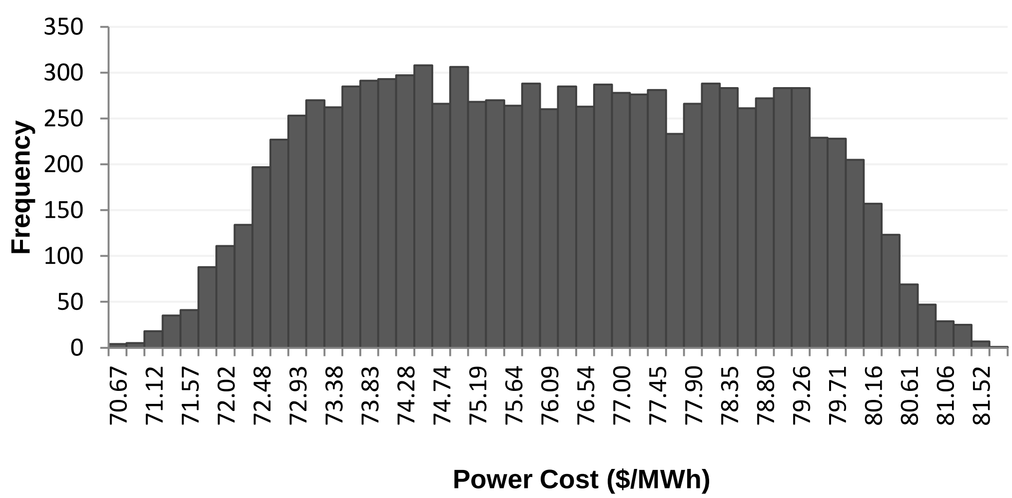


Figure 3-23: Graphical representation of Monte-carlo results

According to the Monte-Carlo simulation results, the base case power cost range is $76.33 ± $4.76 /MWh at a 95% confidence level. The results are shown in in Table 3-23.

Table 3-23: Monte-Carlo results for direct combustion power cost

Result	90% (1.645 σ)		95% (1.960 σ)	
	Low	High	Low	High
Cost ($/MWh)	72.31	80.30	71.57	81.08

3.9 Conclusions

Compared to the coal power generation, triticale straw power generation for Alberta based on direct combustion technology is not economically viable even at any large plant size up to 1000 MW. The lowest power cost with the existing technology is $76.33 /MWh at the largest unit size of 300 MW. However, if manufacturing larger boiler units than 300 MW were feasible, there a lower power cost can be achievable. The power cost could be reduced to $75.02 /MWh if the plant was installed with a 595 MW capacity single boiler unit. The direct combustion power cost is most sensitive to capital cost variations. If the capital cost can be reduced by 20%, the power cost drops to $67.85 /MWh. For this sensitivity scenario, the optimum plant size also reduces to 497 MW with optimum power cost of $67.61 /MWh.

Table 3-24: Power cost summary

Scenario	Power Cost ($/MWh)	Remarks
1. Base case – 300 MW	76.33	Not competitive with fossil power.
2. Optimum feasible power cost	76.33	At 300 MW, largest unit size considered.
3. Without equipment sizing limitations	70.70	Optimum plant size - 595 MW
4. Reduce capital cost by 20%	67.85	Optimum plant size - 497 MW

Discontinuities occur at the multiple unit size capacities in the power cost curve. The curve is almost flat for plant capacities greater than 300 MW. It can be shown that the power cost from 130 to 900 MW is within 5% of the lowest power cost at the largest base case unit size. This behaviour occurs because the reduction of the capital cost per unit of capacity achieved by the economy of scale offsets the increase in the straw transportation cost, which increases with larger plant capacities. This result means that power plants which are lower and higher than the optimum size in the size range of 130 to 900 MW can be operated with a cost penalty of less than 5%. Changes in the power plant capital cost and plant efficiency impacts the power cost significantly.

Even though, the triticale straw to power via direct combustion is economically not competitive in the present context, biomass power production still has the potential to succeed with the carbon credits. This is discussed in detail in the next chapter.

References

Allnorth Consultants. "Cost Benefit Analysis." Biomass Power Generation. Allnorth Consultants Ltd, 2010.

Bain, R. L., W. A. Amos, M. Downing, and R. L. Perlack. Highlights of Biopower Technical Assessment: State of the Industry and the Technology. Technical Report, National Renewable Energy Laboratory, U.S.A, 2003.

Barreto, L., and S. Uddin. "Biomass-fired Cogeneration Systems with CO2 Capture and Storage." Renewable Energy 32 (2007): P. 1006-1019.

Bastiaans, R. Energy from Biomass. University of Technology, Eindhoven. http://w3.wtb.tue.nl/fileadmin/wtb/ct-pdfs/Energy_from_Biomass/Lecture_8_2010.pdf, 2010.

Biomass Energy Center. Moisture Content. 2008. http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,177178&_dad=portal&_schema=PORTAL (accessed 8 10, 2010).

Brown, G., A. D. Hawkes, A. Bauen, and M. A. Leach. Biomass Applications. Available from: http://www.eusustel.be/public/documents_publ/WP/WP3/Biomass, EUSUSTEL, 2006.

Cameron, J. B., A. Kumar, and P. C. Flynn. "Straw to Power: Economics and Barriers – A Canadian Case." 2004 ASAE/CSAE Annual International Meeting. Ottawa, Ontario, Canada, 2004. Paper Number: 048039.

Cameron, J. B., A. Kumar, and P. C. Flynn. "The Impact of Feedstock Cost on Technology Selection and Optimum Size." Biomass and Bioenergy 31, no. 2-3 (2007): 137-144.

Capital Power Income. Williams Lake Power Plant. 2011. http://www.capitalpowerincome.ca/en-ca/operations/Canada/Pages/williams.aspx (accessed 02 23, 2011).

Canada Visa. www.Canadavisa.com. 2009. http://www.canadavisa.com/canada-salary-wizard.html (accessed 04 13, 2009).

Checkel, M. D., M. Raynolds, and R.A. Fraser. Application of Monte Carlo Analysis to Life Cycle Assessment. SRE Technical Paper Series, Society of Automotive Engineers, 1999.

Coxworth, E., L. T. Smith, and M. Stumborg. "Sustainability and Economic Issues for Cereal Crop Residue Export." Canadian Journal of Plant Science 76, no. 4 (1996): 669-673.

DeFusco, J.P., P.A. McKenzie, and M.D. Fick. "Bubbling fluidized bed or Stoker-Which is the right choice for your renewable energy project?" CIBO Fluid Bed Combustion XX Conference. Lexington, Kentucky, USA: The Babcock & Wilcox Company, USA, 2007.

EPA. Biomass Combined Heat and Power Catalog of Technologies. U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007.

Fleuren, W., A. J. A. Konings, J. H. W. Lindeman, A. E. Pfeiffer, H. Pustjens, and R. D. Smeets. Opportunities for a 1000 MWe Biomass-fired Power Plant in the Netherlands. KEMA Power Generation & Sustanables, 2005.

Graham, R. L., R. Nelson, J. Sheehan, R. D. Perlack, and L. L. Wright. "Current and Potential U.S. Corn Stover Supplies." Biofuels (American Society of Agronomy) 99 (2007): 1-11.

Gustavsson, L., and R. Madlener. "CO2 Mitigation Costs of Large-Scale Bioenergy Technologies in Competitive Electricity Markets." Energy 28, no. 14 (2003): P. 1405-1425.

Haq, Z. Biomass for Electricity Generation. http://www.eia.doe.gov/oiaf/analysispaper/biomass/pdf/biomass.pdf, 2002.

Hartman, M. "Direct Seeding - Estimating the value of crop residues." Alberta Agriculture and Rural Development, 2008.

Hughes, E., D. O'Connor, and D. Tillman. Biomass Cofiring Update 2002. Electric Power Research Institute, 2003.

Huijbregets, M. A. J.; Norris, G.; Bretz, R.; Ciroth, A.; Maurice, B.; Bahr, B.; Weidema, B.; Angelina, S. H.; Beaufort, S. H. "Framework for Modelling Data Uncertainity in Life Cycle Inventories." Int J LCA 6, no. 3 (2001): 127-132.

IEA. "Biomass for power generation and CHP." IEA Energy Technology Essentials, January 2007.

IHS. Power Plant Construction Costs Falling for All Types of New Plants. http://press.ihs.com/article_print.cfm?article_id=4051 Accessed on 2009/06/10, 2009.

Kampman, B. E., L. C. den Boer, and H. J. Croezen. "Biofuels under development." CE, 2005.

Khan, A.A., W. de Jong, P.J. Jansens, and H. Spliethoff. "Biomass Combustion in Fluidized Bed Boilers: Potential Problems and Remedies." Fuel Processing Technology, no. 90 (2009): 21-50.

Kumar, A, J B Cameron, and P C Flynn. "Biomass Power Cost and Optimum Plant Size in Western Canada." Biomass and Bioenergy 24 (2003): 445-464.

Kumar, A., and P. Flynn. Site Visit to Alholmens 240 MW Power Plant Pietarsaari, Finland. Trip Report, Department of Mechanical Engineering, University of Alberta, BIOCAP Canada, 2005.

Kumar, A., P. C. Flynn, and S. Sokhansanj. "Biopower Generation from Mountain Pine Beetle Infested Wood in Canada: An economical opportunity for greenhouse gas mitigation." Renewable Energy 33, no. 6 (2008): 1354-1363.

Larson, J.A., B.C. English, and L. Lambert. Economic Analysis of the Conditions for Which Farmers will Supply Biomass Feedstocks for Energy Production. University of Tennessee, 2007.

Levelton Consultants, and Envirochem Services Inc. Feasibility Study: Identifying Economic Opprtunities for Bugwoood and Other Biomass Resources in Alberta and BC. Alberta Energy Research Institute, 2008.

Lundqvist, R. Fluidized Bed Combustion of Unconventional Fuels; A Few Studies from Operating Boilers." Presented at IEA Fluidized Bed Technology. 1999.

Mann, M.K., and P. L. Spath. "Life Cycle Assessment of a Biomass Gasification Combined-Cycle System." NREL, Midwest Research Institute, 1997.

McKendry, P. Energy Production from Biomass (part 3): Gasification Technologies. Bioresource Technology, no. 83 (2002): 55–63.

Meier, M.A. Eco-Efficiency Evaluation of Waste Gas Purification Systems in the Chemical Industry. Dissertation, Zurich, 1997.

OPET. The world´s largest biofuel CHP plant Alholmens Kraft, Pietarsaari. VTT Energy, 2001.

Overend, R.P. The Average Haul Distance and Transportation Work Factors for Biomass Delivered to a Central Plant. Biomass 2 (1982): 75-79.

Pauly, D. "Fertlizer Prices Effect the value of Hay and Straw." The Blade, August 2008: P. 3.

Phelps, S.M., B. Beres, E. Johnson, C. Pozniak, and S. Chant. 2008 Western Canadian Ethanol Feedstock Trial Interim Report. Western Applied Research Corporation, 2009.

Prairie Practitioners Group. "Straw Procurement Business Case." 2008.

Sarkar, S., and A. Kumar. "A Review of Techno-Economics of Bio-Hydrogen Production Technologies." ASABE Annual I nternational Meeting. Minneapolis, Minnesota, 2007.

Sarkar, S., and A. Kumar. "Techno-Economic Assessment of Biohydrogen Production from Forest Biomass in Western Canada." Transaction of the ASABE 52 , no. 2 (2009): 1-2.

Schnitkey, G., D. Lattz, and J. Siemens. "Machinery Cost Estimates." Farm Business Management Handbook, 2000.

Searcy, E. Selection of a Biomass Proceesing Technology. A Thesis, University of Alberta, 2009.

Sherrington, C, J Bartley, and D Moran. "Farm-level Constraints on the Domestic Supply of Perennial Energy Crops in the UK." Energy Policy, no. 36 (2008): 2504– 2512.

Sieusahai, G. "Personal Communication." Agriculture Research Division, Alberta Agriculture & Rural Development. 2010.

Sokhansanj, S, A.F. Turholow, J Stephen, and M Stum. "Analysis of Five Simulated Straw Harvest Scenarios." Canadian Biosystems Engineering , no. 50 (2008): 2.27-2.35.

Sokhansanj, S. "IBSAL Model." UBC Biomass and Bioenergy Research Group. 2008. http://www.biomass.ubc.ca/IBSAL.html (accessed 07 28, 2010).

Sokhansanj, S.; Mani, S.; Turhollow, A.; Kumar, A.; Bransby, D.; Lynd, L.; Laser, M. "Large-Scale Production, Harvest And Logistics of Switchgrass (Panicum virgatum L.) – Current Technology and Envisioning a Mature Technology." Biofpr-Biofuels, Bioproducts & Biorefining (Society of

Chemical Industry and John Wiley & Sons, Ltd), no. 3 (2009): P. 124–141.

Spath, P., A. Aden, T. Eggeman, M. Ringer, B. Wallace, and J. Jechura. Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly- Heated Gasifier. Technical Report, National Renewable Energy Laboratory, 2005.

Stat Canada. Census of Agriculture. 2006. http://www.statcan.ca (accessed 4 19, 2009).

Stinger Inc. "Stinger 6500." 2009. http://www.stingerltd.com/products/stacker/stinger_stacker.htm (accessed 08 25, Accessed on 2010).

The Centre for Biomass Technology. "Straw at Power Plants." "Straw for Energy Production", Technology-Environment-Economy, 1998.

Uddin, N. Techno-economic Assessment of a Biomass-based Cogeneration Plant with CO2 Capture and Storage. Interim Report, International Institute for Applied Systems Analysis, Austria, 2004.

Van den Broek, R., A. Faaji, and A. Van Wijk. "Biomass Combustion Power Genertion Technologies." Department of Science, Technology and Society, Utrecht University, Netherland, 1995, 58-60.

Van der Berg, N.W., G. Huppes, E.W. Lindeijer, B.L. van der Ven, and M.N. Wrisberg. Quality Assessment for LCA. CML Report vol. 152, Leiden: Centre of Environmental Science, 1999.

Weidema, B.P. "Multi-User Test of the Data Quality Matrix for Product Life Cycle Inventory Data." Int. J. LCA 3, no. 5 (1998): 259-265.

Zundel, P. E., A.J. Hovingh, L. Wuest, D. MacElveney, and T. D. Needham. " Silviculture Systems for the Production of Energy Biomass in Conventional." University of Brunswick, Canada, 1996.

4 Life Cycle Assessment of Direct Combustion of Triticale Straw for Power Generation

4.1 Introduction

The life cycle assessment of the impacts of electricity production from triticale straw via direct combustion is the initial step in the environmental assessment of this conversion pathway and can help to explain the benefits of utilizing triticale straw for power generation in Canada. The results can also serve as a measure for evaluating triticale straw as an energy producing feedstock in comparison with the other biomass feedstocks and fossil fuel options that are currently being utilized in Canada. Recently, the life cycle assessment (LCA) of GHG emissions became a key decision making criterion along with the economic parameters. Many LCA studies on biomass power generation at small plant sizes from 9-25 MW range have been published (Liu et al., 2010; Sebastián et al., 2010; Suramaythangkoora and Gheewala, 2008), however none of these studies have assessed the utilization of triticale straw as a feedstock for power generation.

This LCA study is a cradle to grave analysis starting from triticale crop cultivation followed by straw harvesting and finally its utilization for electricity production. This study has closely followed the LCA methodology documented in ISO 14040 and ISO 14044 (International Organization for Standardization, 2006). The environmental impacts are determined by considering the whole product life cycle, which includes material extraction and refining, manufacturing, transport and disposal. The process includes the collection of input and output data inside the system boundary (inventory analysis) and the analysis of the environmental performance of these inputs and outputs (impact assessment) (Weinzettel et al., 2009). The focus of the LCA here is to estimate the GHG emissions, energy consumption, and CO2 mitigation cost of direct combustion technology for power generation that uses triticale straw as the feedstock. The base case scenario considers a 300 MW direct combustion power plant using triticale straw. The major unit processes involved in the pathway of direct combustion for electricity generation from triticale straw include farming the triticale, harvesting and collection, transportation of triticale straw, power plant construction, plant operation and decommissioning.

4.2 Goal and Scope

This LCA is aimed at determining the primary energy use and global warming mitigation potential of electricity production using triticale straw. The results of the study will enable the interested parties to compare the energy and GHG emissions of triticale straw power with those of other available biomass feedstock. The study also focuses on investigating the variation of the life cycle GHG emissions and energy with key parameters.

4.2.1 Key Objectives

The specific objectives of the LCA were

- Determination of the life cycle energy consumption for production of 1 MWh of electricity;
- Quantification of the life cycle CO_2 emissions for production of 1 MWh of electricity;
- Estimation of CO_2 abatement potential;
- Determination of carbon credits required by the triticale based power to be competitive with the coal based power in Alberta;
- Identification and evaluation of key sensitivities; and
- Estimation of the uncertainty in the results.

4.2.2 Functional Unit

The LCA functional unit is the yardstick for comparing these results with those from other LCA studies. Hence, the GHG emissions and energy involved with producing 300 MW of electricity is estimated by using 1 MWh of electricity as the functional unit.

4.2.3 Methodology

The product life cycle considered in the study has the four stages detailed below (Cooper and Vigon, 2001).

- Material Production: Material production involves the extraction and processing of all the materials relevant to the LCA inputs. The extraction itself involves the activities related to the acquisition of natural resources. For example, it could be the mining of coal or the harvesting of biomass. The processing involves the production of other fossil fuels, chemicals, fertilizers, lubricants, etc.
- Manufacturing and Construction: This stage involves the machinery production activities, vehicle production, plant construction, and other building constructions.
- Use, Repair and Maintenance: Machinery, vehicles, and building related ongoing activities are considered here.
- Decommissioning, Material Recovery and Disposal: Decommissioning of the power plant and other buildings, material recovery from machines and vehicles, and disposal of waste.

The material recovery includes an open loop where the recovered and recycled material can be used to manufacture similar products.

4.2.4 Unit Processes

The complete power production life cycle is divided into the five unit processes shown in Figure 4-1. Each unit process consists of several sub processes which cumulatively contribute to energy consumption and GHG emissions.

4.2.4.1 System Boundary

All the key activities from triticale farming to electricity production have been considered.

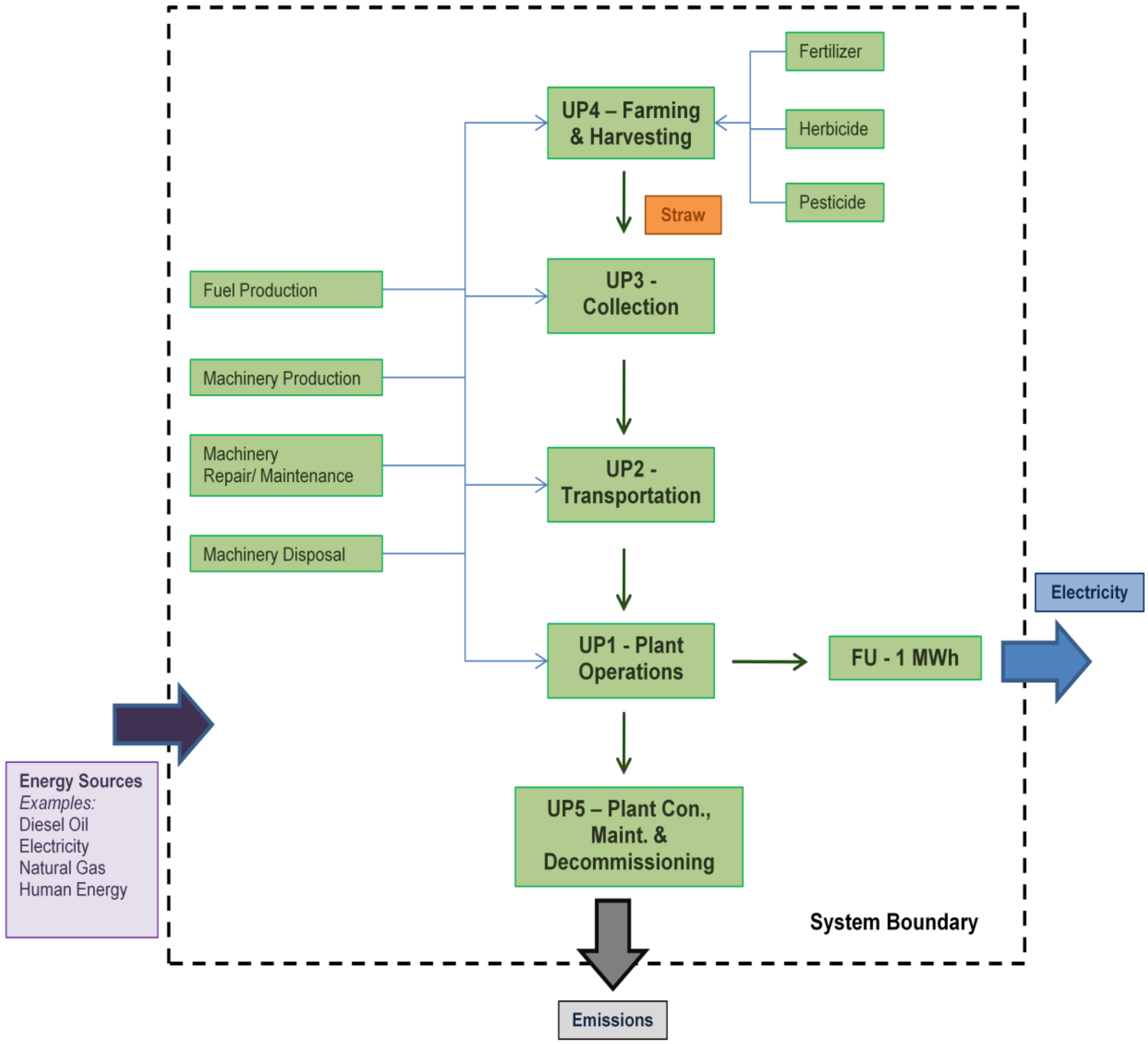


Figure 4-1: Life Cycle Boundary of the Study

4.3 Life Cycle Energy and Emissions Inventory

Energy is the prime input to any agricultural production and has many different forms such as mechanical energy, human energy, fuel energy, and electrical energy. Except for the human effort in the field, all the energy forms are associated with emissions.

4.3.1 Farming and Harvesting

When trying to estimate the energy consumption in triticale farming, this study deals with both pre-farm and on-farm energy inputs. Most farming practises used for triticale are very similar to those for wheat (Alberta Agriculture, 2005). Many studies were reviewed to identify the types of machinery used for wheat farming in North America. The machinery specifications selected for the calculations are similar to the existing machinery parameters on Canadian prairie farms (Nagy, 1999).

Low tillage systems are being promoted and increasingly used by farmers in Western Canada, especially in the prairies. Alberta Agriculture and Rural Development highlights the need to switch to reduced-tillage or zero-tillage systems to protect the soil from erosion (Vanderwel and Abday, 2001). Hence, this study has considered a zero-tillage system in the base case scenario.

4.3.1.1 Farming Operations

Energy consumption in triticale farming operations such as seeding, fertilizer broadcasting, spraying irrigation, and field transportation has been taken into account. The farming area needed to supply biomass to a 300 MW plant is about 0.7 million hectares per year, based on an average yield of triticale straw. The largest applicable machinery sizes were selected wherever possible to obtain the maximum benefits of economy of scale. When wheat is considered, there are many types of machineries used, from one farm to another. However, it is reasonable to assume that the machinery selection for future triticale farming will be based on readily available options. Table 4-1 provides a description of the machines considered in all the studied farm operations.

Table 4-1: Farming Operations (Nagy, 1999)

Operation	Diesel Usage	Power (hp)	Work Rate
Banding Granular Fertilizer	48.2	300	8.9
Banding Anhydrous Ammonia	49.8	300	10.0
Seeding	39.6	300	10.0
Chemical Applicators	21.5	250	26.1
High Clearance Sprayers	48.9	300	58.6
Harvest- Combine Class 7	43.0	300	3.9[18]

4.3.1.2 Machinery Embodied Energy

The indirect energy input of agricultural machinery includes many different energy forms. Direct energy inputs to farming machinery can be measured or analysed. However, the indirect energy inputs are difficult to quantify and analyse. Most studies have approximated these inputs as a percentage of the total energy consumption. The indirect energy types relevant to farm machinery are manufacturing energy, repair and maintenance energy, transportation energy, and storage energy.

Agricultural machinery is usually kept in either cheaply constructed buildings or outdoors (Mikkola and Ahokas, 2010). With outdoor storage, no energy or emissions are involved. The indoor storage facility considered here also consumes negligible energy compared to the total life cycle energy. The repair and maintenance (R&M) of agricultural machinery need a considerable amount of energy compared to the manufacturing energy of the machinery. Mikkola and Ahokas (2010) have reported that the R&M energy is 55% of the machinery manufacturing energy.

The energy and GHG emissions involved in supplying the farm machinery for the field is also an important indirect energy consideration. The embodied energy of a machine consists of the raw materials and parts' manufacturing energy, assembly energy, and transport energy. For a tractor used in the prairies, this total embodied energy is 55.8 MJ/kg, and the R&M energy is 26.4 MJ/kg (Nagy,

[18]This value is adjusted for the yield in this study.

1999). For trucks, the total embodied energy is 100.2 MJ/kg, including the R&M and lubricants' indirect energy contributions (Nagy, 1999).

4.3.1.3 Fertilizer Production

When the system boundary of a life cycle analysis is expanded to include the indirect energy inputs, the fertilizer production becomes a significant energy and GHG emissions' contributor. One third of the USA crop production life cycle energy input is consumed by the fertilizer sector (Gellings and Parmenter, 1998). Considering the large variety of fertilizer types used and their complicated manufacturing processes, the estimation of the energy and GHG emission coefficients is difficult. The major emissions during fertilizer production are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Table 4-2 shows the CO_2 equivalent emissions of fertilizer manufacturing.

According to Patzek (2004), the energy usage for fertilizer production depends on the age of a plant, since a newer plant uses more energy efficient technologies than an older plant. The fertilzer manufacturing energy of European factories seems to be less than that of North American factories. Patzek (2004) assumes that the energy requirement for ammonia production in North America is 54 MJ/ kg N.

The GHG emissions from ammonia production in Canada are 1.68 kg CO_2/kg NH_3 (Natural Resources Canada, 2008). In urea plants based on natural gas, some of the CO_2 emisions are recovered for urea production. Hence, the actual released CO_2 amount is 1.07 kg CO_2/kg NH_3 (Natural Resources Canada, 2008). Nevertheless, the highest CO_2 emissions are 1.68 kg CO_2/kg NH_3 (Natural Resources Canada, 2008). This level of GHG emissions is used in this analysis. The nitrogen, potassium and phosporous-based fertilizer production coefficients analysed by Nagy (1999) are also used in this study. The pottasium and phosporous production emissions are taken from EBAMM v1.1, ERG Biofuel Analysis Meta-Model; 2006 version (Energy and Resources Group, 2006).

The types of fertilizer applied and the respective application rates are given in section 2.4.1, and the total energy amounts associated with fertilizer prodution are calculated accordingly. The energy required to produce fertilizer consists of the indirect energy consumptions for producing, packaging and transporting fertilizer.

Table 4-2: Literature review on fertilizer production energy and emissions

Fertilizer	Energy Coefficient (MJ/kg)	Emission Coefficient (kg CO_2/kg)	Source	Country
Nitrogen	43.2	2.64	(Daugherty, 2001)	Sweden
	76.6	-	(Gellings and Parmenter, 1998)[19]	USA
	54.43	-	(Patzek, 2004)	USA
	56.9	-	(Shapouri, 2004)[20]	USA
	50.9		(Graboski, 2002)[21]	USA
	57.5	3.14	(De Oliveira et al., 2005)	USA
	64.04	-	(Nagy, 1999)[22]	Canada
	-	4	(Energy and Resources Group 2006)[23]	USA
	-	1.95	(Wood and Cowie, 2004)[24]	Canada
Potassium	4.7	0.47	(Daugherty, 2001)	Sweden
	16.0	-	(Gellings and Parmenter, 1998)	USA
	6.8	-	(Patzek, 2004)	USA
	7.0	-	(Shapouri, 2004)	USA
	4.8	-	(Graboski, 2002)	USA
	6.9	0.44	(De Oliveira et al., 2005)	USA
	9.85	-	(Nagy, 1999)	Canada
	-	0.71	(Energy and Resources Group 2006)	USA

[19]Gellings and Parmenter's (1998) original energy values include Produce, Package, Transport and Apply energy. Here, the Apply energy values are deducted since fertilizer application is considered separately.
[20]Original values are in Btu/lb and converted to MJ/kg.
[21]Original values are in Btu/lb and converted to MJ/kg EBAMM v1.1.
[22]Nagy (1999) developed the average energy coefficients for N in Alberta. 64.04 MJ/kg of N is the average Nitrogen production energy for this province.
[23]EBAMM v1.1 is a bio-fuel life cycle energy and emission analysis model based on several studies. This model is available to download at http://rael.berkeley.edu/sites/default/files/EBAMM/
[24]Wood and Cowie (2004) extracted the data for Canada from the Intergovernmental Panel on Climate Change (IPCC) 1996a and 1996b.

Fertilizer	Energy Coefficient (MJ/kg)	Emission Coefficient (kg CO_2/kg)	Source	Country
Phosphorus	6.8	0.008	(Daugherty, 2001)	Sweden
	12.8	-	(Gellings and Parmenter, 1998)	USA
	6.8	-	(Patzek, 2004)	USA
	9.3	-	(Shapouri, 2004)	USA
	1.9	-	(Graboski, 2002)	USA
	7.0	0.61	(De Oliveira et al., 2005)	USA
	9.53	-	(Nagy, 1999)	Canada
	-	1.6	(Energy and Resources Group 2006)	USA

4.3.1.4 Pesticide and Herbicide Production

Pesticides and herbicides also have energy intensive production processes. With increasingly larger numbers of chemicals being used as pesticides and herbicides, the energy needed to produce of these chemicals consumes about 15% of the total energy usage in the agricultural world (Helsel, 2006). Triticale requires less pesticides and herbicides compared to other cereal crops. Section 2.4.2.1 discusses the current herbicide and pesticide recommendations for triticale. An average chemical application scenario is considered in the base case and is in accordance with the specific herbicide and pest control guidelines given by Manitoba Agriculture, Food and Rural Initiatives (Manitoba Agriculture, 2010). The energy values given for the herbicide Achieve 40 DG and the insecticide Decis by Nagy (1999) have been used in this LCA.

Table 4-3: Literature review on chemical production energy and emissions

Chemical Type	Energy Coefficient (MJ/kg)	Emission Coefficient (kg CO2/kg)	Source	Country
Herbicides	266.56	17.24	(De Oliveira et al., 2005)	USA
	261.0	-	(Patzek, 2004)	USA
	355.6	-	(Shapouri, 2004)	USA
	237.3	-	(Wang, 1997)	USA
	313.77	-	(Nagy, 1999)[25]	Canada

[25]The energy coefficient is for Achieve 40 DG, a herbicide recommended for triticale by Alberta Agriculture.

Chemical Type	Energy Coefficient (MJ/kg)	Emission Coefficient (kg CO2/kg)	Source	Country
Pesticides	284.82	18.08	(De Oliveira et al., 2005)	USA
	268.0	-	(Patzek, 2004)	USA
	358.0	-	(Shapouri, 2004)	USA
	243.0	-	(Wang, 1997)	USA
	217.0	-	(Nagy, 1999)[26]	Canada

4.3.1.5 Harvesting

The harvesting operations and machinery details are explained in section 2.4.6. The process energy of harvesting is estimated based on the fuel consumption and efficiency of each machine (Sokhansanj, 2008).

4.3.2 Collection

The straw collection process and conditions are discussed in sections 2.5 and 3.5.2. The machinery data for straw collection and handling are given in Table 4-4.

Table 4-4: Machinery used for straw collection and transportation [27]

Machine	Capacity	Diesel Usage (L/hr)	Power (hp)
Rake	30 (Dry tonne/hr)	14.1	85
Baler	20 (Dry tonne/hr)	58.0	350
Stinger	8 (bales/load)	58.0	350
Bale Loader	2 (bales/load)	56.1	350
Bale Wrapper	60 (bales/hr)	3.3	20
Truck	34 (bales/load)	91.2	550
Shredder	40 (Dry tonne/hr)	24.9	150

[26]The pesticide energy coefficient is based on Decis, which is recommended by the Manitoba Agriculture Crop Guide for triticale.
[27]The machinery data were obtained from the IBSAL Model (Sokhansanj, 2008).

4.3.3 Transportation

In a complete life cycle analysis of freight transportation, the life cycle phases of the vehicles, infrastructure, and fuels have to be included. The triticale power plant has to be located near consumers or the existing infrastructure. Hence, it is assumed that the infrastructure for transportation (i.e., roads) is available and that no significant additional road construction is required. Even though minor differences could exist, the LCA analysis of transportation always takes a regional perspective. Most types of vehicles used in different regions of North America are similar and only the fuel consumption varies due to the differences in terrain and extreme weather conditions (Facanha & Horvath, 2006). The transportation inventory data also include the production, operation and disposal of trucks.

The transportation distances were calculated by assuming a geometrically rectangular road grid over the flat terrain of Alberta. If we consider truck versus rail transportation, the energy requirements are 1.3 $MJt^{-1}km^{-1}$ for trucks and 0.68 $MJt^{-1}km^{-1}$ for trains (Pootakham and Kumar, 2006). However, truck transportation is the only transportation mode analysed in this study.

4.3.4 Plant Operations

The main environmental benefit of biomass based energy is that it is nearly carbon neutral over the full life cycle. The CO_2 emitted during the conversion of biomass to electricity is the same as the amount of atmospheric CO_2 absorbed by the plants during the growth phase.

4.3.4.1 Feedstock pre-treatment for direct combustion

Although any type of biomass can be combusted in power plants, combustion is easiest when the moisture content is less than 50% (McKendry, 2002). The moisture content of the triticale straw is assumed to be 15% db (Food and Agriculture Organization, 2004). Therefore, drying is not required for the direct combustion pathway. By using shredders, the straw bales are shredded to a length of about 8 inches before being fed to the boiler. The shredder data were extracted from the IBSAL model (Sokhansanj, 2008).

4.3.4.2 Ash disposal

Ash is assumed to be spread in fields as a form of nutrient replacement. The ash transportation distance is considered to be 50 km. The trucks for the transportation of ash are assumed to be the same as those used to transport straw bales. The inventory data relevant to the production, use, and disposal of trucks are also included.

4.3.5 Plant Construction, Maintenance and Decommissioning

4.3.5.1 Construction

The data for the energy and emissions of plant construction were derived from previous studies (Elsayed et al., 2003; Elsayed and Mortimer, 2001). However, to quantify the energy inputs and emissions accurately, a list of the construction operations, material requirements, and the machinery types and usages is required. Such data are available for small scale biomass plants in the range of 1 – 30 MW. The primary energy input to construct a 20 MW wheat straw fired plant is estimated to be 1050 TJ (Elsayed et al., 2003). It can be further derived that 102 MJ of primary energy input is required to produce 1 GJ of electrical energy. Elsayed et al (2003) also report that the CO_2 emissions during the construction of this plant are 56,200 tonnes. Based on these data, the energy and emissions have been scaled up for a 300 MW plant size.

4.3.5.2 Plant Maintenance

For many existing plants, some general data exist for the energy consumed in maintenance activities and their corresponding emissions. It has been estimated that the energy required for power plant maintenance activities is usually between 2.5% to 5% of the plant construction energy (Elsayed and Mortimer, 2001). In this study, the energy and emissions for plant maintenance are assumed to be 3% of the energy and emissions during the construction of the plant.

4.3.5.3 Decommissioning

According to some studies, the primary energy input and relevant CO_2 emissions of plant decommissioning are in the range of 3% to 5% of the energy and emissions associated with plant construction (Elsayed and Mortimer, 2001). Here, the percentage is assumed to be 5%. The recycling of metals, including construction and plant machinery metals, is within the considered life cycle boundaries. All non-recyclables are landfilled at a distance of 50 km from the plant.

4.3.6 Fuel Production

Diesel fuel is used for the farming machinery and transportation. Diesel production in Canada is considered to be different from that in the rest of the world as Canadian diesel fuel is derived from tar sand synthetic oil (Rollefson et al., 2004). Rollefson and colleagues calculated that the complete life cycle emissions during diesel production in Canada are 1.204 kg CO2 eq./kg. These researchers considered a mix comprised of 27% light crude onshore (or conventional), 10% light crude offshore, and 63% heavy oil. This mix is considered appropriate for Western Canada (Rollefson et al., 2004). This mentioned study included the emissions during oil production, oil transport to the refinery, oil refining, fuel storage and distribution, and fuel dispensing. The characteristics of diesel fuel reported in Rollefson et al.'s study include a density and HHV of 0.843 kg/l and 45.8 MJ/kg, respectively.

Petroleum based diesel needs 1.1995 MJ of fossil energy to produce 1 MJ of fuel energy (Sheehan et al., 1998). Another study calculated the energy of diesel production as 1.186 MJ/MJ of diesel (Cheminfo-Services and $(S\&T)^2$ Consultants, 2000).

4.3.7 Recycling and Waste Disposal

The steel, iron and aluminum used in all machinery, plant equipment and construction are considered to be fully recycled. The amount of steel used in farm machinery is assumed to be 98% of the total weight, wherever the exact value is unavailable (Mann & Spath, 1997). The recycling energy and GHG emissions were extracted from previous literature (ICF Consulting, 2005).

Table 4-5: Energy and GHG emissions benefit of recycling [28]

Energy Intensity	Raw Material (GJ/t)	Recycled Material (GJ/t)	Energy Saved (GJ/t)	GHG Emissions Saved (kg/t)
Steel	25.5	9.7	15.8	1,180
Aluminum	120.3	16.8	103.5	6,490

The concrete used in the plant is assumed to be landfilled, and the relevant energy and GHG emissions are included in the analysis. The waste collection, transport to the landfill, and heavy equipment operations in the landfill are included in the energy associated with landfilling, which is calculated to be 0.15 GJ/t (ICF Consulting, 2005). The GHG emissions of the total landfilling process are 14.6 kg eCO_2/t of waste (ICF Consulting, 2005).

4.3.8 Input Data and Assumptions

The assumptions and data given in Table 3-1 are valid for the life cycle analysis as well. The additional assumptions and data needed are listed below.

Table 4-6: Input data and assumptions

Items	Values	Comments/Remarks
Calorific value of diesel	45.8 MJ/kg	Rollefson et al. (2004)
Bale weight	0.58 t	Calculated.
Bale density	10 lb/ ft^3	Sokhansanj (2008)
Plant capacity	300 MW_e	Same as in Chapter 3.
Plant efficiency	25% $0<C\leq50$ 30% $50<C\leq150$ 34% $150<C\leq300$ 38% $300<C\leq600$ 40% $600<C\leq900$ 42% $900<C$	The efficiency profile is assumed based on the data listed in: Kumar et al. (2003); McKendry (2002); Kumar and Flynn (2005); IEA (2007)
Plant scale factor	0.75	Kumar et al. (2003)

[28] The recycling data were extracted from a report by ICF Consulting (2005).

4.4 Impact Assessment

4.4.1 Life Cycle Energy Analysis

Biomass systems need fossil fuel based energy in the form of fuel oil and electricity in all upstream and in-plant operations. As shown in Table 4-7, the agricultural phase consumes the largest percentage of the energy. If triticale is regarded as an energy crop, the corresponding energy and GHG emissions associated with the farming and harvesting operations need to be allocated for both the straw and the grain. The allocation has been done based on the weight and by using the straw to grain ratio. Therefore, 52% of the total energy input and GHG emissions have been allocated to the straw.

Table 4-7: Life cycle energy consumption for base case

Unit Process	PJ/Year	GJ/dt	GJ/MWh	Percentage
Farming and Harvesting	2,194	1.11	0.98	56.0%
Collecting	451	0.25	0.20	11.5%
Transportation	1,164	0.70	0.52	29.7%
Plant Operations	71	0.04	0.03	1.8%
Plant Construction, Maintenance & Decommissioning	39	0.02	0.02	1.0%
Total	3,919	2.12	1.75	

4.4.1.1 Net energy ratio

The net energy of the system is defined as the energy produced in the form of electricity divided by the life cycle fossil fuel energy consumption and describes the energy production per unit of fossil energy consumption (Keoleian and Volk, 2005). The net energy ratio, regarded as an indicator of the energy performance, is used to compare alternative power producing technologies and feedstocks. The life cycle efficiency, on the other hand, is a measure of the overall system efficiency as well. The key point to note is that the life cycle efficiency of fossil-fuelled power generation systems gives a negative value or energy deficit.

Table 4-8: Energy ratios

Ratio[29,30]	Value
Net Energy Ratio, E_g/E_{ff}	6.84
Life Cycle Efficiency, $(E_g - E_u)/E_{fs}$	17.4%

4.4.2 Life Cycle Emission Analysis

Table 4-9 presents the GHG emissions from the unit processes and the percentage contribution to the total emissions in the base case scenario.

Table 4-9: CO_{2e} Emission for base case

Unit Process	kt CO_{2e}/Year	kg CO_{2e}/dt	kg CO_{2e}/MWh	Percentage
Farming and Harvesting	76.0	38.3	34.0	34.8%
Collecting	35.8	19.5	16.0	16.4%
Transportation	98.5	59.6	44.1	45.1%
Plant Operations	5.9	3.6	2.6	2.7%
Plant Construction, Maintenance & Decommissioning	2.4	1.5	1.1	1.1%
Total	218.6	122.5	97.9	

The life cycle GHG emission for triticale straw based power production is 97.9 kg CO_{2e}/MWh. The main contributor to life cycle emissions is feedstock transportation. Farming and harvesting contribute to about 35% of the total GHG emissions due to the usage of several diesel based field operations' equipment. Plant construction and related activities emit only about 1% of the total GHGs.

Table 4-10 shows the CO_2 mitigation potential of triticale power generation compared to Alberta's grid mix, which is coal based and natural gas based power production. The GHG abatement potential increases with the increasing plant size due to the increased efficiency of conversion.

[29] E_{ff} – Fossil fuel energy; E_g – Energy delivered to the grid; Source - Mann and Spath (1999).

[30] E_u – Upstream process energy; E_{fs} – Feedstock energy; Source - Rafaschieri et al. (1999).

Table 4-10: Comparative CO_2 Mitigation Potential

Emission Source	Life Cycle Emission (kg CO_{2e}/MWh_e)	Comparative Mitigation (Mt CO_{2e}/Year)
Grid Mix[32]	1092	2.20
Coal[31]	1155	2.33
Natural Gas[32]	790	1.53

Table 4-11: CO_2 Abatement Potential for Different Plant Sizes

Capacity (MW)	Efficiency (%)	CO_2 Emission (Mt CO_{2e}/Year)	CO_2 Emission (kg CO_{2e}/MWh)	CO_2 Abatement ($MtCO_{2e}$/Year)	Life Time CO_2 Abatement ($MtCO_{2e}$)
25	25	0.020	107.5	0.18	5.5
50	25	0.041	108.9	0.37	11.0
75	30	0.052	92.6	0.56	16.7
100	30	0.071	95.3	0.74	22.3
150	30	0.112	100.5	1.11	33.2
200	34	0.136	91.1	1.49	44.7
250	34	0.176	94.7	1.86	55.7
300	34	0.219	98.0	2.22	66.6
350	38	0.231	88.5	2.62	78.5
400	38	0.271	91.0	2.98	89.4
450	38	0.313	93.3	3.35	100.4
500	38	0.355	95.5	3.71	111.3
550	38	0.400	97.6	4.07	122.2
600	38	0.445	99.6	4.43	133.0
650	40	0.461	95.3	4.82	144.7
700	40	0.506	97.0	5.19	155.6
750	40	0.551	98.7	5.55	166.4
800	40	0.598	100.3	5.91	177.2
850	40	0.645	101.9	6.27	188.0
900	40	0.693	103.5	6.62	198.7
950	42	0.698	98.7	7.03	210.8
1000	42	0.745	100.1	7.39	221.6

[31] The value is estimated from life cycle data in McCulloch et al. (2000).
[32] McCulloch et al. (2000).

4.5 Discussion

The LCA in this study is aimed at determining the environmental impact of using triticale straw for electricity production as an option for replacing coal based power and thereby reducing the carbon footprint in electricity generation. The life cycle GHG emission in producing power through the direct combustion of triticale straw is 98 kg CO_{2e}/MWh, and the energy input is 1.75 GJ/MWh (the net energy ratio is 6.84). Generally, LCA studies of the straw based power production pathway do not consider farming inputs because straw is regarded as a waste of grain production. If we consider triticale as an energy crop, then it is more reasonable to consider the energy and GHG emissions involved in the farming phase and to use the mass based allocation method to derive the estimates for straw and grain. If the farming inputs are excluded from the study, the life cycle GHG emission and energy input are 63.9 kg CO_{2e}/MWh and 0.77 GJ/MWh, respectively. Liu et al. (2010) analyzed the wheat straw based power production in China and reported life cycle emissions of 24.1 tonne CO_{2e}/GWh and an energy requirement of 0.77 GJ/MWh.[33] Liu et al.'s analysis excludes the GHG emissions during farming and considers straw as a waste. Though the unit energy consumption is similar, the results are not fully comparable due to the differences in regional energy consumption, the GHG emission coefficients, and the different system boundaries.

Based on Alberta's GHG emissions coefficient for power generation as reported in McCulloch et al. (2000), triticale straw power production could save 994 kg CO_{2e}/MWh, so that the annual CO_2 abatement potential is 2.2 Mt for the base case. Keoleian et al. (2005) calculated the GHG emissions from a coal power generation plant to be 1,028 kg CO2 eq. / MWh. Mann and Spath (1999) showed that the life cycle emissions from an average USA coal plant are 1,042 kg CO2 eq. / MWh. The average GHG emissions from a coal power plant in Alberta are 1155 kg CO_2/MWh (McCulloch et al., 2000). The GHG emissions from triticale straw power generation are only 8.5% of the GHG emissions from coal based power in Alberta. Similarly, the energy needed over the full life cycle for triticale

[33] 5.85×10^5 kJ of energy consumed to generate 76.3 GWh per year.

based power generation is only 15% of that required by coal power production (i.e., 11.5 GJ/ MWh) (Heller et al., 2004).

4.6 CO_2 Abatement cost

The biomass based power generation compared to coal-based power presents an opportunity of GHG mitigation. The carbon credits required for triticale straw direct combustion is the value of the GHG abatement cost required for it to be competitive with the coal power in Alberta. Figure 4-2 shows a plot which gives the carbon credit required for the triticale straw based power to be competitive with coal based power. For example, if we consider the electricity cost from the grid is \$50 MWh^{-1}, the carbon credit required is \$26.5 tCO_2^{-1}.

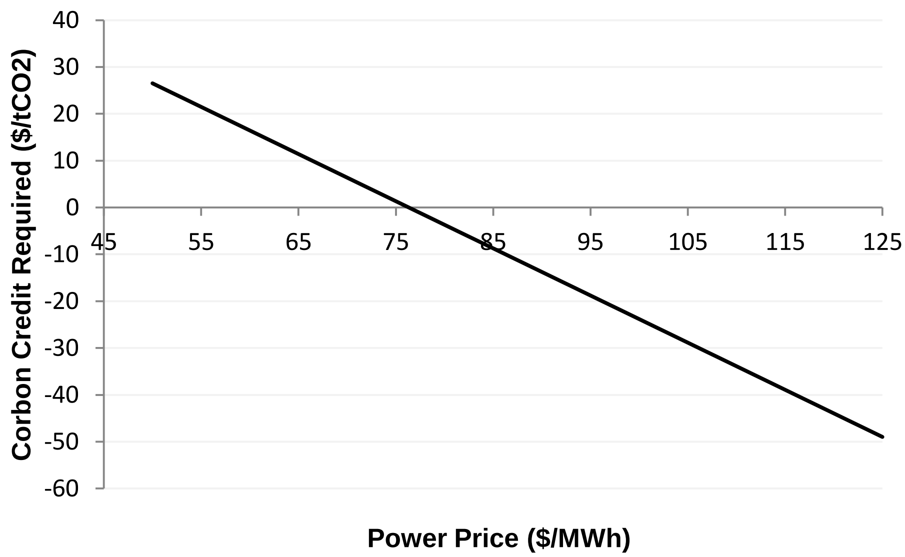


Figure 4-2: Carbon credit for triticale straw based power at different electricity prices

Figure 4-3 illustrates the carbon credits requirement for a direct combustion plant at different sizes, based on a \$60 MWh^{-1} grid power cost. As expected, at lower plant sizes, higher carbon incentives are needed. At 25 MW, a \$39.2 tCO_2^{-1} incentive is required, but as the plant capacities increase, the required incentives decrease rapidly up to the optimum size of the power plant.

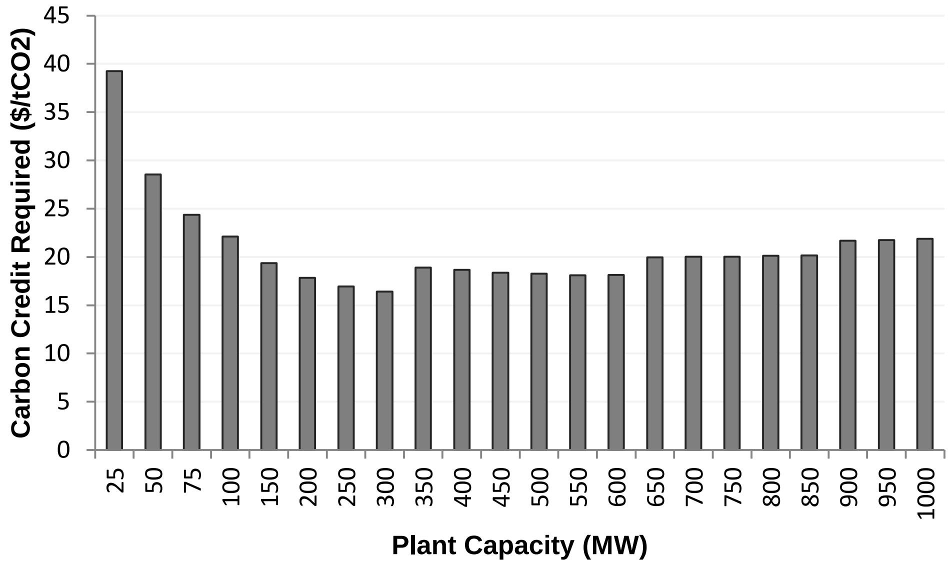


Figure 4-3: Carbon credit requirement for different plant sizes

4.7 Sensitivity Analysis

The influence of the five main assumptions relevant to the characteristics of the base case power plant and feedstock were analysed in a sensitivity analysis. The impact of the variation of these factors on the specific energy consumption and GHG emissions were studied. Table 4-12 summarizes the different sensitivity analysis scenarios.

Table 4-12: Assumptions for sensitivity analysis scenarios

Scenarios	Range	Remarks
1. Plant efficiency	35 - 45%.	IEA (2007) and McKendry (2002)
2. Straw yield	1.1 to 3.8 t/ha	Stat Canada (2009) and Phelps et al. (2009)
3. Straw to grain ratio	0.8 - 1.80	Stephen (2008) and Patterson et al. (1995)
4. Moisture content	12 - 20%	Assumed range.
5. Fraction of triticale land	0.1 - 0.9	Based on Overend (1982).

4.7.1 Plant Efficiency

The plant efficiency of the base case plant is 34%. The variation of the existing direct combustion plant efficiencies with the capacity was explained earlier in section 3.7.3. Table 4-13 shows the impact of variation in plant efficiency on the specific energy consumption and life cycle GHG emissions.

Table 4-13: Impact of plant efficiency on base case energy and emissions

Plant	Emission	% Change	Energy	% Change
30%	113.7	16.2%	2.02	15.3%
31%	109.3	11.7%	1.95	11.1%
32%	105.2	7.5%	1.88	7.1%
33%	101.4	3.6%	1.82	3.5%
34%	97.9	0.0%	1.75	0.0%
35%	94.5	-3.4%	1.70	-3.2%
36%	91.4	-6.6%	1.64	-6.3%
37%	88.5	-9.6%	1.59	-9.1%
38%	85.7	-12.4%	1.55	-11.8%
39%	83.1	-15.1%	1.50	-14.4%

For a 5% efficiency increase for the base case, CO_{2e} emissions decrease by 15% (~14.7 kg CO_{2e}/MWh). The life cycle energy consumption is also reduced by similar percentage, as shown in Table 4-13.

4.7.2 Straw Yield

As explained in sections 2.4.3 and 3.7.4, triticale straw yield is a key factor in determining the specific energy consumption and GHG emissions.

Table 4-14: Straw yield sensitivity results for base case

Grain Yield (t/ha)	Straw Yield (t/ha)	Emission (CO_{2e}/MWh)	Emission Change	Energy (GJ/MWh)	Energy Change
2.5	1.08	154.8	58.6%	2.91	66.2%
3.0	1.41	131.2	34.4%	2.43	38.5%
3.5	1.75	116.1	19.0%	2.12	21.0%
4.0	2.09	105.5	8.1%	1.91	8.9%
4.5	2.43	97.6	0.0%	1.75	0.0%
5.0	2.77	91.5	-6.3%	1.63	-6.9%
5.5	3.11	86.5	-11.4%	1.54	-12.3%
6.0	3.44	82.5	-15.5%	1.46	-16.8%

Grain Yield (t/ha)	Straw Yield (t/ha)	Emission (CO_{2e}/MWh)	Emission Change	Energy (GJ/MWh)	Energy Change
6.5	3.78	79.0	-19.0%	1.39	-20.5%

As per the results in Table 4-14, if we consider the average triticale grain yield for the last eight years, i.e., 2.5 t/ha (Stat Canada, 2009), the emissions would increase by 58.6%, due mainly to the high transportation distances. The sensitivity results highlight the importance of higher grain yields above 4 t/ha (2.09 t/ha straw yield) in order to provide an advantageous environmental gain.

4.7.3 Straw to Grain Ratio (SGR)

Since the straw to grain ratio of triticale is approximated based on wheat and other cereal crops, the impact of the variation in the SGR on the final results must be studied. Table 4-15 shows the impacts of the variation in SGR on specific energy consumptions and GHG emissions.

Table 4-15: Straw to grain ratio sensitivity results for base case

Straw to Grain Ratio	Emission (CO_{2e}/MWh)	Emission Change	Energy (GJ/MWh)	Energy Change
0.80	115.1	17.7%	2.04	16.4%
0.90	108.1	10.4%	1.92	9.6%
1.00	102.5	4.7%	1.83	4.3%
1.10	97.9	0.0%	1.75	0.0%
1.20	94.0	-3.9%	1.69	-3.6%
1.30	90.7	-7.3%	1.64	-6.6%
1.40	87.8	-10.3%	1.59	-9.3%
1.50	85.3	-12.8%	1.55	-11.6%
1.60	83.1	-15.1%	1.52	-13.6%
1.70	81.0	-17.2%	1.48	-15.4%
1.75	80.1	-18.1%	1.47	-16.2%
1.80	79.2	-19.0%	1.46	-17.0%

As Table 4-15 shows, the results change considerably with the SGR. As explained in section 3.7.5, the feasible maximum SGR could be 1.5 and it would reduce emissions by 11.6%.

4.7.4 Moisture Content

Table 4-16 illustrates the GHG emissions variation with changing straw moisture content and the corresponding net calorific value.

Table 4-16: Straw moisture content sensitivity results for base case

Moisture Content	Emission (CO_{2e}/MWh)	Emission Change	Energy (GJ/MWh)	Energy Change
10%	91.0	-7.0%	1.64	-6.5%
11%	92.3	-5.7%	1.66	-5.2%
12%	93.6	-4.3%	1.68	-4.0%
13%	95.0	-2.9%	1.71	-2.7%
14%	96.4	-1.5%	1.73	-1.4%
15%	97.9	0.0%	1.75	0.0%
16%	99.3	1.5%	1.78	1.4%
17%	100.9	3.1%	1.80	2.8%
18%	102.4	4.7%	1.83	4.3%
19%	104.1	6.3%	1.86	5.8%
20%	105.7	8.1%	1.88	7.4%

At the base case plant size, if the moisture content is reduced by 5%, the life cycle GHG emissions are reduced by 6.5%. On the other hand, the safest maximum moisture content for baling is 20% (Vough, 1995), considering the risk of fire. The maximum moisture content of 20% leads to a 7.4% increase in GHG emissions.

4.7.5 Fraction of the Land Devoted to Triticale (Ø)

As shown in section 3.7.7, the land fraction of triticale (Ø) farms would affect the straw collecting area and the average haul distance. The numerical range for Ø was selected from Overend (1982).The effect of Ø on the base case scenario is given in Table 4-17. The highest value of Ø is difficult to estimate. However, if we consider that the assumed Ø value of 0.2 is doubled, the GHG emissions will be reduced by 18%, and the energy requirement will be reduced by 28% compared to the base case.

Table 4-17: Land devoted to triticale sensitivity results for base case

Ø	Average Haul Distance (km)	Emission (CO_{2e}/MWh)	Emission Change	Energy (GJ/MWh)	Energy Change
0.10	142	125.6	28.4%	2.649	51.0%
0.15	116	107.8	10.2%	2.061	17.5%
0.20	101	97.9	0.0%	1.755	0.0%
0.25	90	91.4	-6.6%	1.564	-10.9%
0.30	82	86.7	-11.4%	1.432	-18.4%
0.35	76	83.2	-15.0%	1.336	-23.8%
0.40	71	80.4	-17.8%	1.262	-28.1%
0.45	67	78.1	-20.2%	1.203	-31.4%
0.50	64	76.2	-22.1%	1.155	-34.2%
0.60	58	73.2	-25.2%	1.081	-38.4%
0.70	54	71.0	-27.5%	1.026	-41.5%
0.80	50	69.1	-29.3%	0.984	-43.9%
0.90	47	67.7	-30.9%	0.950	-45.9%

4.7.6 Sensitivity Influence

The above sensitivity scenarios reveal that changes in the assumed sensitivities can have a considerable influence on the final results.

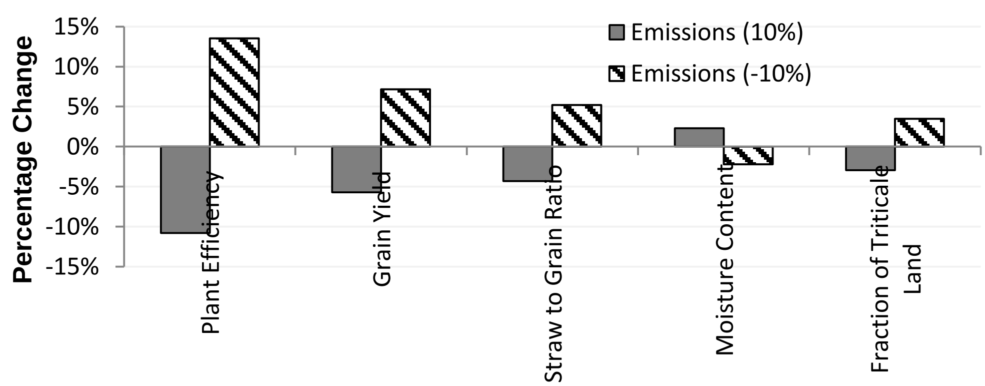


Figure 4-4: Relative influence of emission sensitivities

Figure 4-4 points out that if all sensitivities are changed by a unit percentage, the plant efficiency will have the largest influence on the life cycle emissions, followed by the grain yield.

4.8 Uncertainty Analysis

Some uncertainty is always associated with any life cycle analysis, mainly because of the imperfect system input and output data and the calculation procedures used (Checkel et al., 1999). The quantitative results obtained by using the matrix in Table 3-21 are given in Table 4-18 for energy and the GHG emissions uncertainty of each unit process.

Table 4-18: Uncertainty in LCA Unit Processes

Unit Process	Direct Combustion	
	Energy	**Emission**
Farming	20%	20%
Harvesting	10%	10%
Transportation	10%	10%
Plant Operations	20%	20%
Plant Con., Maint. & Decommissioning	20%	20%

4.8.1 Monte-Carlo Analysis

Based on the assigned unit process uncertainties in Table 4-18, the Monte-Carlo simulation results for the energy and GHG emissions are as given in Figure 4-6. Again, the Montecarlito 1.10 simulation model is used to derive the uncertainty results as explained in section 3.8.2.

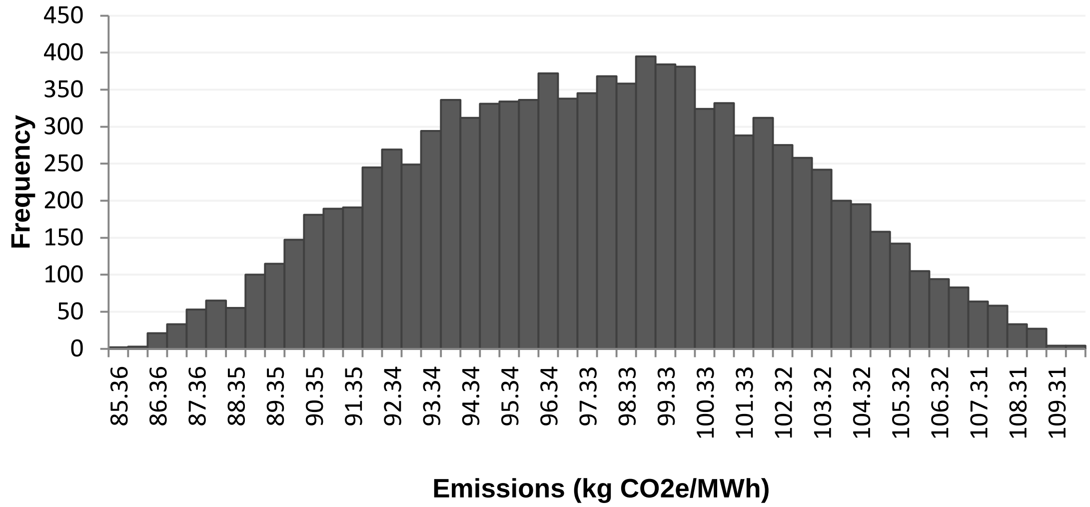


Figure 4-5: Monte Carlo simulation results for CO_{2e} emissions

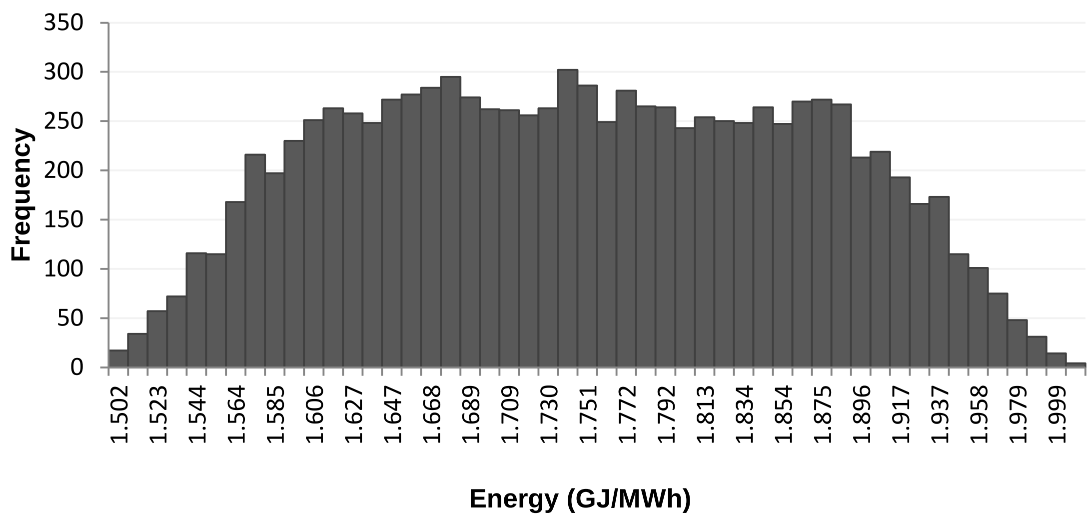


Figure 4-6: Monte Carlo simulation results for energy

Table 4-19: Results with low and high estimates

Result	**95% (1.960 σ)**		
	Low	Mean	High
Energy (GJ/MWh)	1.52	1.75	1.98
Emissions (CO_{2e}/MWh)	88.5	97.9	107.3

4.9 Conclusions

Based on the life cycle analysis of the direct combustion power production, the GHG emissions were 97.9 kg CO_{2e}/MWh. The triticale straw based direct combustion power production could reduce about 90% of the GHG emissions from a same size coal power plant in Alberta. The net energy ratio for triticale straw based power generation is 6.84. Compared to the present Alberta's grid GHG emissions, the annual CO_2 saving is about 2.22 MT or 994 kg CO_{2e}/MWh. With improved technology, suitable plant locations, and more efficient logistic systems, large scale triticale power plants could contribute significantly to Alberta's GHG mitigation efforts.

References

Alberta Agriculture, Food and Rural Development. Triticale Production and Utilization Manual. 2005. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/fcd5464/$FILE/2005triticalemanual.pdf

Brett, K. Triticale: a crop for all seasons. Renewal Now, 2008 : 1. Available from: http://www1.agric.gov.ab.ca/$department/newslett.nsf/pdf/rnw14103/$file/september2008.pdf?OpenElement.

Chaudhary, V. P., B. Gangwar and D. K. Pandey. Auditing Energy Use and Output of Different Cropping Systems in India. Agricultural Engineering Journal 7 (June 2006).

Checkel, M. D., M. Raynolds and R.A. Fraser. Application of Monte Carlo Analysis to Life Cycle Assessment. SRE Technical Paper Series, Society of Automotive Engineers, 1999.

Cheminfo Services and $(S\&T)^2$ Consultants. Ethanol Production in Alberta. 2000.

Cooper, Joyce Smith and Bruce Vigon. Life Cycle Engineering Guidelines. Battelle Columbus Laboratories, 2001.

Daugherty, E.C. Biomass Energy Systems Efficiency: Analyzed through a Life Cycle Assessment. Master's of Science Thesis, Lund University. 2001.

De Oliveira, M.E.D, B.E. Vaughan and E.J. Rykiel. Ethanol as Fuel: Energy, Carbon Dioxide Balances, and Ecological Footprint. Bio Science, 2005.

Elsayed, M. A., R. Matthews and N. D. Mortimer. Carbon and Energy Balances for a Range of Biofuels Options. Resources Research Unit, Sheffield Hallam University, 2003.

Elsayed, M.A. and N. D. Mortimer. Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates. Sheffield Hallam University. 2001.

Energy and Resources Group. ERG Biofuel Analysis Meta-Model. Renewable and Appropriate Energy Lab, University of California, 2006.

Facanha, C. and A. Horvath. Environmental Assessment of Freight Transportation in the U.S. The International Journal of Life Cycle Assessment 11, 4 (2006): 229-239.

Food and Agriculture Organization. UBET Unified Bioenergy Terminology. Food And Agriculure Organization of the United Nations. 2004. http://www.fao.org/docrep/007/j4504e/j4504e00.htm (accessed 4 10, 2010).

Gellings, C. W. and K. E. Parmenter. Energy Efficiency in Fertilizer Production and Use. Encyclopedia of Life Support Systems. 1998.

Graboski, M.S. Fossil Energy Use in the Manufacture of Corn Ethanol. National Corn Growers Association, 2002.

Heller, M. C., G. A. Keoleian, M. K. Mann and T. A. Volk. Life cycle energy and environmental benefits of generating electricity from willow biomass. Renewable Energy 29, 7 (2004): 1023-1042.

Helsel, Z.R. Energy in Pesticide Production and Use. Encyclopedia of Pest Management, 2006 : 157-160.

ICF Consulting. Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: 2005 Update. Environment Canada and Natural Resources Canada, 2005.

International Organization for Standardization, Environmental management- life cycle assessment- principles and framework; 2006. 14040: 2006.

Jurgens, I., B. Schlamadinger and P. Gomez. Bioenergy and the CDM in the Emerging Market for Carbon Credits. Mitigation and Adaptation Strategies for Global Change 11 (2006): 1051-1081.

Keoleian, G. A. and T. A. Volk. Renewable Energy from Willow Biomass Crops: Life Cycle Energy, Environmental and Economic Performance. Critical Reviews in Plant Sciences 24 (2005): 385-406.

Liu H, Polenske KR., Xi Y. and Guo J. Comprehensive evaluation of effects of straw-based electricity generation: A Chinese case. Energy Policy. 2010.

Manitoba Agriculture, Food and Rural Initiatives. Guide to Field Crop Protection. 2010.

Mann, M.K. and P. L. Spath. Life Cycle Assessment of a Biomass Gasification Combined-Cycle System. NREL, Midwest Research Institute, 1997.

McCulloch, M, M Raynolds and M Laurie. Life-Cycle Value Assessment of a Wind Turbine. Alberta, Canada: Pembina Institute, 2000.

McKendry, P. Energy production from biomass (part 2): conversion technologies. Bioresource Technology 83, 1 (2002): 47-54.

Mikkola, H.J. and J. Ahokas. Indirect Energy Input of Agricultural Machinery in Bioenergy Production. Renewable Energy, 35 (2010): 23-28.

Nagy, C. N. Energy Coefficients for Agriculture Inputs in Western Canada. Canadian Agricultural Energy End-Use Data Analysis Centre, 1999.

Natural Resources Canada. Canadian Ammonia Producers Benchmarking Energy Efficiency and Carbon Dioxide Emissions. Canadian Industry Program for Energy Conservation, 2008.

Patzek, T.W. Thermodynamics of the Corn-Ethanol Biofuel Cycle. Critical Reviews in Plant Sciences 23, 6 (2004): 519-667.

Rollefson, J., G. Fu and A. Chan. Assessment of the Environmental Performance and Sustainability of Biodiesel in Canada. National Research Council Canada. 2004.

Schnitkey, G., D. Lattz and J. Siemens. Machinery Cost Estimates. Farm Business Management Handbook. 2000.

Sebastián, F., J. Royo and M., Gómez. Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life Cycle Assessment) methodology. 2010: 1-9.

Shapouri, H. The 2001 Net Energy Balance of Corn-Ethanol. Corn Utilization and Technology Conference. Indianapolis, IN. 2004.

Sheehan, J., V. Camobreco, J. Duffield, M. Graboski and H. Shapouri. Life Cycle Inventoryof Biodiesel and Petroleum Diesel for Use in an Urban Bus. National Renewable Energy Laboratory, U.S. Department of Energy. 1998.

Sokhansanj, S. IBSAL Model. UBC Biomass and Bioenergy Research Group. 2008. http://www.biomass.ubc.ca/IBSAL.html (accessed 07 28, 2010).

Suramaythangkoora, T. and S. H., Gheewala. Potential of practical implementation of rice strawnext term-based previous termpower generationnext term in Thailand. Energy Policy 36, 8 (2008): 3193-3197.

Stat Canada. CANSIM Table 001-0010. Available from: www.statcan.gc.ca, 2009.

Vanderwel, D and S Abday. Alberta Agriculture and Rural Development. 2001. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex2074 (accessed 7 29, 2010).

Vough, L. R. Causes and Prevention of Spontaneous Combustion of Hay. University of Maryland, Available from:

http://www.psla.umd.edu/extension/publications/haycombustionp1c.pdf, 1995.

Wang, M., Saricks, C., Wu, M. Fuel-cycle fossil energy use and greenhouse gas emissions of fuel ethanol produced from U.S. Midwest corn. Argonne National Laboratory, Center for Transportation Research, 1997.

Weinzettel, Jan, Marte Reenaas, Christian Solli and Edgar G. Hertwich. Life cycle assessment of a floating offshore wind turbine. Renewable Energy 34 (2009): 742–747.

Wood, S. and A. Cowie. A Review of Greenhouse Gas Emission Factors for Fertiliser Production. Cooperative Research Centre for Greenhouse Accounting. IEA Bioenergy Task 38, 2004.

5 Conclusions and Recommendations for Future Work

5.1 Conclusions

Triticale straw was analyzed as the feedstock for electricity production via direct combustion. This study focused on the techno-economic assessment of triticale straw based power generation and the GHG abatement potential of large scale triticale straw based power plants. The cost parameters were generated by developing a detailed techno economic model, while the GHG emissions calculation comprised a detailed life cycle analysis of the power generation process adhering to ISO 14040 LCA and ISO 14044 standards. The key findings were the optimum power cost and the subsequent plant capacity, CO_2 abatement, and carbon credit requirements.

Triticale has been identified as a future energy crop for Canada to use to fuel large scale bio-refineries within the next decade. This view is driven by the crop's potentially high yield, tolerance to droughts, low nutrient requirements, and the ability to adapt to any agricultural zone in Canada in all seasons. Triticale is still a minor crop in Alberta, but plans have been developed for a large scale expansion in the coming years. Many high yielding new triticale varieties have been developed in Alberta research facilities. This study used the yield data of these test planting sites because these varieties will be distributed among farmers as a part of the crop expansion program. The base case grain yield was considered as 4,500 kg/ha, which is the approximate average yield of the test sites.

A data intensive techno-economic model was developed by considering the capital cost, field cost, collection cost, transportation cost, operational cost and de-commissioning cost. The capital cost was derived from the capital cost curve plotted by using data from previous similar studies. Historical data were inflated to represent the present market conditions by using the power plant capital cost index (PCCI). The minimum power cost of a direct combustion pathway is $76.33 /MWh at 300 MW unit size, and the power economics with the assumption of unlimited base unit size is given in Table 5-1. By studying the power cost curve, one can conclude that triticale straw power plants could be operated in the range of 150 MW to 1000 MW with a maximum of a 6% cost increase compared to the optimum power cost.

The life cycle of triticale power generation was divided into five stages to develop the life cycle energy and GHG emissions inventory. These stages are farming and harvesting, collection, transportation, plant operations and plant construction, maintenance and de-commissioning. All measurable direct and indirect energy forms were included in the life cycle analysis. This study quantified all energy and GHG emissions involved in farming and harvesting triticale, since this crop is cultivated and harvested primarily for energy generation. At 300 MW, the GHG emission is 97.9 kg CO_{2e}/MWh, and the rest of the key findings are tabulated in Table 5-1.

A major motivation for the research was the desire to evaluate the GHG mitigation potential, in the form of carbon credits, of triticale straw power generation. The carbon credits helped in determining the competitiveness of triticale power against the existing fossil fuel based power generation in Alberta. At 300 MW, the carbon credit required to make triticale based power competitive is 16.4 \$/tCO_{2e}, assuming a grid power cost of 60 \$/MWh. This study found that a triticale straw based power plant could decrease 90% of the GHG emissions of the same sized Alberta coal plant.

Table 5-1: Summary of two technologies

Parameter	Value
<u>Base Case</u>	
Plant Size (MW)	300
Maximum Boiler Capacity (MW)	300
Power Cost ($/MWH)	76.33
Energy (GJ/MWh)	1.75
Emissions (kg CO2e/MWh)	97.9
CO2 Abatement (kg CO2e/MWh)	994
Carbon Credit Required ($/tCO2e)	16.4

Parameter	Value
Optimum Power Cost	
Plant Size (MW)	595
Maximum Boiler Capacity (MW)	Unlimited
Optimum Unit Size (MW)	595
Energy (GJ/MWh)	1.97
Power Cost ($/MWh)	75.02
Emissions (kg CO2e/MWh)	114.8
Carbon Credit Required ($/tCO2e)	15.4

In conclusion, triticale direct combustion is not competitive at any plant scale with the existing coal and natural gas based electricity generation in Alberta. Even with a lowest power cost and optimum size, triticale direct combustion is not economically attractive. It is evident that bio-energy has a higher cost than fossil fuel based energy because of the currently available less efficient conversion technology and logistics, but could become competitive with carbon credits.

5.2 Recommendations for Future Research

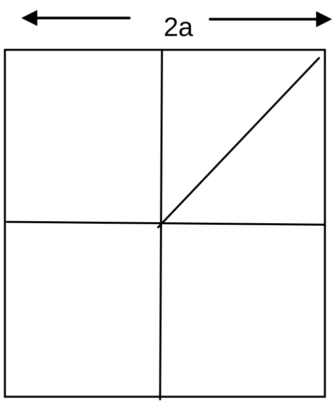
Given the future prospects of triticale straw based power plants in Canada, the following research contributions could improve the competitiveness of triticale straw:

1. It might be useful to investigate the techno-economics of electricity production by using a combined biomass feedstock (i.e., a blend of triticale straw and forest residues). This combination would be ideal until triticale becomes a commercial energy crop that can provide enough biomass to fuel a large scale plant.
2. This study could be extended to include Gasification (BIGCC) and Fast Pyrolysis pathways, as these conversion processes have a high efficiency of conversion.
3. At present, the location of a future triticale straw electricity plant is undeterminable because large scale triticale farms have not yet been established. However, with the ongoing efforts to expand the crop, it might be possible in the future to identify a few locations for initial power plants. Doing so

would definitely allow for far more accurate estimations of the logistic parameters than are currently possible.

Appendix

<u>Transportation Distance Calculation</u>[34] :



b = SQR(2)*a

SQRT(2)*b = SQRT(S)

S - Area

Diagonal - 2b

Transportation Distance -

Side of Square (km)	=	SQRT(S)
Maximum Distance (km)	=	SQRT(S)/SQRT(2)
Average Haul Distance (km)	=	(2/3)* Maximum Distance* T
T - Tortuosity Factor	=	1.27

<u>Triticale harvesting area calculation</u>[34] :

$$\text{Harvesting Area} = \frac{P * 365 \text{ Days} * \text{Capacity Factor}}{100 * M * Ø} \quad (km^2)$$

P - Plant Scale (ODt day^{-1})

M - Biomass Yield (Odt ha^{-1} $year^{-1}$)

Ø - Proportion of the land biomass is grown = 0.02

Table A - 1: Discounted cash flow of the base case

[34] Calculation adopted from (Overend 1982).

Table A – 1: Discounted cash flow of the base case

Plant Capacity – 300 MW

Cost Component ($1000's)/Year	0	1	2	3	4	5	6	7	8
Harvesting & Collection cost				19,799	23,080	25,013	25,513	26,024	26,544
Transportation cost				18,677	22,848	25,318	25,824	26,340	26,867
Ash disposal cost				2,624	3,059	3,315	3,381	3,449	3,518
Shredding Cost				4,118	4,801	5,203	5,307	5,413	5,521
Nutrient Cost				3,784	4,325	4,595	4,687	4,781	4,877
Storage cost				974	994	1,014	1,034	1,055	1,076
Premium for the Farmers				10,282	11,986	12,990	13,250	13,515	13,785
Fixed Operating Cost				2,910	2,968	3,028	3,088	3,150	3,213
Maintenance cost				15,912	16,230	16,554	16,886	17,223	17,568
General Overhead				2,765	2,820	2,876	2,934	2,993	3,052
Reclamation Cost	-	-	-	-	-	-	-	-	-
Capital cost	149,827	262,197	337,111	-	-	-	-	-	-
Total cost	149,827	262,197	337,111	81,846	93,111	99,906	101,904	103,942	106,021
PV of total costs at 10%	149,827	238,361	278,604	61,492	63,596	62,034	57,522	53,339	49,460
MWH				1,839,600	2,102,400	2,233,800	2,233,800	2,233,800	2,233,800
Price for 10% Return ($/MWH)				76.33	77.86	79.41	81.00	82.62	84.27
Revenue for 10% Return				140,415	163,684	177,392	180,940	184,559	188,250
PV of Revenue at 10% Return				105,496	111,798	110,147	102,136	94,708	87,820
Net Revenue				58,569	70,573	77,486	79,036	80,617	82,229

Table A – 1: Continued

Plant Capacity – 300 MW

Cost Component ($1000's)/Year	9	10	11	12	13	14	15	16
Harvesting & Collection cost	27,075	27,617	28,169	28,732	29,307	29,893	30,491	31,101
Transportation cost	27,405	27,953	28,512	29,082	29,664	30,257	30,862	31,479
Ash disposal cost	3,588	3,660	3,733	3,808	3,884	3,962	4,041	4,122
Shredding Cost	5,632	5,744	5,859	5,976	6,096	6,218	6,342	6,469
Nutrient Cost	4,974	5,074	5,175	5,279	5,384	5,492	5,602	5,714
Storage cost	1,097	1,119	1,142	1,164	1,188	1,212	1,236	1,260
Premium for the Farmers	14,061	14,342	14,629	14,922	15,220	15,524	15,835	16,152
Fixed Operating Cost	3,277	3,343	3,410	3,478	3,547	3,618	3,691	3,765
Maintenance cost	17,919	18,277	18,643	19,016	19,396	19,784	20,180	20,583
General Overhead	3,113	3,176	3,239	3,304	3,370	3,437	3,506	3,576
Reclamation Cost	-	-	-	-	-	-	-	-
Capital cost	-	-	-	-	-	-	-	-
Total cost	108,142	110,305	112,511	114,761	117,056	119,397	121,785	124,221
PV of total costs at 10%	45,863	42,527	39,434	36,566	33,907	31,441	29,154	27,034
MWH	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800
Price for 10% Return ($/MWH)	85.96	87.68	89.43	91.22	93.04	94.91	96.80	98.74
Revenue for 10% Return	192,015	195,856	199,773	203,768	207,843	212,000	216,240	220,565
PV of Revenue at 10% Return	81,433	75,511	70,019	64,927	60,205	55,826	51,766	48,001
Net Revenue	83,873	85,551	87,262	89,007	90,787	92,603	94,455	96,344

Table A - 1: Continued

Plant Capacity – 300 MW

Cost Component ($1000's)/Year	17	18	19	20	21	22	23	24
Harvesting & Collection cost	31,723	32,357	33,004	33,664	34,338	35,025	35,725	36,440
Transportation cost	32,109	32,751	33,406	34,074	34,756	35,451	36,160	36,883
Ash disposal cost	4,204	4,288	4,374	4,462	4,551	4,642	4,735	4,829
Shredding Cost	6,598	6,730	6,865	7,002	7,142	7,285	7,431	7,579
Nutrient Cost	5,828	5,945	6,063	6,185	6,308	6,435	6,563	6,694
Storage cost	1,286	1,311	1,338	1,364	1,392	1,419	1,448	1,477
Premium for the Farmers	16,475	16,804	17,140	17,483	17,833	18,189	18,553	18,924
Fixed Operating Cost	3,840	3,917	3,995	4,075	4,156	4,240	4,324	4,411
Maintenance cost	20,995	21,415	21,843	22,280	22,726	23,180	23,644	24,117
General Overhead	3,648	3,721	3,795	3,871	3,949	4,028	4,108	4,190
Reclamation Cost	-	-	-	-	-	-	-	-
Capital cost	-	-	-	-	-	-	-	-
Total cost	126,705	129,239	131,824	134,461	137,150	139,893	142,691	145,545
PV of total costs at 10%	25,068	23,245	21,554	19,987	18,533	17,185	15,935	14,776
MWH	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800
Price for 10% Return ($/MWH)	100.71	102.73	104.78	106.88	109.02	111.20	113.42	115.69
Revenue for 10% Return	224,976	229,476	234,065	238,747	243,522	248,392	253,360	258,427
PV of Revenue at 10% Return	44,510	41,273	38,272	35,488	32,907	30,514	28,295	26,237
Net Revenue	98,271	100,237	102,241	104,286	106,372	108,499	110,669	112,883

Table A - 1: Continued

Plant Capacity – 300 MW

Cost Component ($1000's)/Year	25	26	27	28	29	30	31	32
Harvesting & Collection cost	37,168	37,912	38,670	39,443	40,232	41,037	41,858	42,695
Transportation cost	37,621	38,373	39,140	39,923	40,722	41,536	42,367	43,214
Ash disposal cost	4,926	5,025	5,125	5,227	5,332	5,439	5,547	5,658
Shredding Cost	7,731	7,885	8,043	8,204	8,368	8,535	8,706	8,880
Nutrient Cost	6,828	6,965	7,104	7,246	7,391	7,539	7,690	7,844
Storage cost	1,506	1,537	1,567	1,599	1,631	1,663	1,696	1,730
Premium for the Farmers	19,303	19,689	20,083	20,484	20,894	21,312	21,738	22,173
Fixed Operating Cost	4,499	4,589	4,681	4,774	4,870	4,967	5,067	5,168
Maintenance cost	24,599	25,091	25,593	26,105	26,627	27,159	27,703	28,257
General Overhead	4,274	4,360	4,447	4,536	4,626	4,719	4,813	4,910
Reclamation Cost	-	-	-	-	-	-	-	149,827
Capital cost	-	-	-	-	-	-	-	-
Total cost	148,455	151,425	154,453	157,542	160,693	163,907	167,185	320,356
PV of total costs at 10%	13,702	12,705	11,781	10,924	10,130	9,393	8,710	15,173
MWH	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800	2,233,800
Price for 10% Return ($/MWH)	118.00	120.36	122.77	125.23	127.73	130.29	132.89	135.55
Revenue for 10% Return	263,596	268,868	274,245	279,730	285,324	291,031	296,852	302,789
PV of Revenue at 10% Return	24,329	22,559	20,919	19,397	17,987	16,679	15,466	14,341
Net Revenue	115,140	117,443	119,792	122,188	124,632	127,124	129,667	-17,567

Table A - 2: Direct combustion life cycle data analysis

Operation[35]	Total Energy			Total Emissions		
	GJ	GJ/dt	GJ/MWh	kg CO2	kg CO2/dt	kg CO2/MWh
Farming						
Banding Granular Fertilizer	124,763	0.063	0.056	9,762,203	4.919	4.370
Banding Anhydrous Ammonia	106,662	0.054	0.048	8,377,102	4.221	3.750
Seeding	96,183	0.048	0.043	7,490,633	3.775	3.353
Chemical Applicators	19,586	0.010	0.009	1,527,487	0.770	0.684
High Clearance Sprayers	18,080	0.009	0.008	1,424,045	0.718	0.637
Harvest- Combine Class 7	103,173	0.052	0.046	10,348,161	5.215	4.633
Hebicide Production	140,941	0.071	0.063	9,115,484	4.593	4.081
Fertilizer Production	1,513,993	0.763	0.678	23,442,850	11.813	10.495
Pesticide Production	70,991	0.036	0.032	4,506,406	2.271	2.017
Farm Buildings	21	0.000	0.000	14,799	0.007	0.007
Collecting						
Raking	50,579	0.025	0.023	4,013,593	2.023	1.797
Baling	301,253	0.161	0.135	23,892,767	12.774	10.696
Bale collecting & Moving	63,948	0.038	0.029	5,089,635	3.034	2.278
Bale Loading to Wrapper	26,850	0.016	0.012	2,144,662	1.278	0.960
Bale Wrapping	8,054	0.005	0.004	627,521	0.374	0.281
Transportation						
Loader	26,688	0.016	0.012	2,131,807	1.284	0.954
Truck Transport	1,125,083	0.681	0.504	95,447,772	57.776	42.729
Plant Operations						
Shredding	46,585	0.028	0.021	3,684,503	2.253	1.649
Ash Disposal	8,227	0.005	0.004	1,038,485	0.638	0.465
Plant Equipment Energy	16,612	0.010	0.007	1,194,983	0.734	0.535

[35] Relevant data sources have been discussed in Chapter 3 & 4.

Operation[35]	Total Energy			Total Emissions		
	GJ	GJ/dt	GJ/MWh	kg CO2	kg CO2/dt	kg CO2/MWh
Plant Con., Maint. & Decommissioning						
Construction	36,069	0.022	0.016	2,223,186	1.366	0.995
Maintenance	911	0.001	0.000	40	0.000	0.000
Decommissioning	2,312	0.001	0.001	148,591	0.091	0.067
Total	3,919,348	2.123	1.755	218,588,059	122.501	97.855