University of Alberta

Development of Water Requirement Factors for Biomass Conversion Pathways

by

Shikhar Singh

A thesis submitted to the Faculty of Graduate Studies and Research

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Mechanical Engineering

Fall 2009
Edmonton, Alberta

Examining Committee

Amit Kumar, Mechanical Engineering

John Doucette, Mechanical Engineering

David Bressler, Agricultural, Food, & Nutritional Science

Abstract

This study develops the water requirement factors for different thermo-chemical and biochemical biomass conversion pathways for production of biofuels and biopower. Twelve biomass conversion pathways based on six biomass feedstocks are assessed. For all these pathways integrated water and energy requirement factors are developed. The biomass feedstocks considered for bioethanol production are corn, wheat, corn stover, wheat straw, and switchgrass. The biomass feedstock considered for biodiesel production is canola seed. Three biomass feedstocks are considered for biopower generation using direct combustion of biomass and bio-oil produced from the feedstocks through fast pyrolysis. These three feedstocks are corn stover, wheat straw and switchgrass. The water requirement is also evaluated for biofuels production based on wheat, wheat straw and canola seed in Alberta. Agriculture residues based ethanol production pathways are water and energy efficient, consuming only 0.3 liters of water per MJ of net energy value (NEV), whereas biopower pathways consume about 1.2 – 1.5 liters of water per MJ of NEV due to their lower energy efficiency. The pathway for producing ethanol from switchgrass is the most energy efficient, but consumes 117 liters of water per MJ of NEV. Producing biopower through the direct combustion of switchgrass and from combustion of switchgrass based bio-oil consumes 278 and 344 liters of water per MJ of NEV, respectively. Wheat and corn based ethanol production pathways consume 653 and 409 liters of water per MJ of NEV, respectively. Canola seed based biodiesel production pathway consumes 176 liters of water per MJ of NEV. Water demand in Alberta due to biofuels production will be 12.7% higher than the projected demand in 2025, but it can be met using existing resources.

Acknowledgement

The author would like to express his sincere gratitude to his supervisor, Dr. Amit Kumar for his invaluable guidance, support, and inspiration throughout this study.

The author is also thankful to his friends, especially Susanjib Sarkar, Veena Subramanyam, Arifa Sultana, Arun Bhogal, and Amit Thakur at the Sustainable Energy Research Laboratory for sharing ideas and concepts, and for making author's academic life delightful.

Finally and most of all, the author is eternally indebted to his parents, Kedarnath and Vidhya, and his wife, Smita for their endless support, encouragement, and patience in completing his Master of Science Degree. The author also counts the innocent talks and activities of his son, Aditya as a source of inspiration.

Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

ASME	American Society of Mechanical Engineer
CCC	Canada Council of Canola
°C	Degree Centigrade
CHP	Combined Heat and Power
cm	Centimeter
cm^3	Cubic Centimeter
CO_2	Carbon di Oxide
dam^3	Cubic Decameter
DDG	Dried Distillers Grain
DGS	Distiller Grains and Soluble
DOE	Department of Energy
EIA	Energy Information Administration
g	Gram
GHG	Greenhouse Gas
GW	Giga-Watt
ha	Hectare
HCl	Hydrochloric Acid
Hr	Hour
HHV	High Heating Value
kg	Kilogram
kJ	Kilo Joule
Km	Kilometer

kW	Kilo-Watt
kWh	Kilowatt hour
IEA	International Energy Agency
l	Liter
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
m	Meter
M	Million
MJ	Mega Joule
mm	Millimeter
MW	Mega-Watt
NEB	National Energy Board
NEV	Net Energy Value
NG	Natural Gas
NREL	National Renewable Energy Laboratory
PTC	Performance Test Code
WEF	World Economic Forum
wt%	Weight %

Chapter 1 . Introduction

1.1. Background

The world’s demand for energy is increasing due to increase in population and economic growth. It is projected that the demand for energy will increase by 44% in 2030 compared to the 2006 level (EIA, 2009). About 80% of the current energy demand is being met by fossil fuels while the remainder is being met by nuclear energy and renewable energy (IEA, 2007). This exponential growth in demand of energy and depletion of fossil fuel resources makes it imperative that more renewable energy sources should be used for sustainable development. Currently, renewable energy contributes about 13% (IEA, 2007) of the total energy demand through biomass energy, hydropower, solar energy, wind energy, and geothermal energy. Among these renewable energy technologies, biomass energy, one of the highest potential energy sources, supplies about 10% (IEA, 2007) of total current demand for primary energy.

About 84% of biomass is used in a traditional way for heating and cooking. The remaining 16% of biomass is processed for secondary energy production (Kim et al., 2003). Biomass is available in raw form as wood, crop grain, crop residue etc. ‘As received’ biomass has a low energy density; therefore, it is processed into high energy density products like ethanol, biodiesel, electricity, etc. so that it can be utilized and transported cost effectively. It is important to note that bioenergy is not only renewable, but is assumed nearly carbon neutral energy and hence, helpful in mitigating greenhouse gases. The need for high energy and low carbon dioxide emission provides fresh impetus for bioenergy production (Klein et al., 2009). The use of bioenergy is expected to quadruple by 2030 from its current level (IEA, 2007).

Though economic viability of bioenergy is still a challenge for scientists and researchers, another critical issue pertaining to biomass energy is that biomass production during its growth consumes large amount of water. Water is required not only for biomass production stage but also for biomass conversion stage (Sinclair et al., 1984; Pimentel et al., 2005; Varghese, 2007; King et al., 2008; Pfromm, 2008; RFA, 2008).

Water exists naturally and is limited. Over 97% of the world's water is salty water (Seckler et al., 1998). Of the remaining 3% that is fresh water, only one third is available for use (Seckler et al., 1998). At present, 3400 km^3 of total fresh water is withdrawn for use. 70% of this total fresh water withdrawn worldwide is used for agriculture sector (Seckler et al., 1998; Pimentel et al., 2005), While about 22% and 8% is used for the industrial sector and direct human consumption, respectively (WEF, 2009). From the above statistical figures, it is obvious that the agricultural sector is the most water intensive sector.

The life cycle of biomass conversion to products or energy involves three stages: biomass production, transportation and conversion. As biomass conversion to useful forms also involves the water intensive agriculture/forestry sector, it is obvious that growing demand of bioenergy products will increase the water demand of the future (King et al., 2008). The key issue is the availability of water for meeting the future growth of bioenergy production.

In recent years, conversion of biomass to products such as bioethanol, biodiesel, bio-oil, electricity etc. have gained momentum. To produce these biomass based energy forms, different biomass feedstocks such as wood, agricultural residues, energy crops, cereal crops and oil seeds are being used or experimented so that it can be used in future. Water requirement associated with production of these biomass feedstocks could affect the development of various biomass energy technologies.

1.2. The objective of this study

The overall objective of this research is to determine the water requirement of various thermochemical and biochemical conversion pathways of biomass to energy forms using different biomass feedstocks over the life cycle. Integration of water requirement with net energy value of bioproduct production using different pathways is another aspect of this study. The water requirement for biomass feedstock production stage may vary significantly from one place to other. The results of this research have been applied to assess the impact of biofuels production on Alberta water demand.

The specific objectives of the research are detailed below.

- Selection of biomass feedstocks for bioenergy production.
- Selection of thermochemical and biochemical biomass conversion pathways for bioenergy production.
- Estimation of the direct and indirect water requirement of all stages of the life cycle of biomass conversion to energy for the selected conversion pathways.
- Estimation of the total water requirement per unit production of bioenergy; for example, liters of water per kg of ethanol or liters of water per kg of biodiesel, or liters of water per kWh of electricity.

- Estimation of specific water requirement such as liters of water per MJ of bioenergy.
- Review of the net energy value of different biofuels and biopower and its integration with water requirement.
- Review of biofuel production scenarios in Canada and Alberta.
- Selection of biomass feedstocks and regions in which to grow these crops for biofuels production in Alberta.
- Estimation of water requirement and assessment of the water sustainability of biofuels production in Alberta.

This study is carried out to assess the holistic impact of bioenergy production on water demand and the viability of bioconversion pathways from a water requirement point of view.

1.3. The scope and limitations of this study

The life cycle of biomass conversion to energy can be divided into three stages: crop production and harvesting, transportation of biomass, and conversion of biomass to energy products. To estimate the life cycle water requirement of biomass conversion to energy, water requirement for each stage needs to be calculated. The water requirement for each stage may be direct or indirect requirement. The direct water requirement (e.g. the irrigation water requirement in the agricultural stage) and the indirect water requirement associated with life cycle of major input resources (e.g. water associated with life cycle of fuel, fertilizer required in agricultural stage) are taken into account, however, water associated with minor inputs e.g. lubricant for farming vehicles is ignored. In the transportation stage, direct water requirement is zero and indirect water requirement is negligible compared to that in others stages. In this study crop production and conversion stages are considered for estimation of life water requirement of biomass conversion to energy.

This study focuses not only on biomass conversion to energy forms which are commercially established but also includes bioconversion pathways which are at various stages of development and demonstration but have the potential of being commercialized in future. The process water required to convert biomass into high density energy forms is independent of the location of the plant, but crop production stage requirement are likely to vary substantially (Raddatz et al., 1998; Aden, 2007; Jia et al., 2007; Wright, 2007; King et al., 2008). Data in this study have been collected from literature published for North America.

This study also estimates the water requirement for biofuel production in Alberta. In this analysis, river basins are selected for biofuels' production and the water requirement is estimated for different river basins. It is assumed that available arable land in a river basin is not scattered and so can be used conveniently for crop production to produce biofuels. It is also assumed that pattern of available precipitation matches with the plant water requirement during its growing season.

1.4. The organization of this thesis

This thesis contains six chapters in addition to a table of contents, a list of tables, a list of figures, a list of abbreviations, and four appendices. This thesis is a consolidation of papers, each chapter of which is intended to be read independently. As a result, some concepts and data are repeated.

Chapters 2 and 3 give a detailed analysis of water requirement for different biomass feedstocks conversion to energy using thermochemical and biochemical pathways. Chapter 4 develops an integrated water and energy requirement factors for various biomass feedstocks and their conversion to energy. Chapter 5 is an extension of the results of Chapter 2 for Alberta. This chapter deals with the impacts of biofuels production on Alberta water demand over 25 years. A brief introduction of each chapter is given below.

Chapter 1 includes the background of this study, the objectives of the research, and the limitations of the study.

Chapter 2 includes selection of biomass feedstocks, selection of pathways for biofuels production, development of biomass to biofuels conversion processes, and estimation of the water requirement for each stage of a biofuel's life cycle.

Chapter 3 includes the selection of pathways for electricity production using different lignocellulosic biomass feedstocks, development of biomass to electricity conversion processes, and estimation of each stage's water requirement of electricity production from biomass.

Chapter 4 includes development of an integrated factor of life cycle water and net energy output of different thermochemical and biochemical conversion pathways.

Chapter 5 includes a review of projections of biofuels production in Canada, assessment of Alberta's water requirement, review of water and land availability for agriculture in Alberta, and assessment of land and water requirement for biofuels production in Alberta.

Chapter 6 gives the conclusions of the study. It also recommends future work.

References

Aden, A., 2007. Water usage for current and future ethanol production. Available from: http://epw.senate.gov/public/index.cfm?FuseAction=Files.View&FileStore_id=3d2f1427-d51d-4a54-8739-166853ee1c44. Accessed on: December 4, 2008.

EIA, 2009. International energy outlook 2009. Available from: http://www.eia.doe.gov/oiaf/ieo/highlights.html. Accessed on: 15 July, 2009.

IEA, 2007. Renewable in global energy supply. Available from: http://www.iea.org/textbase/papers/2006/renewable_factsheet.pdf. Accessed on: January 15 2009.

Jia, X., Scherer, F.T., Steele, D.D. 2007. Crop water requirement for major crops in North Dakota and its vicinity area. ASABE/CSBE North Central Intersectional Conference, October 12-13, 2007, North Dakota state university

Kim, S., Dale, B.E., 2003. Global potential bioethanol production from wasted crops and crop residues. Biomass and bioenergy 26 (6), 361-375.

King, C.W., E., W.M., 2008. Water intensity of transportation. Envionmental science and environmental policy 42 (21), 7866-7872.

Klein, K.K., Roy, D.G.L., 2009. The bioenergy frenzy. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop12133. Accessed on: Februrary 15 2009.

Pfromm, P.H., 2008. The minimum water consumption of ethanol production via biomass fermentation. The open chemical engineering journal 2 1-5.

Pimentel, D., Patzek, T.W., 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Natural resources research 14 (1),

Raddatz, R.L., Shaykewich, C.F., 1998. Impact of warm summers on the actual evapotranspiration from spring wheat grown on the eastern Canadian prairies. Canadian Journal of Soil Science 78 (1), 171-179.

RFA, U., 2008. Ethanol facts:environment. Renewable Fuel Association, USA. Available from: http://www.ethanolrfa.org/resource/facts/environment/. Accessed on: November 20, 2008.

Seckler, D., Amarasinghe, U., Molden, D., Silva, R.d., Barker, R., 1998. World water demand and supply, 1990-2025 : scenarios and issues. Available from: http://pdf.usaid.gov/pdf_docs/PNACC575.pdf. Accessed on: January 16, 2009.

Sinclair, T.R., Tanner, C.B., Bennett, J.M., 1984. Water-Use Efficiency in Crop Production. Bioscience 34 (1), 36-40.

Varghese, S., 2007. Biofuels and global water challenges. Institute for agriculture and trade policy, Minneapolis, Minnesota. Available from: <http://www.iatp.org/iatp/publications.cfm?refid=100547>.

WEF, 2009. Thirsty energy: water and energy in the 21st century. Available from: http://www.weforum.org/pdf/ip/energy/energyvision2009.pdf. Accessed on: March 3, 2009.

Wright, R., 2007. Agroclimatic atlas of Alberta: agricultural climate elements. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6301. Accessed on: April 5, 2009.

Chapter 2 . Development of Water Requirement Factors for Liquid Biofuels

2.1. Introduction

As shortage of petroleum derived fuels has become evident, interest in production of biofuels has increased significantly in leading energy consuming countries. In many countries, liquid biofuels (i.e. bioethanol and biodiesel) are being produced on industrial scale using mostly grains.

The current total production of bioethanol is only 1% of the world's gasoline consumption (Varghese, 2007). The world's annual production of ethanol was 56 billion liters in 2006 and it is expected to exceed 100 billion liters by 2010 (Shapouri, H. , 2007). The United States and Brazil are leading producers of bioethanol. The US's ethanol production is expected to grow from its 2007 rate of 6.5 million gallons to 29.6 million gallons in 2030 (EIA, 2009). Currently, Canada produces 578 million liters of ethanol annually (Klein et al., 2009), a production level which is expected to increase to 3754 million liters by 2030 (NEB, 2009).

Similarly, production of biodiesel, which accounted for 5% of the world's biofuel production in 2004 (Aden, 2007), is also increasing. Annual biodiesel production in the US increased tenfold between 2004 and 2006. In 2006, the total production of biodiesel was 287 million gallons, which accounts for only 0.6% of total diesel fuel consumption (GAO, 2007). Biodiesel use in the US is expected to increase to 1.9 billion gallons by 2030, which would be 2.3 percent of total diesel consumption (EIA, 2009). Currently, Canada produces 79 million liters of biodiesel annually (Dietrich, 2009), a production level which is expected to increase to 270 million liters by 2030 (NEB, 2009).

It is predicted that there is scope for exponential growth in biofuel production (Varghese, 2007). With an increase in the production of biofuels, it is obvious that demand for water will also grow, water being one of the key components of current biofuel production. The current level of biofuels production accounts for 1% of total water use (Varghese, 2007) and further increase in biofuels production will increase water demand significantly in many regions.

Only a few studies have been carried out which discuss issues surrounding the water needed to meet the demand for biofuels (Aden, 2007; Varghese, 2007; King et al., 2008; Pfromm, 2008). Aden (2007) briefly talked about the water requirement for producing ethanol from corn and corn stover and his study also includes water requirement for the US corn crop. Varghese (2007) discussed the water requirement for corn based ethanol in the US and sugarcane based ethanol in Brazil. This study also details the processes involved and stresses the significance of the water required to produce the crops involved. King (2008) estimated the water required to produce corn and corn stover based ethanol including the irrigation requirement in the agricultural stage. King (2008) also considered the water required to produce energy used in farming but neglected the water required for fertilizer production. Pfromm (2008) estimated the minimum water requirement for producing ethanol from corn, assuming 100% water recycling. To date studies are specific to a location, and only the water required for irrigation has been considered. The additional water required for the growth of the crop is directly or indirectly fulfilled by precipitation. This study is being carried out to estimate the total water required for biomass production in the agricultural stage, independent of the place of liquid biofuel production.

Liquid biofuels can be produced from different biomass feedstocks. Corn, wheat and sugar cane are popular biomass feedstocks for the production of ethanol but lignocellulosic feedstocks such as corn stover, wheat straw, rice straw and switchgrass are now drawing a lot of attention. As a result, this study includes both grain and lignocellulosic biomass feedstocks for production of biofuels and uses a range of production pathways. The details are given in subsequent sections.

The life cycle of biomass based fuels or chemicals can be divided into three main stages: biomass feedstock production and harvesting, transportation of biomass to the conversion facility, and conversion of biomass to fuels or chemicals. To evaluate the life cycle water requirement of biomass based liquid fuels, this study estimates the requirement for water in each stage. This study also evaluates the indirect water requirement associated with life cycle of major input resources such as water associated with life cycle of fossil fuel production, fertilizer required in the agricultural stage. This study focuses on developing water requirement factors for different commercially established and experimentally successful biofuel pathways.

2.2. Definition of water requirement

In this study, water requirement refers to the total direct and indirect water used to produce biomass crop i.e. crop production stage and to convert biomass crop to biofuel in the conversion stage. The sources of direct water are precipitation, soil moisture, and/or surface or ground as shown in Figure 2-1.

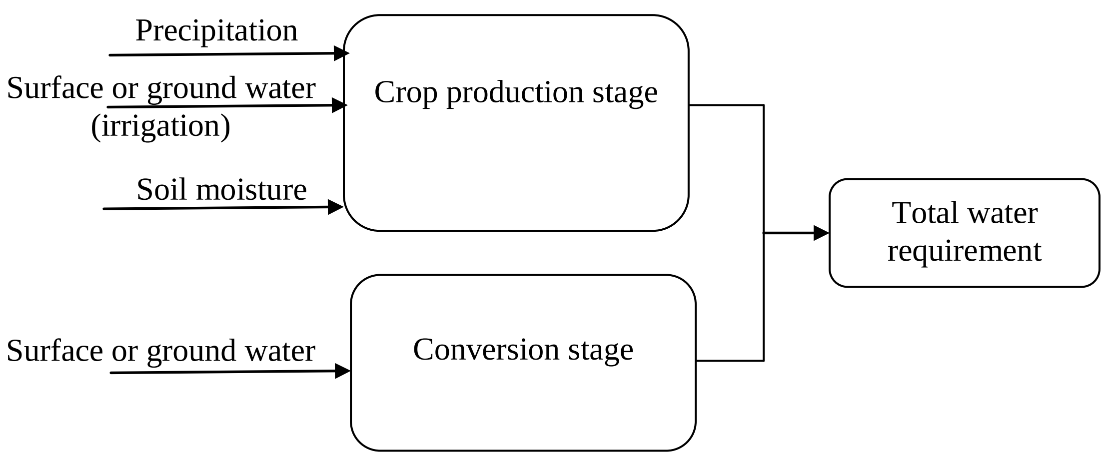

Figure 2-1: Water sources for biofuel production

The direct water requirement in crop production stage is water used to grow crop and this water requirement is dependent upon climatic conditions of the region where crop is grown. The surface water includes water from river, pond, lakes etc. The surface or ground water is used through irrigation. The direct water requirement in conversion stage is the make-up water requirement for the conversion process. The source of this make-up water is surface or ground water. The indirect water requirement in both the stages is the water used during the manufacturing of major inputs such as fertilizers, chemicals, and fuels. The source of this indirect water requirement is surface or ground water. The total water requirement estimated in this study is thus the sum of direct and indirect water requirement for both crop production and conversion stages.

2. 3. Selection of biomass feedstocks for production of biofuels

There are different types of biomass feedstock which can be used for the production of biofuels. These feedstocks can be agricultural based (e.g. corn, corn stover, wheat, wheat straw, switchgrass, canola) or forestry based (e.g. wood, forest residues, willow). The selection of biomass feedstock depends upon availability, process compatibility and efficiency, the energy density of products, the technical feasibility of product use, etc.

Bioethanol is one of the most popular liquid biofuels. It accounts for the largest share of the world's total biofuels' production, and its production is growing rapidly. Currently, bioethanol is produced mainly from cereals and sugarcane. In North America, corn is the major source of ethanol production (Franceschin et al., 2008). The North American reliance on the corn feedstock is the reason this study selected the corn based ethanol pathway to estimate of the life cycle water requirement. Wheat is another potential feedstock for ethanol production in North America. The amount of wheat used for ethanol production represents about 15% of the global demand (Kim et al., 2003). Canada is the sixth largest producer of wheat with about 76% of its annual wheat production being exported (Dominion, 2009). Due to abundance of wheat in Canada, the ethanol production plants are mostly wheat-based. The growth of ethanol based plants is largest in the prairie region where 91% (CANSIM, 2009) of the total annual wheat crop of Canada is grown.

The growing use of crops for biofuel production competes with the use of these crops for food. Lignocellulosic biomass like corn stover, wheat straw, rice straw, etc are also being contemplated as potential sources of bioethanol. These biomass feedstocks can be processed for bioethanol generation utilizing co-current dilute acid pre hydrolysis and enzymatic hydrolysis (Aden et al., 2002). In the USA, 90% of corn stover is left in the field as waste (Kim et al., 2003), making it an attractive option for producing bioethanol. In Canada, residue of most cereal crops is left unused, especially wheat straw which has low protein and digestible dry content for animal feed (Sokhansanj et al., 2006). Based on this information, corn stover and wheat straw are the lignocellulosic biomass feedstocks considered in this study.

Recently switchgrass, an energy crop has attracted interest as a bioenergy feedstock. It has high productivity and can grow in a variety of geographic regions on land of marginal quality with minimum nutrient and water requirement (Sanderson et al., 1996). Like corn stover and wheat straw, this lignocellulosic biomass can be converted into bioethanol. Switchgrass is also considered as a feedstock in this study and is compared with agricultural residues.

The production of biodiesel, second after bioethanol in the biofuels category, is also growing rapidly. Biodiesel can be produced from vegetable oil using grains such as soybean, and canola seed. Soybean is more popular feedstock for biodiesel in the US, but canola seed is the preferred feedstock for biodiesel production in EU and is also gaining popularity in Canada. One of the favorable factors for canola seed as a potential feedstock for biodiesel is its high oil content compared to that of soybean. Canola seed contains 42% oil by wt (CCC, 2006) while soybean seed contains only 18.4% by wt oil (Sheehan et al., 1998). For this reason, this study considered canola seed as a feedstock for the production of biodiesel.

2.4. Selection of biomass to biofuels conversion pathways

Raw biomass can be converted into useful biofuels with high energy density using thermo-chemical and biochemical processes depending upon the constituents of the biomass.

As shown in Figure 2-2, corn and its residue can be utilized in two different ways for bioethanol production. The corn to ethanol pathway is an obvious choice using corn kernels because the glucose polymer of corn kernels can be broken into glucose monomers and subsequently converted to ethanol through fermentation process. There are several plants which are operating commercially to produce ethanol from corn. The life cycle water requirement of this commercially established pathway is useful for understanding the water requirement and also in comparing it with the water requirement of other pathways.

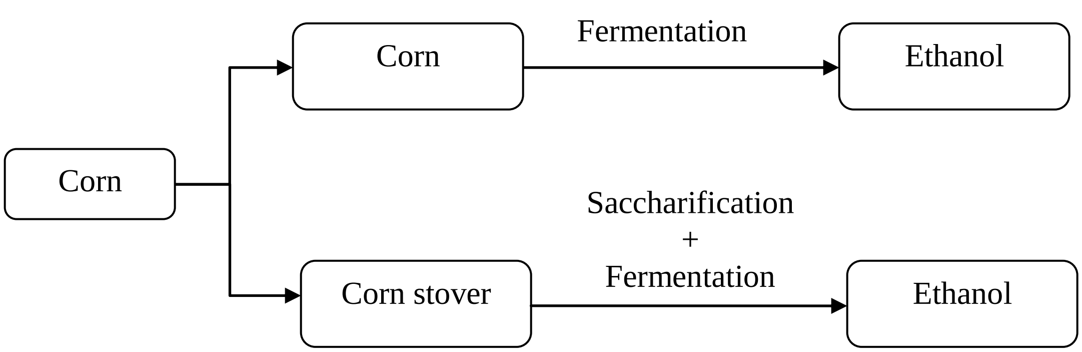

Figure 2-2: Schematic of corn and corn stover based conversion pathways

The glucose polymer of corn kernels is more easily converted to ethanol than is that of corn stover. The cellulose and hemicellulose contents of corn stover are complex polymers of glucose and difficult to break down into monomers for fermentation into ethanol. Pretreatment and saccharification processes are used to breakdown hemicellulose and cellulose respectively, to convert them into simple sugars (Aden et al., 2002). These simple sugars are fermented into ethanol. In this study both the pathways of producing ethanol from corn and corn stover are considered. Further details on the conversion pathways are given in subsequent sections.

As shown in Figure 2-3, wheat can also be utilized for producing biofuels in the same way as corn. Wheat can be used to produce bioethanol by fermentation of starch, whereas wheat straw can be used to produce ethanol through saccharification and fermentation processes (Kerstetter et al., 2001). Further details on the conversion pathways are given in subsequent sections.

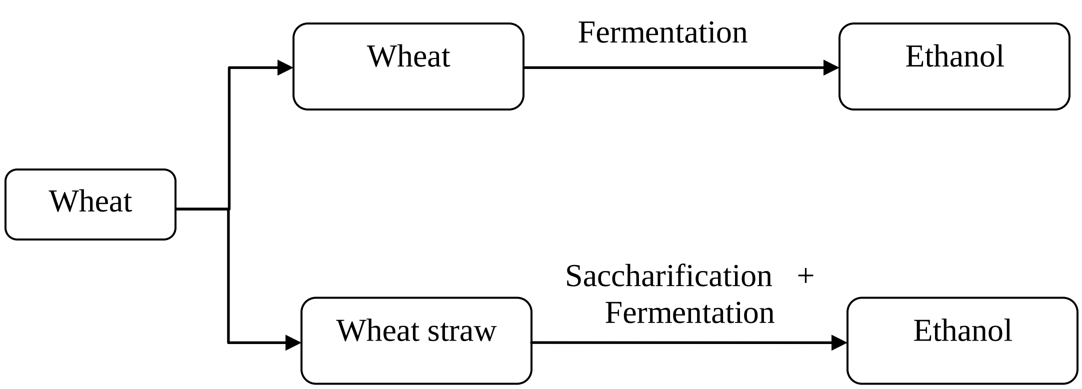

Figure 2-3: Schematic of wheat and wheat straw based conversion pathways

As shown in Figure 2-4, another lignocellulosic biomass, switchgrass, can be utilized for production of ethanol using conversion pathways similar to those of corn stover and wheat straw. These conversion pathways mainly include saccharification and fermentation processes (Spatari et al., 2005). Further details on the conversion pathways are given in subsequent sections.

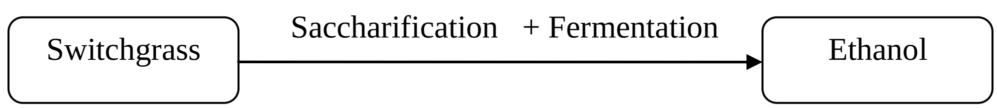

Figure 2-4: Schematic of Switchgrass based conversion pathway

The last feedstock considered for this study is canola seed which can be utilized for producing biodiesel. As shown in Figure 2-5, canola seed is converted into canola seed oil by crushing process (a mechanical process) and this oil is then converted into biodiesel through transesterification process (chemical process) (Rollefson et al., 2004). Further details on the conversion pathways are given in subsequent sections.

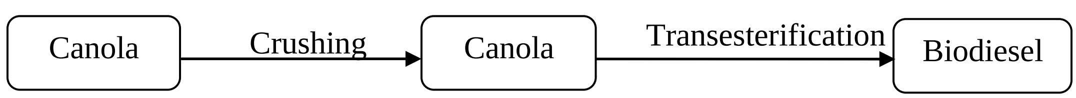

Figure 2-5: Canola seed based bio conversion pathway

2. 5. Corn crop based biofuels production pathways

2. 5.1. Corn production and its water requirement

In the crop production stage, the direct water requirement is the water required for the growth of the plant. Water plays a major role in the development of any plant. It works as a carrier of nutrients throughout the plant and finally evaporates through tiny pores in the leaves. This evaporation is called transpiration (CCC, 2008). Water also evaporates directly from the soil during crop production. The total evaporation of transpiration together with soil evaporation is also called evapo-transpiration. It is primarily responsible for water use in agricultural stage and affects crop yield. The amount of evapo-transpiration depends on the crop type, ambient air temperature, humidity and wind velocity (CCC, 2008).

The water required for evapo-transpiration comes from precipitation, irrigation and soil water. Usually, precipitation is the primary source of crop water. If precipitation is less than the crop requires, moisture in the soil is used by the plant to the maximum possible extent. The moisture stored in soil is utilized by the crop during the growing season. How much water the soil provides depends upon the soil water holding capacity, which varies from region to region. If both sources are unable to meet the crop water requirement together, irrigation is applied by measuring moisture level of the soil (Bauder, 2009). In this study, total crop water requirement is considered for development of life cycle water requirement factors of various biofuels.

2. 5.1.1. Direct water requirement for corn production

In the crop production stage of corn, the water supplied to the crop affects its yield. Corn yields of Canada and the US with their water requirement are shown in Table 2-1.

Table 2-1: Corn yields and water requirement

Country	Yield (kg ha^{-1})	Crop water requirement (mm)	Source
Canada	7,533	500	(OMAFRA, 2009b)
Canada	8,400	533	(Manitoba Agriculture, 2009)
Canada	7,533	510	(McKenzie et al., 1997)
US	13,012	943	(Howell, A.T. et al., 1996)
US	12,260	793	(Howell, A. T. et al., 1998)
US	8,000	600	(Koa et al., 2009)
US	10,625	617	(Payero et al., 2008)
US	9,970	481	(Jia et al., 2007)
US	13,812	838	(Claim, 2009)

Based on the data given in Table 2-1, the average yield of corn is 7,823 kg ha^{-1} with an average crop water requirement of 514 mm in Canada. The average corn yield is 11,280 kg ha^{-1} with an average crop water requirement of 712 mm in the

US. The average moisture content of produced corn is 15.4% (OMAFRA, 2009a). Hence, the average dry yield of corn in North America is 8,568 kg ha^{-1} with an average water requirement of 646 mm i.e. 754.08 liters of water for the production of 1 kg of dry corn.

2.5.1.2. Indirect water required for corn production

In agriculture, indirect water use depends upon the fuel used for farming activities and, as well, on fertilizer requirement. These requirement vary with climatic condition, soil type, fuel type, etc. and may vary significantly in some cases.

Table 2-2: Major inputs of corn crop and their water requirement

Inputs	**Quantity [a] (kg ha^{-1})**	**Water Requirement (liters ha^{-1}) [b]**
Diesel	55.7	147.7 [d]
Gasoline	22.2	60.4 [d]
LPG	23.9	102.9 [d]
Electricity	83.0[c]	38.6 [d]
Natural gas	9.4	0.0 [d]
Nitrogen	178.0	121.6 [e]
Phosphorus	113.4	22.0 [e]
Potassium	79.0	0.1 [e]
Lime	22.2	0.0 [f]

[a] The quantities of inputs are derived from Shapouri et al. (2002).

[b] This water requirement refers to the amount of water required per ha for production of a given quantity of inputs.

[c] The electricity requirement is in kWh ha^{-1}.

[d] Source: King et al. (2008).

[e] Source: Sheehan et al. (1998).

[f] The lime production cycle involves mining, transportation and grinding (West et al., 2001), therefore it is assumed that the water requirement is negligible for production of lime.

The typical energy and fertilizer requirement of corn are shown in Table 2-2. This table also gives the amount of water required to produce a specific quantity of output (for example, 147.7 liters of water is required for the production of 55.7 kg diesel), and other inputs like herbicide, lubricants needed for farm vehicles, etc. have been ignored. The life cycle water requirement of these inputs includes water requirement from mining raw materials, manufacturing each input and delivering it to the farm. Specific water requirement for these products are shown in appendix A. Based on these data, the estimated indirect water requirement for the production of 1 kg of dry corn is 0.06 liter. This requirement is almost negligible compared to the direct water requirement (754.08 liters kg^{-1} of corn) for the production of corn.

2.5.2. Corn to ethanol process

To convert corn into ethanol there are two main processes: the wet grind and the dry grind. In the wet grind process, corn kernels are soaked in water and sulfurous acid to separate the starch rich endosperm, high protein germ and high fiber husk, thereafter the endosperm is processed to produce ethanol. In the dry grind process, unprocessed and heterogeneous corn kernels are only ground into a coarse floor-like consistency before being cooked and fermented as shown in Figure 2-6. After fermentation, ethanol is separated from the mash by distillation process and the solid part of the remaining mash is separated by centrifugal action and dried to obtain byproduct called DDG (Dried Distillers Grain).

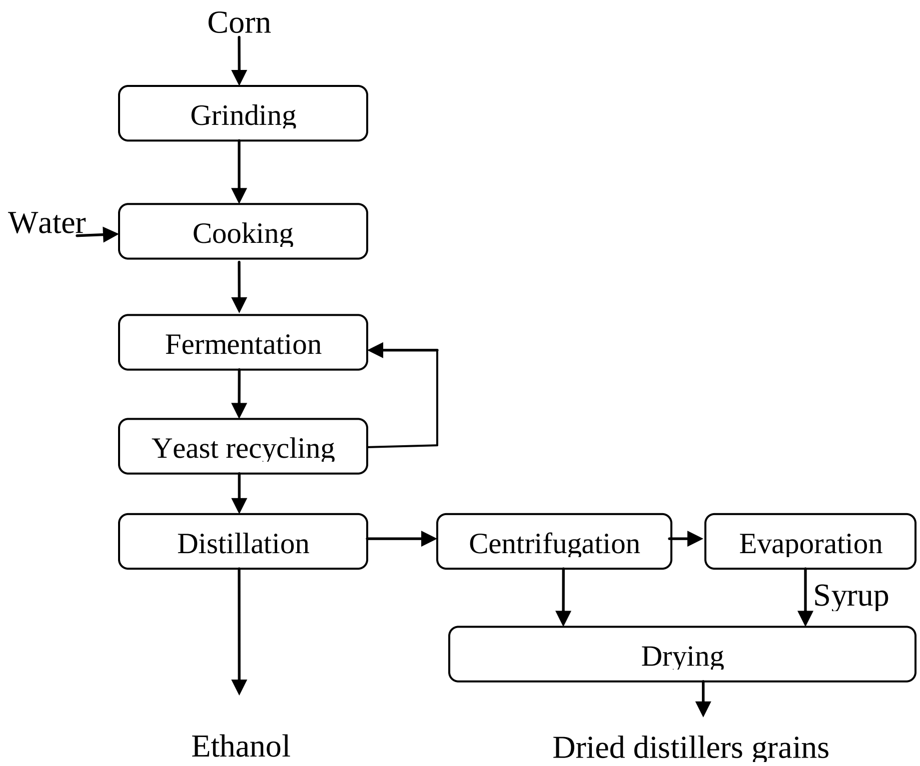

Figure 2-6: Dry grind process to convert corn to ethanol

(derived from DOE (2008))

As a result of the different processing methods, wet milling yields better byproducts than does dry grinding, but it is expensive process (DOE, 2008). As 80% of US ethanol plants are based on dry grind technology (Aden, 2007), the life cycle water requirement of this process is evaluated in this study.

2.5.2.1. The direct water requirement of the corn to ethanol process

Water is used directly to form a mash of corn, which is evaporated after distillation process and recycled for further use in the process, albeit some part of the has been lost. For distillation and drying processes, steam is usually used, part of which is lost as a normal system loss. This total amount of water lost constitutes the water requirement of the ethanol production process. This direct water requirement has not yet been optimized at the industrial level (Franceschin et al., 2008) and has been reported differently by different sources as shown in Table 2-3. Based on the data in this table, the average water requirement of the corn ethanol process is estimated as being 4.53 liters of water for the production of 1 kg of ethanol.

Table 2-3: Water and corn requirement in the corn to ethanol conversion process

Makeup water required for dry milling process (liters per kg of ethanol)	Corn required (kg per kg of ethanol)	Sources
5.45	3.08	(Franceschin et al., 2008)
3.40	3.20	(Johnson, 2006)
4.34	3.04	(Pfromm, 2008)
3.61	3.50	(Lurgi, 2008)
6.65	-	(RFA, 2008)
3.80	-	(Sobolik, 2008)
4.44	-	(Aden et al., 2002)

As shown in Table 2-3, on average 3.21 kg of corn is required to produce 1 kg of ethanol. The moisture content of the corn before being fed into the ethanol production process is 15% (Franceschin et al., 2008). Hence, 2.72 kg of dry corn is required to produce 1 kg of ethanol.

2.5.2.2. The indirect water requirement of the corn to ethanol process

Electricity and natural gas are major inputs of the corn ethanol process. Electricity is used to run auxiliary equipment of the process, and natural gas is used to produce steam for the process. In corn based ethanol production process, 0.52 kWh electricity and 0.085 kg of natural gas (Franceschin et al., 2008) are required to produce 1 kg of ethanol. Considering 1.76 liters of water needed to produce 1 kWh of electricity and no water is needed to produce natural gas (King et al., 2008), the indirect water requirement corresponding to these inputs is 0.91 liter per kg of ethanol.

2.5.3. Corn stover to ethanol process

As shown in Figure 2-7, corn stover is first shredded to a suitable size and then sent to the pretreatment and conditioning section. All lignocellulosic biomass feedstocks are composed of three main components viz. cellulose, hemicellulose and lignin. In the pretreatment section, the hemicellulose part of the corn stover is broken down into monomer glucose using dilute acid treatment, thereafter hydrolyzate slurry is conditioned using lime to make it suitable for further processing.

There are a number of biomass pretreatment technologies which can be used for breaking down hemicellulose. These technologies have been discussed in detail in earlier studies (Larsson et al., 1997; Reith et al., 2001; Aden et al., 2002; Demirbas, 2008). In this study, the pretreatment process is based on the technology proposed by US National Renewable Energy Laboratory (NREL). The details on this technology can be found in Aden et al. (2002). In the next step, cellulose is broken down into monomer glucose by saccharification as proposed by NREL and then fermented into ethanol.

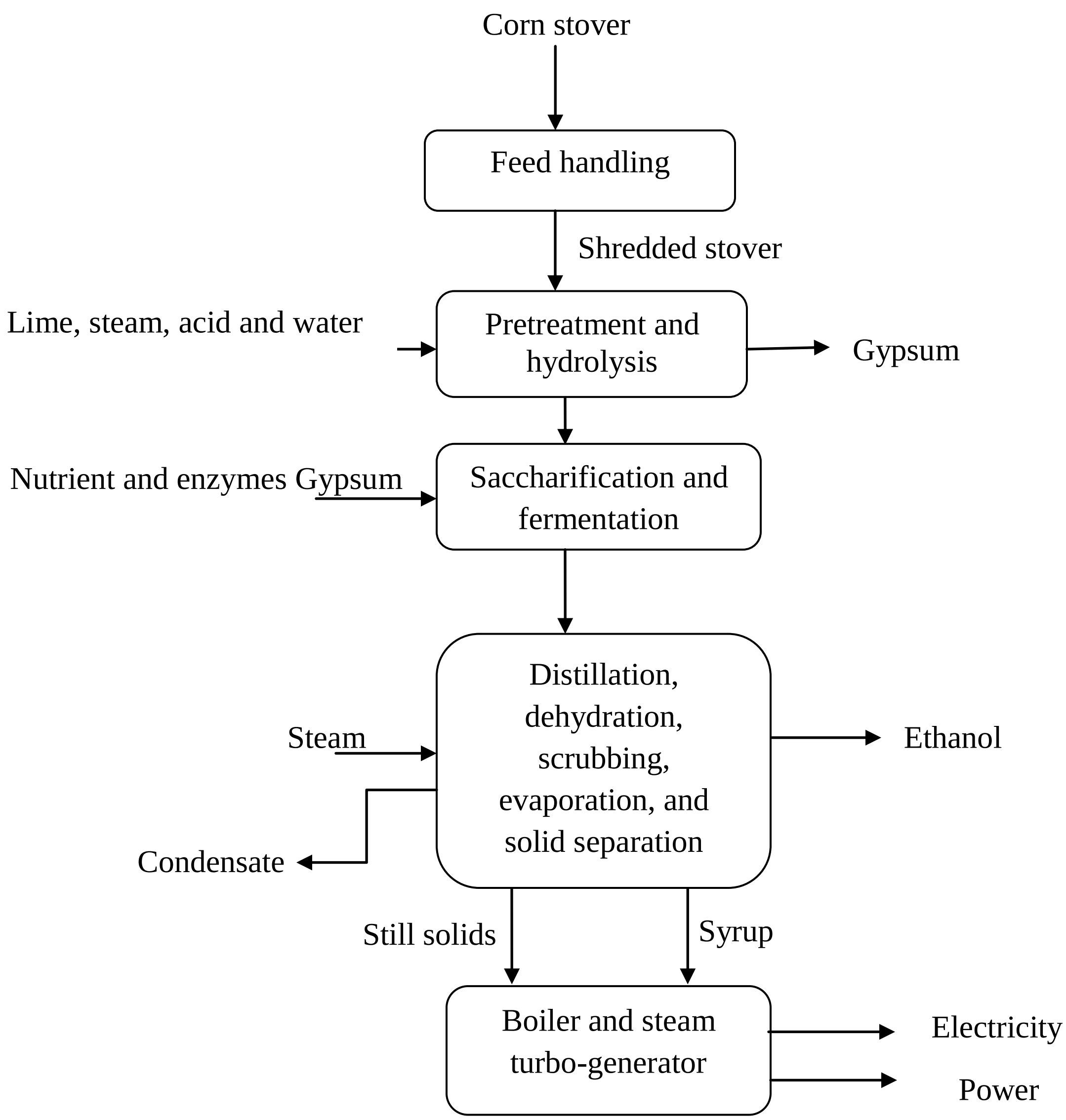

Figure 2-7: The corn stover to ethanol conversion process (derived from the Aden et al. (2002))

Further, ethanol is separated from the slurry through distillation process. The solid residue containing lignin is fed into a boiler to produce steam which is partially used to provide the heat required by the process, with the remaining steam being utilized for power production.

2.5.3.1. The direct water requirement of the corn stover to ethanol process

Water is used in the pretreatment and hydrolyzation of corn stover, this involves cleaning of the corn stover and making slurry of it for further processing. As in the whole process, steam is used as a heating medium, water is lost through vents and traps in the steam distribution system and water is drained off from the boiler to maintain steam quality.

The process model considered for this study also includes power production using steam; therefore, a large amount of cooling water is required for steam condensation in the condenser. This cooling water is cooled in a cooling tower where water is lost through evaporation, and some is drained off intermittently from the system to maintain its quality. In all, the total direct water requirement of this process model is 7.56 liters for the production of 1 kg of ethanol (Aden et al., 2002).

2.5.3.2. The indirect water requirement for the corn stover to ethanol process

To evaluate the indirect water requirement, only the major inputs of the corn stover to ethanol process model are considered. As shown in Table 2-4, the indirect water requirement is minimal for all input materials except enzyme. Based on the calculations shown in appendix B, the total water requirement for 4 percent concentration solution of cellulosic hydrolyzate enzyme is 1.37 liter of water for 1 kg of enzyme.

Table 2-4: Major- inputs for the corn stover to ethanol process and water requirement

Inputs	Quantity[a] (kg per kg of ethanol)	Water requirement[b] (liter)
Dry corn stover	3.38	-
Enzyme	0.28	0.38
Sulfuric acid	0.13	0.03
Lime	0.10	0.00
Corn steep liquor	0.05	0.03

[a] The quantities of inputs are derived from Aden et al. (2002).

[b] The quantities of water requirement for various inputs are calculated based on the details given in the appendix B.

In manufacturing sulfuric acid, water is used to absorb SO_3 for the formation of sulfuric acid. The water is also used as cooling water for integrated power generation unit (ESAA, 2000). This power generation unit receives heat from exothermic reactions of the sulfuric manufacturing process (ESAA, 2000). Based on detailed calculations shown in appendix B, a total of 0.22 liters of water is used to produce 1 kg of sulfuric acid.

Corn steep liquor, a by-product of the corn wet-milling process, is used as a source of nutrients for microorganisms. The steep liquor is 50 percent concentrated solutions (Liggett et al., 1948) i.e. 50% of steep liquor, fed to this process is water. The calculated indirect water requirement for whole ethanol conversion stage is 0.44 liters for production of 1 kg of ethanol using 3.38 kg of dry corn stover (details are given in Appendix B).

2.6. Wheat crop based biofuels production pathways

2.6.1. Wheat production and its water requirement

Like any other crop, wheat yield is also dependent upon water availability during its growing period of the crop. This requirement is direct water requirement of the wheat crop. As fuels and fertilizers are used to produce wheat crop, water is also required to produce these major inputs of wheat fields.

2.6.1.1. Direct water requirement for wheat crop production

To estimate water requirement, we considered studies related to spring wheat from different regions of Canada and adjacent border state of the USA. As shown in Table 2-5, wheat yield can vary from as low as 1,179 kg ha^{-1} in semi-arid regions of Montana to as high as 7,416 kg ha^{-1} in Ontario. It is noted in Table 2-5 that grain yields vary proportionally with water availability.

Table 2-5: Wheat crop yields and water requirement

Region	Yield (kg ha^{-1})	Water use (mm)	Sources
Ontario, Canada	7,416	507	(Shock et al., 2005)
Manitoba, Canada	7,406	460	(Raddatz et al., 1998)
Alberta, Canada	2,251	290	(McKenzie et al., 1997)
Montana, USA	1,179	205	(Lenssen et al., 2007)

Based on the data given in Table 2-5, the average yield of wheat is 4,563 kg ha^{-1} with an average water use of 364 mm. Thus, considering wheat moisture content of 14.6% (Encyclopedia, 2009), the calculated value for average direct water use for wheat is 933.13 liters per kg of dry wheat production.

2.6.1.2. Indirect water requirement for wheat production

Table 2-6 shows average inputs for wheat crops with their water requirement. The water requirement corresponding to each input has been calculated using the specific life cycle water requirement given in Appendix A. Thus, based on an average yield of 4,563 kg of wheat ha-1, the calculated value of indirect water use is 0.07 liter per kg of dry wheat production.

Table 2-6: Wheat crop inputs and their life cycle water requirement

Inputs	Quantity [a] (kg ha^{-1})	Water requirement [b] (liter ha^{-1})
Diesel	41.4	110.4 [d]
Gasoline	7.4	20.1 [d]
LPG	1.4	6.0 [d]
Electricity	37.1 [c]	65.2 [d]
Natural gas	0.01	0.0 [d]
Nitrogen	68.4	46.7 [e]
Phosphorus	24.7	4.8 [e]
Potassium	9.0	0.0 [e]
Lime	44.8	0.0 [f]

[a] The values are derived from Piringer et al. (2006).

[b] This water requirement refers to the amount of water required per ha for production of given quantity of inputs.

[c] Value is in kWh ha^{-1}.

[d] Source: King et al. (2008)

[e] Source: Sheehan et al. (1998)

[f] The lime production cycle involves mining, transportation and grinding (West et al., 2001), therefore, it is assumed that the water requirement is negligible for the production of lime.

2.6.2. Wheat to ethanol process

Like corn, wheat goes through dry grind technology in bioethanol manufacturing process with similar energy and water requirement. The only difference is in the starch content of wheat and corn. The starch content of wheat is lower than corn (Lin et al., 1987). As a result of this difference, more dry wheat is required to produce 1 kg of ethanol.

2.6.2.1. Direct water requirement of wheat for the bioethanol process

To produce 1 kg of ethanol, an average of 3.08 kg of dry wheat is required (Kim et al., 2003; Woods et al., 2005; Fredriksson et al., 2006). It is assumed that an equal amount of water is required to process equal amounts of wheat and corn for ethanol production. Thus, 5.13 liters of water is required directly to produce 1 kg of ethanol from 3.08 kg of wheat.

2.6.2.2. The indirect water requirement for the wheat to ethanol process

The major inputs for this process are electricity and natural gas. It is assumed that the same quantity of these major inputs is required for processing equal amounts of corn and wheat. The electricity and natural gas required to convert 1 kg of corn to ethanol are 0.11 kWh and 0.07 kg respectively. Considering 1.76 liters of water requirement for production of 1 kWh of electricity and zero water requirement for the production of natural gas (King et al., 2008), 1.03 liters of water is required indirectly for production of 1 kg of ethanol from wheat.

2.6.3. Wheat straw to bioethanol process

Like corn stover, wheat straw also goes through hydrolysis, saccharification and fermentation processes but the yield of bioethanol is different depending upon the composition of the biomass feedstock (EERE, 2009b) . The glucan, xylan, arabinan, galactan and mannan content of lignocellulosic biomass affects the ethanol yield of the process. The composition of corn stover, wheat straw and switch grass are shown in Table 2-7.

Table 2-7: Composition of corn stover, wheat straw and switchgrass (percent dry basis)

Component	Corn stover (Ringer et al., 2006)	Wheat straw (Kerstetter et al., 2001)	Switchgrass (Lee et al., 2007)
Glucan	37.4	41.0	37.3
Xylan	21.1	19.0	22.8
Arabinan	2.9	3.5	3.1
Galactan	2.0	2.2	1.4
Mannan	1.6	0.0	0.3
Lignin	18.0	18.0	19.1
Ash	5.2	7.2	5.9
Others	11.8	9.1	10.1

As the composition of wheat straw is slightly different from that of corn stover, 3.32 kg of dry wheat straw (as compared to 3.38 kg of corn stover) is required to produce 1 kg of ethanol (EERE, 2009a; EERE, 2009b). As the percentage of lignin is nearly the same for both the feedstocks, power generation by combustion of lignin in a boiler is the same in both cases.

2.6.3.1. Direct and indirect water requirement of the wheat straw to bioethanol process

As the chemical compositions of corn stover and wheat straw are almost the same, their requirement for direct water and other inputs are assumed to be almost the same as when processing equal amounts of feedstock. Hence, wheat straw to ethanol conversion requires 7.43 liters of water directly and 0.43 liters of water indirectly for the production of 1 kg of ethanol.

2. 7. Switchgrass based bio conversion pathways

2. 7.1. Switchgrass production and its water requirement

Switchgrass can be grown on marginal land with minimal nutrient and water requirement but a good crop yield always requires water and nutrient. The water requirement consists of the direct water needed for crop growth and the indirect water required to manufacture nutrients and fuels for farming.

2.7.1.1. Direct water requirement for switchgrass production

Like any other crop, the yield of switchgrass is also dependent upon the water supplied to the crop during its growing period. Table 2-8 gives the average yield of switchgrass and the water required, as reported in different studies.

Table 2-8: Average yields of switchgrass with water and nitrogen requirement

Switch grass average yield (kg ha^{-1})	Comments on water requirement	Nitrogen requirement (kg ha^{-1})	Source
13,000	Higher yield with higher precipitation observed.	84	(Fuentes et al., 2002)
14,600	Mid season irrigation may double switchgrass yields in dry years.	120	(McLaughlin et al., 2005)
10,300	400 mm rain fall is not sufficient; therefore, irrigation is required for good establishment.	66	(Sharma et al., 2003)
13,300	-	100	(Monti et al., 2008)
13,400	Highest yield with growing season (March –August) rainfall of 676 mm was observed.	168	(Muir et al., 2001)
6,700	855 mm is optimum water requirement.	180	(Koshi et al., 1982)
10,900	1067 mm of irrigation water is normal.	112	(Davison, 2008)
-	More than 510 mm rain fall is required for high yield.	185	(Blade, 2008)

The average yield of switchgrass derived from these studies is 11,700 kg per hectare. In practice, the net crop yield will be approximately 80% of the average yield because of variability in fields, differences in management practices, collection losses, etc (Spatari et al., 2005). It is clear from Table 2-8 that the water requirement for a high yield of switchgrass should exceed 50 cm. The average crop water requirement for a high yield of switchgrass is about 81 cm. Thus, the direct water requirement in the switchgrass production stage is 863.10 liters per kg of switchgrass.

2. 7.1.2. The indirect water required for switchgrass production

The amount of indirect water required depends mainly upon the nitrogen and fossil fuel requirement during production. The nitrogen requirement is the major governing factor for the switchgrass yield, the values reported in different studies are shown in Table 2-8. The average requirement of nitrogen is 118 kg ha^{-1}. Phosphate and potassium fertilizers do not affect the yield of switchgrass (McLaughlin et al., 2005), these are applied only when the P and K levels in the soil fall below 10 ppm and 90 ppm, respectively (Blade, 2008). The average amount of diesel consumed for field operation is 100 liter ha^{-1} (Pimentel et al., 2005). Thus, according to the considering specific water requirement for these inputs given in appendix A, the total indirect water requirement in agricultural stage is 0.03 liter per kg of switchgrass.

2. 7.2. Switchgrass to ethanol process

In this conversion stage from switch grass to ethanol, the NREL model (Aden et al., 2002) was considered for process development. As shown in Table 2-7, switchgrass is composed of glucan, xylan, arabinan, galactan and mannan, the same components of which corn stover and wheat straw are made. Only percentages of these components are different in switchgrass. Due to this compositional difference, the switchgrass to ethanol process produces 1 kg of ethanol using 3.35 kg of switchgrass compared to 3.38 kg of corn stover required (EERE, 2009b). The lignin component of switchgrass (19.1%), which is higher than the lignin component of corn stover (18%), produces approximately 0.07 kWh additional power for 1 kg of ethanol production. (Detailed calculations are given in Appendix C.)

2.7.2.1. The direct and indirect water requirement of the switchgrass to ethanol process

Switchgrass goes through all the stages of corn stover with almost similar input requirement (Spatari et al., 2005). The direct water requirement to process unit mass of biomass feedstock is almost the same as for the corn stover to ethanol process. The only difference is in the water requirement for generating additional electricity generation. Corresponding to this 0.07 kWh of extra generation, direct water requirement for power generation goes up from 0.66 liter to 0.70 liter as shown in Appendix C. After adjusting for the extra water requirement, the switchgrass conversion to ethanol needs 7.55 liter of water directly. As the inputs requirement for switchgrass process are same as for corn stover process, 0.45 liters water is used indirectly to produce 1 kg of ethanol.

2.8. Canola seed based bioconversion pathway

2.8.1. Canola seed production and its water requirement

Canola seed yield depends upon various agronomic practices such as seeding rate and depth and environmental factors such as moisture and temperature. Water availability at the right time, especially at the time of germination, plays a significant role in increasing the yield of canola seed.

2.8.1.1. Direct water requirement for canola seed production

As with other crops, the crop water requirement is the direct water required in the production stage of this pathway. This crop water requirement has a strong relationship with the yield of canola seed crop as shown in Table 2-9.

Table 2-9: Canola seed yield and water requirement

Canola seed yield (kg ha^{-1})	Water requirement (mm)
4064 [a]	480 [a]
2463 [b]	369 [b]
2285 [b]	395 [b]
1916 [b]	351 [b]
1776 [b]	317 [b]
1593 [b]	343 [b]
1537 [b]	282 [b]
922 [b]	210 [b]

[a] These data are taken from Mckenzie et al. (1997)
[b] These data are taken from CCC (2008)

Based on the data of Table 2-9, the average yield of canola seed is 1,785 kg ha^{-1} which requires an average of 324 mm of water during the growing period of the canola seed crop. Thus, the direct requirement in the agricultural stage is 1,815 liters per kg of canola seed.

2.8.1.2. The indirect water requirement for canola seed production

Indirect water requirement for agriculture stage depends upon the fertilizers and energy requirement. A typical input requirement for a canola crop is shown in Table 2-10. The water requirement corresponding to these inputs was calculated using the specific water requirement for each input.

Table 2-10: Major inputs of canola crop and their water requirement

Inputs	Quantity [a] (kg ha^{-1})	Indirect water requirement (liters ha^{-1})
Diesel	37.8	100.39 [b]
Nitrogen	73.5	50.14 [c]
Phosphorus	25.9	5.04 [c]
Potassium	5.6	0.01 [c]
Sulfur	12.4	8.47 [c]

[a] These values have been derived from an earlier study by CCC, (2006)

[b] Source: King et al. (2008)

[c] Source: Sheehan et al. (1998)

Thus, average indirect water requirement is 0.09 liter per kg of production of canola seed. Thus, the total water requirement in the production stage of canola seed is 1815.17 liters per kg of canola seed produced.

2.8.2. The production of canola oil from canola seed

There are two methods of processing oil seeds to extract oil: mechanical crushing and solvent extraction. The mechanical crushing method is only used in relatively small volume production. The solvent extraction method is used on industrial scale and it is commonly used for oil extraction from soybean in the USA (Sheehan et al., 1998). Figure 2-8 shows the steps in production of biodiesel.

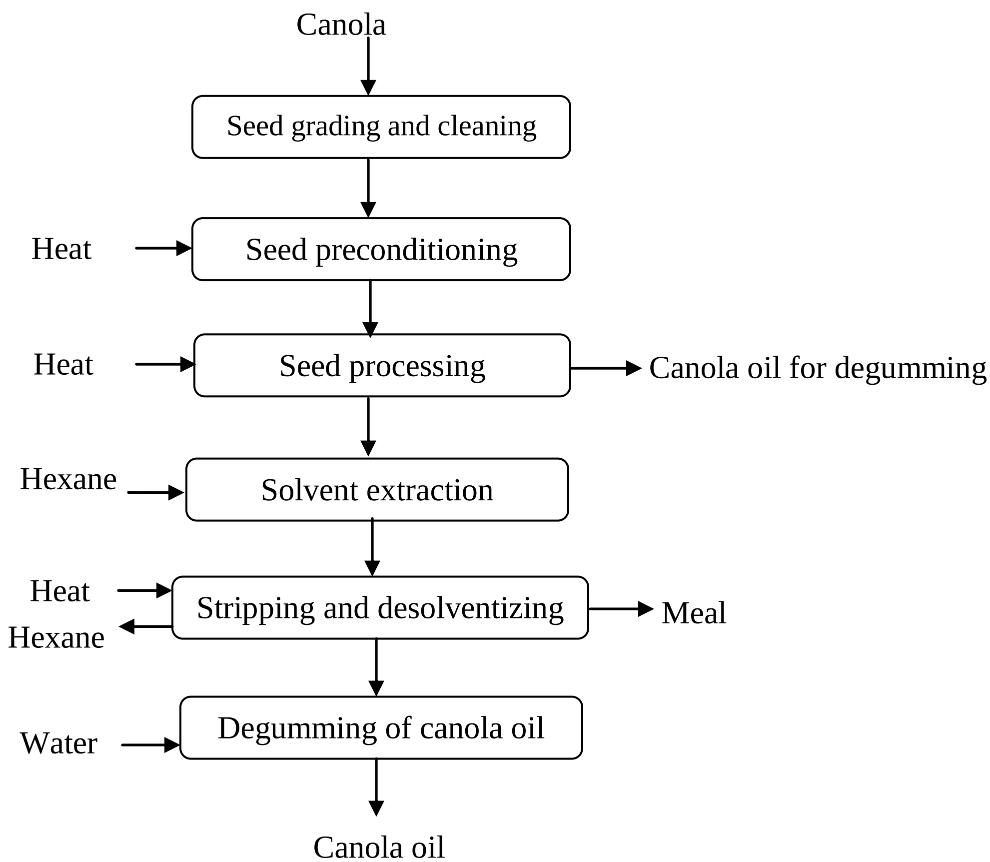

Figure 2-8: Canola seed to canola oil process (derived from CCC (2006))

In Canada, mechanical crushing followed by solvent extraction method is becoming popular for canola seed processing because there is less fugitive emission of solvent i.e. hexane (Rollefson et al., 2004). This method is considered in this study because of its effectiveness and greater oil extraction efficiency. In this method, canola seeds are graded, cleaned and heated to reduce moisture content for better extraction of oil before crushing. In the seed processing stage, seeds are crushed into flakes and canola oil is extracted partially which is further degummed. After crushing, pressed flakes are treated with hexane to dissolve oil and further oil is separated from hexane by applying heat to solution. Finally, in the degumming stage, oil is washed with water to remove phosphatide content of crude canola oil. This process is described in earlier studies (Sheehan et al., 1998; Rollefson et al., 2004; CCC, 2006).

2.8.2.1. The direct water requirement for producing canola oil from canola seed

In this process, direct water is used only to separate the gum from the oil and then most of it is recycled. As a result of this set up, make up water requirement is minimal. The total water used for production of 1 kg of canola oil is 0.01 liter (Sheehan et al., 1998).

2.8.2.2. The indirect water requirement for producing canola oil from canola seed

The major inputs of this process are shown in Table 2-11. The electricity is used to run the auxiliary equipment. About 1.76 liters of water is required for 1 kWh of electricity production (King et al., 2008). Natural gas is used to supply heat for different stages of the process. The water requirement corresponding to natural gas production is zero (King et al., 2008). Hexane is used as the solvent for the process and the water requirement corresponding to its production is zero

(Sheehan et al., 1998). Hence, the calculated value for the total indirect water requirement of the crushing process is 0.24 liter per kg of canola oil using 2.44 kg of canola seed.

Table 2-11: Input data of the canola seed to canola oil process and the water requirement for 1 kg canola oil production

Material	**Quantity [a] (kg)**	**Indirect water requirement (liters)**
Canola seed	2.44	-
Electricity	0.13 [b]	0.24
Natural gas	0.06	0.00
Hexane	0.01	0.00

[a] These values have been derived from an earlier study by (CCC, 2006).
[b] This value is given in kWh.

2.8.3. The production of biodiesel from canola oil

The canola oil to biodiesel conversion process is shown in Figure 2-9. The fatty acid of canola oil is removed by treating it with caustic soda and water.

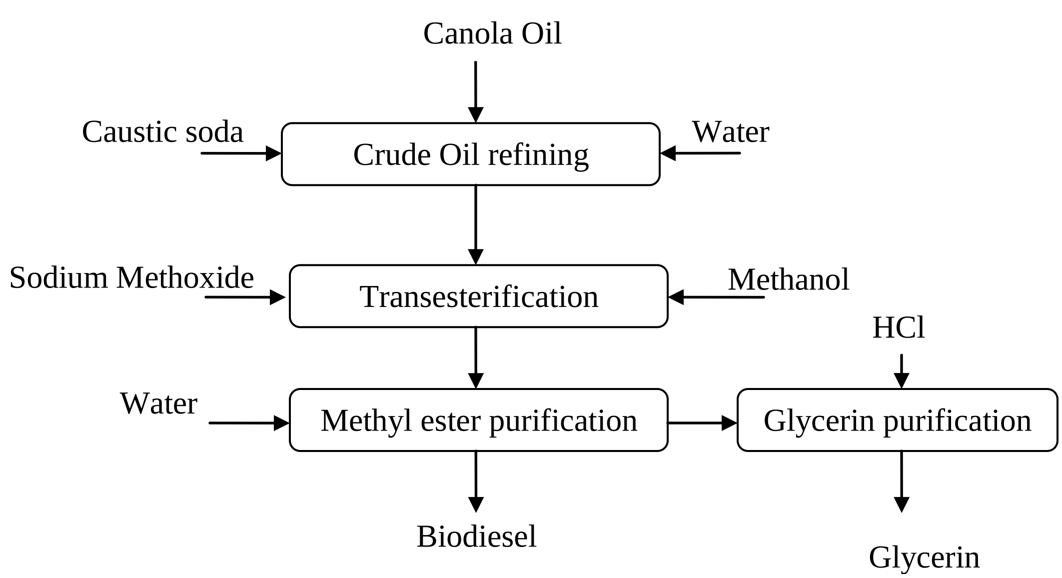

Figure 2-9: The canola oil to biodiesel process [derived from Sheehan et al., 1998)]

The reaction between refined canola oil and methanol takes place in the presence of a catalyst (sodium methoxide) to produce biodiesel and glycerin.

2.8.3.1. The direct water requirement for biodiesel production from canola oil

In the biodiesel production process, water is used directly in the crude canola oil refining and methyl ester purification stages as shown in Figure 2-9. In the canola oil refining stage, soaps are formed by a reaction between fatty acid and caustic soda; these are removed by washing oil with water. In the methyl ester purification stage, water is used to separate biodiesel from glycerin and unreacted methanol. Thus, the total water used in the above two stages is 0.29 liter for 1 kg production of biodiesel (Sheehan et al., 1998). In this evaluation it is assumed that the water and other input requirement for the production of biodiesel from canola is almost the same as for the soybean to biodiesel process because of the similar chemical compositions of the canola and soybean oils (Przybylski, 2008).

2.8.3.2. The indirect water requirement for producing biodiesel from canola oil

The major inputs required to produce of 1 kg of biodiesel are given in Table 2-12. The indirect water requirement corresponding to chemicals and electricity used for the process are calculated on the basis of the specific water requirement for each input as listed in Appendix A.

Table 2-12: Inputs for producing 1 of kg biodiesel and their water requirement

Material	Quantity [a] (kg)	Indirect water requirement [b] (liters)
Crude canola oil	1.04	-
Sodium methoxide	0.02	0.10
Sodium hydroxide	0.02	0.01
Hydrochloric acid	0.08	0.01
Methanol	0.09	0.15
Electricity	0.03[c]	0.05

[a] These values are derived from Sheehan et al. (1998).
[b] These values are calculated and calculation details are given in appendix A.
[c] This value is given in kWh.

Hence, the total indirect water requirement of the transesterification process is 0.32 liter per kg of biodiesel produced using 1.04 kg of canola oil.

2.9. Results and discussion

The water requirement factors for different biofuel pathways are shown in Table 2-13. These factors represent the total water requirement for biofuel pathways over the life cycle. These factors also include the direct water requirement for crop production. This direct water requirement is met by precipitation, soil moisture and/or surface or ground water (through irrigation) and depends on the location. These factors are useful for only comparing the biofuel pathways. These factors do not exactly represent the consumptive use of water for biofuel. The actual consumption can be estimated by subtracting the water available from precipitation and soil moisture from these water requirement factors to grow crop in a specific region.

Table 2-13: Life cycle water requirement of different biofuels

Biofuel pathways	Dry biomass (kg per kg of biofuel)	Water requirement (liters kg^{-1}) [a]				Biofuel lower heating value (MJ kg^{-1})	Water requirement (liter per MJ)		Water requirement factor (liter per MJ)
		Agriculture stage [b]		Conversion stage					
		Direct	Indirect	Direct	Indirect		Agriculture stage	Conversion stage	
Corn – ethanol	2.72	2054.3	0.16	4.53	0.91	26.7[c]	76.9	0.20	77.1
Corn stover – ethanol	3.38	0.0	0.00	7.56	0.44	26.7[c]	0.0	0.30	0.3
Wheat – ethanol	3.08	2877.8	0.20	5.13	1.03	26.7[c]	107.8	0.23	108.0
Wheat straw - ethanol	3.32	0.0	0.00	7.43	0.43	26.7[c]	0.0	0.29	0.3
Switchgrass – ethanol	3.35	3405.4	0.13	7.55	0.43	26.7[c]	127.5	0.30	127.8
Canola seed – biodiesel	2.53	4592.7	0.23	0.30	0.56	37.0[d]	124.1	0.02	124.2

[a] liters per kg of ethanol for ethanol pathways and liters per kg of biodiesel for biodiesel pathway.

[b] Water requirement is corresponding to dry biomass requirement for production of 1kg biofuel.

[c] Source: Shapouri, H. et al. (2002)

[d] Source: Sheehan et al (1998)

Of all the biofuels' production pathways considered, corn stover to ethanol and wheat straw to ethanol pathways are the most water efficient options (See Table 2-13). The reason is that both these biomass feedstocks are residues of food crops and water required in production stage of crop is allocated to the food crop, not residue. The switchgrass to ethanol pathway is another lignocellulosic biomass based pathway. This pathway also consumes almost the same amount of water i.e. 7.98 liters per kg of ethanol in the conversion process. What makes this pathway water intensive is high water requirement in crop production stage.

Apart from agriculture residue based pathways, the most efficient biofuel pathway is the corn to ethanol pathway for which the water requirement is 77.15 liter MJ^{-1}. Though the wheat ethanol pathway consumes almost the same amount of water in the conversion stage, this pathway is more water intensive than the corn to ethanol pathway.

The first reason for the high water requirement in the wheat to ethanol conversion pathway is high dry feedstock consumption for conversion process. The corn ethanol process consumes 2.72 kg of dry corn in producing one kg of ethanol while wheat to ethanol pathway consumes 3.08 kg of dry wheat per kg of ethanol production due to lower starch content of wheat. As water requirement in agriculture stage corresponds to these quantities, more water is required for wheat. This result shows that the yield of the conversion process plays an important role in determining the water requirement of a biofuel pathway.

The second reason for high water requirement in wheat to ethanol conversion pathway is water use efficiency of crops. While corn consumes 754 liters of water in producing for 1 kg of dry corn, wheat crop consumes 889 liters of water in producing of 1 kg of dry wheat. This result shows that water use efficiency is also dominant factor in determining water requirement for any biofuel. The water use efficiency may vary for the same crop according to its variety and climatic conditions of the region where it grown (Sinclair et al., 1984; Howell, T. A., 2001; Efetha, 2009). In this study, water use efficiency of crops is average of different North American regions reported by different studies. An exact evaluation of the water requirement for biofuel production in a specific region will need further study about variety of crop and climatic conditions.

By comparison, switchgrass consumes 1015 liters of water per kg of dry biomass produced and the switchgrass to ethanol conversion pathway consumes 3.35 kg of dry biomass per kg of ethanol. Based on these factors, this pathway consumes 3413 liters of water per kg of bioethanol, and it is the most water intensive of all the bioethanol pathways.

Although the dry mass requirement and the conversion stage water requirement are the lowest for the canola seed to biodiesel pathway, its total water requirement i.e. 124 liters MJ^{-1} is almost equal to that of switchgrass. The reason for this is canola seed's poor water use efficiency in production stage (i.e. 1815 liters of water required to produce 1 kg of canola seed). The favorable factor for this pathway is the higher LHV of biodiesel

(37.0 MJ per kg) which compensates for its poor water use efficiency; without it otherwise this pathway would have been worse than the switchgrass pathway.

This study has also evaluated the water requirement associated with the life cycle of major inputs in both stages: the agricultural and conversion stages as shown in Table 2-13. These requirement are based on typical requirement of fuels and other inputs which may vary substantially in type and quantity depending on location, production technology and process model. As the water requirement associated with these inputs is not significant compared to that of the agricultural stage water requirement, the total water requirement is not affected significantly.

2.10. Conclusions

The life cycle water requirement of six biofuel processing pathways have been evaluated: corn to bio ethanol, corn stover to bio ethanol, wheat to bio ethanol, wheat straw to bio ethanol, switch grass to bio ethanol and canola seed to bio diesel. This study has evaluated both the direct water requirement involved in producing the feedstocks and that involved in converting these feedstocks to biofuels. AS well, this study has taken into account the indirect water requirement associated with the life cycle of inputs in both the stages.

The crop water requirement plays a dominant role in determing the total water requirement of any biofuel. As the crop water allocation for agricultural residues, corn stover and wheat straw is considered to be zero, these are the most water efficient pathways (consuming approximately 8 liters of water for production of 1 kg of ethanol). Though the water requirement of switchgrass based pathways is almost same in conversion stage, the total water requirement is very high because production stage water requirement is approximately 3,413 liters per kg of ethanol produced.

Though the crop water requirement for feedstocks is a dominant factor, process conversion efficiency, i.e. the dry mass requirement per unit mass of biofuel, also plays an important role in determining the total water requirement. The conversion efficiency of the process decides, how much biomass is required per unit of biofuel produced, thus it indirectly governs the production stage water requirement. As a result, corn to ethanol production pathway consuming 2.72 kg of dry corn to produce 1 kg of ethanol is more water efficient than the wheat based pathway which consumes 3.08 dry kg of wheat per kg of ethanol produced. Their water requirement are 2,056 liters and 2,884 liters per 1 kg of ethanol, respectively.

The energy density or heating value per unit mass of biofuel may be a crucial factor for water efficiency. For instance, the canola seed to biodiesel pathway consumes 4,594 liters water to produce of 1 kg of biodiesel. This dwarfs the water requirement of the other ethanol pathways but the LHV for biodiesel is 37.0 MJ kg^{-1} compared to 26.7 MJ kg^{-1} of ethanol, reducing water requirement per MJ to the level of the switchgrass to ethanol pathway.

References

Aden, A., 2007. Water usage for current and future ethanol production. Available from: http://epw.senate.gov/public/index.cfm?FuseAction=Files.View&FileStore_id=3d2f1427-d51d-4a54-8739-166853ee1c44. Accessed on: December 4, 2008.

Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., 2002. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Task No. BFP2.A410. National renewable energy laboratory, Cole Boulevard, Golden, Colorado, USA. Available from: <http://www.p2pays.org/ref/38/37696.pdf>.

Bauder, J.W., 2009. Wheat irrigation. Available from: http://waterquality.montana.edu/docs/irrigation/wheatirrigation.shtml. Accessed on: March 30 2009.

Blade, 2008. Switch management guide. Blade energy crop. Available from: http://www.bladeenergy.com/SwitchgrassResources.aspx. Accessed on: January 1, 2008.

CANSIM, 2009. Agriculture. Canada Statistics. Available from: http://dc1.chass.utoronto.ca/cgi-bin/cansimdim/c2_subjects.pl. Accessed on: March 20, 2009.

CCC, 2006. A review of environmental assessments of biodiesel displacing fossil diesel. Canada Canola Council, Available from:

CCC, 2008. Canola growers manual. Available from: http://canola-council.org/chapter4.aspx#ch4_sec2. Accessed on: 6 December, 2008.

Claim, W., 2009. Corn yield response to water. Available from: http://waterclaim.org/charts/corn%20and%20water.htm. Accessed on: 15 Januray, 2009.

Davison, J., 2008. Switchgrass varieties for western nevada. Available from: http://www.unce.unr.edu/publications/files/ag/other/fs9965.pdf. Accessed on: January 9, 2009.

Demirbas, A., 2008. Conversion of Corn Stover to Chemicals and Fuels Energy Sources 30 (9), 788-796.

Dietrich, J., 2009. Central peace conservation society biodiesel project. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop12154. Accessed on: February 20, 2009.

DOE, 2008. The US dry mill ethanol industry. Department of Energy, USA. Available from: http://www.brdisolutions.com/pdfs/drymill_ethanol_industry.pdf. Accessed on: November 15, 2008.

Dominion, H., 2009. Wheat. Available from: http://www.thecanadianencyclopedia.com/index.cfm?PgNm=TCE&Params=A1ARTA0008543. Accessed on: 2009, January 18

EERE, U., 2009a. Biomass feedstock composition and property database. Energy Efficiency and Renewable Energy, USA. Available from: http://www1.eere.energy.gov/biomass/feedstock_databases.html. Accessed on: January 20, 2009.

EERE, U., 2009b. Theoretical ethanol yield calculator. Energy Efficiency and Renewable Energy, USA. Available from: http://www1.eere.energy.gov/biomass/ethanol_yield_calculator.html. Accessed on: February 21, 2009.

Efetha, A., 2009. Irrigation management of canola. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr4425. Accessed on: 2 April, 2009.

EIA, 2009. Annual energy outlook. Available from: http://www.eia.doe.gov/oiaf/aeo/overview.html. Accessed on: 15 May, 2009.

ESAA, 2000. Production of sulphuric acid. 3. European fertilizer manufacturers' association, Brussels. Available from: <http://cms.efma.org/PRODUCT%20STEWARDSHIP%20PROGRAM/images/EFMABATSUL.pdf>.

Franceschin, G., Zamboni, A., Bezzo, F., Bertucco, A., 2008. Ethanol from corn: a technical and economical assessment based on different scenarios. Chemical engineering research and design 86 (5), 488–498.

Fredriksson, H., Baky, A., Bernesson, S., Nordberg, A., Noren, O., Hansson, P.A., 2006. Use of on-farm produced biofuels on organic farms - Evaluation of energy balances and environmental loads for three possible fuels. Agricultural Systems 89 (1), 184-203.

Fuentes, R.G., Taliaferro, C., 2002. Trends in new crops and new uses : Biomass yield stability of switchgrass cultivars. 276-282. ASHS Press, Alexandria, VA, USA.

GAO, 2007. DOE lacks a strategic approach to coordinate increasing production with infrastructure development and vehicle needs. United States Government Accountability Office. Available from: http://www.gao.gov/new.items/d07713.pdf. Accessed on: May 15 2009.

Howell, A.T., Evett, S.R., Tolk, J.A., Schneider, A.D., Steiner, J.L. 1996. Evapotranspiration of corn - southern high plains. Evapotranspiration and irrigation scheduling, November 3-6, 1996, San Antonio, TX

Howell, A.T., Tolk, A.J., Schneider, A., Evett, R.S., 1998. Evapotranspiration, yield, and water use efficiency of corn hybrids differing in maturity. P American Society of Agronomy 90 3-9

Howell, T.A., 2001. Enhancing water use efficiency in irrigated agriculture. Agronomy Journal 93 (2), 281-289.

Jia, X., Scherer, F.T., Steele, D.D. 2007. Crop water requirement for major crops in North Dakota and its vicinity area. ASABE/CSBE North Central Intersectional Conference, October 12-13, 2007, North Dakota state university

Johnson, J.C., 2006. Technology assessment of biomass ethanol: a multi-objective, life cycle approach under uncertainty. Massachusetts Institute of Technology, B.S. Chemical Engineering

Kerstetter, J.D., Lyons, J.K., 2001. Wheat straw for ethanol production in washington: a resource, technical, and economic assessment. Washington state university cooperative, Available from: <http://www.energy.wsu.edu/documents/renewables/WheatstrawForEthanol.pdf>.

Kim, S., Dale, B.E., 2003. Global potential bioethanol production from wasted crops and crop residues. Biomass and bioenergy 26 (6), 361-375.

King, C.W., E., W.M., 2008. Water intensity of transportation. Envionmental science and environmental policy 42 (21), 7866-7872.

Klein, K.K., Roy, D.G.L., 2009. The bioenergy frenzy. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop12133. Accessed on: Februrary 15 2009.

Koa, J., Piccinnib, G., 2009. Corn yield responses under crop evapotranspiration-based irrigation management. Agricultural water management 96 (5), 799-808.

Koshi, P.T., Stubbendiek, J., Eck, H.V., Mccully, W.G., 1982. Switchgrass: forage yield, forage quality and water use efficiency. Range management 35 (5), 623-627.

Larsson, M., Galbe, M., Zacchi, G., 1997. Recirculation of process water in the production of ethanol from softwood. Bioresource technology 60 143-151.

Lee, D., Owens, V., Boe, A., Jeranyama, P., 2007. Composition of herbaceous biomass feedstocks. Available from: http://ncsungrant.sdstate.org/uploads/publications/SGINC1-07.pdf. Accessed on: February 19 2009.

Lenssen, A.W., Johnson, G.D., Carlson, G.R., 2007. Cropping sequence and tillage system influences annual crop production and water use in semiarid Montana, USA. Field Crops Research 100 (1), 32-43.

Lin, F.D., Knabe, D.A., Tanksley, T.D., 1987. Apparent digestibility of amino-acids, gross energy and starch in corn, sorghum, wheat, barley, oat groats and wheat middlings for growing-pigs. Journal of Animal Science 64 (6), 1655-1663.

Lurgi, A., 2008. Bioethanol. Available from: http://www.lurgi.com/website/fileadmin/user_upload/pdfs/13_Bioethanol-E.pdf. Accessed on: December 5 2008.

Manitoba Agriculture, F.A.R.I., 2009. Introduction to corn production. Available from: http://www.gov.mb.ca/agriculture/crops/specialcrops/bii01s01.html. Accessed on: January 16 2009.

McKenzie, R., Dunn, R., 1997. Irrigated crop recommendations. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex139. Accessed on: December 3 2008.

McLaughlin, S.B., Kszos, L.A., 2005. Development of switchgrass (Panicum virgatum) as a bioenergy feedstock in the United States. Biomass and bioenergy 28 (6), 515-535.

Monti, A., Bezzia, G., Pritonia, G., Venturia, G., 2008. Long-term productivity of lowland and upland switchgrass cytotypes as affected by cutting frequency. Bioresource technology 99 (16), 7425-7432.

Muir, J., Sandersonb, M.A., Ocumpaughc, W.R., M. Jonesa, R., L. Reedd, R., 2001. Biomass production of ‘alamo’ switchgrass in response to nitrogen, phosphorus, and row spacing. Agronomy Journal 93 896-901.

NEB, 2009. Canada's energy future - reference case and scenarios to 2030. National Energy Board, Canada. Available from: http://www.neb.gc.ca/clf-nsi/rnrgynfmtn/nrgyrprt/nrgyftr/2007/nrgyftr2007chptr5-eng.html. Accessed on: March 25 2009.

OMAFRA, 2009a. Equilibrium moisture content. Ontario Ministry of Agriculture, Food and Rural Affairs. Available from: http://www.omafra.gov.on.ca/english/crops/pub811/3harves.htm#table324. Accessed on: January 15 2009.

OMAFRA, 2009b. Corn: other problems affecting corn production. Ontario Ministry of Agriculture, Food and Rural Affairs. Available from: http://www.omafra.gov.on.ca/english/crops/pub811/3othpro.htm#drought. Accessed on: January 15 2009.

Payero, J., David., T.D., Irmak, S., Davison, D., Petersen, J.L., 2008. Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate. Agricultural water management 95 (8), 895-908

Pfromm, P.H., 2008. The minimum water consumption of ethanol production via biomass fermentation. The open chemical engineering journal 2 1-5.

Pimentel, D., Patzek, T.W., 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Natural resources research 14 (1),

Przybylski, R., 2008. Canola oil : physical and chemical properties. Available from: http://www.canola-council.org/uploads/Chemical1-6.pdf. Accessed on: December 5, 2008.

Raddatz, R.L., Shaykewich, C.F., 1998. Impact of warm summers on the actual evapotranspiration from spring wheat grown on the eastern Canadian prairies. Canadian Journal of Soil Science 78 (1), 171-179.

Reith, J.H., Veenkamp, J.M., Ree, R.V. 2001. Co-production of bioethanol, electricity and heat from biomass wastes. The first european conference on agriculture & renewable energy, 2001, RAI, Amsterdam, The Netherlands

RFA, U., 2008. Ethanol facts:environment. Renewable Fuel Association, USA. Available from: http://www.ethanolrfa.org/resource/facts/environment/. Accessed on: November 20, 2008.

Ringer, M., Putsche, V., Scahill, J., 2006. Large-scale pyrolysis oil production: A technology assessment and economic analysis. NREL/TP-510-37779. National renewable energy laboratory, Cole Boulevard, Colorado. Available from: <http://www.forestbioproducts.umaine.edu/documents/37779.pdf>.

Rollefson, J., Fu, G., Chan, A., 2004. Assessment of the environmental performance and sustainability of biodiesel in Canada. National research council, Canada, Available from: <http://studio255.com/crfa/pdf/res/2004_11_NRCBiodieselProjectReportNov04.pdf>.

Sanderson, M.A., Reed, O.R.L., McLaughlin, S.B., Wullschleger, S.D., Congcr, B.V., Parrish, D.J., Wolf, D.D., Taliaferro, C., Hopkins, A.A., Ocumpaugh, W.R., Hussey, M.A., Read, J.C., Tischler, C.R., 1996. Switchgrass as a sustainable bioenergy crop. Bioresource technology 56 (1), 83-93.

Shapouri, H., 2007. Global perspectives on biofuels- what's the potential/ future. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop12125. Accessed on: February 20, 2009.

Shapouri, H., Duffield, J.A., Wang, M., 2002. The energy balance of corn ethanol: an update. USDA, Washington, DC. Available from: <http://www.transportation.anl.gov/pdfs/AF/265.pdf>.

Sharma, N., Piscioneri, I., Pignatelli, V., 2003. An evaluation of biomass yield stability of switchgrass (Panicum virgatum L.) cultivars. Energy conversion and management 44 (18), 2953-2958.

Sheehan, J., Camobreco, V., James, D., Graboski, M., Shapouri, H., 1998. Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. USDA, Cole Boulevard Golden, Colorado. Available from: <http://www.nrel.gov/docs/legosti/fy98/24089.pdf>.

Shock, C.C., Feibert, E.B.G., Saunders, L., 2005. Water management for drip-irrigated spring wheat. Available from: http://www.cropinfo.net/AnnualReports/2005/WheatDripIrr05.html. Accessed on: February 21, 2009.

Sinclair, T.R., Tanner, C.B., Bennett, J.M., 1984. Water-Use Efficiency in Crop Production. Bioscience 34 (1), 36-40.

Sobolik, J., 2008. Biomass 08: Ethanol plants explore water recycling options. Available from: http://www.biomassmagazine.com/article.jsp?article_id=1610. Accessed on: November 15, 2008.

Sokhansanj, S., Mani, S., Stumborg, M., Samson, R., Fenton, J., 2006. Production and distribution of cereal straw on the Canadian prairies. Available from: http://engrwww.usask.ca/oldsite/societies/csae/protectedpapers/c0556.pdf. Accessed on: January 15, 2009.

Spatari, S., Zhang, Y., MacLean, H.L., 2005. Life cycle assessment of switchgrass- and cornstover-derived ethanol-fueled automobiles. Environmental science and technology 39 (24), 9750-9758.

Varghese, S., 2007. Biofuels and global water challenges. Institute for agriculture and trade policy, Minneapolis, Minnesota. Available from: <http://www.iatp.org/iatp/publications.cfm?refid=100547>.

West, T.O., Marland, G., 2001. A synthesis of carbon sequestration, carbon emissions and net carbon flux in agriculture: comparing tillage practices in the United States. Agriculture ecosystems and environment 91 (1-3), 217-232.

Woods, J., Brown, G., Estrin, A., 2005. Bioethanol greenhouse gas calculator. Available from: http://www.hgca.com/document.aspx?fn=load&media_id=2324&publicationId=2732. Accessed on: February 18, 2009.

Chapter 3 . Development of Water Requirement Factors for Biopower Generation using Thermochemical Pathways

3.1. Introduction

Electricity is one of the most popular forms of energy; it which can be transmitted, distributed and utilized more conveniently than most other forms of energy. While world's demand for energy is expected to increase by 44 % from 2006 to 2030, the demand for electricity will grow by 77 % from 2006 to 2030. This increase in the demand for electricity will be met at the highest growth rate (2.9 %) by renewable energy, followed by natural gas and coal. This renewable energy supply will be led by hydropower, wind power and biopower (biomass based power). While in developing countries hydroelectric power plants will be in the forefront of green electricity production, in developed countries wind and biomass based power plants will be significant contributors of renewable electricity (EIA, 2008). The biomass contribution to renewable electricity increased significantly in the past decade, although it was only 11 % of total renewable electricity production in 2006. It has contributed 29.3 % to the total growth of renewable electricity from 1996 to 2006 (Gavrilescu, 2008).

Biomass, which is the oldest form of energy, is still utilized mainly in a conventional way for producing heat. The processing of biomass to convert it into secondary energy is led by charcoal production and is followed by electricity generation (WEC, 2007). At present, the old rankine cycle based power generation technology in which biomass is directly combusted in the boiler is used to produce electricity. Currently, this technology using biomass produces 30 GW of electricity, this is only 1% of installed capacity of all the world's power plants (Demirbas et al., 2009). In this conventional method, the efficiency of biomass conversion is low; other technologies for generating power from biomass feedstocks are at different stages of development, demonstration and commercialization. These technologies which are at doorstep of commercialization are gasification and pyrolysis (Demirbas et al., 2009). The above facts and figures suggest that there is great potential for generating electricity form biomass feedstocks. A fresh impetus for the biomass based power plants is very low net emission of CO_2 over the production life cycle (from crop production to electricity generation).

As this renewable energy depends on the water intensive agricultural sector (as discussed in Chapter 2), an increase in biopower generation in a specific region increases the demand for water. This study estimates the water requirement factors for electricity generation using different biomass feedstocks and different thermochemical conversion pathways. In this study, water requirement of crop production and conversion stages are evaluated. The direct and indirect water requirement for each stage are considered in this study. The water requirement for transportation stage (from field to power plant) is not evaluated as water requirement is negligible for this stage (King et al., 2008). Details on selection of biomass feedstocks and thermochemical pathways for biopower production are given in subsequent sections.

3.2. Definition of water requirement

In this study, water requirement refers to the total direct and indirect water used to produce biomass crop i.e. crop production stage and to convert biomass to biopower in conversion stage. The sources of direct water are precipitation, soil moisture, and/or surface or ground as shown in Figure 3-1.

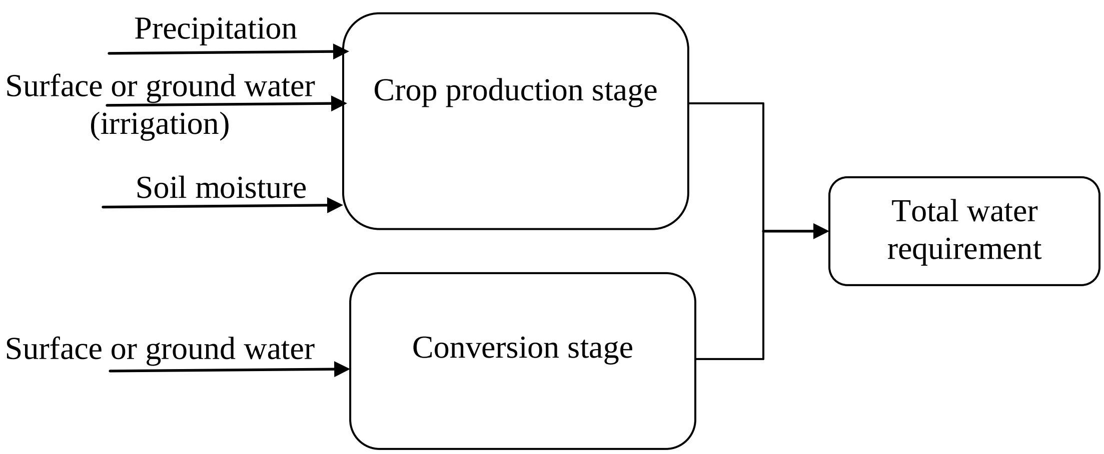

Figure 3-1: Water sources for biopower production

The direct water requirement in crop production stage is water used to grow crop and this water requirement is dependent upon climatic conditions of the region where crop is grown. The surface water includes water from river, pond, lakes etc. The surface or ground is used through irrigation. The direct water requirement in conversion stage is the make-up water requirement for the conversion process. The source of this make-up water is surface or ground water. The indirect water requirement in both the stages is water used during the manufacturing of major inputs such as fertilizers, chemicals, and fuels. The source of this indirect water requirement is surface or ground water. The source of this indirect water requirement is surface or ground water. The total water requirement estimated in this study is thus the sum of direct and indirect water requirement for both crop production and conversion stages.

3.3. Selection of biomass feedstocks for electricity generation

There are different types of biomass feedstocks for electricity generation, such as whole forest biomass, forest residues, agriculture crops, energy crops and municipal solid waste. This study considers only that biopower is produced from the non-food portion of agricultural crops. Electricity generation from agricultural crops and energy crops is water intensive at the production stage. This stage is explored in detail in this study.

As discussed earlier in Chapter 2, corn stover and wheat straw are abundantly available in North America and most of these feedstocks are not utilized for any specific purpose. There has been recent increase in the use of these lignocellulosic biomass feedstocks for the production of fuels and chemicals. There is also a lot of interest in utilizing switchgrass, an energy crop, for the production of fuels and chemicals. As well, these lignocellulosic biomass feedstocks can be utilized in thermochemical pathways (e.g., direct combustion, pyrolysis) for the production of electricity.

3.4. Selection of biomass to electricity conversion pathways

Currently, biomass is utilized in solid form to produce power, mostly by directly combusting it in a boiler. Biomass can be converted into liquid and gas, using pyrolysis and gasification pathways, which can further be utilized to produce power. This study evaluates the life cycle water requirement for various thermochemical pathways for the production of power are evaluated.

In recent years, many countries and organizations have become interested in fast pyrolysis for the thermochemical dissociation of lignocellulosic biomass into liquid. Fast pyrolysis of biomass produces a dark viscous liquid known as bio-oil (Kumar, A. et al., 2009) It has high energy density as compared to 'as received' biomass (Kumar, A. et al., 2009). It can be stored and transported and it is used commercially as a substitute for fuel oil to produce heat and electricity by direct combustion (DES, 2007). The water requirement of this new conversion pathway is compared with the water requirement of the biopower production by direct combustion pathway. As shown in Figure 3-2, corn stover can be utilized in two thermochemical pathways to produce electricity.

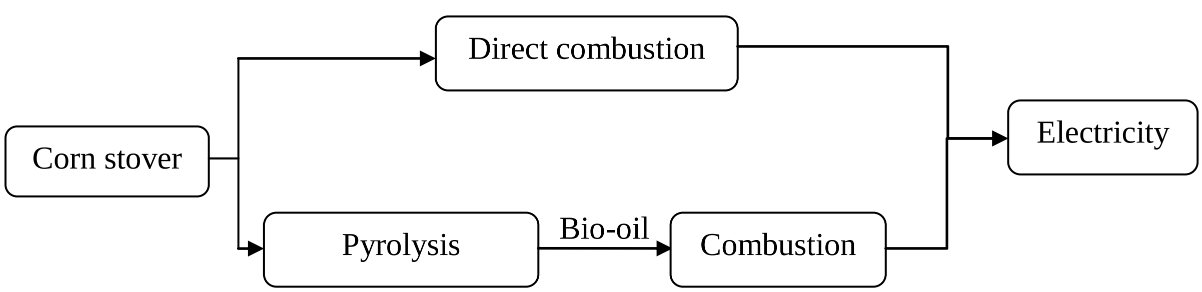

Figure 3-2: Electricity generation from corn stover

The direct combustion of corn stover produces electricity by combusting directly corn stover in a boiler. In the fast pyrolysis pathway, corn stover goes through thermochemical decomposition process to produce bio-oil which is then combusted in a boiler to produce steam; this steam drives a steam turbine to produce electricity. In the direct combustion pathway, water requirement is evaluated for two stages: the corn stover production stage; and the direct combustion stage. This evaluation is used to assess the life cycle water requirement to produce electricity. In the pyrolysis pathway, the water requirement is evaluated for three stages: corn stover production, pyrolysis, and combustion. These are used to estimate the life cycle water requirement for this pathway.

Similarly, wheat straw can be utilized to produce electricity using the two thermochemical pathways discussed above. This is shown in Figure 3-3.

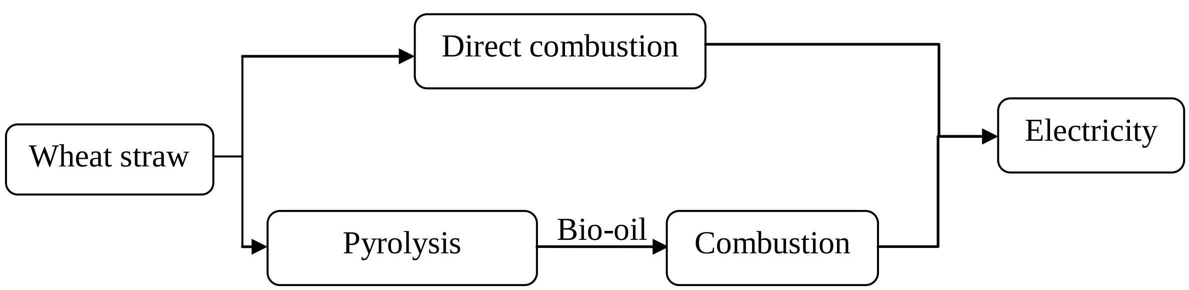

Figure 3-3: Electricity generation from wheat straw

The life cycle water requirement for both these pathways are calculated in this study. Switchgrass can also be utilized for producing power through the two pathways as shown in Figure 3-4.

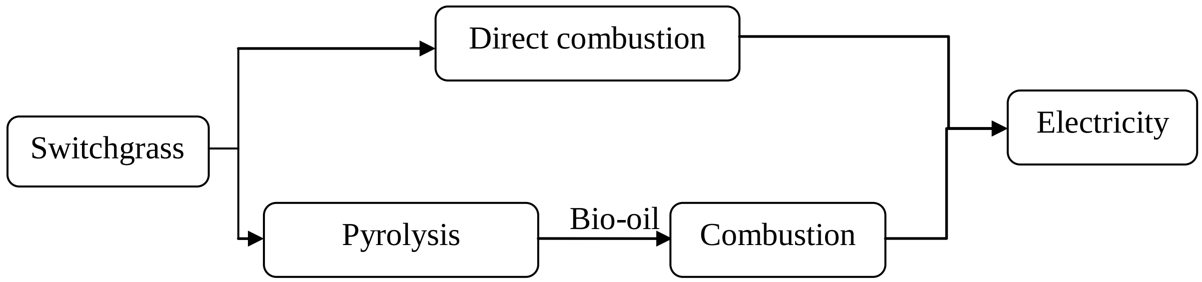

Figure 3-4: Electricity generation from switchgrass

3.5. The water requirement for corn stover based biopower production pathways

3.5.1. The water requirement for corn stover production

Water plays a major role in the development of any crop. Water availability during growth period decides not only the yield of grain but also growth of residual parts such as stem and leaves of the plant. The grain yield of a plant has a relationship with the yield of residues of the plant. Corn stover yield is related to corn kernel yield. It is defined as corn stover to grain dry weight ratio and it is approximately 1 (Perlack et al., 2003; Petrolia, 2008). The average yield of corn in the North America is 8,568 dry kg ha^{-1} (as explained in Chapter 2). Based on this, corn stover yield is 8,568 dry kg ha^{-1}. This amount of corn stover cannot be practically recovered completely from the field because of poor collection efficiency and other field requirement (Aden et al., 2002; Perlack et al., 2003). It is technically required to leave a part of corn stover in the field to maintain soil nutrient and carbon levels and to control soil erosion (Aden et al., 2002; Perlack et al., 2003; Shinners et al., 2007). As a result of above limitations and requirement, only 35 % of the produced corn stover can be used for biopower production. Based on 35 %

availability, only 2,999 kg of corn stover can be collected per hectare. Total water requirement for corn is 754.18 liters for production of 1 kg of dry corn (as explained in Chapter 2). If this water requirement for corn is shared between corn and corn stover on the basis of dry weight, 1,077.46 of water is required for production of 1 kg corn stover.

It is important to understand that corn stover is agricultural residue and corn stover will be produced along with corn in any way; therefore, the assumption in this study is that water requirement during growth of corn is only attributed to corn and not to corn stover (as explained in Chapter 2).

3. 5.2. Corn stover to electricity through direct combustion

3. 5.2.1. Direct combustion based electricity generation process

The water requirement for conversion of corn stover to electricity depends upon the thermochemical pathway used for electricity generation. The pathway for electricity generation could be based on using condensing steam turbine and generator or heat and power generation using back pressure steam turbine and generator (Drbal et al., 1996) . In this study, electricity production is based on steam generation in a corn stover fired boiler and use of this generated steam in a condensing steam turbine as shown in Figure 3-5.

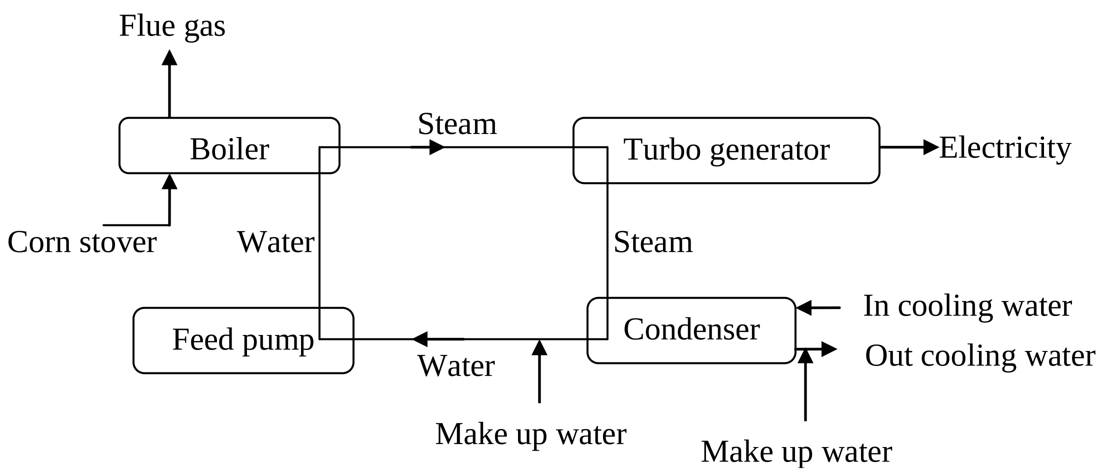

Figure 3-5: Power generation using corn stover as feed stock

[derived from Wiltsee (2000)]

Water requirement in this type of biomass power plant depends upon type of cooling water system. There are typically two types of cooling systems. These include open cooling water system and closed cooling water system (Drbal et al., 1996)). In open cooling water system, the water is taken from river, pond or lake and it is returned back to these water reservoirs at higher temperature while in closed cooling water system, the cooling water is circulated through cooling tower to dissipate the heat to atmosphere (Perry et al., 1999). The water withdrawal in former case is huge but the consumption is minimal compared to the later. The environmental regulations are likely to favor closed cooling water systems as the water withdrawal is low (Gerdes et al., 2008). In this study, the closed cooling system is considered to evaluate water requirement for electricity generation.

3.5.2.2. Water requirement in a direct combustion based electricity generation process

In any rankine cycle based power plant, water requirement is governed dominantly by cooling water requirement for steam condensation in a condenser. This cooling water takes away heat from the condenser and releases it to the atmosphere through evaporative cooling in a cooling tower. The evaporation and blow down losses of cooling tower creates a demand for makeup water. In a power plant, cooling water is also used for plant auxiliaries like compressors, oil coolers, which is about 10% of cooling water requirement in a condenser (Chapman, 1996). The make-up water for cooling system is a major component of the total water requirement. There are also other minor water requirement which include make-up water for steam and feed water cycle and general service water. These requirement are approximately 1.5% and 1% of maximum steam flow, respectively (Chapman, 1996).

3.5.2.3. Corn stover requirement for unit electricity production

To evaluate corn stover requirement for production of 1 kWh of electricity in a direct combustion power plant, McNeil Generating Station, Burlington, Vermont (Wiltsee, 2000) was considered as model plant. McNeil power plant is equipped with grate fired boiler which can burn wide range of fuels with varying moisture contents. Biomass feedstock can be fed conveniently in this type of boiler (Yin et al., 2008). The biomass feedstock for McNeil grate fired boiler is 60% softwood and 40% hard wood at 55% moisture content. This boiler can also be used to burn corn stover. The moisture content of corn stover is 15%. As corn stover contains high percentage of chlorine in comparison to wood (Yin et al., 2008), it may pose high temperature corrosion problem in boiler. Except this operational problem, it is assumed that the plant can run with existing auxiliaries using corn stover as feedstock.

As chemical properties, calorific value and moisture content of both biomass feedstocks are different, the biomass feedstock quantity required for power production is different. The chemical properties of both corn stover and wood are shown in Table 3-1. The quantity of corn stover depends upon net heat rate (reciprocal of net plant efficiency) of the plant. The net heat rate of wood in McNeil power plant is 14,685 kJ kWh^{-1}. This net plant heat rate depends upon boiler efficiency and turbine efficiency (Wiltsee, 2000).

The turbine efficiency depends upon inlet and outlet steam pressure and temperature, and is not affected by the type of biomass feedstock combusted in the boiler. The boiler efficiency depends on the chemical properties of biomass feedstock used in the boiler. The boiler heat losses for corn stover and wood are calculated in accordance with ASME Standard PTC 4.1. The net heat rate for corn stover based power plant was derived from data on wood based power plant. This is explained in detail in Appendix D. The net heat rate of corn stover based power plant is 12,354 kJ kWh^{-1}. Hence, 0.68 kg dry corn stover produces 1 kWh electricity.

Table 3-1: Ultimate analysis (wt% dry basis) and higher heating value (kJ per kg dry basis) of different biomass feedstocks

	Hard wood [a]	Soft wood [b]	Corn stover [c]	Wheat straw [d]	Switch grass [e]	Corn stover bio-oil [f]	Switch grass bio-oil [g]
%C	50.2	52.7	46.9	43.9	47.0	56.0	55.3
%H	6.2	6.3	5.4	5.3	5.3	6.7	6.9
%O	43.5	40.8	38.9	38.8	41.4	35.9	36.9
%N	0.1	0.2	0.7	0.6	0.5	0.1	0.3
%S	0.1	0.1	0.2	0.2	0.1	1.1	0.8
%Ash	-	0.6	7.7	10.2	5.7	0.1	0.1
HHV ($kJkg^{-1}$)	20,000	21,000	18,154	17,423	18,610	23,567	23,900

[a] Source: (Ragland et al., 1991)

[b] Source: (Ragland et al., 1991; Gupta et al., 2003)

[c] Source: (Parikh et al., 2007; Kumar, Ajay. et al., 2008)

[d] Source: (EERE, 2009)

[e] Source: (Larson et al., 2005)

[f] Source: (Agblevor et al., 1996)

[g] Source: (Agblevor et al., 1996)

3.5.2.4. Water requirement in conversion of corn stover to electricity

As explained in section 3.5.2.2, the water requirement in a power plant is related to steam flow to turbine. The quantity of steam flow is independent of feedstock used in the boiler. Therefore, water requirement for generation of 1 kWh electricity is same for wood and corn stover based power plants.

The cooling water requirement for McNeil plant to condense steam in condenser is 176.6 liters for 1 kWh net electricity generation (details are explained in Appendix E). The total cooling water circulation rate of cooling tower including auxiliary cooling water (which is 10 % of condenser cooling water) is 194.3 liters. This amount of cooling water is recycled in the system and is cooled down by the cooling tower by 8.8 °C temperature (Wiltsee, 2000). The makeup water requirement due to evaporation loss corresponding to this cooling water flow rate in cooling tower is 2.60 liters (details given in Appendix E). About 4.03 kg steam is required to produce 1 kWh of electricity. Make up water requirement for feed water and steam system is 1.5 % of steam flow and is about 0.06 liters. Service water requirement is 1 % of steam flow and is about 0.04 liters. Hence, total 2.70 liters (2.6 liters plus 0.06 liters plus 0.04 liters) water is required to generate 1 kWh of electricity.

3.5.3. Conversion of corn stover to bio-oil through fast pyrolysis

3.5.3.1. Fast pyrolysis process

Fast pyrolysis of biomass materials produces three energy products: char, non-condensable gases and bio-oil and water mixture. The product yields differ from one biomass feedstocks to other depending on their chemical properties.

Fast pyrolysis of biomass requires heat to maintain operating temperature and dry the feedstock. It also needs electricity to run auxiliary equipments. The heat and power requirement of the process may be fulfilled either by external system or by integrated system utilizing char and non-condensable gases as a source of energy. As integrated system has more viability at commercial scale (Ringer et al., 2006), this type of process is considered for this study. Many companies have developed fast pyrolysis based bio-oil production system which require minimal amount of external energy (DES, 2007; Dynamotive, 2007; ENSYN, 2009). A simplified schematic diagram of this process is given in Figure 3-6.

In this process, char and non-condensable gases are combusted to produce heat and a part of the heat is utilized to produce electricity in the power plant. Also a part of heat is utilized to maintain temperature of the recycle carrier gas through heat exchanger for the pyrolysis process. After fast pyrolysis, charcoal and ash are separated from other gaseous products in the cyclone. Thereafter, condensation of gaseous products takes place in two stages and bio-oil is separated from noncondensable gases.

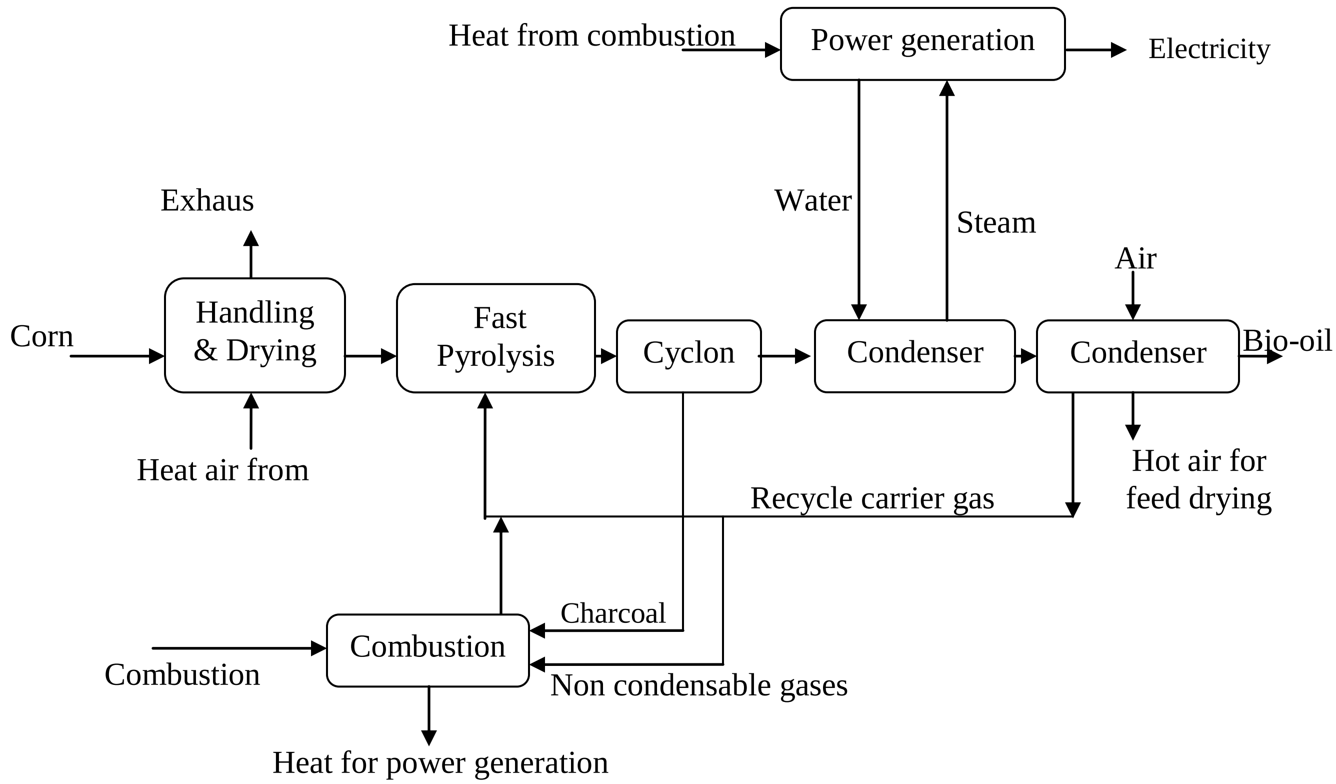

Figure 3-6: Fast pyrolysis of biomass

[derived from Ringer et al. (2006)]

During the condensation stage I, heat of pyrolysis products and carrier gas is used to produce steam and this steam is also utilized to produce power. A part of total produced power is used to run the process itself and remaining is the byproduct of this process model. During condensation stage II, carrier gas is further cooled by air in the condenser II (as shown in Figure 3-6) and bio-oil is liquefied. The heat recovered from this stage by air is used to dry feedstock. In drying feedstock, moisture level is reduced to 7 % (Ringer et al., 2006).

3.5.3.2. Fast pyrolysis of corn stover and the products' yields

Though basic products of pyrolysis are bio-oil, charcoal and noncondensable gases, the final products are bio-oil and electricity. To evaluate production quantity of bio-oil and electricity, National Renewable Energy Laboratory's (NREL) process model of wood fast pyrolysis (Ringer et al., 2006) is considered as the base model for this study. As NREL's model used wood containing 50 % moisture as feedstock, energy and mass balance of NREL's model was modified based on the chemical properties of corn stover (shown in Table 3-1) and hence, the products yield (shown in Table 3-2).

Table 3-2: Product yields from fast pyrolysis of corn stover, wheat straw and switchgrass pyrolysis

Pyrolysis Products	Wood (Ringer et al., 2006) (% by wt)	Corn stover (Agblevor et al., 1996) (% by wt)	Switchgrass (Agblevor et al., 1996; Dynamotive, 2007) (% by wt)	Wheat straw [a] (% by wt)
Gas	13.1	13.2	12.0	12.0
Char	16.2	11.4	15.6	15.6
Water	10.8	6.7	6.0	6.0
Bio-oil	59.9	54.9	54.0	54.0

[a] Dynamotive (2007) study show products yield of wheat straw and switchgrass are same.

In fast pyrolysis, product yields depend upon molecular structures of biomass feedstocks. The product yields of different biomass feedstocks are different as shown in Table 3-2. These products yields are based on dry weight basis. Though fast pyrolysis of biomass feedstocks takes place in the absence of oxygen, water is formed because of reaction between inherent oxygen and hydrogen of the biomass feedstock. In fast pyrolysis, feedstock is dried to maximize product yields and to reduce water content in bio-oil. In this study, feedstock is dried to a moisture level of 7% (Ringer et al., 2006). Therefore, 1.45 kg dry corn stover produces 1 kg bio-oil containing 20.6 % moisture in this process model (detailed calculation given in Appendix F).

Net power generation depends on lower heating value (LHV) of feedstock, bio-oil yield, heat, and power requirement of the pyrolysis process. The LHV of corn stover is 16.5 MJ per kg (Morey et al., 2006) which is lower than the LHV of wood of 19.5 MJ per kg (Bridgwater et al., 2002). As a result of low LHV, corn stover process gets less heat after bio-oil generation for power generation. Bio-oil yield from fast pyrolysis of corn stover is lower than fast pyrolysis of wood and more heat for power generation is available in corn stover based fast pyrolysis. Lower moisture content of corn stover, 15 % (Aden et al., 2002) instead of 50 % of wood, saves heat for drying of feedstock and power for air fan. As dry air quantity is less for corn stover, the auxiliary power required to run air supply fan is less. While 61.1 kWh per dry tonne grinding energy is required to reduce wood size to 2 mm, only 23.5 kWh per dry tonne (Mani et al., 2004) grinding energy is required to reduce corn stover size to 2 mm. As a result of this, less auxiliary power is required in case of corn stover based fast pyrolysis. In fast pyrolysis, heat is also lost with high temperature ash. As ash content of corn stover is 7.7 % (Parikh et al., 2007) instead of 0.92 % (Ringer et al., 2006) of wood, the heat loss in ash is higher in case of corn stover. As a result of above differences, during fast pyrolysis of corn stover 0.17 kWh of electricity is produced along with 1 kg bio-oil production. The detailed heat and mass balance calculations are given in Appendix F.

3.5.3.3. Water requirement for fast pyrolysis of corn stover

In fast pyrolysis, cooling water is used for different purposes as shown in Table 3-3. Cooling water is used to condense steam in the integrated power plant of fast pyrolysis process. In comparison with wood based pyrolysis, the quantity of cooling water is higher for corn stover based fast pyrolysis plant due to 0.03 kWh more power generation along with 1 kg bio-oil production. Cooling water is also used in scrubbing to extract vapor of bio-oil from the recycled carrier gas. As temperature of bio-oil is high after condensing, it is cooled down to 33°C (Ringer et al., 2006) using cooling water. During cooling of water in the cooling tower evaporation loss occurs. About 0.92 liters of make-up water is required to produce 1 kg bio-oil as shown in Table 3-3 (Detailed calculations are given in Appendix G) (Ringer et al., 2006).

Table 3-3: Make-up water requirement for fast pyrolysis for production of bio-oil from wood, corn stover, wheat straw and switchgrass

Purpose	Make up water (liter per kg of bio-oil)			
	Wood	Corn stover	Wheat straw	Switchgrass
Bio-oil cooling	0.01	0.01	0.01	0.01
Bio-oil vapor cooling	0.05	0.05	0.05	0.05
Steam condensing	0.50	0.70	0.77	1.02
Steam system	0.03	0.04	0.04	0.05
Ash quenching	0.02	0.18	0.24	0.13
Total	0.61	0.98	1.11	1.27

As steam is produced for power generation, steam system losses loss is 3 % of steam flow to turbine (Ringer et al., 2006). As ash content of corn stover is 7.7 % which is higher than 0.92 % (Ringer et al., 2006) of wood, the generated quantity of hot ash is higher and accordingly water required to quench is higher as explained in Appendix G.

Hence, total of 0.98 liters water is required in the corn stover based fast pyrolysis process to produce 1 kg bio-oil.

3.5.4. Conversion of corn stover derived bio-oil to electricity

Water requirement in electricity generation stage depends upon the whole process. One of the ways of electricity production from bio-oil is through its direct combustion in a boiler to produce steam. This steam is used in a steam turbo generator. Gas turbine and diesel generator are other ways which can be utilized to generate electricity. Use of bio-oil as fuel to produce heat and power by direct combustion has been established at industrial scale (DES, 2007). In this study, direct combustion of bio-oil is considered for electricity production.

3.5.4.1. Bio-oil requirement for electricity production

To evaluate the bio-oil requirement for power generation, McNeil Generating Station, Burlington, Vermont (Wiltsee, 2000) was considered as process model. The key difference in using bio-oil as compared to other biomass is that it has low pH due to which it is corrosive to carbon steel. Most of the equipment handling bio-oil needs to be made of stainless steel. Though McNeil plant is wood based, the major equipments viz. boiler fans, feed pumps, turbine auxiliaries are similar to any oil based plant except oil skid assembly instead of wood conveying system in boiler. As a result of this difference, auxiliary power requirement for these two cases is slightly different. This difference in auxiliary power will not affect water requirement significantly, hence it is neglected in this study. As shown in Table 3-2, chemical properties and moisture content of wood and bio-oil are different; boiler heat losses are different. Therefore, net heat rate of the plant was reduced from 14,685 kJ kWh^{-1} to 12,351 kJ kWh^{-1}. Therefore, 0.66 kg of corn stover derived bio-oil is required to produce 1 kWh electricity (Detailed calculations are given in Appendix D).

3.5.4.2. Water requirement for corn stover derived bio-oil conversion to electricity

Water requirement for this pathway of production of electricity from corn stover is same as it was for pathway of direct combustion of corn stover for production of electricity. This is because cooling water requirement in condenser and auxiliaries are independent of fuel being used in the boiler as explained in section 4.2.4. Hence, 2.70 kg of make-up water will be required to produce 1 kWh electricity.

3.6. Wheat straw based biopower production pathways

3.6.1. Water requirement for wheat production

Like corn stover, wheat straw is also residue and is left after grain is removed. In this study, water used for the production of wheat is attributed to wheat grains only as grains will be produced in any way to fulfill food requirement.

If whole crop is being used for bioenergy, then water requirement for grain and straw can be divided on the basis of yields of grain and straw. The yield of straw can be calculated using average straw to grain ratio. This straw to grain ratio for wheat is 1.1 (Sokhansanj et al., 2006). As explained in the chapter 2, average dry yield of wheat is 3,897 kg ha^{-1}.

With this grain yield, average yield of wheat straw is 4,286 kg ha^{-1}. Like corn stover, 4,286 kg ha^{-1} wheat straw cannot be recovered completely from field because an average 1,125 kg ha^{-1} of wheat straw is left in the field to protect soil (Sokhansanj et al., 2006). Therefore, the net dry yield of wheat is 3161 kg ha^{-1}. Total water requirement for wheat crop is 933.20 liters for production of 1 kg of dry wheat. If this water requirement of wheat is shared between wheat and wheat straw on the basis of dry weight, 602.5 liters of water is required for production of 1 kg wheat straw.

3.6.2. Conversion of wheat straw to electricity through direct combustion

Similar to corn stover case, wheat straw is combusted in a boiler to produce steam and this steam is utilized in the steam turbo generator to produce electricity as shown in Figure 3-5.

3.6.2.1. Wheat straw requirement for production of electricity

The quantity of wheat straw required for electricity generation depends on chemical properties which are shown in Table 3-1. Depending on the plant net heat rate, required biomass quantity can be evaluated. In this study, wheat straw based power generation was based on technology similar to McNeil generating station (Wiltsee, 2000). Like any other fuel, net heat rate of wheat straw based power plant is affected by the boiler heat losses. Therefore, heat losses of wheat straw based boiler was calculated and the net heat rate of the plant was adjusted as explained in Appendix D. Based on this estimation, the net heat rate of wheat straw based power plant is 12,373 kJ kg^{-1} and 0.71 kg of dry wheat straw is required to produce 1 kWh electricity.

3.6.2.1 Water requirement in electricity generation from wheat straw

In this process, water is utilized as cooling water, for production of steam and service water as explained in section 4.2.2. As water requirement in the direct fired power plant is independent of fuel being fired in boiler, total water requirement is 2.70 liters for 1 kWh electricity generation as explained in the Appendix E.

3.6.3. Conversion of wheat straw to bio-oil through fast pyrolysis

Similar to corn stover, power and heat integrated fast pyrolysis system is considered for wheat straw. Final products of this process are bio-oil and electricity as shown in Figure 3-6.

3.6.3.1. Fast pyrolysis of wheat straw and various products' yields

The energy and mass balance of fast pyrolysis mainly depends on bio-oil, charcoal and non-condensable gases yield. As shown in Table 3-2, products' yields for different biomass feedstock are different. As a result, bio-oil yield and power generation will be different for wheat straw than any other feedstock. To assess the yield of bio-oil and power generation, NREL bio-oil production model (Ringer et al., 2006) of wood is considered for wheat straw.

Similar to earlier discussed fast pyrolysis process, wheat straw moisture content is reduced from 15% to 7% (Kerstetter et al., 2001) before feeding the wheat straw to pyrolysis chamber. Therefore, 1.48 kg dry wheat straw produces 1 kg of bio-oil containing 20.0 % moisture (detailed calculation given in Appendix F).

The LHV of wheat straw is 16.6 MJ (Mohan et al., 2006) instead of 19.3 MJ (Bridgwater et al., 2002) for wood. The moisture content of wheat straw is 15% (Kerstetter et al., 2001) instead of 50 % for wood. The grinding energy required for size reduction of corn stover to 2 mm is 52.9 kWh per dry tonne (Mani et al., 2004) instead of 61.1 kWh per dry tonne of wood. As a result of above differences, fast pyrolysis of 1.48 kg of dry wheat straw produces 1 kg of bio-oil along with 0.16 kWh of electricity (detailed calculations are given in Appendix F).

3.6.3.2. Water requirement for fast pyrolysis of wheat straw

During fast pyrolysis of wheat straw, water is used for steam condensation, vapor condensation, product cooling, make-up water for steam system and water for ash quenching. Water requirement for bio-oil cooling and bio-oil vapor cooling is same as the corn stover case as produced bio-oil quantity is same. As wheat straw based fast pyrolysis plant produces 0.05 kWh more power than wood based plant, water requirement for steam condensing and steam system is higher than wood based plant as shown in Table 3-3. Similarly, water requirement for ash quenching is higher because ash content of wheat straw is 10.2% (EERE, 2009) as compared to 0.92% (Ringer et al., 2006) for wood. Hence, wheat straw based process requires using 1.11 liters of make-up water to produce 1 kg of bio-oil. The detailed calculations related to these water requirement are given in Appendix G.

3.6.4. Conversion of wheat straw based bio-oil to electricity

Wheat straw derived bio-oil can be used to produce electricity using the conversion pathway as shown in Figure 3-5. The direct combustion of bio-oil in a boiler is followed by electricity generation in steam turbo-generator. It is assumed that chemical properties of wheat straw derived bio-oil is same as of corn stover derived bio-oil on the basis of similar chemical properties of wheat straw and corn stover (as shown in Table 3-1). The boiler heat losses and plant net heat rate are calculated for this case accordingly. The net heat rate of wheat straw derived bio-oil based plant is 12,351 kJ kWh^{-1}. About 0.66 kg of wheat straw derived bio-oil produces 1 kWh of electricity.

The water requirement is 2.70 liters per kWh of electricity generation and is same as in any other case as water requirement is independent of fuel fired in the boiler.

3.7. Switchgrass based biopower conversion pathways

3.7.1. Water requirement for switchgrass production

As discussed in the chapter 2, direct water requirement for switchgrass is 863.10 liters per kg of switchgrass with high yield of 11,700 kg ha^{-1}. This crop can be grown with minimum nutrient and fuel requirement. The indirect water requirement corresponding to the amount of nutrient and fuel is 0.03 liters per kg of switchgrass.

3.7.2. Switchgrass to electricity through direct combustion

3.7.2.1. Switchgrass requirement for electricity production

To calculate switchgrass requirement in conversion stage, McNeil Generating Station, Burlington, Vermont (Wiltsee, 2000) was considered again as model plant. Similar to corn stover and wheat straw, heat losses for switchgrass based power plant is different than that of wood based power plant. The chemical composition and heating value of switchgrass are shown in Table 3-1. On the basis of these properties, net heat rate of switchgrass based power plant is 12,269 kJ kWh^{-1}. Based on this, switchgrass power plant requires 0.66 kg dry switchgrass to produce 1 kWh. The detailed calculations are given in Appendix D.

3.7.2.2. Water requirement for conversion of switchgrass to electricity

Similar to other direct combustion electricity generation, make-up water is supplied to replenish the cooling water system losses, steam and service water system losses. This make-up water requirement is independent of fuel being fired in boiler as explained in Appendix E. Hence, 2.70 liters of make-up water is required to produce 1 kWh of electricity.

3.7.3. Conversion of switchgrass to bio-oil through fast pyrolysis

The products of switchgrass pyrolysis are charcoal, bio-oil and noncondensable gases as shown in Table 3-2. To evaluate water requirement in this switchgrass based process, wood based NREL fast pyrolysis model (Ringer et al., 2006) is considered.

3.7.3.1. Product yields from conversion of switchgrass to bio-oil

In the fast pyrolysis process, 15% moisture content of switchgrass is reduced to 7% before pyrolysis chamber. In this process, 1.48 kg of dry switchgrass produces 1 kg bio-oil containing 20.0 % moisture (detailed calculation given in Appendix F).

Another product of this process is electricity. The amount of electricity generation along with 1 kg of bio-oil production depends on the products yield of switchgrass. Fast pyrolysis and chemical properties of switchgrass are shown in Tables 3-1 and 3-2. Therefore, wood based pyrolysis process is modified in accordance with switchgrass properties as explained in Appendix F. The lower heating value of switchgrass is 17.5 MJ kg^{-1} (Larson et al., 2005) and it has high ash content of 5.7% (Larson et al., 2005). As compared to wood, the amount of heat available for power production is lower but lower moisture content of 15% (Larson et al., 2005)) saves heat energy and power also. The grinding energy for size reduction of switchgrass to 2 mm is 64.9 kWh per dry tonne (Mani et al., 2004) and it increases auxiliary power requirement. As a result of above differences, switchgrass based pyrolysis plant produces 0.28 kWh electricity along with 1 kg of bio-oil production (detailed calculation given in Appendix F).

.

3.7.3.2. Water requirement for conversion of switchgrass to bio-oil

As shown in Table 3-3, water is used as cooling water and for generation of steam in this process. Water requirement for bio-oil cooling and its recovery from volatile gas is same as that of wood because of the equal amount of bio-oil production. But the cooling water requirement for steam condensation is higher than that of wood due to 0.12 kWh more electricity generation. Similarly, make-up water requirement to meet steam system losses is higher in case of switchgrass based boil-oil production. Also quenching water requirement is higher in the switchgrass case because of high ash content of 5.7%. Hence, the whole process of conversion of switchgrass to bio-oil requires 1.27 liters make-up water to produce 1 kg of bio-oil.

3.7.4. Conversion of switchgrass based bio-oil to electricity

Similar to earlier cases of corn stover and wheat straw, heat losses from the boiler is calculated using switchgrass derived bio-oil. The chemical properties of switchgrass based bio-oil are given in Table 3-1. The calculated plant heat rate is also given in Table 3-1 (detailed calculations are in Appendix E). The net heat rate of plant using switchgrass based bio-oil for electricity production is 12,322 kJ kWh^{-1}. Hence 0.64 kg of switchgrass based bio-oil having HHV of 23,900 kJ kg^{-1} is required to produce 1 kWh of electricity.

The water requirement is same as in earlier cases of corn stover and wheat straw. This is because the cooling water requirement for condenser and auxiliary is same in all the cases. Hence, 2.70 liters of make-up water is required to produce 1 kWh of electricity.

3.8. Results and discussion

The water requirement of biopower production using three different feedstocks (i.e., corn stover, wheat straw and switchgrass) using two different pathways for each case was evaluated and are shown in Table 3-4. These factors represent the total water requirement for biopower pathways over the life cycle. These factors also include the direct water requirement for crop production. This direct water requirement is met by precipitation, soil moisture and/or surface or ground water (through irrigation). These factors are useful for only comparing the biopower pathways. These factors do not exactly represent the consumptive use of water for biopower. The actual consumption can be estimated by subtracting the water available from precipitation and soil moisture from these water requirement factors to grow crop in a specific region.

The corn stover and wheat straw based pathways are evaluated for two scenarios. In first scenario, these biomass feedstocks are considered as agricultural residue and water requirement for crop production stage is allocated only for the grain production. In second scenario, these biomass feedstocks are considered a part of crop production. In this scenario, water requirement for crop production is shared between the grain and these biomass feedstocks based on their mass.

In first scenario, where corn stover and wheat straw are considered as crop residue, the direct combustion pathways for power generation based on these residues are the most water efficient. As shown in Table 3-4, water requirement for 1 kWh electricity production by direct combustion of corn stover and wheat straw is 2.70 liters. Similarly, power generation through combustion of bio-oil produced through fast pyrolysis of crop residue is less water efficient option as compared to direct combustion of residues for power generation. This pathway of electricity production through bio-oil consumes 3.01 liters and 3.10 liters of water for corn stover and wheat straw respectively. Based on these results, switchgrass based both the conversion pathways are the water intensive pathways, consuming 672.13 liters and 823.67 liters water for 1 kWh generation through direct combustion and fast pyrolysis pathways, respectively.

In second scenario, where corn stover and wheat straw are considered part of crop production and water is allocated for their production, the water requirement in biomass production stage makes these biomass feedstock based pathways water intensive. The wheat straw based direct combustion pathway is the most water efficient by consuming only 430.57 liters water kWh^{-1}. Corn stover based pathway through fast pyrolysis is the most water intensive by consuming 927.45 liters of water per kWh among all the feedstocks and pathways.

Table 3-4: Life cycle water requirement of different biopower pathways

Biopower pathways	Biomass requirement (dry kg kWh^{-1})	Agriculture Residue	Water requirement (liter kWh^{-1})				
			Feedstock production stage		Conversion stage		Total
			Direct	Indirect	Direct	Indirect	
Corn stover - electricity	0.68	Yes	0.00	0.00	2.70	0.0	2.70
		No	733.08	0.14	2.70	0.0	735.92
Corn stover – bio-oil – electricity	0.86	Yes	0.00	0.00	3.01	0.0	3.01
		No	924.27	0.17	3.01	0.0	927.45
Wheat straw – electricity	0.71	Yes	0.00	0.00	2.70	0.0	2.70
		No	427.84	0.03	2.70	0.0	430.57
Wheat straw – bio-oil – electricity	0.88	Yes	0.00	0.00	3.10	0.0	3.10
		No	612.45	0.04	3.10	0.0	615.59
Switchgrass – electricity	0.66	No	669.41	0.03	2.70	0.0	672.13
Switchgrass – bio-oil – electricity	0.81	No	820.66	0.03	2.98	0.0	823.67

If direct combustion and fast pyrolysis pathways for same biomass are compared, water requirement for conversion stage of fast pyrolysis pathway is higher than that of direct combustion pathway. In fast pyrolysis based pathways, water is required for bio-oil vapor scrubbing, bio-oil cooling and ash cooling in addition to water requirement in combustion stage. These additional cooling requirement in pyrolysis stage also increases heat loss of this pathway. This is the reason, why more biomass feedstock is required for power generation through pyrolysis.

Water requirement of conversion stage was evaluated for specific thermochemical conversion pathways. These water requirement may differ depending upon processes of the pathways. For example, bio-oil pathway considers that charcoal is utilized to produce electricity in fast pyrolysis process, in another scenario charcoal may be sold for better commercial viability of the plant. In this case, dry biomass requirement for electricity production will be higher and hence the water requirement.

Similarly in any other model, bio-oil can also be utilized in a gas turbine or a diesel generator to produce electricity instead of its direct combustion in a boiler to produce steam and power. If gas turbine or diesel generator is used for bio-oil conversion to electricity, water requirement will be minimal. This will make electricity production from bio-oil pathways more water efficient than direct combustion pathways based on crop residues as there wouldn't be any water requirement for steam generation. The efficiency of gas turbine or diesel generator will decide the dry biomass feedstock requirement and ultimately the water efficiency.

This study also evaluated water requirement associated with life cycle of major inputs in both biomass production and conversion stages as shown in Table 3-4. These estimations are based on typical requirement of fuels and other inputs which may vary substantially in type and quantity depending location, agricultural production technology and conversion process. But water requirement associated to these input is not significant compare to biomass production stage water requirement, hence the total water requirement will not affected significantly.

3.9. Conclusions

Life cycle water requirement of six biopower production pathways: corn stover to electricity, corn stover to electricity through conversion to bio-oil, wheat straw to electricity, wheat straw to electricity through conversion to bio-oil, switchgrass to electricity, switchgrass to electricity through conversion to bio-oil were evaluated. This study evaluated direct water requirement of biomass production and conversion stage. This study also estimated the indirect water requirement associated with inputs of fuels and chemicals in the both the stages.

The crop water requirement plays dominant role in deciding the total water requirement of any biopower. If water requirement for feedstock production stage for corn stover and wheat straw are not attributed to these residues, the pathways based on these biomass feedstocks are the most water efficient pathways. It consumes approximately 2.7 liters of water for 1 kWh electricity generation by direct combustion and approximately 3.0 liters of water for 1 kWh of electricity generation through fast pyrolysis process.

Otherwise, if crop water requirement is allocated to these biomass feedstocks, the wheat straw based pathways are water efficient, consuming 430.57 liters and 615.59 liters of water for 1 kWh of electricity generation through direct combustion and fast pyrolysis pathways respectively. Corn stover is the more water intensive feedstock consuming 735.92 liters and 927.45 liters water for 1 kWh of electricity generation through direct combustion and fast pyrolysis, respectively.

Though crop water requirement for feedstocks is one of the dominant factors, process conversion efficiency i.e. dry mass requirement per unit mass of biopower also plays an important role in determining the total water requirement. For example, switchgrass conversion stage water requirement for both the pathways are approximately 3.0 liters. About 0.66 kg of switchgrass is required for 1 kWh of electricity generation through direct combustion and 0.81 kg of switchgrass is required for 1 kWh of electricity generation through fast pyrolysis pathways. As a result of this, their biomass production stage requirement is significantly different. The total water requirement for switchgrass based power plant is 672.13 liters and 823.67 liters for 1 kWh of biopower generation from direct combustion and fast pyrolysis pathways, respectively.

References

Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., 2002. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Task No. BFP2.A410. National renewable energy laboratory, Cole Boulevard, Golden, Colorado, USA. Available from: <http://www.p2pays.org/ref/38/37696.pdf>.

Agblevor, F.A., Besler, S., Wiselogel, A.E., 1996. Production of oxygenated fuels from biomass : Impact of feedstock storage. Petroleum science and technology 14 (4), 589-612.

Bridgwater, A.V., Toft, A.J., Brammer, J.G., 2002. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renewable and Sustainable Energy Reviews 6 (3), 181-248.

Chapman, R.G., 1996. Water treatment. In F. D. Drbal, P. Boston, L. K. Westra and B. Veatch., Power plant engineering. Springer, New York.

Demirbas, M.F., Balat, M., Balat, H., 2009. Potential contribution of biomass to the sustainable energy development. Energy conversion and management 50 (7), 1746-1760.

DES, 2007. Dynamotive products. Dynamotive Energy Systems. Available from: http://www.dynamotive.com/en/technology/products.html. Accessed on: Jan 1, 2009.

Drbal, F.D., Boston, P., Westra, L.K., Veatch., B., 1996. Power plant engineering. In R. G. Chapman, Water treatment. Springer, New York, USA.

Dynamotive, 2007. Dynamotive products. Dynamotive Energy Systems. Available from: http://www.dynamotive.com/en/technology/products.html. Accessed on: Jan 1, 2009.

EERE, U., 2009. Biomass feedstock composition and property database. Energy Efficiency and Renewable Energy, USA. Available from: http://www1.eere.energy.gov/biomass/feedstock_databases.html. Accessed on: January 20, 2009.

EIA, 2008. International Energy Outlook 2008. Available from: http://www.eia.doe.gov/oiaf/ieo/pdf/world.pdf. Accessed on: 15 January, 2009.

EIA, 2009. International energy outlook 2009. Available from: http://www.eia.doe.gov/oiaf/ieo/highlights.html. Accessed on: 15 July, 2009.

ENSYN, 2009. Ensysn - Fuel the future. Available from: http://www.ensyn.com/. Accessed on: May 12, 2009.

Gavrilescu, M., 2008. Biomass power for energy and sustainable development. Envionmental engineering and management journal 7 (5), 617-640.

Gerdes, K., Nichols, C., 2008. Water requirement of existing and emerging thermoelectric plant technologies. DOE/NETL-402/080108. National energy technology laboratory, Available from: <http://www.netl.doe.gov/energy-analyses/pubs/WaterRequirement.pdf>.

Gupta, M., Yanga, J., Roya, C., 2003. Specific heat and thermal conductivity of softwood bark and softwood char particlesq. Fuel 82 (8), 919-927.

Kerstetter, J.D., Lyons, J.K., 2001. Wheat straw for ethanol production in washington: a resource, technical, and economic assessment. Washington state university cooperative, Available from: <http://www.energy.wsu.edu/documents/renewables/WheatstrawForEthanol.pdf>.

King, C.W., E., W.M., 2008. Water intensity of transportation. Envionmental science and environmental policy 42 (21), 7866-7872.

Kumar, A., Pootakham, T., 2009. A comparison of pipeline versus truck transport of bio-oil. Bioresource Technology (Accepted, in-press)

Kumar, A., Wang, L., Dzenis, Y., Jones, D.D., Hanna, M.A., 2008. Thermogravimetric characterization of corn stover as gasification and pyrolysis feedstock. Biomass and bioenergy 32 (5), 460-467.

Larson, E.D., Jin, H., Celik, F.E., 2005. Gasification based fuels and electricity production from biomass without and with carbon capture and storage. Princeton environmental institute, Princeton university, Princeton, NJ. Available from: <http://www.princeton.edu/pei/energy/publications/texts/IK-Larson-et-al-GHGT8-FINAL-21-Apr-06-with-citation.pdf>.

Mani, S., Tabil, L.G., Sokhansanj, S., 2004. Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass. Biomass & bioenergy 27 (4), 339-352.

Mohan, D., Pittman, C.U., Steele, P.H., 2006. Pyrolysis of wood/biomass for bio-oil: A critical review. Energy & Fuels 20 (3), 848-889.

Morey, R.V., Tiffany, D.G., Hatfield, D.L., 2006. Biomass for electricity and process heat at ethnol plants. American society of agricultural and biological engineers 22 (5), 723-728.

Parikh, J., Channiwala, S.A., Ghosal, G.K., 2007. A correlation for calculating elemental composition from proximate analysis of biomass materials. Fuel 86 (12-13), 1710-1719.

Perlack, R.D., Turhollow, A.F., 2003. Feedstock cost analysis of corn stover residues for further processing. Energy 28 (14), 1395-1403.

Perry, R.H., Green, D.W., Maloney, J.O., 1999. Perry's Chemical Engineers' Handbook. In Evaporative cooling. McGraw-Hill, New York, USA.

Petrolia, D.R., 2008. The economics of harvesting and transporting corn stover for conversion to fuel ethanol: A case study for Minnesota. Biomass and bioenergy 32 (7), 603-612.

Ragland, K.W., Aerts, D.J., Baker, A.J., 1991. Properties of wood for combustion analysis. Bioresource technology 37 161-168.

Ringer, M., Putsche, V., Scahill, J., 2006. Large-scale pyrolysis oil production: A technology assessment and economic analysis. NREL/TP-510-37779. National renewable energy laboratory, Cole Boulevard, Colorado. Available from: <http://www.forestbioproducts.umaine.edu/documents/37779.pdf>.

Shinners, K.J., Binversie, B.N., 2007. Fractional yield and moisture of corn stover biomass produced in the northern US corn belt. biomass and bioenergy 31 (8), 576-584.

Sokhansanj, S., Mani, S., Stumborg, M., Samson, R., Fenton, J., 2006. Production and distribution of cereal straw on the Canadian prairies. Available from: http://engrwww.usask.ca/oldsite/societies/csae/protectedpapers/c0556.pdf. Accessed on: January 15, 2009.

WEC, 2007. Survey of energy resources 2007. Available from: http://www.worldenergy.org/publications/survey_of_energy_resources_2007/bioenergy/713.asp. Accessed on: 15 July, 2009.

Wiltsee, 2000. Lessons learned from existing biomass power plants. National renewable energy laboratory, Valencia, California. Available from: <http://www.nrel.gov/docs/fy00osti/26946.pdf>.

Yin, C., Rosendahl, L.A., Kær, S.K., 2008. Grate-firing of biomass for heat and power production. Progress in energy and combustion 34 (6), 725-754.

Chapter 4 . The Integration of Life Cycle Energy and Water Requirement Factors for Bioenergy Pathways

4.1 Introduction

Bioenergy is renewable but it consumes fossil fuels during its production. That is why bioenergy is not considered completely carbon neutral. With increased interest in the issue of global warming, the fossil fuel requirement for bioenergy production has become a critical factor. From an environmental perspective, the higher the fossil fuel requirement for producing of bioenergy the higher the greenhouse gas emissions. There are different metrics for presenting the amount of fossil fuel required in a bioenergy life cycle: life cycle energy efficiency, energy balance, net energy value, or energy ratio. In this study, net energy value (NEV) is used to compare different bioenergy pathways. The net energy value can be defined as the energy content of bioenergy plus credits for co-products minus direct and indirect input of fossil fuels (Morey et al., 2006). Over the last several years, there has been substantial study work done on estimating the net energy value for different bioproducts using different biomass feedstocks (Sheehan et al., 1998; ANL. et al., 2001; Armstrong et al., 2002; Shapouri et al., 2002; Sheehan et al., 2004; Morey et al., 2006). This study considers the, net energy value of all the bioenergy pathways discussed in Chapters 2 and 3.

As discussed in Chapters 2 and 3, water requirement is another critical factor in determining the most environmentally efficient bioenergy pathway. In Chapters 2 and 3, water requirement factors for producing bioenergy are calculated (i.e., liters of water for 1 MJ of ethanol biodiesel or electricity). These factors help decision- makers find the most water efficient pathway but they do not provide information on the energy efficiency of the pathway. This study provides a detailed review of the net energy value (NEV) for different pathways using different biomass feedstocks. Some values are not available in the literature, and so were calculated separately. Once the net energy value for each pathway was determined, the NEVs were integrated with the water requirement factors for each of the respective pathways. This resulted in a new factor, environmental efficiency, which is a combination of energy requirement and water requirement for different bioconversion pathways. It also gives information on the greenhouse gas (GHG) emissions reduction capability of various bioconversion pathways. This study considers all the 12 pathways using 6 different biomass feedstocks to produce biofuel and biopower, as discussed in Chapters 2 and 3.

4.2. The net energy value (NEV) of biofuel pathways

The net energy value for any biofuel production pathway depends upon several factors. The main factors which affect the life cycle energy requirement of a bioconversion pathway include: types of fuel consumed directly or indirectly over the life cycle, technology used for bioconversion, bioconversion efficiency, byproducts utilization and plant capacity. In this study, a range of energy data on converting of biomass are collected and studied to determine the water requirement factor based on the NEV.

The Net energy value for a biofuel is calculated by subtracting the fossil energy input per unit of biofuel from the total energy content of that biofuel (i.e., MJ of energy required per MJ of energy content). The total energy content of a biofuel can be considered in terms of its higher heating value (HHV) or lower heating value (LHV) (Shapouri et al., 2002). This study considers the, higher heating values of biofuels. Data were converted to HHV wherever available data were on the LHV basis. The LHV and HHV of ethanol are 21,184 kJ liter^{-1} and 23,403 kJ liter^{-1} respectively (Shapouri et al., 2002). Similarly, the LHV and HHV of biodiesel are 32737 kJ liter^{-1} and 35931 kJ liter^{-1}, respectively (Sheehan et al., 1998).

4.2.1 The net energy value for ethanol produced from corn

Currently, corn is the most popular feedstock for producing of ethanol. There has been a lot of discussion on the NEV for the corn-based ethanol. As shown in Table 4.1, the net energy value, for the corn to ethanol pathway varies from 3,978 MJ liter^{-1} to 15,446 MJ liter^{-1}. The main reason for the variation is due to the type of fuel used in the conversion process.

Table 4-1: The Net energy value for different biofuels using different feedstocks

Pathway	Net energy value [a] (kJ liter^{-1})	Sources	Min - Max (kJ liter^{-1})	Average (kJ liter^{-1})
Corn - Ethanol	5,883	(Shapouri et al., 2002)	3,978-1,5446	8,570
	8,490	(Wang et al., 1999)		
	3,978 - 15,446	(Wang et al., 2007)		
	8,119	(Lavigne et al., 2007)		
	11,701	(ANL. et al., 2001)		
	6,631	(Graboski, 2002)		
	8,313	(Levelton et al., 2000b)		
Wheat - Ethanol	4,337-22,767	(Punter et al., 2004)	3,490-22,767	9,050
	3,490	(Armstrong et al., 2002)		
	13,044	(ADEME, 2002)		
	12,895	(Elsayed et al., 2003)		
Corn stover - Ethanol	23,879	(Sheehan et al., 2004)	19,329-25,119	22,189
	25,119	(Lavigne et al., 2007)		
	20,686	(Luo et al., 2009)		
	19,329	(Blottnitz et al., 2007)		
	21,932	(Levelton et al., 2000a)		
Wheat straw - Ethanol	19,329	(Blottnitz et al., 2007)	19,329-22,809	20,741
	22,809	(Elsayed et al., 2003)		
	20,085	(Levelton et al., 2000a)		
Switchgrass - Ethanol	22,411	(Levelton et al., 2000a)	22,411-23,719	23,065
	23,719	(Schmer et al., 2008)		
Canola seed - Biodiesel	21,605	(Elsayed et al., 2003)	18,253-24,997	22,170
	24,997	(ADEME, 2002)		
	18,253	(Armstrong et al., 2002)		
	23,806	(Janulis, 2004)		

[a] These are based on HHVs of ethanol i.e. 23,403 kJ liter^{-1} (Shapouri et al., 2002) and of biodiesel i.e. 35,931 kJ liter^{-1} (Sheehan et al., 1998).

In the US, most ethanol plants use natural gas as fuel and the NEV for corn based ethanol produced using natural gas is approximately 5,600 kJ per liter of bioethanol (Wang et al., 2007). With increased interest in reducing of GHG emissions and with volatility in the price of natural gas, other alternatives such as DGS (Distiller grains and soluble), wood chips are being considered as a substitute for natural gas (Wang et al., 2007).

As reported in different studies the variation in NEV, is due to differences in assumptions and data on corn yield, fertilizer requirement for the corn crop, the conversion efficiency of the ethanol plant, etc.

Though most researchers reported positive NEVs for corn based ethanol, the studies by Pimentel (1991; 2001; 2005) reported the NEV of corn based ethanol as negative i.e. more energy was consumed through the input of fossil fuel than was contained in the bioethanol. In this study, only positive values for NEVs are considered in evaluating and comparing water requirement factors for different pathways.

4.2.2. The net energy value for ethanol produced from wheat

As with the corn to ethanol pathway, the net energy value for this pathway also varies widely depending on the heat and power supply for the ethanol plant. As shown in Table 4-1, the net energy value varies from 3,490 to 22,767 kJ per liter of ethanol.

Punter et al. (2004) reported a net energy value of 4,337 kJ per liter of ethanol with natural gas and imported electricity as input fuels for the ethanol plant. In this study, a net energy value is reported as high as 22,767 kJ per liter of ethanol when a wheat straw based CHP power plant is considered for the heat and power requirement of the ethanol plant in place of a fossil fuel based power plant (Table 4-1).

4.2.3. The net energy value for ethanol produced from corn stover

Unlike corn and wheat based ethanol, corn stover based ethanol shows little variation in NEV. The reason is that heat and power requirement for a lignocellulosic based ethanol plant are filled by an integrated power plant. The Integrated power plants uses residue (i.e. a lignin rich byproduct) as input fuel (Aden et al., 2002; Sheehan et al., 2004; Blottnitz et al., 2007). In a study by Sheehan et al. (2004) on ethanol produced from corn stover , the reported figure for the net energy value is greater than the HHV of ethanol (23,403 kJ liter^{-1}). In this study, the byproduct energy credit are of has greater energy value than the fossil fuel energy used in this bioconversion pathway.

4.2.4. The net energy value for ethanol produced from wheat straw

The net energy value for producing ethanol from wheat straw varies from 19,329 kJ per liter of ethanol to 22,809 kJ per liter of ethanol as shown in Table 4-1. For all the studies considered in Table 4-1 the process for producing of ethanol from wheat straw is similar to that for producing it from corn stover.

4.2.5. The net energy value for ethanol produced from switchgrass

Switchgrass is another lignocellulosic biomass which is processed like corn stover and wheat straw to produce ethanol. The energy required for the process is supplied by burning the byproduct (i.e. lignin) of the ethanol plant (Levelton et al., 2000a; Schmer et al., 2008). The fertilizer required to produce switchgrass is lower than annual crops (Schmer et al., 2008) . As a result, the average net energy value for the switchgrass conversion pathway is higher than those of other lignocellulosic based ethanol production pathways.

4.2.6. The net energy value for biodiesel produced from canola seed

In this bioconversion pathway, fossil fuel based energy is used directly and indirectly during different stages of canola seed production, oil extraction and transesterification. The Net energy requirement depends on climatic conditions and the technologies used for agriculture and the conversion plant (Janulis, 2004). The values shown in Table 4-1 for the biodiesel production pathway depend on the assumptions and data considered in calculating fossil energy use. The average NEV for the canola seed to biodiesel pathway is 22,170 kJ per liter of biodiesel.

4.3. The net energy value for biopower production pathways

The biopower production pathways can be divided into three stages: feedstock production, transportation and conversion. This study considers two pathways for the production of biopower. These are: direct combustion of biomass feedstocks in a boiler and combustion of bio-oil produced through fast pyrolysis process.

As discussed in Chapter 3, both pathways are self-reliant regarding heat and power requirement because they use some of the power and heat generated in the integrated power plant. The fossil fuel based energy required in conversion stage is only for ash transporting from the power plant to the field. This study considers direct and indirect fossil energy requirement for producing feedstock and transporting of feedstock and ash.

4.3.1. The fossil fuel based energy input for producing biomass and transporting it to a biopower plant

The energy required during the production and transportation stages of three biomass feedstocks (corn stover, wheat straw and switchgrass) are shown in Table 4-2. Feedstock production requires direct energy such as diesel for farming activities i.e. baling. It also requires indirect energy such as that used to produce fertilizer.

The transportation stage involves loading, trucking, unloading and stacking. The energy required per unit of biomass for trucking varies with trucking distance

This trucking distance of depends on the capacity of the plant, the yield of biomass feedstock, land utilization factor and road winding factor (Kumar et al., 2007).

Table 4-2: The Fossil energy input producing biomass and transporting it to a biopower plant

Biomass feedstock	Stage	Input energy (kJ kg^{-1})	Comments/Sources
Corn stover	Production stage[a]	589	(Lavigne et al., 2007).
		850	(Levelton et al., 2000a).
	Production and transportation[b]	1,143	(Sheehan et al., 2004).
Wheat straw	Production stage[a]	1,070	(Elsayed et al., 2003).
		820	(Levelton et al., 2000a).
Switchgrass	Production stage[a]	662	(Schmer et al., 2008).
		670	(Levelton et al., 2000a).
		436	(Wang et al., 1999)
	Transportation[c,d]	569	Derived from Kumar (2007) for 800 dry tonnes capacity plant.
		589	Derived from Kumar (2007) for 1000 dry tonnes capacity plant.

[a] Feedstocks production requires required for producing fertilizer, handling and baling of the feedstock.
[b] The value is adjusted for a 1000 dry tonnes plant for transportation.
[c] Transportation involves loading, trucking, unloading and stacking biomass feedstock. The energy input for trucking is adjusted according to biopower plant capacity.
[d] It is assumed in this study that the input energy for transportation is same for corn stover, switchgrass and wheat straw.

As discussed in Chapter 3, the capacity of a direct combustion based biopower plant is 50 MW. For a plant of this size both direct combustion and fast pyrolysis pathways require approximately 800 and 1000 dry tonnes of biomass feed stock per day. The energy requirement for trucking is derived from Kumar and

Sokhansanj (2007) and has been adjusted for the size of the plants. It is assumed that the energy requirement during the transportation stage is the same for all biomass feedstocks. The energy required for the size reduction of feedstock is also included in this study.

4.3.2. Biomass feedstocks and the fossil fuel based energy required to generate electricity through the direct combustion and fast pyrolysis pathways

The quantities required per unit generation of electricity generated through direct combustion and fast pyrolysis is shown in Table 4-3 for different biomass feedstock. The amount of biomass feedstock required for direct combustion is lower than that required for fast pyrolysis because heat losses in the conversion stage are lower. Energy requirement corresponding to the quantity of feedstocks are shown in Table 4-3 for the feedstock production, transportation, and ash transportation stages.

The ash content of corn stover, wheat straw and switchgrass is 7.7% (Parikh et al., 2007), 10.2% (EERE, 2009) and 5.7% (Larson et al., 2005), respectively. In this study, it is considered that the total ash recovered from the pyrolysis and combustion stages is returned to the field to reduce fertilizer consumption and prevent soil erosion (Elsayed et al., 2003). It is also assumed that transportation of ash consumes energy at the same rate (i.e. MJ tonne $^{-1}$ km$^{-1)}$ as does the transportation of biomass feedstock (Elsayed et al., 2003).

Table 4-3: The Net energy value for biopower produced through different pathways using different biomass feedstocks

Pathway	Biomass requirement [a] (dry kg kWh^{-1})	Energy input for biopower production ($MJ\ kWh^{-1}$)		Net energy Value [c] ($kJ\ kWh^{-1}$)
		Biomass production and transportation	Ash transportation[b]	
Corn stover - Electricity	0.68	1,234	30	2,336
Corn stover – Bio-oil – Electricity	0.86	1,254	39	2,307
Wheat straw – Electricity	0.71	1,515	41	2,044
Wheat straw – Bio-oil - Electricity	0.88	1,534	53	2,013
Switchgrass – Electricity	0.66	1,159	21	2,419
Switchgrass – Bio-oil – Electricity	0.81	1,178	27	2,394

[a] Data are taken from Chapter 3.

[b] It is considered that ash generated by the plant will be sent back to the field at the same rate of energy consumption i.e. MJ $tonne^{-1}$ km^{-1}(Elsayed et al., 2003).

[c] Estimated by subtracting all energy inputs from the total energy content i.e. 3600 kJ per kWh of electricity.

The net energy value for each pathway is shown in Table 4-3. This net energy value is calculated by subtracting all energy inputs from the energy value of 1 kWh i.e. 3,600 kJ per kWh.

4.3. Results and discussion

Table 4-4 shows the water requirement and net energy values for 12 pathways using 6 biomass feedstocks. Water requirement for these 12 pathways, taken from Chapters 2 and 3, include the amount of water used directly or indirectly over the life cycle of biofuel production. The water in the agriculture stage is used mainly to grow crop. These water requirement are good for comparing the bioenergy pathways but these factors do not represent the actual consumptive use. The reason is that crop water requirement is fulfilled partially or completely by precipitation and soil moisture which is not consumptive use. The actual consumptive use for a specific region can be evaluated by subtracting available water from precipitation from these factors.

As shown in Table 4-4 the net energy values for biofuel or biopower are calculated as a percentage of the total energy content of the biofuel or biopower. The higher heating value for bioethanol and biodiesel are considered as total energy contents.

Table 4-4: Integrated water and energy requirement factors for biofuel and biopower produced by different pathways from different biomass feedstocks

Pathways	Water requirement[1,2] (liters $liter^{-1}$)		Net energy value[3] (kJ $liter^{-1}$)	NEV (% of total energy value)	Water requirement per NEV (liters MJ^{-1})		
	Agriculture	Conversion			Agriculture	Conversion	Total
Corn - Ethanol	1,623.0	4.3	3,978	17	408.0	1.0	409.0
			15,446	66	105.1	0.3	105.4
Corn stover - Ethanol	0.0	6.3	22,189	95	0.0	0.0	0.3
Wheat - Ethanol	2,273.5	4.9	3,490	15	651.5	1.4	652.9
			22,767	97	99.9	1.2	100.1
Wheat straw - Ethanol	0.0	6.2	20,741	89	0.0	0.3	0.3
Switchgrass - Ethanol	2690.4	6.3	23,065	99	116.6	0.3	116.9
Canola seed - Biodiesel	3,904.0	0.7	24,347	62	176.1	0.03	176.1
Corn stover – Electricity	0.0	2.7	2,336	65	0.0	1.2	1.2
Corn stover – Bio-oil – Electricity	0.0	3.0	2,307	64	0.0	1.3	1.3
Wheat straw – Electricity	0.0	2.7	2,044	57	0.0	1.3	1.3
Wheat straw – Bio-oil - Electricity	0.0	3.1	2,013	56	0.0	1.5	1.5
Switchgrass – Electricity	669.4	2.7	2,419	67	276.7	1.1	277.8
Switchgrass – Bio-oil – Electricity	820.7	3.0	2,394	66	342.8	1.2	344.0

[1] For the electricity pathway, liters kWh^{-1}.
[2] All data are taken from the result sections of Chapters 2 and 3.
[3] For the electricity pathway, kJ kWh^{-1}.

The NEV for the wheat to ethanol pathway is the lowest at 15%. The NEV for grain based ethanol depends mainly on the heat and power sources for the conversion process (Wang et al., 2007). About 15% of the NEV is for existing ethanol plants where natural gas is used as fuel for heat and electricity is imported from the grid (Punter et al., 2004). This low NEV can be improved to a maximum of 97% by utilizing wheat straw in a combined heat and power (CHP) plant that supplies energy to an ethanol plant. As shown in Table 4-4, although the energy efficiency of the wheat to ethanol based pathway can be improved, but the water requirement cannot be reduced further.

Similarly as shown in Table 4-4, the NEV for the corn to ethanol pathway is the second lowest at 17% this NEV refers to ethanol plants which use natural gas as fuel; most existing plants are based on this technology (Wang et al., 2007). The NEV for the corn to ethanol pathway can be improved to 66% by using wood chips as a source of heat and by importing electricity (Wang et al., 2007). The NEV for this pathway can be improved further, to over 90%, if corn stover is used in the CHP plant, but the water requirement of this pathway will remain much higher than that of agricultural residue based pathways.

The NEV for the switchgrass to ethanol pathway is the highest at 99%, primarily because of its low nutrient requirement as a crop and its sufficient byproduct (electricity) production during conversion stage. These two factors reduce the fossil energy required in the crop production and transportation stages. Among the lignocellulosic based feedstock based ethanol production pathways, the switchgrass to ethanol pathway has the highest NEV followed by the corn stover and wheat straw to ethanol pathways at 95% and 89% respectively. Though corn stover and wheat straw are both agricultural residues, the NEV for wheat straw is lower than that for corn stover because more nutrients are lost when wheat straw is used.

Though the switchgrass based ethanol production pathway is the best than other conversion pathway from an energy requirement point of view, it consumes 116.9 liters of water for each MJ of NEV produced. From a water requirement perspective, the agricultural residue based ethanol production pathway is, at 0.3 liters/unit production, the most water efficient. The main reason is that water requirement in the feedstock production stage is attributed to the grain and only a small amount of water is consumed during the conversion stage. Agricultural residue is also used for biopower production, but the water requirement for these pathways is higher than for ethanol production. The reason for the higher water requirement in producing biopower is the higher cooling water requirement in the production stage and the correspondingly high evaporation loss in the cooling tower.

In the biopower production pathway, the cooling water requirement is higher than that of the ethanol production pathway for any given lignocellulosic biomass feedstock. This means more heat is lost from the system in the biopower production pathway. For this reason, biopower production is not as energy efficient as ethanol production for lignocellulosic biomass.

In biopower production, the switchgrass based pathway is better than the agricultural residue based pathway due to switchgrass low nutrients requirement for a given lignocellulosic biomass. The NEV for biopower production through direct combustion is slightly higher than that for biopower production through combustion of bio-oil from fast pyrolysis. This is due to additional heat losses in fast pyrolysis.

The NEV for biodiesel production is 68%. This value is much higher than that for existing grain based ethanol production pathways due to low energy requirement in the conversion stage. Though the NEV for this biofuel is sufficiently high, this pathway is not water efficient because growing the grain requires high water requirement.

4.4. Conclusion

This study has evaluated the, life cycle fossil fuel based energy requirement of 12 different biofuel and biopower production pathways using 6 different biomass feedstocks, and has calculated the net energy values for each pathway. The energy requirement of these biofuels and biopower production pathways were integrated with corresponding water requirement to develop integrated energy and water requirement factors, which indicate the water and energy efficiency of the pathway.

The grain based ethanol production pathways using existing technology are least energy efficient because they consume great amounts of energy in the conversion stage. The NEV for the wheat based and corn based ethanol production pathways are 15% and 17% of the total energy value for ethanol, respectively. These pathways are also water inefficient, consuming large amounts of water during crop production. 409.0 and 652.9 liters per MJ of NEV, respectively. The energy efficiency of these pathways can be improved by changing the fuel and technology used for supplying heat and power to the conversion stage.

The ethanol production pathways based on lignocellulosic biomass feedstocks (corn stover, wheat straw and switchgrass) are the most energy efficient. The NEV for the switchgrass based ethanol production pathway is 99% of the total energy value for ethanol. This is the highest NEV for any of the pathways, but this pathway is water intensive because a large amount of water is consumed in the crop production stage. The NEVs for the corn stover and wheat straw based ethanol production pathways are 95% and 89% of the total energy value for ethanol, respectively. These pathways are also the most water efficient, consuming 0.3 liter of water for 1 MJ of NEV in the conversion stage.

The NEVs for biopower production pathways based on lignocellulosic feedstocks are lower than that for ethanol production pathways based on the same feedstock. This is due to high heat losses in the conversion stage and to the varying NEVs for these pathways which range from 56% to 67% of the total energy value for electricity. The corn stover and wheat straw based biopower production pathways are water efficient, consuming 1.2 – 1.5 liters of water for 1 MJ of NEV for electricity.

The NEV for canola seed based biodiesel is higher than that for grain based ethanol. It is 68% of total energy value of biodiesel. This pathway is water intensive consuming 160.4 liters for 1 MJ of NEV.

References

ADEME, 2002. Energy and greenhouse gas balances of biofuels' production chains in France. Agence de l'Environnement et de la Maîtrise de l'Energie, Available from: <http://www.ademe.fr/partenaires/agrice/publications/documents_anglais/synthesis_energy_and_greenhouse_english.pdf>.

Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., 2002. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Task No. BFP2.A410. National renewable energy laboratory, Cole Boulevard, Golden, Colorado, USA. Available from: <http://www.p2pays.org/ref/38/37696.pdf>.

ANL., GMC., BP., Exxonmobil., Shell., 2001. Well-to-wheel energy use and greenhouse gas emission of advanced fuel/vehicles systems - North American Analysis. Available from: <http://www.transportation.anl.gov/pdfs/TA/163.pdf>.

Armstrong, A.P., Baro, J., Dartoy, J., Groves, A.P., Nikkonen, J., Rickeard, D.J., 2002. Energy and greenhouse gas balance of biofuels for europe - an update. 2/02. Brussels, Belgium. Available from: <http://www.senternovem.nl/mmfiles/26601_tcm24-124161.pdf>.

Blottnitz, V., Harro, Curran, M.A., 2007. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. Journal of Cleaner Production 15 (7), 607-619.

EERE, U., 2009. Biomass feedstock composition and property database. Energy Efficiency and Renewable Energy, USA. Available from: http://www1.eere.energy.gov/biomass/feedstock_databases.html. Accessed on: January 20, 2009.

Elsayed, M.A., Mathews, R., Mortimer, N.D., 2003. Carbon and energy balances for a range of biofuels options. B/B6/00784/REP URN 03/836. Available from: <http://www.berr.gov.uk/files/file14925.pdf>.

Graboski, M.S., 2002. Fossil energy use in the manufacturer of corn ethanol. Colorado School of Mines, Available from: <http://oregon.gov/ENERGY/RENEW/Biomass/docs/FORUM/FossilEnergyUse.pdf>.

Janulis, P., 2004. Reduction of energy consumption in biodiesel fuel life cycle. Renewable Energy 29 (6), 861-871.

Kumar, A., Sokhansanj, S., 2007. Switchgrass (Panicum vigratum, L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. Bioresource Technology 98 (5), 1033-1044.

Larson, E.D., Jin, H., Celik, F.E., 2005. Gasification based fuels and electricity production from biomass without and with carbon capture and storage. Princeton environmental institute, Princeton university, Princeton, NJ.

Available from: <http://www.princeton.edu/pei/energy/publications/texts/IK-Larson-et-al-GHGT8-FINAL-21-Apr-06-with-citation.pdf>.

Lavigne, A., Powers, S.E., 2007. Evaluating fuel ethanol feedstocks from energy policy perspective: A comparative energy assessment of corn and corn stover. Energy Policy 35 (11), 5918-5930.

Levelton, E.L., Inc., S.T.C., 2000a. Assessment of net emission of greenhouse gases from ethanol blended gasoline in canada: lignocellulosic feedstocks R-2000-2. Richmond, B.C., Canada. Available from: <http://www.oregon.gov/ENERGY/RENEW/Biomass/docs/FORUM/GHG_Lig.PDF>.

Levelton, E.L., Inc., S.T.C., 2000b. Assessment of net emisssion of greenhouse gases from ethanol - gasoline bleneds in southern ontario R-2000-1. Richmond, BC. Available from: <http://www.oregon.gov/ENERGY/RENEW/Biomass/docs/FORUM/GHG_Eth.PDF>.

Luo, L., van der Voet, E., Huppes, G., 2009. An energy analysis of ethanol from cellulosic feedstock-Corn stover. Renewable and Sustainable Energy Reviews 13 (8), 2003-2011.

Morey, R.V., Tiffany, D.G., Hatfield, D.L., 2006. Biomass for electricity and process heat at ethnol plants. American society of agricultural and biological engineers 22 (5), 723-728.

Parikh, J., Channiwala, S.A., Ghosal, G.K., 2007. A correlation for calculating elemental composition from proximate analysis of biomass materials. Fuel 86 (12-13), 1710-1719.

Pimentel, D., 1991. Ethanol fuels: energy security, economics, and the environment. Journal of agriculture and environmental ethics 4 (1), 1-13.

Pimentel, D., 2001. Limits of biomass utilization. Encyclopedia of Physical Science and Technology

Pimentel, D., Patzek, T.W., 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Natural resources research 14 (1),

Punter, G., Rickeard, D., Larivé, J.F., Edwards, R., Mortimer, N., Horne, R., Bauen, A., Woods, J., 2004. Well-to-wheel evaluation for production of ethanol from wheat. FWG-P-04-024. LowCVP fuels working group, Available from: <http://www.lowcvp.org.uk/assets/viewpoints/Biofuels%20WTW%20final%20report.pdf>.

Schmer, M.R., Vogel, K.P., Mitchell, R.B., Perrin, R.K., 2008. Net energy of cellulosic ethanol from switchgrass. Proceedings of the National Academy of Sciences of the United States of America 105 (2), 464-469.

Shapouri, H., Duffield, J.A., Wang, M., 2002. The energy balance of corn ethanol: an update. USDA, Washington, DC. Available from: <http://www.transportation.anl.gov/pdfs/AF/265.pdf>.

Sheehan, J., Aden, A., Paustian, K., Killian, K., Brenner, J., Walsh, M., Nelson, R., 2004. Energy and environmental aspects of using corn stover for fuel ethanol. Industrial ecology 7 (3-4),

Sheehan, J., Camobreco, V., James, D., Graboski, M., Shapouri, H., 1998. Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. USDA, Cole Boulevard Golden, Colorado. Available from: <http://www.nrel.gov/docs/legosti/fy98/24089.pdf>.

Wang, M., C., S., Santini, D., 1999. Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions. Transportation Technology R&D Center, Argonne, Illinois. Available from: <http://www.transportation.anl.gov/pdfs/TA/58.pdf>.

Wang, M., Wu, M., Huo, H., 2007. Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. doi:10.1088/1748-9326/2/2/024001. Argonne, IL. Available from: <http://www.iop.org/EJ/article/1748-9326/2/2/024001/erl7_2_024001.pdf?request-id=277675e0-5ef9-4a55-be5c-3bd758932128>.

Chapter 5 . Impact of Biofuels' Production on Water Demand in Alberta

5.1. Introduction

Biofuels production is growing worldwide because it is considered nearly carbon neutral. The United States, Brazil, and the European Union have made substantial progress in this direction in the last decade. In 2006, these countries together accounted for 75% of the world's total biofuels' production (Varghese, 2007). Similarly, Canada, which has also made progress in production with bio-fuels has bioethanol and biodiesel production plants operating on commercial scale, but produces less than 1% of total fuel use in Canada (Klein et al., 2009). A study projected that bioethanol will replace 10% of the gasoline use and biodiesel will replace 2% of the diesel use by 2030 in a most optimistic scenario (NEB, 2009).

Currently, corn and soybean are major feedstocks for the production of bioethanol and biodiesel, respectively, in the US. Sugarcane is the main feedstock for bioethanol production in Brazil. Wheat and canola seed are major substrates for bioethanol and biodiesel production, respectively, in Canada where these crops are grown extensively (Baron, 2009). Use of these food crops for energy production competes with its use as food. There is growing interest to produce cellulosic bioethanol using feedstocks such as agricultural residues and corn stover. The technologies for production of bioethanol from agricultural residues are at various stages of development, demonstration and commercialization. There are a number of research efforts being made to facilitate the development of cellulosic bioethanol by reducing its capital and operating costs (GAO, 2007).

Canada's Prairie provinces (Manitoba, Saskatchewan and Alberta) are considered a hub of grain based agriculture. About 91% of Canadian wheat production and 99% of Canadian canola seed production come from these three western provinces (CANSIM, 2009). These facts and figures suggest that there is significant potential for growth of biofuels' industries in western Canada.

Alberta is one of the key Prairie provinces. This study focuses on Alberta based biofuels' industries. Currently, the commercial production of bioethanol and biodiesel is in its preliminary stage in Alberta. There is only one bioethanol production facility. Situated in Red Deer and using wheat as feedstock, it has production capacity of 28 million liters per year and an expansion capacity of up to 40 million liters per year (Racz, 2007).

Biofuels, especially those which are grain and seed based, are water intensive as discussed in earlier chapters. Development of these industries in a region would increase water demand significantly for that specific region. The technology for producing cellulosic ethanol is not yet fully developed, but the demand for biofuels is growing. It is expected that grain and oil seed based plants will lead biofuel production in Alberta. This study develops a scenario in which impact on water demand due to increase in biofuel production increase in Alberta is investigated. This study also tries to answer the question: is Alberta ready to produce wheat and canola seed based biofuels as projected? As water supply of Alberta is already under stress in many regions, it is imperative to know how much water will be required in future for biofuels production in Alberta. This study helps in understanding the issues at stake.

Compared to other parts of Canada, Alberta has a dry climate. Alberta covers about 7% of total land area of Canada but it has only 2% of Canada water supply (Alberta Environment, 2009). Water allocation in the southern region of Alberta, where most of the crops are produced is capped by the Alberta government. There is limited availability of water for irrigation of further crop production is (Alberta Environment, 2007).

This study estimates the future water requirement to produce biofuels and its possible impacts on Alberta's water resource. This study is based on the assumption that the cereal crops which are grown currently will be used for food only and additional crops will be produced to meet the demand for biofuels. This study projects the water demand for Alberta with biofuels production up to 2025.

5.2. Bioethanol and biodiesel demand projection in Canada and in Alberta

5.2.1. Bioethanol and biodiesel demand projection in Canada

Currently, Canada is producing 578 million liters of ethanol (Klein et al., 2009) and 79 million liters of biodiesel annually (Dietrich, 2009). The Canadian government plans to further increase the share of biofuels in gasoline and diesel. The Department of Environment, Canada intends to implement a federal regulation under the Canadian Environment Protection Act, 1999 (Environment Canada, 2006). Under this regulation, the gasoline sold by producers and importers will contain no less than 5% bioethanol by volume (Environment Canada, 2006). It is expected that this regulation will be implemented in 2010. Similarly, regulation of 2% biodiesel in diesel fuel and heating oil is planned to be implemented by 2012 (Environment Canada, 2006).

The projected demand for bioethanol and biodiesel over 25 years is shown in Table 5-1 (NEB, 2009). These are very optimistic projections, based on the objective to balance economic, environmental and energy requirement of the future.

In the most optimistic scenario, it is assumed that there will be only 0.2% growth in energy demand in the transportation sector, which is much lower than past growth due to efficiency improvement, behavioral changes, and slower economic growth (NEB, 2009).

Table 5-1: Biofuels demand in Canada

Year	Canadian biofuel requirement [a] (million liters)		Alberta biofuel production share (Scenario #1) [b] (million liters)			Alberta biofuels production share (Scenario # 2) [c] (million liters)		
	Bio ethanol	Bio diesel	Grain based ethanol	Straw based ethanol	Bio diesel	Grain based ethanol	Straw based ethanol	Bio diesel
2005	0	0	0	0	0	0	0	0
2010	1,462	128	526	0	43	526	0	43
2015	2,548	183	769	148	62	917	0	62
2020	3,370	240	769	444	82	1,213	0	82
2025	3,754	270	769	582	92	1,351	0	92

[a] Source : NEB (2009).
[b] Scenario # 1 is discussed in section 4.2.3.
[c] Scenario # 2 is discussed in section 4.2.4.

It is further assumed that the technology for production of grain based ethanol is already commercialized, so grain based technology will take the lead in ethanol production. In later years, ethanol production based on lignocellulosic technology will start in Canada (2009). About 5% (by volume) of 2030 gasoline demand will be met by grain based ethanol technology and 5% (by volume) will be met by lignocellulosic based ethanol technology (NEB, 2009). The projected demand of biodiesel is 2% (by volume) of the total diesel use in Canada by 2030 (NEB, 2009).

5.2.2. Selection of biomass feedstocks for biofuels production in Alberta

In Canada, wheat is the main feedstock for ethanol production (Racz, 2007). In future, small percentage of the ethanol requirement may be fulfilled by corn, wood or energy crops such as switchgrass. In this study, ethanol based on wheat and wheat straw is considered.

Among the varieties of wheat grown in Canada, the most popular is spring wheat, which is high in starch and yield 25% more than other varieties. These qualities make spring wheat the most suitable wheat for ethanol production (Racz, 2007). At present Alberta accounts for 36% of the total spring wheat production of Canada (CANSIM, 2009). Some new varieties of wheat are being developed which could provide higher yields i.e. triticale.

Similarly, canola seed which contains 42% oil by weight is a preferred feedstock for biodiesel production (Canada Canola Council, 2006). Currently, 34% of Canadian canola seed is produced in Alberta (CANSIM, 2009).

.

Another biomass feedstock, one which is likely to be the future of the bioethanol industry, is lignocellulosic biomass, i.e.s agricultural residues and wood. At present, the cost of ethanol from lignocellulosic biomass is $2.07 per gallon (Osborne, 2007) due to high capital and operational costs. The Department of Energy (DOE) has set target to reduce the cost of production to $1.07 per gallon of ethanol by 2012 to make this technology cost competitive (GAO, 2007). It is expected that this technology will start contributing significantly to Alberta's biofuel production in 8 to 10 years (Racz, 2007).

5.2.3. Alberta's share in meeting demand for Canada's bioethanol and biodiesel (Scenario # 1)

In this study, it is assumed that Alberta will produce biofuels to meet its demand in Canada in proportion to the production level of wheat and canola seed in Alberta i.e. ethanol production in Alberta will be 36% of Canada's ethanol production of Canada and biodiesel production in Alberta will be 34% of Canada's biodiesel production.

In scenario #1, it is assumed that production of wheat based ethanol will reach 769 million liters (5% of the 2030 gasoline demand) by 2015, due to an increasing demand for ethanol and delays in lignocellulosic feedstocks based ethanol production technology. It is assumed that commercial scale production of lignocellulosic ethanol will start after 2012 (which is the target of The Department of Energy) (GAO, 2007) and this technology will meet the remaining demand for bioethanol in 2015 i.e. 148 million liters (as shown in Table 5-1).

5.2.4. Alberta's share in meeting Canada's demand for bioethanol and biodiesel (Scenario # 2)

Production of lignocellulosic ethanol is likely to increase in future as this pathway does not compete with food. In this study, we have considered a pessimistic scenario. In this scenario # 2, it is assumed that Canadian ethanol industries will be based primarily on wheat in 2025, as shown in Table 5-1.

5.3. Water requirement and yield for wheat crop in Alberta

As explained in Chapter 2, water plays an important role in the development of any crop. This crop water requirement, which basically decides the total water requirement for the production of biofuels, depends on ambient temperature, humidity level, soil texture, and wind velocity during growing period of the crop (Canada Canola Council, 2008). As a result, crop water requirement varies for same the crop from place to place.

In Alberta, spring wheat requires up to 480 mm of water during the growing season (McKenzie et al., 1997; Efetha, 2008; Wright, 2008; Bauder, James W. , 2009b). With good growing conditions and proper management, 400 mm of water is required to achieve maximum yield (Wright, 2008). In this study, an average crop water requirement of 440 mm for wheat crop is considered to estimate the total water requirement of wheat based ethanol production in Alberta.

Crop yield is also a deciding factor for estimating water requirement. The yield of any crop varies with weather conditions from year to year. This study averages wheat yield of Alberta over eight years, from 2001 to 2008. The average yield was 2,738 kg per hectare (CANSIM, 2009).

5.4. Water requirement and yield for the canola seed crop in Alberta

In Alberta, canola seed (canola) consumes up to 480 mm (McKenzie et al., 1997; Bauder, James W., 2009a; Efetha, 2009) of water during the growing season, but it performs well in cold condition if more than 380 mm (Bauder, James W., 2009a) of water is available. This study considers 430 mm to be the average amount of water required by canola seed. It also adopts, the canola seed yield of 1763 kg per hectare from 2001 to 2008 was in Alberta as the average yield in Alberta (CANSIM, 2009).

5.5. Precipitation and soil moisture levels in Alberta

Crop water requirement is normally fulfilled by precipitation during the growing period of the crop. When there is inadequate precipitation, soil moisture and/or irrigation supplement the water requirement of crop. Basically, precipitation is the source of water which is utilized by the crop directly or indirectly in the through irrigation or soil moisture. When water is withdrawn from a river for irrigation purpose, it is part of a limited water source i.e. precipitation. Irrigation could affect the sustainability of the river.

In Alberta, the growing season for spring wheat and canola seed normally runs from late April to early September. In general 50 to 60% of annual precipitation occurs in this period (Wright, 2007a). In Alberta, this growing season precipitation is generally less than the crop water requirement; therefore, crop water requirement is fulfilled by soil moisture and irrigation (Wright, 2007b).

Table 5-2: Average precipitation (1 May to 31 August), spring soil moisture and irrigation for wheat and canola seed crops in Alberta by river basin over 30 years

River basin	Level of precipitation[c] (mm)	Available soil moisture[d] (mm)	Irrigation requirement (mm)	
			Wheat crop	Canola seed
Milk	200	75	165	155
Oldman	240	100	100	90
Bow	275	90	75	65
South Saskatchewan	200	75	165	155
Red Deer	250	60	130	120
Battle[a]	250	50	140	130
North Saskatchewan	290	90	60	50
Beaver	275	75	90	80
Athabasca	300	100	40	30
Peace[b]	275	75	90	80
Hay	240	100	100	90
Liard	250	-	-	-

[a] This river basin includes Sounding Creek.
[b] This river basin includes Slave, Athabasca, Great Slave and Buffalo Lakes.
[c] Source : Wright (2008).
[d] Source :Wright (2007b).

As precipitation level in Alberta is distributed unevenly and varies significantly (Alberta Environment, 2009), 12 river basins of the Alberta are considered in this study in order to assess the irrigation requirement for wheat and canola seed in individual river basin. The total precipitation during crop growing period i.e. from May 1st to August 31st of different basins of Alberta is shown in Table 5-2.

This precipitation level is the average over 30 years (from 1971 to 2000) of the precipitation for the growing period.

Available soil moisture is a vital supplement in region where precipitation level is below the crop water requirement. In Alberta, soil moisture which is stored during the non-growing season (i.e. September 1 to April 30) is very useful during the growing season (i.e. May 1 to August 31) whenever precipitation fails to meet the crop water requirement. Crops use only about 50 % of the total moisture holding capacity of the soil (Wright, 2007b). The soil moisture available for the plant is decided by the depth of the roots of the crop (Canada Canola Council, 2008). The active root zone of wheat and canola seed plants is 1.0 m (Efetha, 2008) and 1.2 m (Canada Canola Council, 2008), respectively.

The available soil moisture also depends on soil texture. About 120 cm (root depth) of fully water saturated clay soil can provide 200 mm of water to plants. The same root depth in sandy soil can provide only 100 mm of water to the plants (Wright, 2007b). In Alberta, different river basins have soils of different textures; Table 5-2 shows the average available soil moisture of different river basins for root depth of 120 mm.

5.6. Water availability and use in Alberta

To meet fresh water requirement of a specific region, there are two sources: surface water and ground water. Surface water is the primary source of water, whereas ground water is used only for small industrial, commercial or residential purposes where surface water is not available. In Alberta, 97% of the water supply in Alberta is met by surface water and remaining 3% is met by ground water (Alberta Environment, 2007). Availability makes it reasonable that only surface water use be considered for biofuel production in this study.

In Alberta, the availability of the surface water in different river basins is measured by river flow. The allocation and use of the natural flow of twelve river is shown in Table 5-3. Water in southern rivers (i.e. Milk, Oldman, Bow, South Saskatchewan, Red Deer) is used heavily. The water use (% of natural flow) in northern rivers (i.e. Athabasca and Peace) and central rivers (i.e. Beaver and North Saskatchewan) is very low.

Under 1909 international boundary waters treaty, the US is entitled to 75% and 25% of the natural water flow from the Milk and St. Mary rivers, respectively (Alberta Environment, 2006). In milk river basin (which includes the St. Mary river), 22.1% of the natural flow is already being used; therefore, it is difficult to increase water use in this basin.

Under the 1969 master agreement on apportionment between Alberta and Saskatchewan, 50% of the natural flow of the Oldman, Bow, South Saskatchewan, Red Deer, Battle river, North Saskatchewan, and Beaver rivers is allocated to Saskatchewan (Alberta Environment, 2004b).

In Alberta, 70% of the water used is withdrawn from those rivers during the crop growing period from May to August by the agricultural sector (Alberta Environment, 2007). As a result of this variance in demand, about 25% of the annual flow, after apportionment obligations, goes to Saskatchewan every year due to lack of demand (AEDA, 2009).

The Alberta government has capped the water allocations of the Oldman, Bow, South Saskatchewan and Red Deer river basins under the 1991 South Saskatchewan basin allocation regulation (Alberta Environment, 2007) so water use from these rivers cannot be increased. The water use of the Battle river has not been capped by the Alberta government, but it seems difficult to increase water use here due to above mentioned limitations and extremely high allocation of natural flow i.e. 278%.

The 1969 Masters agreement also applies to the North Saskatchewan and Beaver rivers but low water use (3% and 7% of the natural flow, respectively) provides the scope for irrigation.

Table 5-3: Water allocations, current and future use by river basin in Alberta

River basin	Water allocation as % of natural flow[a]	2005 [b] Surface water use (dam^3)	2005 [b] Surface water use (as % of natural flow)	2025[c] Projected surface water use (dam^3)	2025[c] Projected surface water use (as % of natural flow)
Milk	25%	53,901	22.1	55,801	22.9
Oldman	70%	1,134,540	35.6	1,245,512	39.1
Bow	70%	1,133,931	31.0	1,332,041	36.4
South Saskatchewan	70%	65,414	16.5	68,494	17.3
Red Deer	30%	191,788	17.2	210,267	18.8
Battle	278%	71,588	25.3	93,369	33.0
North Saskatchewan	30%	182,714	3.0	246,812	3.8
Beaver	20%	10,856	7.0	10,875	6.6
Athabasca	5%	247,143	1.6	451,066	3.0
Peace	1%	114,127	0.5	134,044	0.6
Hay	1%	2,806	0.5	2,158	0.4
Liard	0%	50	0.0	50	0.0

[a] Source: Alberta Environment (2009).
[b] Source: Alberta Environment (2007).
[c] Source: Alberta Environment (2007).

The water use of the northern rivers (i.e. Athabasca, Peace, Hay and Liard River) is being monitored under the 1997 Mackenzie River basin transboundry agreement (Alberta Environment, 2004a) but there is no agreement on water allocation between the provinces for these river basins. Water, in these river basins is abundantly available for use as shown in Table 5-3, therefore, irrigation could be increased comfortably.

The water use projected for 2025 by river basin and demand sector is shown in Tables 5-3 and 5-4, respectively. This 2025 water use projection is based mainly on two assumptions (Alberta Environment, 2007). First assumption is that Southern Alberta can further utilize the Oldman and Bow river basins water for irrigation within the water allocation limit decided by the 1991 South Saskatchewan River Basin Allocation Regulation. The second assumption is that water demand in Athabasca river basin will go up due to expansion of the bitumen upgrade industry.

Table 5-4: Projected percentage changes in water use from 2005 to 2025 by sector in Alberta

Sector	Water use (dam^3)[a] 2005	2025	% change from base year water use	% of change as % of total increase in water use
Municipal	114,332	143,229	25.3	4.5
Agricultural	2,175,955	2,471,046	13.6	46.0
Commercial	54,181	82,343	52.0	4.4
Petroleum	231,011	491,027	112.6	40.5
Industrial	175,520	179,456	2.2	0.6
Others	457,859	483,388	5.6	4.0
Total	3,208,858	3,850,489	20.0	100.0

[a] Source: Alberta Environment (2007)

This change is water use is reflected in the Oldman, Bow and Athabasca river basins as shown in Table 5-3. Major changes are reflected in agricultural and petroleum sectors as shown in Table 5-4. The remaining water changes in different sectors are due to changes in Alberta’s population, livestock population etc..

5.7. Available arable land in Alberta by river basin

The land required for biofuel production is a crucial factor. As wheat and canola seed crops need arable land, it is important to assess the availability of arable land. In Alberta, about 31% of the land is arable, about 19% is being currently used for agricultural purposes and the remaining 12% is to be utilized for agricultural purposes (Alberta Environment, 2007).

Table 5-5: Total used and unused arable land by river basin in Alberta

River basin	Arable land (km^2)[a]	Arable land in use[a] (km^2)	% unused land of total unused land
Milk	10996	6295	7
Oldman	21227	12499	12
Bow	13966	8257	8
South Saskatchewan	11327	4567	10
Red Deer	48743	28473	27
Battle	23213	14538	11
North Saskatchewan	31057	22115	10
Beaver	5842	3149	3
Athabasca	16128	10497	6
Peace	23794	16947	6
Hay	2063	1292	1
Liard	0	0	0

[a] Source: (Alberta Environment, 2007)

It is clear from Tables 5-4 and 5-5 that most of the remaining arable land in the Alberta is available in the southern river basins (i.e. Milk, Oldman, Bow, South Saskatchewan, Red Deer and Beaver rivers), where water scarcity exists. Less arable land is available in the northern river basins where water is abundantly available.

5.8. Irrigation and selection order of river basins for wheat and canola seed production

For sustainability of the biofuels industry, the life cycle water requirement of biofuels should be as low as possible. Based on Chapter 2 it can be concluded that a great deal of water is required to produce crops for biofuel production. This crop water requirement can be fulfilled by precipitation, soil moisture and irrigation. Precipitation is primary source of water supply for crops in any region. If precipitation is not enough, soil moisture is utilized by the plant. If soil moisture falls below 50% of total moisture (Wright, 2007b), it becomes necessary to irrigate the crop. The irrigation requirement can be calculated using the following formula.

Irrigation requirement = Crop water requirement – Precipitation – Soil moisture

Basically soil moisture is stored precipitation from the non-growing season. These are naturally available water but irrigation is extra requirement for a specific region. Irrigation water is withdrawn directly from rivers and its impact on the water availability of a river basin is considerable; therefore, in this study, river basins with minimum irrigation water requirement are given first priority as sites for growing biomass crop. This minimum irrigation criterion is used to select river basins for growing wheat and canola seed for biofuel production.

The crop water requirement of 440 mm and 430 mm for wheat and canola seed, respectively, were used to calculate the irrigation requirement for different river basins: these are shown in Table 5-2. It is clear from this table that southern river basins (top 6 river basins of Table 5-2) are water scarce zones. As water is already scarce in these zones, setting up biofuels industries would not be sustainable there.

It is clear that the water requirement in the Athabasca river basin is the lowest among the bottom 6 river basins (as shown in Table 5-2). It is only 40 mm and 30 mm for wheat and canola seed, respectively. As the available arable land in the Athabasca river basin would not be able to produce the all biofuels for which Alberta is accountable, the remaining biofuels production would have to be produced in the next river basin. The next river basin is the North Saskatchewan river basin where 60 mm and 50 mm of irrigation is required for production of wheat and canola seed, respectively. It is followed by Peace and Beaver River basins where 90 mm and 80 mm of irrigation would be required for wheat and canola seed, respectively.

5.9. Irrigation management in Alberta

The quantity of water withdrawn from a river is always more than what is actually supplied to the crop. Water is lost through seepage and evaporation which being conveyed from river to field or farm. The term for this is termed as conveyance efficiency (Rogers et al., 1997). In the field, water is also lost in the form of drift, evaporation and percolation below the root zone, depending upon the type of irrigation system. This is referred to as irrigation efficiency (Rogers et al., 1997).

The Alberta Irrigation Projects Association estimates irrigation efficiency to be about 71% (AIPA, 2006). In Alberta, seepage losses and evaporation losses are estimated to be about 2.5% and 4% of license volume, respectively (AIPA, 2006).

5.10. Availability of lignocellulosic biomass feedstocks in Alberta

For lignocellulosic biomass based ethanol production, the availability of lignocellulosic biomass is an important issue. This biomass can be wood or agricultural residues from any cereal crop. In Alberta, wheat and barley is produced in significant quantity, and currently, most of the residues from these crops are not utilized for any specific purpose; only a small portion of these residues are utilized for livestock and preventing soil erosion (Sokhansanj et al., 2006). In this study, these lignocellulosic residues are considered as potential feedstocks for ethanol production. On average in Alberta, 5.09 and 2.60 million tonnes of wheat and barley straw, respectively is available annually after livestock and soil erosion use (Sokhansanj et al., 2006). In Alberta, south, central and north east zones produce about 75% (Atkinson, 2001) of total Alberta wheat production. This makes it more favorable to locate the lignocellulosic biomass based ethanol plant in central regions i.e. the South Saskatchewan and Red Deer river basins.

5.11. Results and discussion

The demand for water with and without biofuels production in 2025 is shown in Table 5-6. With biofuels production, future water demand projections for few river basins are higher than that of the reference case projection (which was without biofuels production). In the base year, (2005) biofuels production is zero and water requirement for two scenarios (with and without lignocellulosic bioethanol production) are same as for reference case. Water requirement in 2025 for the two scenarios with biofuels production for different river basins are different than that for 2025 reference case as shown in Table 5-6. There are significant changes in water use in the North Saskatchewan, Athabasca and Peace River basins. The water projections and calculation methodology from 2005 to 2025 at 5 years interval are given for both scenarios in Appendix H.

The water requirement for the North Saskatchewan river basin is 11.6% and 16.1% of the natural flow in the scenarios # 1 and # 2, respectively, in contrast to 3.8%, as given in the reference case. Because the projected water use of this river for 2025 is lower than the current percentage water use for southern Alberta rivers, it is expected that this water demand will be manageable.

Table 5-6: Albert water demand without and with biofuels production by river basin in 2025

River basin	2025 water use without biofuels [a]		2025 water use with biofuels Scenario # 1		Scenario # 2	
	(dam^3)	(% of natural flow)	(dam^3)	(% of natural flow)	(dam^3)	(% of natural flow)
Milk	55,801	22.9	55,801	22.9	55,801	22.9
Oldman	1,245,512	39.1	1,245,512	39.1	1,245,512	39.1
Bow	1,332,041	36.4	1,332,041	36.4	1,332,041	36.4
South Saskatchewan	68,494	17.3	70,300	17.7	68,494	17.3
Red Deer	210,267	18.8	212,073	19.0	210,267	18.8
Battle	93,369	33.0	93,369	33.0	93,369	33.0
North Saskatchewan	246,812	3.8	760,769	11.6	1,058,492	16.1
Beaver	10,875	6.6	10,875	6.6	10,875	6.6
Athabasca	451,066	3.0	792,321	5.2	792,554	5.2
Peace	134,044	0.6	134,044	0.6	512,420	2.3
Hay	2,158	0.4	2,158	0.4	2,158	0.4
Liard	50	0	50	0.0	50	0.0

[a] Source: Alberta Environment (2007)

Similarly, the water requirement for the Athabasca river basin will go up from 3.0 % to 5.2% for both the scenarios. Though this is significant portion of total increase in water demand for 2025, there is so much unused water flow; it will have little impact on the water supply in Athabasca river basin. Water will not be a constraint for the production of biofuels but arable land is limited for the production of crops. When all the available arable land in the Athabasca river basin is in use, crops will be produced in the Peace river basin as per scenario # 2. As a result, water use for the Peace river will increase from 0.6 % to 2.3 % of natural flow.

The water demand for the South Saskatchewan and Red Deer rivers will be increased by 0.4% and 0.2% of their natural flow, respectively in scenario # 1, when lignocellulosic biomass based ethanol plants are set up in these river basins. This shows that lignocellulosic biomass based ethanol plants do not change water demand of any region significantly. In this study, only wheat straw is considered to fulfill future ethanol requirement but at least 2.6 million tonnes of barley straw (mostly southern region) is also available for ethanol production (Sokhansanj et al., 2006). If lignocellulosic biomass based technology for ethanol production becomes cost competitive in the future, Alberta will be able to produce more ethanol without significantly affecting the water supply of southern Alberta.

To illustrate the impact of producing biofuel, Table 5-7 shows the water demand projections for 2025 by sector. The percentage change in demand from 2005 is shown in Table 5-7. In agricultural sector, the water demand is projected to rise to 13.6 % with respect to base year (2005) in reference case whereas the projected increase are 52.7% and 83.6% for scenarios # 1 and # 2, respectively.

The water demand in the petroleum sector is not affected by biofuels production i.e. water requirement for both scenarios and reference case is same. The demand for water use in the petroleum sector is projected to increase by 112.6 % in the reference case but change in the petroleum sector is only 17.3 % of total change in water demand in scenario # 1. This is due to significant increase in water demand in agricultural sector for biofuels.

Table 5-7: 2025 water use of Alberta with biofuels production by sector

Sector	Year 2025 water use (dam^3)		% change from year 2005 water use		% of change as % of total increase in water use	
	Scenario # 1	Scenario # 2	Scenario # 1	Scenario # 2	Scenario # 1	Scenario # 2
Municipal	143,229	143,229	25.3	25.3	1.9	1.3
Agricultural	3322,323	3,995,826	52.7	83.6	76.4	83.7
Commercial	82,343	82,343	52.0	52.0	1.9	1.3
Petroleum	491,027	491,027	112.6	112.6	17.3	12.0
Industrial	187,003	186,222	6.5	6.1	0.8	0.5
Others	483,388	483,388	5.6	5.6	1.7	1.2
Total	4709,313	5,382,034	46.8	67.7	100	100

The demand for water use in the industrial sector will be 5.6% of total water use in 2025 for both scenarios, as compared to 2.2% in the reference case. This is due to water requirement for bioethanol and biodiesel manufacturing stages.

As far the total water demand in Alberta is concerned in 2025, the reference case projects an increase in water demand of 20% from the 2005 level, whereas scenarios # 1 and # 2 project increases of 46.8% and 67.7%, respectively.

5.12. Conclusion

In this study, two scenarios of biofuels production were developed to assess the impact of this production on the water demand in Alberta. In scenario #1, biofuels production in Alberta was considered using wheat and wheat straw based ethanol production and canola seed (canola oil) based biodiesel production. In scenario#2, biofuels production in Alberta was considered based on wheat and canola seed only. The water requirement in both the scenarios were calculated along with the water demand projected for 2025.

Southern Alberta has 64% of the unused total arable land in Alberta (Alberta Environment, 2007), but biofuels production from grain and oil is not feasible in this region because there is not enough water to meet high irrigation water requirement. The present availability of water and arable land in Alberta indicates that the Athabasca, North Saskatchewan and Peace River basins of northern Alberta have 21% of the unused arable land, whereas only 1.6%, 2.8% and 0.5% of natural flow of the respective rivers is currently being used.

In 2025, Alberta will have to produce 3,754 million liters of ethanol and 270 million liters of biodiesel to meet the projected levels. If biofuels are produced from the crops grown in the abovementioned northern river basins, the water requirement to meet these biofuels demand in 2025 will be 858,824 dam^3 and 1,531,545 dam^3 for scenarios # 1 and #2, respectively. As a result, water use in 2025 will be 46.8% and 67.7% higher than that 2005 for scenarios # 1 and # 2, respectively. Alberta should be able to meet the demand for biofuels in 2025 sustainably as water requirement of these river basins for biofuel production will increase to 5.2%, 0.6% and 11.6 % of natural flow in scenario # 1 and 5.2%, 2.3% and 16.1 % of natural flow for scenario # 2.

In scenario # 1, study of lignocellulosic ethanol production shows that wheat straw is available in sufficient quantity in Alberta to meet the ethanol demand in 2025. As wheat straw is mainly available in the southern and central regions of Alberta, the wheat straw based ethanol production plants will be based in the Red Deer and South Saskatchewan River basins. The production of lignocellulosic bioethanol will also be sustainable, increasing the water requirement in the Red Deer and South Saskatchewan rivers only slightly, by 0.2 % and 0.4 % of the natural flow, respectively.

References

AEDA, 2009. Sustainable water management and economic development in Alberta. Alberta Economic Development Authority. Available from: https://aeda.alberta.ca/reportsandstudies/aedastudies/Documents/AEDAWaterStudy-Final%20version%20with%20appendix.pdf. Accessed on: March 20, 2009.

AIPA, 2006. Alberta irrigation sector improves efficiency of water use. Alberta Irrigation Project Association. Available from: http://www.fossilwater.ca/fossilwater-report-aug-sep06.pdf. Accessed on: March 30, 2009.

Alberta Environment, 2004a. Mackenzie river basin transboundary waters master agreement (1997). Available from: http://www3.gov.ab.ca/env/water/GWSW/Quantity/WaterinAlberta/Apportionment/TB_Transboundary/TB11_mackenzie_river_basin_tma.html. Accessed on: March 15, 2009.

Alberta Environment, 2004b. Master agreement on apportionment (1969). Available from: http://www3.gov.ab.ca/env/water/GWSW/Quantity/WaterinAlberta/Apportion ment/TB_Transboundary/TB5_master_agree_apportionment.html. Accessed on: March 15, 2009.

Alberta Environment, 2006. Boundary waters treaty (1909). Available from: http://www3.gov.ab.ca/env/water/GWSW/Quantity/WaterinAlberta/pubs/SharingtheWaters-Supplement.pdf. Accessed on: March 15 2009.

Alberta Environment, 2007. Current and future water use in Alberta. Available from: http://www.assembly.ab.ca/lao/library/egovdocs/2007/alen/164708.pdf. Accessed on: March 02, 2009.

Alberta Environment, 2009. Water in Alberta. Available from: http://www3.gov.ab.ca/env/water/gwsw/quantity/waterinalberta/index.html. Accessed on: March 25, 2009.

Atkinson, G., 2001. Census of agriculture for Alberta. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd5726. Accessed on: April 15 2009.

Baron, V., 2009. A Canadian perspective on land management risks associated with biofuels and their production. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop12131. Accessed on: February 25, 2009.

Bauder, J.W., 2009a. The right strategy for irrigating your canola crop. Available from: http://waterquality.montana.edu/docs/irrigation/canolastrategy.shtml. Accessed on: April 3, 2009.

Bauder, J.W., 2009b. Wheat irrigation. Available from: http://waterquality.montana.edu/docs/irrigation/wheatirrigation.shtml. Accessed on: March 30 2009.

Canada Canola Council, 2006. A review of environmental assessments of biodiesel displacing fossil diesel. Canada Canola Council, Available from: <http://www.canolacouncil.org/uploads/Environmental_Analysis_FINAL-July-8.pdf>.

Canada Canola Council, 2008. Canola growers manual. Available from: http://canola-council.org/chapter4.aspx#ch4_sec2. Accessed on: December 6, 2008.

CANSIM, 2009. Agriculture. Canada Statistics. Available from: http://dc1.chass.utoronto.ca/cgi-bin/cansimdim/c2_subjects.pl. Accessed on: March 20, 2009.

Dietrich, J., 2009. Central peace conservation society biodiesel project. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop12154. Accessed on: February 20, 2009.

Efetha, A., 2008. Irrigation management of soft white spring wheat. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr4429. Accessed on: 30 March, 2009.

Efetha, A., 2009. Irrigation management of canola. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr4425. Accessed on: 2 April, 2009.

Environment Canada, 2006. Notice of intent to develop a federal regulation requiring renewable fuels. Available from: http://www.ec.gc.ca/Ceparegistry/documents/notices/g1-14052_n1.pdf. Accessed on: March 30, 2009.

GAO, 2007. DOE lacks a strategic approach to coordinate increasing production with infrastructure development and vehicle needs. United States Government Accountability Office. Available from: http://www.gao.gov/new.items/d07713.pdf. Accessed on: May 15 2009.

Klein, K.K., Roy, D.G.L., 2009. The bioenergy frenzy. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop12133. Accessed on: Februrary 15 2009.

McKenzie, R., Dunn, R., 1997. Irrigated crop recommendations. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex139. Accessed on: December 3 2008.

NEB, 2009. Canada's energy future - reference case and scenarios to 2030. National Energy Board, Canada. Available from: http://www.neb.gc.ca/clf-nsi/rnrgynfmtn/nrgyrprt/nrgyftr/2007/nrgyftr2007chptr5-eng.html. Accessed on: March 25 2009.

Osborne, S., 2007. Energy in 2020: assessing the economic effects of commercialization of cellulosic ethanol. Available from: http://www.ethanolrfa.org/resource/cellulosic/documents/cellulosic2007.pdf. Accessed on: March 25, 2009.

Racz, V.J., 2007. Canadian biofuel Industry: western canada perspective and opportunities. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop12127. Accessed on: February 22, 2009.

Rogers, D.H., Lamm, F.R., Alam, M., Trooien, T.P., Clark, G.A., Barnes, P.L., Mankin, K., 1997. Irrigation management series. Available from: http://www.oznet.ksu.edu/library/ageng2/mf2243.pdf. Accessed on: January 25, 2009.

Sokhansanj, S., Mani, S., Stumborg, M., Samson, R., Fenton, J., 2006. Production and distribution of cereal straw on the Canadian prairies. Available from: http://engrwww.usask.ca/oldsite/societies/csae/protectedpapers/c0556.pdf. Accessed on: January 15, 2009.

Varghese, S., 2007. Biofuels and global water challenges. Institute for agriculture and trade policy, Minneapolis, Minnesota. Available from: <http://www.iatp.org/iatp/publications.cfm?refid=100547>.

Wright, R., 2007a. Agroclimatic atlas of Alberta: agricultural climate elements. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6301. Accessed on: April 5, 2009.

Wright, R., 2007b. Agroclimatic atlas of Alberta: soil moisture conditions in alberta. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6302. Accessed on: April 5, 2009.

Wright, R., 2008. May 1 to August 31 total precipitation: 1961 to 2000. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6435?opendocument. Accessed on: March 30, 2009.

Chapter 6 . Conclusion and Recommendations for Future Work

6.1. Conclusion

The life cycle water and fossil energy requirement for twelve biomass conversion pathways using six biomass feedstocks were assessed to develop water requirement factors. These pathways are categorized into biofuel (i.e. ethanol and biodiesel) production pathways and biopower production pathways. The biomass conversion technologies for the biofuels' (ethanol and biodiesel) production are based on biochemical processes, whereas the biomass conversion technologies for biopower generation are based on thermochemical processes. The biomass feedstocks considered for the biofuel production are corn, wheat, corn stover, wheat straw, switchgrass and canola seed. The biomass feedstocks considered for the biopower generation are corn stover, wheat straw and switchgrass.

The life cycle of bioenergy production consists of three stages: crop production, biomass feedstock transportation, and its conversion. In this study, the life cycle water requirement for the crop production and conversion stages are evaluated for all the biomass conversion pathways, but the water requirement for the transportation stage is ignored. The life cycle energy requirement for all three stages and for all biomass conversion pathways is considered. This study takes into account not only direct water and fossil fuel based energy requirement but also the indirect water and fossil fuel based energy requirement associated with inputs of the biofuels' life cycle.

In this study, a future scenario is developed of water requirement for biofuels' production in Alberta using wheat, wheat straw and canola seed. The impact on different water basins in Alberta over twenty five years due to the development of biofuel production plants is also assessed.

6.1.1. The water and fossil fuel based energy requirement of biofuel pathways

The life cycle water and energy requirement are evaluated for six different biofuel production pathways: corn to bioethanol, corn stover to bioethanol, wheat to bioethanol, wheat straw to bioethanol, switchgrass to bioethanol and canola seed to biodiesel.

The crop water requirement plays a dominant role in deciding the total water requirement of any biofuel production pathway. Among all the biofuels' production pathways, corn stover to ethanol and wheat straw to ethanol are the most water efficient pathways. These pathways based on lignocellulosic biomass feedstocks consume approximately 8 liters of water for production of 1 kg of ethanol. These feedstocks are the residues of agricultural crops and water attributed to these feedstocks in crop production stage is zero.

The life cycle water requirement of the switchgrass based ethanol production pathway is very high because a great deal of water is required for crop growth. The switchgrass to ethanol production pathway requires approximately 3,413 liters of water per kg of ethanol produced. The water requirement for biomass conversion stage to ethanol is nearly the same for all the lignocellulosic feedstocks.

Similarly, corn and wheat based ethanol are also water intensive due to the water requirement in crop production stage. The water requirement for these pathways are 2,060 liters and 2,884 liters per kg of ethanol produced, respectively. The water requirement for the canola seed to biodiesel pathway is 4,594 liters per kg of biodiesel produced.

The life cycle water requirement for the biodiesel production pathway is greater than that for any of the ethanol production pathways; if, however, the water requirement for production of 1 MJ of biofuel is compared for all the pathways, the water requirement for biodiesel is lower because LHV for biodiesel is 37.0 MJ kg^{-1} compared to 26.7 MJ kg^{-1} of ethanol.

The power and heat requirement in conversion stage plays a dominant role in deciding the life cycle fossil fuel based energy requirement in all the biofuel production pathways. Grain based ethanol production pathways using current technology are the least energy efficient as they consume large amount of energy in conversion stage. The net energy values (NEV) for wheat and corn based ethanol are 3,978 kJ and 3,490 kJ per liter of ethanol, respectively (this corresponds to 15% and 17% of total energy value of ethanol). The energy efficiency of these pathways could be improved in future by substituting fossil fuel by renewable fuel and also by implementing efficient technologies for supplying heat and power to conversion stage.

The ethanol production pathways based on lignocellulosic biomass feedstocks (corn stover, wheat straw and switchgrass) are energy efficient than the grain based ethanol production pathways. The NEV for switchgrass based ethanol is 23,065 kJ per liter of ethanol (99% of the total energy value for ethanol) and it has the highest NEV of all the ethanol production pathways. The NEVs for corn stover and wheat straw based ethanol are 22,189 kJ and 23,065 kJ per liter of ethanol (95% and 89% of the total energy value of ethanol), respectively.

The NEV for canola seed based biodiesel is higher than that for grain based ethanol due to low energy requirement in its conversion stage. The NEV for biodiesel is 24,347 kJ per liter of biodiesel (68% of the total energy value for biodiesel).

6.1.2. The water and fossil fuel based energy requirement of biopower pathways

The life cycle water and energy requirement of six biopower production pathways are evaluated. These pathways include: corn stover to electricity, corn stover to electricity through conversion to bio-oil, wheat straw to electricity, wheat straw to electricity through conversion to bio-oil, switchgrass to electricity, and switchgrass to electricity through conversion to bio-oil.

The crop water requirement plays a dominant role in determining the total water requirement of biopower production pathways. The biopower production pathways based on agriculture residues (corn stover and wheat straw) are the most water efficient pathways because water requirement for crop production stage is not attributed to these residues. These pathways consume approximately 2.7 liters of water per kWh of electricity generation by direct combustion and approximately 3.0 liters of water per kWh of electricity generation through combustion of bio-oil produced through fast pyrolysis of biomass.

Process conversion efficiency (the dry biomass requirement per unit of electricity production) also plays an important role in determining the total water requirement. One kWh of power generation using 0.66 kg of switchgrass through direct combustion consumes 672.13 liters of water, whereas one kWh of power generation using 0.81 kg of switchgrass through fast pyrolysis pathway consumes 823.67 liters of water.

In the biopower production pathways, heat and power in conversion stage is supplied within the system. Fossil fuel is consumed during the crop production and feedstock transportation stages only. The net energy value for switchgrass based biopower production is greater than that for agriculture residues based pathways. This is because switchgrass crops require few nutrients. The net energy value for switchgrass based biopower is 2,419 kJ per kWh (67% of the total energy value for electricity) for electricity generation through direct combustion. The value for biopower generation through fast pyrolysis is 2,394 kJ per kWh (66% of the total energy value of electricity).

Corn stover and wheat straw are residues of crop but extra nutrients are supplied to the field to replenish the nutrients lost along with the corn stover or straw. As wheat straw is richer in nutrients than corn stover, the NEV for wheat straw based biopower is lower than that for corn stover based biopower. The net energy value for wheat straw based biopower is 2,044 kJ per kWh (57% of the total energy value for electricity) for generation through direct combustion, whereas it is 2,013 kJ per kWh (56% of total energy value of electricity) for generation through fast pyrolysis pathway. The net energy value for corn stover based biopower is 2,336 kJ per kWh (65% of total energy value for electricity) for generation through direct combustion whereas it is 2,307 kJ per kWh (64% of the total energy value for electricity) generated through fast pyrolysis.

The NEV for biopower generated through direct combustion pathways is slightly higher than that generated through fast pyrolysis for any given lignocellulosic biomass. This is due to additional heat losses in the fast pyrolysis pathway.

6.1.3. The development of integrated water and energy requirement factors for production of biofuels and biopower

The energy requirement of the biofuels and biopower pathways are integrated with their water requirement to develop factor which indicate the combined water and energy efficiency of the pathways. This integrated factor is water requirement for 1 MJ of net energy value (NEV) of biofuel or biopower.

Agriculture residues based ethanol production pathways consume only 0.3 liter of water per MJ of NEV. These pathways are both water and energy efficient. The NEV for biopower production pathways based on lignocellulosic biomass is lower than that for ethanol production pathways for the same feedstock. This is due to high heat losses in the conversion stage. Due to their lower energy efficiency, the biopower production pathways based on agriculture residues consumes 1.2 – 1.5 liters of water per MJ of NEV which is slightly higher than ethanol production pathways. Although switchgrass based ethanol production pathway is the most energy efficient, this pathway consumes 100.1 liters water per MJ of NEV due to poor water efficiency. The water requirement factor for the wheat to ethanol production pathway is highest i.e. 652.9 liters of water per MJ NEV. This pathway is neither energy efficient nor water efficient. Similarly, the corn to ethanol pathway is both water and energy intensive, consuming 409.0 liters of water per MJ of NEV.

6.1.4. Biofuels production in Alberta and their water requirement

Two scenarios of biofuels production are developed to assess their impact on water demand in Alberta. In scenario # 1, biofuels production in Alberta includes ethanol production from wheat and wheat straw, and biodiesel produced from canola seed (canola oil). In scenario # 2, biofuels production in Alberta includes ethanol production from wheat and biodiesel production from canola seed. The water requirement in both scenarios are calculated along with water demand in Alberta projected for 2025.

Southern Alberta has 64% of the unused arable land in the province (Alberta Environment, 2007), but biofuels production from grain and canola seed is not feasible in this region because there is not enough water to meet high irrigation water requirement. Data on the present availability of water and arable land in Alberta indicate that the Athabasca, North Saskatchewan and Peace River basins of northern Alberta have 21% of the unused arable land in the province whereas only 1.6%, 2.8% and 0.5% of the natural flow of these rivers is currently being used.

In 2025, Alberta will have to produce 3,754 million liters of ethanol and 270 million liters of biodiesel to meet the projected levels. If biofuels are produced from the crops grown in the above-mentioned northern river basins, the water requirement to meet these levels of biofuels demand in 2025 will be 858,824 dam^3 and 1,531,545 dam^3 for scenarios # 1 and # 2, respectively. As a result, water use in 2025 will be 46.8% and 67.7% higher than that 2005 for scenarios # 1 and # 2, respectively. The province of Alberta should be able to meet biofuels demand in 2025 sustainably because the water requirement of these river basins for biofuel production will have increased by 5.2%, 0.6% and 11.6% of the natural flow in scenario # 1 and 5.2%, 2.3% and 16.1% of natural flow for scenario # 2.

6.2. Recommendations for future research

This study includes evaluation of the water requirement of twelve different thermochemical and biochemical conversion pathways of biomass to energy forms using six different biomass feedstocks. It also includes the integration of water requirement with net energy value for final bioproducts using different pathways and biomass feedstocks. The results of this study have been applied to assess impact of biofuels production in water demand in Alberta. Some opportunities for future research on these studies are subjects are given below.

- Crop yield and crop water requirement is a crucial factor for determining the life cycle water requirement of a pathway. The yield and water requirement of the crop also depend on crop variety, climatic conditions, soil type, and field practices. In this study, yield and water requirement for the crops are collected from different sources and averaged. In this study, yield and water requirement of the crops is based only on the conditions in the North America, therefore, further study could focus on developing range of yields and water requirement for other climatic conditions.

- The water requirement for the conversion stage of bioenergy pathways may vary with process model. In this study, water requirement are evaluated using a specific process models. Further work could consider all possible process models to convert biomass feedstock to a bioproduct and range of water requirement could be developed.

- This study considered two technologies for biopower generation, direct combustion of biomass and combustion of bio-oil produced from pyrolysis of biomass. One more technology, which is at doorstep of commercialization, is biomass gasification technology. This technology could be studied using different biomass feedstocks and water and energy requirement could be assessed and compared with those of other technologies.

- In this study, six biomass feedstocks from the first and second generation of bioenergy are considered. There are, however, third generation biomass feedstocks; one of these feedstocks is microalgae. It is in an experimental stage and intensive research is being conducted to test its viability. A study could be carried out to evaluate the life cycle water and energy requirement of microalgae derived biofuels.

- This study also estimated water requirement for biofuel production in the Province of Alberta. To evaluate the irrigation water requirement of a crop in a specific river basin, it is assumed that the pattern of available precipitation matches with the plant water requirement during its growing season. An experimental study could be conducted in each river basin of Alberta to estimate the irrigation water requirement for wheat and canola seed crops.

Appendix A

Water Requirement for Major Agricultural Inputs

A-1. Water requirement major inputs of agricultural inputs

In agriculture stage, different types of fossil fuel used for different farming equipments to different farm activities such as ploughing, harrowing, cutting, transportation and baling, etc. The fuels used for these farming operations are diesel, gasoline, LPG, natural gas and electricity. The water required to produce these fuels is given in Table A-1.

Table A-1: Life cycle water requirement for production of different fuels

Inputs	Water requirement [a] (liters kg^{-1})
Diesel	2.65
Gasoline	30.94
LPG	4.22
Natural gas	0.00
Electricity [b]	1.76

[a] Source: King et al. (2008); unit is liters kWh^{-1} for electricity.
[b] Water requirement for electricity is considered on the basis of current US energy mix (King et al., 2008).

In agriculture, farm chemicals play pivotal roles. The fertilizers are used as nutrient for the crops, herbicides are added to protect crops, and lime is added to maintain the pH of soil. Life cycle water of the farm chemicals are given in Table A-2.

Table A-2: Life cycle water requirement for production of farm chemicals

Inputs	Water requirement [a] (liters kg-1)
Phosphorus	0.19
Potassium	0.001
Sulfur	0.68
Lime [b]	0.00

[a] Source: Sheehan et al. (1998)

[b] Lime production process includes mining, transportation and grinding of lime stone (West et al., 2001), that is why zero water requirement for its production is considered in this study.

Appendix B

Water requirement for Enzyme (Used for Saccharification of Lignocellulosic Biomass) and Sulfuric Acid Production

B-1. Water requirement for enzyme production (used for saccharification of lignocellulosic biomass)

The major inputs of enzyme production process are cellulosic hydrolyzate, water and electricity (Sheehan et al., 2004). The quantity of these inputs for 100 kg enzymes production is given in Table B-1. The cellulosic hydrolyzate is 4% concentration solution i.e. 63.7 liters of water (96% of hydrolyzate manufactured) is used to manufacture 66.3 kg of cellulosic hydrolyzate (Sheehan et al., 2004).

Table B-1: Major inputs and water requirement for 100 kg of enzyme production

Major inputs	Quantity [a] (kg)	Water requirement (liters)
Cellulosic hydrolyzate	66.3	63.7
Water	39.1	39.1
Electricity [b]	19.5	34.3
Total	-	137.1

[a] Source: (Sheehan et al., 2004)
[b] Unit is kWh

The water is also used for this process indirectly with electricity. Electricity consumes 1.76 liters of water for 1 kWh production (King et al., 2008). Therefore, total water requirement for 100 kg of enzyme production is 137.1 liters.

B-2. Water requirement for sulfuric acid production

Sulfuric acid production process is based on exothermic reaction. As a result, great amount of heat is generated. This heat is utilized to generate electricity in the power plant. A sulfuric plant of capacity 1250 tonne per day is able to produce 15000 kWh electricity (ESAA, 2000). Considering 2.7 liters water for 1 kWh generation (refer Appendix E), 0.04 liter water is required to produce 1 kg sulfuric acid.

The final step of sulfuric acid manufacturing process is absorption of SO_3 into water, this reaction is given below. In this reaction, 0.18 liter of water is required to produce 1 kg of sulfuric acid.

$$\underset{80\ kg}{SO_3} + \underset{18\ kg}{H_2O} \longrightarrow \underset{98\ kg}{H_2SO_4}$$

Thus, total water require to produce 1 kg of sulfuric acid is 0.22 liter.

Appendix C

Water Requirement to Produce Power in Lignocellulosic Biomass based Ethanol Plant

C-1. Power generation in ethanol production process using corn stover wheat straw and switchgrass

In a lignocellulosic biomass based ethanol plant, electricity is produced using the waste of the plant as fuel. This waste contains lignin which primarily provides the energy. The lignin content of corn stover is 18% and total power generation along with 1 kg of ethanol is 1.22 kWh (Aden et al., 2002). The wheat straw also contains same amount of lignin (Kerstetter et al., 2001), therefore, it is assumed that wheat straw based ethanol plant also produces 1.22 kWh of electricity along with 1 kg of ethanol production. The lignin content of switchgrass is 19.1% (Lee et al., 2007). In this study, it is assumed that it produces more power in proportion to its lignin content i.e. 1.29 kWh (1.22 x19.1/18.1 kWh).

C-2. Water requirement to produce power in ethanol production process using corn stover, wheat straw and switchgrass

In corn stover based ethanol plant, 0.66 liters of makeup water is required to produce 1.22 kWh. The wheat straw based ethanol plant consumes same amount of water. The switchgrass based ethanol plant consumes 0.70 liters (0.66x1.29/1.22 liters) of water along with 1 kg ethanol production.

Appendix D

Feedstock Requirement of Biomass Power Plant

D-1. Direct combustion biomass power plant and net plant heat rate

Net heat rate of power plant is heat required to produce 1 kWh of electricity. This heat rate is basically reciprocal of net efficiency of the power plant. The plant net efficiency is combination of boiler efficiency, turbine efficiency, steam system efficiency and auxiliary equipments efficiency (Wiltsee, 2000). Among these efficiencies, the boiler efficiency is dependent upon biomass feedstock fed to boiler. The efficiency of the remaining systems is independent of biomass feedstock fed into the boiler. In this study, wood based McNeil (Wiltsee, 2000) power plant is considered model plant. The boiler losses of this plant are modified according to chemical properties of biomass feedstocks to determine the net plant heat rate of different biomass feedstock based power plant.

D-1-1. Boiler heat losses of wood based power plant

Gross generation	= 54.0 MW
Net generation	= 50.0 MW

McNeil wood based plant uses 60 % hardwood and 40 % soft with 55 % moisture as a result of which wood ultimate analysis and calorific value on wet basis will be as follows.

% C	23.0 %	Source: (Ragland et al., 1991; Gupta et al., 2003)
% H	2.8 %	
% O	19.1 %	
% Moisture	55.0 %	
HHV	9180 kJ/kg	

Boiler heat losses with this wood are as follows.

Air temperature	= 20 °C
Flue gas temperature	= 140 °C (Wiltsee, 2000)
O_2 % in flue gas	= 4% (Wiltsee, 2000)
Specific heat of flue gas	= 0.98 kJ/kg/K (EEGIA, 2009)
Enthalpy of vapor at 1 psia and 140 °C	= 2768 kJ/kg
Enthalpy of moisture in liquid state at 20°C	= 83.91 kJ/kg

<u>Theoretical air for combustion in boiler</u>

$$\underset{12}{C} + \underset{32}{O_2} = \underset{44}{CO_2}$$

12 kg carbon needs 32 kg oxygen for complete combustion.

Oxygen required for 0.23 kg carbon = <u>32/12 X 0.23</u> kg

$$\underset{4}{2H_2} + \underset{32}{O_2} = \underset{36}{2H_2O}$$

4 kg hydrogen needs 32 kg oxygen for complete combustion

Therefore oxygen required for 0.028 kg hydrogen = <u>32/4 X 0.028</u> kg

As fuel contains 0.191 kg oxygen already, the net oxygen required will be

= 32/12 X 0.23 + 32/4 X 0.028-0.191 = <u>0.64 kg</u>

Theoretical air required = 0.64 x 100 / 23
(O_2 is 23% of air by wt) = 2.8 kg per kg of wood burnt

For the complete combustion of fuel, more than theoretical air is required air to be supplied, which can be calculated as follows.

Excess air = 100 x O_2 % in flue gas / (21 – O_2 % in flue gas) (EEGIA, 2009)

= 100 x 4 / (21 – 4) = 23.5 %

Therefore, total dry flue gas = 2.8 + 2.8 x 23.5/100

= <u>3.5 kg per kg of wood burnt</u>

Heat losses of boiler as ASME PTC 4.1

1. Dry flue gas loss

= dry flue gas per kg of fuel x sp. heat of flue gas x (flue gas temperature – air temperature)

= 3.5 x 0.98 x (140-20) = <u>402 kJ/kg of fuel burnt</u>

2. Heat loss due to moisture in fuel

= moisture per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

= 0.55 x (2768 – 83.91) = 1476 kJ per kg of fuel burnt

3. Heat loss due to H_2O from combustion of H_2

= 9 x hydrogen per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

= 9 x 0.028 x (2768 – 83.91)

= 678 kJ/kg of fuel burnt

Total heat loss in boiler = 402 + 1476 + 678

= 2556 kJ/kg per kg of fuel burnt

Wood based plant net heat rate = 14685 kJ/kWh

Wood HHV on wet basis = 9180 kJ/kg

Wood required for 1 kWh generation = 14685/9180 = 1.6 kg

Heat lost in boiler for 1 kWh generation = 1.6 x 2556 = 4090 kJ/kWh

Heat used by the rest of system of power plant = 14685 – 4090 = 10595 kJ/kWh

In this study, it is considered that 10595 kJ kWh^{-1} is used by the rest of process (other than boiler) to produce 1 kWh in any power plant and this much amount of heat does not change with the type of biomass that is being fed to the boiler.

D-1-2. Net heat rate and dry biomass requirement of corn stover based power plant

Gross generation = 54.0 MW

Net generation = 50.0 MW

Corn stover based plant will use the corn stover of following properties.

% C	39.9 %	Source: (Aden et al., 2002; Gupta et al., 2003; Parikh et al., 2007)
% H	4.6 %	
% O	33.0 %	
% Moisture	15.0 %	
HHV	15431 kJ/kg	

Boiler heat losses with this corn stover are as follows.

Air temperature = 20 °C

Flue gas temperature = 140 °C (Wiltsee, 2000)

O_2 % in flue gas = 4% (Wiltsee, 2000)

Specific heat of flue gas = 0.98 kJ/kg/K (EEGIA, 2009)

Enthalpy of vapor at 1 psia and 140 °C = 2768 kJ/kg

Enthalpy of moisture in liquid state at 20°C = 83.91 kJ/kg

<u>Theoretical air for combustion in boiler</u>

$C + O_2 = CO_2$

12 32 44

12 kg carbon needs 32 kg oxygen for complete combustion.

Oxygen required for 0.399 kg carbon = 32/12 X 0.399 kg

$$2H_2 + O_2 = 2H_2O$$
$$4 \quad 32 \quad 36$$

4 kg hydrogen needs 32 kg oxygen for complete combustion

Therefore oxygen required for 0.046 kg hydrogen = 32/4 X 0.046 kg

As fuel contains 0.33 kg oxygen already, the net oxygen required will be

= 32/12 X 0.399 + 32/4 X 0.046-0.33 = 1.1 kg

Theoretical air required = 1.1 x 100 / 23 = 4.69 kg per kg of corn stover
(O_2 is 23% of air by wt)

For the complete combustion of fuel, more than theoretical air is required air to be supplied, which can be calculated as follows.

Excess air = 100 x O_2 % in flue gas / (21 – O_2 % in flue gas)

(EEGIA, 2009)

= 100 x 4 / (21 – 4) = 23.5 %

Therefore, total dry flue gas = 4.69 + 4.69 x 23.5/100

= 5.9 kg per kg of wood burnt

Heat losses of boiler as ASME PTC 4.1

1. Dry flue gas loss

= dry flue gas per kg of fuel x sp. heat of flue gas x (flue gas temperature – air temperature)

= 5.9 x 0.98 x (140-20) = 683 kJ/kg of fuel burnt

2. Heat loss due to moisture in fuel

= moisture per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

= 0.15 x (2768 – 83.91) = 403 kJ per kg of fuel burnt

3. Heat loss due to H_2O from combustion of H_2

= 9 x hydrogen per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

= 9 x 0.046 x (2768 – 83.91)

= 1111 kJ/kg of fuel burnt

Total heat loss in boiler = 683 + 403 + 1111 = 2197 kJ/kg per kg of fuel burnt

HHV of corn stover = 15431 kJ/kg

Heat available to rest of the plant after boiler = 15431 -2197 =13234 kJ/kg

Heat utilized by rest of the plant = 10595 kJ/kWh

Biomass required for the plant = 10595/13234 = 0.80 kg/kWh

Net heat rate of corn stover power plant = 0.80 x 15431 = 12354 kJ/kWh

Dry corn stover required = 0.80 x 15/100 = 0.68 kg/kWh

D-1-3. Net heat rate and dry biomass requirement of wheat straw based power plant

Gross generation	= 54.0 MW
Net generation	= 50.0 MW

wheat straw based plant will use wheat straw of following properties on wet basis.

% C	37.3 %	Source: (EERE, 2009)
% H	4.5 %	
% O	33.0 %	
% Moisture	15.0 %	
HHV	15818 kJ/kg	

Boiler heat losses with this switchgrass will be as follows.

Air temperature	= 20 °C
Flue gas temperature	= 140 °C (Wiltsee, 2000)
O_2 % in flue gas	= 4% (Wiltsee, 2000)
Specific heat of flue gas	= 0.98 kJ/kg/K (EEGIA, 2009)
Enthalpy of vapor at 1 psia and 140 °C	= 2768 kJ/kg
Enthalpy of moisture in liquid state at 20°C	= 83.91 kJ/kg

Theoretical air for combustion in boiler

$C + O_2 = CO_2$
12 32 44
12 kg carbon needs 32 kg oxygen for complete combustion.

Oxygen required for 0.373 kg carbon = 32/12 X 0.373 kg

$2H_2 + O_2 = 2H_2O$
4 32 36

4 kg hydrogen needs 32 kg oxygen for complete combustion

Therefore oxygen required for 0.045 kg hydrogen = 32/4 X 0.045 kg

As fuel contains 0.33 kg oxygen already, the net oxygen required will be

= 32/12 X 0.373 + 32/4 X 0.045-0.33 = 1.02 kg

Theoretical air required (O_2 is 23% of air by wt) = 1.07 x 100 / 23 = 4.46 kg per kg of wheat straw

For the complete combustion of fuel, more than theoretical air is required air to be supplied, which can be calculated as follows.

Excess air = 100 x O_2 % in flue gas / (21 – O_2 % in flue gas)

(EEGIA, 2009)

= 100 x 4 / (21 – 4) = 23.5 %

Therefore, total dry flue gas = 4.46 + 4.46 x 23.5/100

= 5.5 kg per kg of wheat straw burnt

Heat losses of boiler as ASME PTC 4.1

1. Dry flue gas loss

   = dry flue gas per kg of fuel x sp. heat of flue gas x (flue gas temperature – air temperature)

   = 5.5 x 0.98 x (140-20) = 636 kJ/kg of fuel burnt

2. Heat loss due to moisture in fuel

   = moisture per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

   = 0.15 x (2768 – 83.91) = 403 kJ per kg of fuel burnt

3. Heat loss due to H_2O from combustion of H_2

   = 9 x hydrogen per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

   = 9 x 0.045 x (2768 – 83.91)

   = 1088 kJ/kg of fuel burnt

Total heat loss in wheat straw based boiler = 636 + 403 + 1088

= 2127 kJ/kg per kg of fuel burnt

HHV of wheat straw = 14809 kJ/kg

Heat available to rest of the plant after boiler = 14809 -2127 =12682 kJ/kg

Heat utilized by rest of the plant = 10595 kJ/kWh

Wheat straw required for the plant = 10595/12682 = 0.84 kg/kWh

Net heat rate of wheat straw power plant = 0.84 x 14809 = 12373 kJ/kWh

Dry wheat straw required = 0.84 x 15/100 = 0.71 kg/kWh

D-1-4. Net heat rate and dry biomass requirement of switchgrass based power plant

Gross generation = 54.0 MW

Switchgrass based plant will use switchgrass of following properties on wet basis.

% C	40.0 %	Source: (Larson et al., 2005)
% H	4.5 %	
% O	35.2 %	
% Moisture	15.0 %	
HHV	15818 kJ/kg	

Boiler heat losses with this switchgrass are as follows.

Air temperature = 20 °C

Flue gas temperature = 140 °C (Wiltsee, 2000)

O_2 % in flue gas = 4% (Wiltsee, 2000)

Specific heat of flue gas = 0.98 kJ/kg/K (EEGIA, 2009)

Enthalpy of vapor at 1 psia and 140 °C = 2768 kJ/kg

Enthalpy of moisture in liquid state at 20°C = 83.91 kJ/kg

<u>Theoretical air for combustion in boiler</u>

$C + O_2 = CO_2$
12 32 44
12 kg carbon needs 32 kg oxygen for complete combustion.

Oxygen required for 0.40 kg carbon = 32/12 X 0.40 kg

$2H_2 + O_2 = 2H_2O$
4 32 36

4 kg hydrogen needs 32 kg oxygen for complete combustion

Therefore oxygen required for 0.045 kg hydrogen = 32/4 X 0.045 kg

As fuel contains 0.352 kg oxygen already, the net oxygen required will be

= 32/12 X 0.40 + 32/4 X 0.045-0.352

= 1.07 kg

Theoretical air required = 1.07 x 100 / 23
(O_2 is 23% of air by wt) = 4.67 kg per kg of switchgrass

For the complete combustion of fuel, more than theoretical air is required air to be supplied, which can be calculated as follows.

Excess air = 100 x O_2 % in flue gas / (21 – O_2 % in flue gas) (EEGIA, 2009)

= 100 x 4 / (21 – 4) = 23.5 %

Therefore, total dry flue gas = 4.67 + 4.67 x 23.5/100

= 5.8 kg per kg of switchgrass burnt

Heat losses of boiler as ASME PTC 4.1

4. Dry flue gas loss

   = dry flue gas per kg of fuel x sp. heat of flue gas x (flue gas temperature – air temperature)

   = 5.8 x 0.98 x (140-20) = 667 kJ/kg of fuel burnt

5. Heat loss due to moisture in fuel

   = moisture per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

   = 0.15 x (2768 – 83.91) = 403 kJ per kg of fuel burnt

6. Heat loss due to H_2O from combustion of H_2

   = 9 x hydrogen per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

   = 9 x 0.045 x (2768 – 83.91)

   = 1088 kJ/kg of fuel burnt

Total heat loss in boiler = 667 + 403 + 1088 = 2157 kJ/kg per kg of fuel burnt

HHV of switchgrass = 15818 kJ/kg

Heat available to rest of the plant after boiler = 15818 -2157 =13661 kJ/kg

Heat utilized by rest of the plant = 10595 kJ/kWh

Switchgrass required for the plant = 10595/13661 = 0.78 kg/kWh

Net heat rate of switchgrass power plant = 0.78 x 15818 = 12269 kJ/kWh

Dry switchgrass required = 0.78 x 15/100 = 0.66 kg/kWh

D-1-5. Net heat rate and dry biomass requirement of corn stover derived bio-oil based power plant

Cornstover derived bio-oil based plant uses bio-oil of following properties on wet basis.

% C	44.4%	Source: (Agblevor et al., 1996)
% H	5.3 %	
% O	28.5 %	
% Moisture	20.6 %	
HHV	18712 kJ/kg	

Boiler heat losses with this corn stover derived bio-oil are as follows.

Air temperature = 20 °C

Flue gas temperature = 140 °C (Wiltsee, 2000)

O_2 % in flue gas = 4% (Wiltsee, 2000)

Specific heat of flue gas = 0.98 kJ/kg/K (EEGIA, 2009)

Enthalpy of vapor at 1 psia and 140 °C = 2768 kJ/kg

Enthalpy of moisture in liquid state at 20°C = 83.91 kJ/kg

Theoretical air for combustion in boiler

$$C + O_2 = CO_2$$
12 32 44

12 kg carbon needs 32 kg oxygen for complete combustion.

Oxygen required for 0.44 kg carbon = 32/12 X 0.44 kg

$$2H_2 + O_2 = 2H_2O$$
4 32 36

4 kg hydrogen needs 32 kg oxygen for complete combustion

Therefore oxygen required for 0.053 kg hydrogen = 32/4 X 0.053 kg

As fuel contains 0.285 kg oxygen already, the net oxygen required will be

= 32/12 X 0.44 + 32/4 X 0.053-0.285 = 1.31 kg

Theoretical air required = 1.31 x 100 / 23 = 5.71 kg per kg of oil burnt
(O_2 is 23% of air by wt)

For the complete combustion of fuel, more than theoretical air is required air to be supplied, which can be calculated as follows.

Excess air = 100 x O_2 % in flue gas / (21 – O_2 % in flue gas) (EEGIA, 2009)

= 100 x 4 / (21 – 4) = 23.5 %

Therefore, total dry flue gas = 5.71 + 5.71 x 23.5/100

= 7.0 kg per kg of oil burnt

Heat losses of boiler as ASME PTC 4.1

1. Dry flue gas loss

   = dry flue gas per kg of fuel x sp. heat of flue gas x (flue gas temperature – air temperature)

   = 7.0 x 0.98 x (140-20) = 821 kJ/kg of fuel burnt

2. Heat loss due to moisture in fuel

   = moisture per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

   = 0.206 x (2768 – 83.91) = 553 kJ per kg of fuel burnt

3. Heat loss due to H_2O from combustion of H_2

   = 9 x hydrogen per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

   = 9 x 0.053 x (2768 – 83.91)

   = 1285 kJ/kg of fuel burnt

Total heat loss in boiler = 821 + 553 + 1285 = 2659 kJ/kg per kg of fuel burnt

HHV of corn stover derived bio-oil = 18712 kJ/kg

Heat available to rest of the plant after boiler = 18712 -2659 =16052 kJ/kg

Heat utilized by rest of the plant = 10595 kJ/kWh

Bio-oil required for the plant = 10595/16052 = 0.66 kg/kWh

Net heat rate of corn stover derived bio-oil based power plant

= 0.66 x 18711 = 12351 kJ/kWh

Moisture free bio-oil required = 0.66 x 20.6/100 = 0.52 kg/kWh

D-1-6. Net heat rate and dry biomass requirement of switchgrass derived bio-oil based power plant

Switchgrass derived bio-oil based plant uses bio-oil of following properties on wet basis.

% C	44.4%	Source: (Agblevor et al., 1996; Larson et al., 2005)
% H	5.5 %	
% O	29.5 %	
% Moisture	20.0 %	
HHV	19120 kJ/kg	

Boiler heat losses with this corn stover derived bio-oil will be as follows.

Air temperature = 20 °C

Flue gas temperature = 140 °C (Wiltsee, 2000)

O_2 % in flue gas = 4% (Wiltsee, 2000)

Specific heat of flue gas = 0.98 kJ/kg/K (EEGIA, 2009)

Enthalpy of vapor at 1 psia and 140 °C = 2768 kJ/kg

Enthalpy of moisture in liquid state at 20°C = 83.91 kJ/kg

Theoretical air for combustion in boiler

$C + O_2 = CO_2$
12 32 44
12 kg carbon needs 32 kg oxygen for complete combustion.

Oxygen required for 0.44 kg carbon = 32/12 X 0.44 kg

$2H_2 + O_2 = 2H_2O$
4 32 36

4 kg hydrogen needs 32 kg oxygen for complete combustion

Therefore oxygen required for 0.055 kg hydrogen = 32/4 X 0.055 kg

As fuel contains 0.295 kg oxygen already, the net oxygen required will be

= 32/12 X 0.44 + 32/4 X 0.055-0.295 = 1.31 kg

Theoretical air required = 1.31 x 100 / 23 = 5.71 kg per kg of oil burnt
(O_2 is 23% of air by wt)

For the complete combustion of fuel, more than theoretical air is required air to be supplied, which can be calculated as follows.

Excess air = 100 x O_2 % in flue gas / (21 – O_2 % in flue gas)
(EEGIA, 2009)

= 100 x 4 / (21 – 4) = 23.5 %

Therefore, total dry flue gas = 5.71 + 5.71 x 23.5/100

= 7.1 kg per kg of oil burnt

Heat losses of boiler as ASME PTC 4.1

1. Dry flue gas loss

   = dry flue gas per kg of fuel x sp. heat of flue gas x (flue gas temperature – air temperature)

   = 7.1 x 0.98 x (140-20) = 819 kJ/kg of fuel burnt

2. Heat loss due to moisture in fuel

   = moisture per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

   = 0.20 x (2768 – 83.91) = 537 kJ per kg of fuel burnt

3. Heat loss due to H_2O from combustion of H_2

   = 9 x hydrogen per kg of fuel x (enthalpy of vapor at 1 psia and flue gas temperature – enthalpy of liquid at air temperature)

   = 9 x 0.055 x (2768 – 83.91)

   = 1324 kJ/kg of fuel burnt

Total heat loss in boiler = 819 + 537 + 1324 = 2678 kJ/kg per kg of fuel burnt

HHV of corn stover derived bio-oil = 19120 kJ/kg

Heat available to rest of the plant after boiler = 19120 -2678 =16440 kJ/kg

Heat utilized by rest of the plant = 10595 kJ/kWh

Bio-oil required for the plant = 10595/16440 = 0.64 kg/kWh

Net heat rate of corn stover derived bio-oil based power plant

= 0.64 x 19120 = 12322 kJ/kWh

Moisture free bio-oil required = 0.64 x 20.0/100 = 0.52 kg/kWh

Appendix E

Water Requirement of Biomass Power Plant

E-1. Make up water requirement in a power plant

Water requirement of the biomass is independent of the biomass or any other fuel fired in the boiler. In this study, Mc Neil plant (Wiltsee, 2000) is considered as base model to estimate make up water requirement.

E-1-1. Cooling water requirement and evaporation loss in power plant

The parameters of Mc Neil power plant are as follows.

Maximum net generation	= 54.0 MW	
Steam flow to turbine at 54.0 MW generation	= 217440 kg/hr	
Cooling water required to condense steam	= 9538200 kg/hr	(Wiltsee, 2000)
Cooling water required to produce 1 kWh	= 953200 / 54000	
	= 176.6 liters	

In a power plant, there is always water required for auxiliaries such as for air compressors, oil coolers and total cooling water required for these auxiliaries cooling is 10 % of condenser cooling water flow (Chapman, 1996).

Cooling water required for auxiliaries equipment = 10/100 x 9538200 =953820 kg/hr

Total cooling water required for power plant = 9538200 + 953820 = 10492020 kg/hr

Total cooling water required to produce 1 kWh = 194.3 liters

The cooling water is cooled down in cooling tower and a part of cooling water is evaporated in cooling tower to cool remaining cooling water and it depends upon cooling tower range, cooling water flow rate (Perry et al., 1999).

Temperature range across cooling tower = 8.8 °C (Wiltsee, 2000)

Water lost in evaporation during cooling of water = 0.00085 x temperature range across cooling tower x 1.8 x flow rate

Source : (Perry et al., 1999)

= 0.00085 x 8.8 x 1.8 x 10492020

= 140520 kg/hr

Water lost in cooling tower to produce 1 kWh = 140520/54000 = 2.60 liters

E-1-2. Make up water requirement of steam and service water systems of power plant

Water is lost in a power plant from steam and feed water cycle at 1.5% of steam flow (Chapman, 1996).

Water lost in steam and feed water cycle

= 1.5 % of steam flow = 1.5/100 x 217440 = 3262 kg/hr

Water lost in steam and feed water cycle to produce 1 kWh = 3262/54000

= 0.06 liters

Water is also lost form service system and make up water is required at 1% of steam flow (Chapman, 1996).

Water lost in service water system = 1 % of steam flow (Chapman, 1996)

= 1.0/100 x 217440 = 2174 kg/hr

Water lost in service water system to produce 1 kWh = 2174 / 54000 = 0.04 liters

E-1-3. Total make up water requirement of a power plant

In addition to abovementioned water losses, water is also lost in a power plant as cooling tower blow but this water is returned back to the reservoir from where make up water is taken. In this study, only consumptive use of water is considered. That is why; make up water corresponding to blow down loss is not considered.

Total make up water requirement = 140520 + 3262 + 2174

= 145956 kg/hr

Make up water required to produce1 kWh electricity

= 145956 / 54000

= 2.70 liters/kWh

Appendix F

Bio-oil and Electricity Production in Pyrolysis Plant Integrated with Power Plant

F-1. Pyrolysis plant integrated with power plant

The pyrolysis process is a thermo-chemical process. The products of this process are bio-oil, charcoal and non condensable gases and products' yields differ for different biomass feedstocks depending upon their chemical properties. In this study, wood based pyrolysis model of NREL (Ringer et al., 2006) is considered as base model and heat and mass balance of the process is modified in accordance with chemical properties of different biomass feedstocks. The NREL model of wood pyrolysis uses charcoal and non condensable gases to produce heat and power. The heat is used completely by the pyrolysis process itself. The produced power is partially used by the process and remainder is sold as by product. While bio-oil yield depends upon molecular structures of biomass feedstocks, the quantity of electricity generation depends upon yields of charcoal and noncondensable gases. To evaluate electricity generation along with 1 kg of bio-oil production, the NREL model of wood is modified for different feedstocks.

F-2. Mass and energy balance of corn stover based pyrolysis process

The corn stover has different products yield from pyrolysis process, LHV, moisture content, and ash content of feedstock from those of wood, therefore the bio-oil yield and electricity generation is different.

F-2-1. Net heat available for the integrated power plant after bio-oil yield

The lower heating value (LHV) of corn stover is lower than that of wood, as a result of which the heat available for extra power production is lower for corn stover but lower yield of bio-oil in case of corn stover increases the heat availability for power production.

Pyrolysis plant capacity for NREL model = 550000 kg dry biomass feedstock per day

= 22917 kg per hr

LHV of wood	= 19.3 MJ kg^{-1} (Bridgwater et al., 2002)
Bio-oil yield in wood pyrolysis	= 59.9 % (Ringer et al., 2006)
LHV of moisture free bio-oil	= 21.2 MJ kg^{-1} (Bridgwater et al., 2002)
Heat available for rest of process	= 550000 x (19.3 – 21.2 x 0.599)
	= 3630660 MJ per day

LHV of corn stover	= 16.5 MJ kg^{-1} (Morey et al., 2006)
Bio-oil yield in corn stover pyrolysis	= 54.9 % (Agblevor et al., 1996)

LHV of moisture free bio-oil = 21.2 MJ kg^{-1} (Bridgwater et al., 2002)

Heat available for rest of process = 550000 x (16.5 – 21.2 x 0.549)

= 2676575 MJ per day

Less heat available in corn stover pyrolysis process
= 3630660- 2676575
= 954085 MJ per day

F-2-2. Saving in heat and power due to low moisture content of corn stover

The moisture content of corn stover is only 15% compared to 50% of wood. The heating air required to dry feedstock to level of 7% moisture is lower for corn stover. As a result of which, power of air supply fan and heat of process is saved in the case of corn stover.

Pyrolysis plant capacity = 550 dry tonne per day

F-2-2-1. Saving in heat

Wood quantity with 50 % moisture = 1100 tonne per day

Wood quantity with 7 % moisture = 591 tonne per day

Moisture removed in drying = 1100 – 591 = 509 tonne per day

Air required to carry this moisture = 353124 kg/hr

Corn stover quantity with 15 % moisture = 647 tonne per day

Corn stover quantity with 7 % moisture = 591 tonne per day

Moisture removed in drying = 56 tonne per day

Air required to carry this moisture = (353124/509) x 56

	= 38646 kg/hour
Net saving in air flow	= 353124-38646 = 314478 kg/hour
Air temperature before condenser II	= 25 °C
Air temperature after condenser II	= 200 °C
Average specific heat of air	= 1.015 kJ/kg/K
Saving in heat	= 314478 x (200-25) x 1.015
	= 55859213 kJ/ hr
	= 1340621 MJ/day

F-2-2-2. Saving in power

<u>For wood based pyrolysis</u>

Air flow	= 353124 kg/hr
Air enthalpy at inlet of fan	= -36184.40 MJ/hr
Air enthalpy at outlet of fan	= -35824.50 MJ/hr
Energy added by the fan	= 360 MJ/hr
Energy added by the fan per kg of air	= 360 / 353124 = 1.02 kJ/kg
Fan efficiency	= 80 %
Energy required by fan per kg of air	= 1.02/0.80 = 1.27 kJ/kg

<u>For corn stover based pyrolysis</u>

Saving in air flow	= 314478 kg/hr
Saving in energy added to fan	= 314478 x 1.27 = 400.64 MJ/hr
	= 111 kW

F-2-3. Saving in grinding power used for feedstock size reduction

Energy required for size reduction of wood per hour = 1400 kWh

Corn stover required per day = 647 tonne

Energy required for size reduction of corn stover = 20.0 kWh/tonne (Sokhansanj et al., 2006)

Energy required for size reduction of corn stover = 20*647/24 = 539 kWh/hr

Saving in power = 1400 – 539

= 861 kW

F-2-4. Loss of heat due to high ash content

The ash content of feedstock is separated in the pyrolysis along with charcoal and it is removed after combustion of charcoal from cyclone. The temperature of this ash at the time removal is 1796.6 °C. The exiting ash is quenched in the mixer with water to reduce temperature to 60 °C and then ash is separated from water using filter and disposed off. The ash content of corn stover is higher than that of wood. That is why, heat loss is higher along with ash in the corn stover case.

<u>For wood based pyrolysis</u>

Plant capacity = 550 dry tonne per day

= 22.92 dry tonne per hr

Ash content in wood (dry basis) = 0.92 % (Ringer et al., 2006)

Ash quantity processed = 211 kg/hr

Ash temperature before mixer = 1796.6 °C

Ash temperature after mixer = 60 °C

Water quantity required = 3316 kg/hr

Water temperature before mixer = 25°C

Water temperature after mixer = 60°C

Specific heat of water = 4.186 kJ/kg/°C

Heat lost along with ash = 3316 X (60-25) X 4.186

= 485842 kJ/hr

Specific heat of ash = 485842/(1796.6-60)/211

= 1.327 kJ/kg/°C

As ash entered the pyrolysis system along with feedstock at temperature 25°C, total heat loss with ash will include the heat loss for disposing ash at 60°C.

Total heat loss = 211 X (1796.6-25) X 1.327

= 495634 kJ/hr

<u>For corn stover based pyrolysis</u>

Ash content in corn stover (% dry basis) = 7.7 % (Parikh et al., 2007)

Ash quantity processed = 22.92 x 1000 x (7.7/100)

= 1765 kg/hr

Total heat loss = 1765 x (1796.6-25) x 1.327

= 4066285 kJ/hr

Extra heat loss in corn stover pyrolysis = 4066285-495634

= 3570651 kJ/hr = 85696 MJ/day

F-2-5. Net power generation in corn stover pyrolysis process

Less net heat available to process due to low LHV = -954085 MJ/day

Saving in heat loss due to low moisture = 1340621 MJ/day

Loss of heat due to high ash content = -85696 MJ/day

Net saving in heat = -954085+1340621-85696

= 300840 MJ/day

Considering power plant efficiency 33 %, this heat saving can be converted into power.

Power equivalent to net heat saving = 1149 kW

Total power generation of wood based pyrolysis plant = 4900 KW

Total power generation of corn stover based pyrolysis plant = 4900 + 1149 = 6049 kW

Net generation of wood based pyrolysis plant = 588 kW

Saved air fan energy in corn stover case = 111 kW

Saved grinding energy in corn stover case = 861 kW

Extra generation in corn stover based pyrolysis plant = 1149 kW

Total net power generation in corn stover case = 588+1149+111+861

= 2709 kW

Biooil production = 380.2 tonne per day

= 15842 kg per hr

Net power generation along with 1 kg bio-oil production = 2709/15842

= 0.17 kWh

F.3 Mass and energy balance of wheat straw based pyrolysis process

The pyrolysis products yields, LHV, moisture content, and ash content of wheat straw are different from those of wood. The amount of electricity generation in a wheat straw based pyrolysis plant along with bio-oil is different from that of wood.

F-3-1. Net heat available for the integrated power plant after bio-oil yield

The lower heating value (LHV) of wheat straw is lower than that of wood, as a result of which the heat available for extra power production is lower for wheat straw but lower yield of bio-oil in case of wheat straw increases the heat availability for power production.

Pyrolysis plant capacity for NREL model = 550000 kg per day

LHV of wheat straw = 16.6 MJ kg^{-1} (Larson et al., 2005; Morey et al., 2006)

Bio-oil yield = 54.0 % (Agblevor et al., 1996; Boateng et al., 2007)

LHV of moisture free bio-oil = 21.2 MJ kg^{-1} (Bridgwater et al., 2002)

Heat available for rest of process = 550000 x (16.6 – 21.2 x 0.54)

= 2828742 MJ per day

Heat available for rest of process in wood based pyrolysis

= 3630660 MJ per day (from section F.1.1)

Less heat available in wheat straw pyrolysis process

= 3630660- 2828742 = 801918 MJ per day

F-3-2. Saving in heat and power due to low moisture content of wheat straw

The moisture content of wheat straw is only 15 % compared to 50 % of wood. The heating air to dry feedstock to level of 7 % moisture is lower for wheat straw. As a result of which, power of air supply fan and heat of process is saved in the case of wheat straw.

In the case of corn stover, moisture level is also reduced from 15 % to 7 % level and 1340621 MJ/day of heat and 111 kW of power are saved compared to wood. Similarly, 1340621 MJ/day of heat and 111 kW of power are saved in the case of wheat straw.

F-3-3. Saving in grinding power used for feedstock size reduction

Energy required for size reduction of wood per hour = 1400 kWh

Wheat straw required per day = 647 tonne

Energy required for size reduction of corn stover = 45.0 kWh/tonne (Sokhansanj et al., 2006)

Energy required for size reduction of corn stover = 45 x 647/24 = 1214 kWh/hr

Saving in power = 1400 – 1214 = 186 kWh/hr

F-3-4. Loss of heat due to high ash content

Similar to corn stover, ash content of wheat straw is higher than that of wood, as a result of which heat loss on account of ash is higher.

<u>For wheat straw based pyrolysis</u>

Ash content in wheat straw (% dry basis) = 10.2 % (Parikh et al., 2007)

Ash quantity processed = feed stock flow x ash %

= 22.92 x 1000 x (10.2/100)

= 2338 kg/hr

Total heat loss = 2338 x (1796.6-25) x 1.327

= 5386507 kJ/hr

Extra heat loss in wheat straw pyrolysis = 5386507-495634

= 4890873 kJ/hr = 117381 MJ/day

F.3.5 Net power generation in wheat straw pyrolysis process

Less net heat available to process due to low LHV = -801918 MJ/day

Saving in heat loss due to low moisture = 1340621 MJ/day

Loss of heat due to high ash content = -117381 MJ/day

Net saving in heat = -801918+1340621-117381

= 421322 MJ/day

Considering power plant efficiency 33 %, this heat saving can be converted into power.

Equivalent power of net heat saving = 1609 kW

Total power generation of wood based pyrolysis plant = 4900 KW

Total power generation of wheat straw based pyrolysis plant= 4900 + 1609 = 6509 kW

Net generation of wood based pyrolysis plant = 588 kW

Saved air fan energy in wheat straw case = 111 kW

Saved grinding energy in corn stover case = 186 kW

Extra generation in wheat straw based pyrolysis plant = 1609 kW

Total net power generation in wheat straw case =588+186+111+1609

= 2495 kW

Biooil production containing 20.0% moisture = 371.6 tonne per day

= 15484 kg per hr

Net power generation with 1 kg bio-oil production = 2495/15484

= 0.16 kWh

F.4 Mass and energy balance of switchgrass based pyrolysis process

As switchgrass has different pyrolysis products yield, LHV of feedstock, moisture content, and ash content from those of wood, the bio-oil yield and electricity generation is different.

F.4.1 Net heat available for the integrated power plant after bio-oil yield

The lower heating value (LHV) of switchgrass is lower than that of wood, as a result of which the heat available for extra power production is lower for switchgrass but lower yield of bio-oil in case of switchgrass increases the heat availability for power production.

Pyrolysis plant capacity for NREL model = 550000 kg per day

LHV of switchgrass = 17.5 MJ kg^{-1} (Larson et al., 2005)

Bio-oil yield in switchgrass pyrolysis = 54.0 % (Boateng et al., 2007)

LHV of moisture free bio-oil = 21.2 MJ kg^{-1} (Bridgwater et al., 2002)

Heat available for rest of process = 550000 x (17.5 – 21.2 x 0.54)

= 3323742 MJ per day

Heat available for rest of process in wood based pyrolysis

= 3630660 MJ per day (from section F.1.1)

Less heat available in switchgrass pyrolysis process

= 3630660- 3323742 = 306918 MJ per day

F.4.2 Saving in heat and power due to low moisture content of switchgrass

The moisture content of switchgrass is only 15 % (Larson et al., 2005) compared to 50 % of wood. The heating air required to dry feedstock to level of 7 % moisture is lower for switchgrass. As a result, power of air supply fan power and heat of process is saved.

In the case of corn stover, moisture level was reduced from 15 % to 7 % level and 1340621 MJ/day heat and 111 kW power saved. Similarly, 1340621 MJ/day heat and 111 kW power are saved in the switchgrass case.

F.4.3. High grinding power requirement for feedstock size reduction

Energy required for size reduction of wood per hour = 1400 kWh

Wheat straw required per day = 647 tonne

Energy required for size reduction of switchgrass = 55.2 kWh/tonne (Sokhansanj et al., 2006)

Energy required for size reduction of switchgrass = 55.2 x 647/24 = 1488 kWh/hr

More power requirement for switchgrass = 1488 – 1400 = 88 kWh/hr

F.4.4 Loss of heat due to high ash content

Similar to corn stover, ash content of switchgrass is higher than that of wood, as a result of which heat loss on account of ash would be higher.

For switchgrass based pyrolysis

Ash content in switchgrass (% dry basis)	= 5.7 % (Agblevor et al., 1996)
Ash quantity processed	= feed stock flow x ash %
	= 22.92 x 1000 x (5.7/100)
	= 1306 kg/hr
Total heat loss	= 1306 x (1796.6-25) x 1.327
	= 3010107 kJ/hr
Extra heat loss in switchgrass pyrolysis	= 3010107-495634
	= 2514473 kJ/hr = 60347 MJ/day

F.4.5 Net power generation in switchgrass pyrolysis process

Less net heat available to process due to low LHV	= -306918 MJ/day
Saving in heat loss due to low moisture	= 1340621 MJ/day
Loss of heat due to high ash content	= -60347 MJ/day
Net saving in heat	= -306918+1340621-60347

= 973355 MJ/day

Considering power plant efficiency 33 %, this heat saving can be converted into power.

Equivalent power of net heat saving	= 3718 kW
Total power generation of wood based pyrolysis plant	= 4900 KW
Total power generation of switchgrass based pyrolysis plant	= 4900 + 3718
	= 8618 kW
Net generation of wood based pyrolysis plant	= 588 kW
Saved air fan energy in switchgrass case	= 111 kW
High grinding energy in switchgrass case	= -88 kW
Extra generation in switchgrass based pyrolysis plant	= 3718 kW
Total net power generation in switchgrass case	= 588-88+111+3718
	= 4328 kW
Biooil production containing 20.0% moisture	= 371.6 tonne per day
	= 15484 kg per hr
Net power generation with 1 kg bio-oil production	= 4328/15484
	= 0.28 kWh

Appendix G

Water Requirement for Pyrolysis Process

G.1 Water requirement for wood based pyrolysis process

<u>Bio-oil production</u>

Dry feedstock quantity required	= 550 tonne per day
Bio-oil yield on dry basis	= 59.9 %
Water content in bio-oil	= 23.6 %
Total bio-oil production	= 550 x (59.9/100) x (100 /
(100-23.6))	= 431.2 tonne per day
	= 17967 kg/hr

<u>Water requirement</u>

Power generation	= 4900 kW
Steam flow	= 15577 kg/hr
Water lost from the steam system	
at @ 3 % ((Ringer et al., 2006) of steam flow	= <u>467.3 liters/hr</u>
	<u>= 0.03 liters/kg of bio-oil</u>
Ash quantity disposing off	= 211 kg/hr
Quenching of ash and water lost with ash	= <u>331.6 liters/hr</u>
	= 0.02 liters/kg of bio-oil
Cooling water for product cooling	= 14805 liters/hr

Cooling water for scrubbing to recover bio-oil = 64198 liters/hr

Cooling water for steam condensing = 585107 liters/hr

Total cooling water flow rate = 664110 liters/hr

Cooling water range across cooling tower = 8 °C

Water lost in evaporation during cooling of water = 0.00085 x temperature range across cooling tower x 1.8 x flow rate Source : (Perry et al., 1999)

=0.00085 x 8 x 1.8 x 664110

=<u>10160.9 liters/hr</u>

= 0.56 liters/kg of bio-oil

Total water lost in the process = 467.3 + 331.6 + 10160.9

= 10959.8 liters/hr

Water lost per kg of bio-oil production =10959.8/17967 = <u>0.61 liters/kg</u>

G.2 Water requirement for corn stover based pyrolysis process

<u>Bio-oil production</u>

Dry feedstock quantity required = 550 tonne per day

Bio-oil yield on dry basis = 54.9 % (Agblevor et al., 1996)

Water content in bio-oil = 20.6 % (Agblevor et al., 1996)

Total bio-oil production = 550 x (54.9/100) x (100 / (100-20.6))

= 380.2 tonne per day = 15842 kg/hr

Water requirement

Power generation = 6049 kW

Steam flow = 15577 x 6049/4900 = 19230 kg/hr

Water lost from the steam system

at @ 3 % ((Ringer et al., 2006) of steam flow = 577 liters/hr

= 0.04 liters/kg of bio-oil

Ash quantity disposing off = 1765 kg/hr

Quenching of ash and water lost with ash = 331.6 / 211 x 1765

= 2774 liters/hr

= 0.18 liters/kg of bio-oil

Cooling water for product cooling = 14805 / 17967 x 15842

= 13053 liters/hr

Cooling water for scrubbing to recover bio-oil = 64198 / 17967 x 15842

= 56602 liters/hr

Cooling water for steam condensing = 585107/4900 x 6049

= 722314 liters/hr

Total cooling water flow rate = 791969 liters/hr

Cooling water inlet outlet temperature difference = 8 °C

Water lost in evaporation during cooling of water = 0.00085 x temp diff x 1.8 x flow rate Source : (Perry et al., 1999)

=0.00085 x 8 x 1.8 x 664110

=11051 liters/hr

= 0.76 liters/kg of bio-oil

Total water lost in the process = 577 + 2774 + 11051

= 12117 liters/hr

Water lost per kg of bio-oil production =12117/15842

= 0.98 liters/kg of bio-oil

G.3 Water requirement for wheat straw based pyrolysis process

Bio-oil production

Dry feedstock quantity required = 550 tonne per day

Bio-oil yield on dry basis = 54.0 %
(Agblevor et al., 1996; Boateng et al., 2007)

Water content in bio-oil = 20.0 % (Agblevor et al., 1996)

Total bio-oil production = 550 x (54.0/100) x (100 / (100-20.0)) = 371.6 tonne per day

= 15484 kg/hr

Water requirement

Power generation = 6509 kW

Steam flow	= 15577 x 6509/4900
	= 20693 kg/hr
Water lost from the steam system	
at @ 3 % ((Ringer et al., 2006) of steam flow	= 621 liters/hr
	= 0.04 liters/kg of bio-oil
Ash quantity disposing off	= 2338 kg/hr
Quenching of ash and water lost with ash	= 331.6 / 211 x 2338
	= 3674 liters/hr
	= 0.24 liters/kg of bio-oil
Cooling water for product cooling	= 14805 / 17967 x 15484
	= 12759 liters/hr
Cooling water for scrubbing to recover bio-oil	= 64198 / 17967 x 15484
	= 55326 liters/hr
Cooling water for steam condensing	= 585107/4900 x 6509
	= 777263 liters/hr
Total cooling water flow rate	= 845348 liters/hr
Cooling water inlet outlet temperature difference	= 8 °C
Water lost in evaporation during cooling of water	= 0.00085 x temp diff x 1.8 x flow rate Source : (Perry et al., 1999)
	=0.00085 x 8 x 1.8 x 845348
	=12934 liters/hr
	= 0.84 liters/kg of bio-oil

Total water lost in the process = 621 + 3674 + 12934

= 17228 liters/hr

Water lost per kg of bio-oil production =17228/15484

= 1.11 liters/kg of bio-oil

G.4 Water requirement for switchgrass based pyrolysis process

Bio-oil production

Dry feedstock quantity required = 550 tonne per day

Bio-oil yield on dry basis = 54.0 % (Boateng et al., 2007)

Water content in bio-oil = 20.0 % (Boateng et al., 2007)

Total bio-oil production = 550 x (54.0/100) x (100 / (100-20.0)) = 371.6 tonne per day

= 15484 kg/hr

Water requirement

Power generation = 8618 kW

Steam flow = 15577 x 8618/4900 = 20693 kg/hr

Water lost from the steam system

at @ 3 % ((Ringer et al., 2006) of steam flow = 822 liters/hr

= 0.05 liters/kg of bio-oil

Ash quantity disposing off	= 1306 kg/hr
Quenching of ash and water lost with ash	= 331.6 / 211 x 1306
	= 2053 liters/hr
	= 0.13 liters/kg of bio-oil
Cooling water for product cooling	= 14805 / 17967 x 15484
	= 12759 liters/hr
Cooling water for scrubbing to recover bio-oil	= 64198 / 17967 x 15484
	= 55326 liters/hr
Cooling water for steam condensing	= 585107/4900 x 8618
	= 1029033 liters/hr
Total cooling water flow rate	= 1097118 liters/hr
Cooling water inlet outlet temperature difference	= 8 °C
Water lost in evaporation during cooling of water	= 0.00085 x temp diff x 1.8 x flow rate Source : (Perry et al., 1999)
	=0.00085 x 8 x 1.8 x 1097118
	=16786 liters/hr
	= 1.08 liters/kg of bio-oil
Total water lost in the process	= 822 + 2053 + 16786
	= 19661 liters/hr

Water lost per kg of bio-oil production =19661/15484 = 1.27 liters/kg of bio-oil

Appendix H

Crop, Land and Water Requirement for Production of Biofuels in Alberta

H-1. Crop, land and water requirement for biofuels production in Alberta (Scenario # 1)

In this scenario, it is assumed that ethanol production in Alberta would be based on wheat and wheat straw and biodiesel production would be based on canola seed. The quantity of ethanol production from wheat and wheat straw and biodiesel production from canola seed are shown in table A1.

To calculate the biomass feedstock requirement for ethanol and biodiesel production, 3.61 kg of wheat per kg of ethanol, 3.90 kg of wheat straw per kg of ethanol, 2.53 kg of canola seed per kg of ethanol are considered (yields are taken from Chapter 2).

In this study, it is assumed that current level of wheat and canola seed production will be used for food only and the required quantity of these feedstocks for biofuels production will be grown separately. The wheat straw requirement in 2025 is 4979 million kg which is lower than current level of wheat straw production (5490 million kg), therefore, it is considered that current production level of wheat straw is able to meet the cellulosic ethanol demand in 2025.

On the basis of last 8 years average crop yields 2738 kg per hectare (CANSIM, 2009) for wheat and 1763 kg per hectare (CANSIM, 2009) for canola seed in Alberta, the arable land requirement for both feedstocks are calculated.

The river basin with the lowest irrigation requirement is given priority to grow the crops. On this basis, Athabasca river basin land selected first to grow crops, thereafter, North Saskatchewan. The available arable land in these two river basins is sufficient to meet the biofuels requirement in 2025.

In Athabasca region, irrigation requirement is 40 mm and 50 mm for wheat and canola seed respectively (Wright, 2007a; Wright, 2007b). In North Saskatchewan River basin, the irrigation requirement is 50 mm and 60 mm for wheat and canola seed respectively (Wright, 2007a; Wright, 2007b).

This irrigation water is applied with irrigation efficiency (71%) and transferred from river to fields with seepage losses (2.5%) and evaporation losses (4%) in Alberta (AIPA, 2006). Thus, total water withdrawn from the river is crop water requirement plus losses.

Table H-1: Crop, land and water requirement for biofuels production in Alberta

Resource requirement		2005	2010	2015	2020	2025
Bio-fuels demand (million liters)	Ethanol from wheat	0	526	769	769	769
	Ethanol from straw	0	0	149	444	583
	Biodiesel	0	128	183	240	270
Crops requirement (million kg)	Wheat	0	1499	2190	2190	2190
	Wheat straw	0	0	1269	3799	4979
	Canola seed	0	274	392	517	581
Land requirement by crop (km^2)	Wheat	0	5475	7998	7998	7998
	Canola seed	0	1556	2227	2933	3298
Land requirement by river (km^2)	Athabasca	0	5631	5631	5631	5631
	North Saskatchewan		1400	4594	5300	5665
Agricultural water requirement (dam^3)	Athabasca	0	339294	339294	339294	339294
	North Saskatchewan	0	126546	415205	479023	511984
Industrial water requirement by feedstock (dam^3)	Ethanol from wheat	0	2558	3727	3737	3737
	Ethanol from straw	0	0	921	2756	3613
	Biodiesel	0	93	133	176	198
Industrial water requirement by river basin (dam^3)	Athabasca	0	2123	2131	2015	1961
	North Saskatchewan	0	528	1739	1897	1973
	South Saskatchewan	0	0	460	1378	1806
	Red Deer	0	0	460	1378	1806

The conversion stage water requirement for all three pathways is considered as industrial water requirement. Water requirement for 1 liter production of ethanol from wheat and wheat straw in conversion stages are 4.9 liters and 6.2 liters respectively (as explained in chapter 2). Water requirement for 1 liter of biodiesel from canola seed is 0.7. Thus, total conversion water requirement calculated and divided between the Athabasca and North Saskatchewan River basins in the ratio of land requirement for biofuels production. As cellulosic ethanol production mainly would be in central region of Alberta, water requirement of cellulosic ethanol production stage is equally divided between South Saskatchewan and Red Deer river basins.

H.2 Crop, land and water requirement for biofuels production in Alberta (Scenario # 2)

Table H-2: Crop, land and water requirement for bio-fuels production in Alberta

Resource requirement		2005	2010	2015	2020	2025
Bio-fuels demand (million liters)	Ethanol	0	526	917	1213	1351
	Biodiesel	0	43	62	82	92
Crops production (million kg)	Wheat	0	1499	2613	3456	3849
	Canola seed	0	274	392	517	581
Land requirement by crop (km^2)	Wheat	0	5475	9543	12622	14058
	Canola seed	0	1556	2227	2933	3298
Land requirement by river basin (km^2)	Athabasca	0	5631	5631	5631	5631
	North Saskatchewan	0	1400	6139	8942	8942
	Peace	0	0	0	982	2783
Agricultural water requirement (dam^3)	Athabasca	0	339294	339294	339294	339294
	North Saskatchewan	0	126546	554831	808195	808195
	Peace	0	0	0	133113	377291
Industrial water requirement by feedstock (dam^3)	Wheat	0	2558	4458	5897	6568
	Canola seed	0	93	133	176	198
Industrial water requirement by river basin (dam^3)	Athabasca	0	2123	2197	2198	2195
	North Saskatchewan	0	528	2395	3491	3486
	Peace	0	0	0	383	1085

In this scenario, it is assumed that cellulosic ethanol plant will not be fully developed and ethanol will be produced using wheat only till 2025 in Alberta. The biodiesel will be produced using canola seed. The wheat and canola seed requirement are calculated to produce ethanol and biodiesel, respectively using yield of the respective process as discussed in scenario # 1.

The total land requirement is calculated to produce wheat and canola seed using respective crop yields as discussed in scenario # 1. In this scenario, arable lands available in Athabasca and North Saskatchewan river basins are not be enough to produce the required quantity of crops, therefore, arable land of Peace River basin is also considered for the production of crops. In the Peace River basin, 90 and 80 mm level irrigation is required to produce wheat and canola seed crop (Wright, 2007a; Wright, 2007b). The industrial water requirement is calculated as discussed in scenario # 1 and divided among three river basins in the ratio of arable land used for production of these crops.

References

Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., 2002. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Task No. BFP2.A410. National renewable energy laboratory, Cole Boulevard, Golden, Colorado, USA. Available from: <http://www.p2pays.org/ref/38/37696.pdf>.

Agblevor, F.A., Besler, S., Wiselogel, A.E., 1996. Production of oxygenated fuels from biomass : Impact of feedstock storage. Petroleum science and technology 14 (4), 589-612.

AIPA, 2006. Alberta irrigation sector improves efficiency of water use. Alberta Irrigation Project Association. Available from: http://www.fossilwater.ca/fossilwater-report-aug-sep06.pdf. Accessed on: March 30, 2009.

Boateng, A.A., Daugaard, D.E., Goldberg, N.M., Hicks, K.B., 2007. Bench-scale fluidized-bed pyrolysis of switchgrass for bio-oil production. Industrial and engineering chemistry research 46 (7), 1891-1897.

Bridgwater, A.V., Toft, A.J., Brammer, J.G., 2002. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. Renewable and Sustainable Energy Reviews 6 (3), 181-248.

Chapman, R.G., 1996. Water treatment. In F. D. Drbal, P. Boston, L. K. Westra and B. Veatch., Power plant engineering. Springer, New York.

EEGIA, 2009. Assessment of boilers and thermic fluid heaters. Energy Efficiency Guide for Industry in Asia. Available from: http://www.energyefficiencyasia.org/energyequipment/assessment_boiler_indirectmethod.html. Accessed on: June 15, 2009.

EERE, U., 2009. Biomass feedstock composition and property database. Energy Efficiency and Renewable Energy, USA. Available from: http://www1.eere.energy.gov/biomass/feedstock_databases.html. Accessed on: January 20, 2009.

ESAA, 2000. Production of sulphuric acid. 3. European fertilizer manufacturers' association, Brussels. Available from: <http://cms.efma.org/PRODUCT%20STEWARDSHIP%20PROGRAM/images/EFMABATSUL.pdf>.

Gupta, M., Yanga, J., Roya, C., 2003. Specific heat and thermal conductivity of softwood bark and softwood char particlesq. Fuel 82 (8), 919-927.

Kerstetter, J.D., Lyons, J.K., 2001. Wheat straw for ethanol production in washington: a resource, technical, and economic assessment. Washington state university cooperative, Available from: <http://www.energy.wsu.edu/documents/renewables/WheatstrawForEthanol.pdf>.

King, C.W., E., W.M., 2008. Water intensity of transportation. Envionmental science and environmental policy 42 (21), 7866-7872.

Larson, E.D., Jin, H., Celik, F.E., 2005. Gasification based fuels and electricity production from biomass without and with carbon capture and storage.

Princeton environmental institute, Princeton university, Princeton, NJ. Available from: <http://www.princeton.edu/pei/energy/publications/texts/IK-Larson-et-al-GHGT8-FINAL-21-Apr-06-with-citation.pdf>.

Lee, D., Owens, V., Boe, A., Jeranyama, P., 2007. Composition of herbaceous biomass feedstocks. Available from: http://ncsungrant.sdstate.org/uploads/publications/SGINC1-07.pdf. Accessed on: February 19 2009.

Morey, R.V., Tiffany, D.G., Hatfield, D.L., 2006. Biomass for electricity and process heat at ethnol plants. American society of agricultural and biological engineers 22 (5), 723-728.

Parikh, J., Channiwala, S.A., Ghosal, G.K., 2007. A correlation for calculating elemental composition from proximate analysis of biomass materials. Fuel 86 (12-13), 1710-1719.

Perry, R.H., Green, D.W., Maloney, J.O., 1999. Perry's Chemical Engineers' Handbook. In Evaporative cooling. McGraw-Hill, New York, USA.

Ragland, K.W., Aerts, D.J., Baker, A.J., 1991. Properties of wood for combustion analysis. Bioresource technology 37 161-168.

Ringer, M., Putsche, V., Scahill, J., 2006. Large-scale pyrolysis oil production: A technology assessment and economic analysis. NREL/TP-510-37779. National renewable energy laboratory, Cole Boulevard, Colorado. Available from: <http://www.forestbioproducts.umaine.edu/documents/37779.pdf>.

Sheehan, J., Aden, A., Paustian, K., Killian, K., Brenner, J., Walsh, M., Nelson, R., 2004. Energy and environmental aspects of using corn stover for fuel ethanol. Industrial ecology 7 (3-4),

Sheehan, J., Camobreco, V., James, D., Graboski, M., Shapouri, H., 1998. Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. USDA, Cole Boulevard Golden, Colorado. Available from: <http://www.nrel.gov/docs/legosti/fy98/24089.pdf>.

Sokhansanj, S., Mani, S., Stumborg, M., Samson, R., Fenton, J., 2006. Production and distribution of cereal straw on the Canadian prairies. Available from: http://engrwww.usask.ca/oldsite/societies/csae/protectedpapers/c0556.pdf. Accessed on: January 15, 2009.

West, T.O., Marland, G., 2001. A synthesis of carbon sequestration, carbon emissions and net carbon flux in agriculture: comparing tillage practices in the United States. Agriculture ecosystems and environment 91 (1-3), 217-232.

Wiltsee, 2000. Lessons learned from existing biomass power plants. National renewable energy laboratory, Valencia, California. Available from: <http://www.nrel.gov/docs/fy00osti/26946.pdf>.

Wright, R., 2007a. Agroclimatic atlas of Alberta: agricultural climate elements. Available from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6301. Accessed on: April 5, 2009.

Wright, R., 2007b. Agroclimatic atlas of Alberta: soil moisture conditions in alberta. Available from:

http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6302. Accessed on: April 5, 2009.