

ABSTRACT

GONZALEZ, RONALDS. Biomass Supply Chain and Conversion Economics of Cellulosic Ethanol. (Under the direction of Hasan Jameel, Daniel Saloni, Richard Phillips, Robert Abt and Jeff Wright.)

Cellulosic biomass is a potential and competitive source for bioenergy production, reasons for such acclamation include: biomass is one the few energy sources that can actually be utilized to produce several types of energy (motor fuel, electricity, heat) and cellulosic biomass is renewable and relatively found everywhere. Despite these positive advantages, issues regarding cellulosic biomass availability, supply chain, conversion process and economics need a more comprehensive understanding in order to identify the near short term routes in biomass to bioenergy production. Cellulosic biomass accounts for around 35% to 45% of cost share in cellulosic ethanol production, in addition, different feedstock have very different production rate, (dry ton/acre/year), availability across the year, and chemical composition that affect process yield and conversion costs as well. In the other hand, existing and brand new conversion technologies for cellulosic ethanol production offer different advantages, risks and financial returns. Ethanol yield, financial returns, delivered cost and supply chain logistic for combinations of feedstock and conversion technology are investigated in six studies.

In the **first study**, biomass productivity, supply chain and delivered cost of fast growing Eucalyptus is simulated in economic and supply chain models to supply a hypothetical ethanol biorefinery. Finding suggests that Eucalyptus can be a potential hardwood grown specifically for energy. Delivered cost is highly sensitive to biomass productivity,

percentage of covered area. Evaluated at different financial expectations, delivered cost can be competitive compared to current forest feedstock supply.

In the **second study**, Eucalyptus biomass conversion into cellulosic ethanol is simulated in the dilute acid pretreatment, analysis of conversion costs, cost share, CAPEX and ethanol yield are examined.

In the **third study**, biomass supply and delivered cost of loblolly pine is simulated in economic and supply chain models specifically for biomass to bioenergy production. The study suggest that this species can be profitably managed for biomass production with rotation length of 11 to 12 years and with a stand tree density of 1,200 trees per acre. Optimum rotation length is greatly affected by seedlings costs and biomass productivity.

In the **fourth study**, a evaluation of seven different feedstocks (loblolly pine, natural mixed hardwood, Eucalyptus, switchgrass, miscanthus, corn stover and sweet sorghum) is made in terms of supply chain, biomass delivered costs, dollar per ton of carbohydrate and dollar per million BTU delivered to a biorefinery. Forest feedstocks present better advantages in terms of a well established supply chain, year round supply and no need for biomass storage. In the same context biomass delivered costs, as well as cost to delivered one ton of carbohydrate and one million BTU is lower in forest feedstocks.

In the **fifth study**, conversion costs, profitability and sensitivity analysis for a novel pretreatment process, green liquor, are modeled for ethanol production with loblolly pine, natural mixed hardwood and Eucalyptus as feedstocks, evaluated in two investment scenarios: green field and repurposing of an old kraft pulp mill. Better financial returns are

perceived in the natural hardwood - repurposing scenario, mainly due to lower CAPEX and lower enzyme charge and cost.

In the **sixth study**, conversion cost, CAPEX, ethanol yield and profitability for the thermochemical process (indirect gasification and production of mixed alcohol) is simulated for loblolly pine, natural hardwood, eucalyptus, corn stover and switchgrass. Higher ethanol yield with forest feedstock (due to higher content of %C and %H) result in better economic performance, when compare to agriculture biomass.

This research indicates that forest feedstock outperform agriculture biomass in terms of delivered costs, supply chain, ethanol yield and process profitability. Loblolly pine seems to be more suitable for thermochemical processes, while hardwood suit better for biochemical conversion (based on the technologies studied).

© Copyright 2011 by Ronalds Gonzalez

All Rights Reserved

Biomass Supply Chain and Conversion Economics of Cellulosic Ethanol

by
Ronalds W. Gonzalez

A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Forest Biomaterials

Raleigh, North Carolina

2011

APPROVED BY:

Dr. Jeffery Wright

Dr. Richard Phillips

Dr. Hasan Jameel
Chair of Advisory committee

Dr. Daniel Saloni
Co-Chair of Advisory committee

Dr. Robert Abt

DEDICATION

Carmen Teresa, Lorena, Liliana, Mary, Jurgen (familia Stock), Jesus (familia Espinoza), Dilia, Donald, Alejandro, my best friend Rodolfo, Sole, Ingrid, Orlando, Pirri, Guille, Saloni (s), Pineda, Cornelio, Smurfit Kappa, ETA Smurfit Kappa Carton de Venezuela, Wood and Paper Science Department (NCSU) and my friends at NCSU and Raleigh.

To those people who supported me, – you gave me all.

BIOGRAPHY

Ronalds Gonzalez was born in Barrio Bolivar, Acarigua, Portuguesa, Venezuela, in 1980. Ronalds was raised by his Grandma Carmen Teresa (the most fair and pure person he has even known). At age of 15, Ronalds met his most influent organization “Smurfit Kappa” and with a scholarship from this company studied at ETA Smurfit Carton de Venezuela, where he learned and was trained in forestry and pulp and paper. In 2005 Ronalds receive his degrees in Engineering and Accounting at Universidad de los Andes. In late 2005, He worked with a very nice team who taught him about “business” in real life. In 2007 arrived to the land of opportunities, married Liliana Rivero, and in December 2008 finished his master, two years later concludes his PhD in economics of ethanol production at North Carolina State University.

TABLE OF CONTENTS

LIST OF FIGURES	xi
LIST OF TABLES	xvi
1 PREFACE.....	1
2 BACKGROUND.....	4
2.1 Biofuels from biomass	6
2.2 Ethanol	6
2.3 Why cellulosic ethanol.....	7
2.4 Conversion of cellulosic biomass into ethanol.....	9
2.4.1 Physico-chemical pretreatment.....	10
2.4.2 Chemical pretreatment	11
2.5 Enzymatic hydrolysis	14
2.5.1 Endoglucanase	15
2.5.2 Exoglucanase	15
2.5.3 Betaglucosidase.....	15
2.6 Biomass composition	16
2.7 Why biomass composition is important.....	18
2.8 Types of cellulosic biomass and availability in US	20
2.9 Biomass an important cost driver in conversion	21
2.10 Financial indicators	23
2.11 Net present value.....	24
2.12 Internal rate of return.....	24
2.13 EBITDA	25
2.14 Free cash flow	25
2.15 REFERENCE.....	26

3	RESEARCH OBJECTIVES.....	36
4	Exploring the Potential of <i>Eucalyptus</i> for Energy Production in the Southern United States: Financial Analysis of Delivered Biomass	39
4.1	Abstract	39
4.2	Introduction	40
4.2.1	An alternative.....	42
4.2.2	Silviculture for Eucalyptus Bioenergy Plantations in the Southern US:	44
4.3	Material and methods	47
4.3.1	General assumptions	47
4.3.2	Financial analysis assumptions	50
4.4	Results and discussion.....	52
4.4.1	Establishment and maintenance costs	52
4.4.2	Harvesting and freight.....	53
4.4.3	Biomass delivered costs	54
4.4.4	Biomass division supply chain scenario	55
4.4.5	Investor supply chain scenario.....	56
4.4.6	Carbohydrate delivered costs.....	58
4.4.7	Depletion, revenue, EBITDA, new fixed capital and deferred charges and free cash flow trends	60
4.4.8	Effect of forest covered area and annual demand on biomass delivered cost ..	62
4.5	Conclusions	65
4.6	Reference.....	67
5	Converting <i>Eucalyptus</i> Biomass into Ethanol: Financial and Sensitivity analysis in a Co-Current Dilute Acid Process.	72
5.1	Abstract	72
5.2	Introduction	73
5.3	Materials and methods	74

5.3.1	Reactions yields	76
5.3.2	Chemical composition	77
5.3.3	Financial model assumptions	78
5.4	Results and discussions	80
5.4.1	Ethanol production cost drivers	80
5.4.2	Sensitivity of biomass delivery cost	82
5.4.3	Sensitivity analysis of carbohydrate composition.....	84
5.4.4	Sensitivity analysis of enzyme costs	87
5.5	Conclusions	88
5.6	References	90
6	Loblolly Pine for Biomass-Bioenergy: Silviculture and Delivered Costs.....	93
6.1	Abstract	93
6.2	Introduction	94
6.3	Materials and methods	99
6.3.1	General assumptions	103
6.3.2	Investment scenarios	103
6.3.3	Moisture content	103
6.3.4	Rotation length.....	104
6.3.5	Productivity.....	104
6.3.6	Stand tree density	104
6.3.7	Supply production per year	105
6.3.8	Chemical composition	105
6.3.9	Financial analysis assumptions	105
6.3.10	Life time of the project for financial evaluation:	105
6.3.11	Discount rate and internal rate of return	106
6.3.12	Equity	106
6.3.13	Land value.....	106
6.3.14	Terminal value	106

6.3.15	Deferred charges	107
6.3.16	Depletion.....	107
6.3.17	Currency.....	107
6.3.18	After tax analysis	107
6.3.19	Biomass delivered price	108
6.3.20	Working capital.....	108
6.3.21	Silviculture support system for loblolly plantation FASTLOB2	108
6.4	Results	109
6.4.1	Plantation establishment and maintenance costs	109
6.4.2	Harvesting costs	110
6.4.3	Freight.....	111
6.4.4	Financial optimum rotation length and stand tree density, Biomass Division Supply Chain Scenario:	111
6.4.5	Financial optimum rotation length and stand tree density, Investor Supply Chain (ISC) scenario	114
6.4.6	Biomass and carbohydrate delivered price to achieve 6%, 8% and 10% IRR (BDSC)	116
6.4.7	Sensitivity analysis.....	117
6.4.8	Seedling cost	118
6.4.9	Productivity.....	119
6.4.10	Percent of covered area.....	121
6.4.11	Annual supply	123
6.4.12	Raw material cost, benchmarking loblolly pine	125
6.4.13	Carbohydrate delivered price	127
6.5	Conclusion.....	128
6.6	References	130
7	Biomass to Cellulosic Ethanol in Southern U.S.: Supply Chain and Delivered Cost	135
7.1	Abstract	135
7.2	Introduction	136

7.3	Material and methods	138
7.3.1	Feedstock selection	138
7.3.2	Feedstock description.....	139
7.3.3	Basis for evaluation.....	147
7.3.4	Establishment, maintenance cost and harvesting cost	149
7.3.5	Freight	149
7.3.6	Storage and biomass loss	150
7.4	Results and Discussion.....	151
7.4.1	Annual productivity and total required area for production	151
7.4.2	Sourcing freight distance	153
7.4.3	Delivered cost	154
7.4.4	Carbohydrate and BTU delivered cost.....	156
7.4.5	Supply chain.....	158
7.5	Conclusions	159
7.6	References	160
8	Economics of cellulosic ethanol production: green liquor pretreatment for softwood and hardwood, greenfield and repurpose scenarios.....	170
8.1	Abstract	170
8.2	Introduction	171
8.3	Material and methods.....	174
8.3.1	Green liquor pretreatment.....	174
8.3.2	Basis for evaluation.....	176
8.3.3	Feedstock	177
8.3.4	CAPEX	179
8.3.5	General assumptions	180
8.3.6	Enzyme costs and dosage.....	182
8.3.7	Reaction rates and yield	183

8.3.8	Process Simulation.....	184
8.4	Results and Discussion.....	185
8.4.1	Production costs	185
8.4.2	Financial indicators	187
8.4.3	Ethanol yield	189
8.4.4	Sensitivity analysis.....	190
8.5	Conclusions	191
8.6	References	193
9	Economics of Cellulosic Ethanol Production in a Thermochemical Pathway for Softwood, Hardwood, Corn Stover and Switchgrass.....	198
9.1	Abstract	198
9.2	Introduction	199
9.3	Material and methods.....	202
9.3.1	Thermochemical process	202
9.3.2	Gasification process simulation	203
9.3.3	Major unit process description.....	204
9.3.4	Simulation modification.....	205
9.3.5	Operation parameters	206
9.3.6	Feed preparation.....	206
9.3.7	Gasification	207
9.3.8	Gas cleanup and conditioning.....	207
9.3.9	Alcohol Synthesis	208
9.3.10	Alcohol Separation.....	208
9.3.11	Heat and Power	208
9.3.12	Feedstock	209
9.3.13	CAPEX	210
9.3.14	General assumptions	212

9.3.15	Ethanol and propanol yield	213
9.4	Results and Discussion.....	213
9.4.1	Production costs	213
9.4.2	Financial indicators	214
9.4.3	Alcohol yield.....	216
9.4.4	Minimum ethanol selling price (MESP):.....	217
9.4.5	Sensitivity analysis.....	218
9.4.6	Moisture content variation in raw material	220
9.4.7	Effect of raw material on profitability, isolating raw material cost	221
9.5	Conclusions	222
9.6	References	224

LIST OF FIGURES

Figure 2-1 Cellulosic biofuel and advanced biofuel production requirements in the U.S. Source (EPA, 2010)	5
Figure 2-2 Cellulosic biofuel and advanced biofuel production requirements in the U.S. Source (RFA, 2010)	8
Figure 2-3 World production share of bioethanol in 2009. Source (RFA, 2010).....	9
Figure 2-4 Sensitivity analysis of ash content in a thermochemical process.....	19
Figure 4-1 Regions where freeze tolerant eucalypt species can grow	45
Figure 4-2 Establishment and maintenance cost per hectare for eucalypt plantations in the Southern U.S.	53
Figure 4-3 Eucalypt biomass delivered costs and component costs (\$ Mg-1) back calculated to achieve 6% IRR in Southern U.S. Biomass Division Supply Chain scenario.....	54
Figure 4-4 Biomass delivered cost (\$ Mg-1) at 6%, 8% and 10% IRR and at 16.8, 22.4 and 28 Mg ha-1 y-1 for eucalypt plantations in the Southern U.S.	56
Figure 4-5 Effect of productivity (Mg ha-1 y-1) on net plantable area and land investment for eucalypt plantations in Southern U.S.	57
Figure 4-6 Eucalypt biomass delivered cost and component costs, Investor Supply Chain Scenario, \$ Mg-1 back calculated to achieve 6% IRR at 16.8, 22.4 and 28 Mg ha ⁻¹ year ⁻¹ ...	59
Figure 4-7 Eucalyptus carbohydrate delivered costs in the Investor Supply Chain and Biomass Division Supply Chain Scenarios, back calculated to achieve 6%, 8% and 10% IRR, at a productivity of 16.8 Mg ha-1 y-1.	60

Figure 4-8 Revenue, Depletion, EBITDA, New fixed capital and Deferred charges at 6% IRR and supply of 453,592 Mg y-1 of eucalypt biomass for the ISC scenario considering productivity of 22.4 Mg ha-1 y-1.....	61
Figure 4-9 Effect of percentage of covered area on freight costs (\$ Mg ⁻¹) and delivered cost (\$ Mg ⁻¹) in two investment scenarios ISC and BDSC, evaluated at 22.4 Mg ha ⁻¹ y ⁻¹ and back calculated at 6% IRR.	64
Figure 4-10 Effect of annual biomass supply and site productivity (Mg ha y) in freight distance (km) and delivered cost (\$ Mg-1) in the BDSC scenario.	64
Figure 5-1 Summary of the dilute acid prehydrolysis followed by enzymatic hydrolysis process for ethanol production.....	75
Figure 5-2 Cost drivers in ethanol production in the co-current dilute acid prehydrolysis model (year 2009).	81
Figure 5-3 Biorefinery sensitivity to biomass delivered cost	83
Figure 5-4 Biorefinery sensitivity to total carbohydrate in biomass.....	84
Figure 5-5 Effect of chemical composition on ethanol yield (liter Mg-1) and power production	85
Figure 5-6 Lignin and carbohydrate content in biomass and electricity available to sell per year.....	87
Figure 5-7 Effect of enzyme cost on NPV and IRR values of the conversion process	88
Figure 6-1 Structure cost of plantation establishment and maintenance for loblolly pine (based on 1,000 trees per acre or 2,471 trees per hectare).....	110

Figure 6-2 Biomass delivered price (\$ Dt-1) for loblolly pine at 988, 1483, 1977, 2471, 2695 and 3459 trees ha-1 with rotation length from 7 to 15 years, freight distance 30 miles, 8% IRR.....	112
Figure 6-3 Effect of stand tree density (trees per hectare) on NPV of the project and productivity (Dt ha ⁻¹ year ⁻¹).....	114
Figure 6-4 Effect of IRR on biomass and carbohydrate delivered prices.....	117
Figure 6-5 Effect of seedling cost on biomass delivered price.....	119
Figure 6-6 Effect of productivity on biomass delivered price and acres required to supply 453,592 Dt (500,000 BDT per year).....	120
Figure 6-7 Effect of covered area on biomass delivered price (\$ Dt-1), freight cost (\$ Dt-1) and freight miles for a supply of ~454K Dt per year (500K BDT per year)	123
Figure 6-8 Effect of annual supply on \$ BDT-1 delivered, freight costs (\$ BDT ⁻¹) and freight miles.....	124
Figure 6-9 Equivalent carbohydrate cost in corn and loblolly pine biomass.....	128
Figure 7-1 Biomass productivity and hectares required for production to supply 453,597 dry ton yr-1	152
Figure 7-2 Sourcing distance (km) and productivity (dry ton ha-1 yr-1) for the different feedstocks.....	154
Figure 7-3 Biomass delivered cost for each of the feedstock, considering 5% covered area and annual supply of 453,597 dry ton year-1	156
Figure 7-4 Delivered cost per ton of carbohydrate and \$ per million BTU.....	157

Figure 8-1 Brief description of major barriers identified in cellulosic ethanol production ..	171
Figure 8-2 Illustration of green liquor recovery in a Kraft pulping process	176
Figure 8-3 Production costs, cash cost and share cost for ethanol for natural mixed hardwood in the repurposing green liquor scenario.....	186
Figure 8-4 NPV and IRR for the six combinations of biomass and investment.....	187
Figure 8-5 Total CAPEX and CAPEX per liter of ethanol for the six biomass and investment combinations	188
Figure 8-6 Ethanol yield, CAPEX per liter of ethanol and payback for each biomass and investment combination	190
Figure 8-7 Sensitivity analysis +/- 25% of CAPEX, yield (liter ethanol/dry ton), biomass cost and enzyme cost	191
Figure 9-1 Gasification process for ethanol production	203
Figure 9-2 Ethanol production costs (US\$ per gallon ethanol) and cost share (%), using loblolly pine as feedstock. 1 gallon = 3.7854 liters	214
Figure 9-3 NPV and IRR for the each of the feedstock	215
Figure 9-4 IRR, ethanol yield (liter per dry metric ton) and payback (years) for each of the biomass	216
Figure 9-5 Ethanol production and CAPEX per liter of ethanol	217
Figure 9-6 Minimum ethanol selling price back calculated to achieve 12% IRR for each of	218

Figure 9-7 Sensitivity analysis +/- 25% in price, ethanol yield, CAPEX and biomass cost for loblolly pine, natural mixed hardwood, switchgrass and corn stover 219

Figure 9-8 Effect of moisture content in biorefinery profitability 221

Figure 9-9 Gasification process for ethanol production 222

LIST OF TABLES

Table 2-1 Average biomass composition for several cellulosic feedstocks	18
Table 2-2 Ultimate composition analysis for several cellulosic biomass	20
Table 4-1 Average chemical components for eucalypts (Gomides <i>et al.</i> , 2006).....	50
Table 5-1 Model validation results	76
Table 5-2 WinGEMS modeled reactions	77
Table 5-3 Average chemical components for eucalypts (Gomides <i>et al.</i> 2006).....	78
Table 5-4 Operative material cost assumed in the simulation	80
Table 6-1 Biomass delivered price (\$ Dt-1) back calculated to achieve 8%IRR, Biomass Division Supply Chain Scenario	112
Table 6-2 Biomass delivered cost (\$ Dt-1) to achieve 8%IRR, Investment Supply Chain scenario	115
Table 6-3 Raw material costs analyses since the perspective of the biorefinery	127
Table 7-1 Chemical composition for the forest and agriculture feedstock	146
Table 7-2 Biomass productivity, rotation length and harvesting window	148
Table 7-3 Trees per hectare, establishment and maintenance cost and harvesting cost for the different feedstocks	150
Table 8-1 Basis for evaluation	176

Table 8-2 Chemical constituents of southern mixed hardwood, Loblolly Pine and Eucalyptus	178
Table 8-3 Delivered cost, rotation length, productivity, moisture content, covered area and annual supply assumed for natural mixed hardwood, Eucalyptus and Pine	178
Table 8-4 Capital expenditure for the biorefinery, greenfield and repurposing	180
Table 8-5 Modeled chemical and enzyme cost, and majors assumptions used in the economic analysis.....	182
Table 8-6 Enzyme doses for each of the biomass.....	183
Table 8-7 Reaction yields and conversion factors	184
Table 8-8 Reaction yields and conversion factors	185
Table 9-1 Biomass delivered cost, rotation length, productivity, moisture content and annual supply.....	210
Table 9-2 Chemical composition of the feedstock	210
Table 9-3 Capital expenditure for a green field biorefinery	211
Table 9-4 Major assumptions used in the financial analysis	212

1 PREFACE

The world is actively looking in a myriad of sources, pathways and technologies to sustainably produce energy in order to lower dependence of energy supply from non secure sources, as well as reduce CO₂ footprint and improve local economy. Countries as US, Brazil and Sweden have undertaken big efforts in this task. Sweden (as 2010) has replaced energy from oil to the second place, with expectation to increase the energy share from sustainable energy sources (mainly biomass), this has been the result of intensive government promotion as well as incentives. With respect to liquid biofuel production U.S. and Brazil are the major producers of bioethanol in the world, with a remarkable increase in production and number of facilities in the last years. Bioethanol production in these two countries has relied mainly in corn grain (U.S.) and sugar cane (Brazil), which has called the attention of the society regarding the use of food based raw material for energy production, this controversy received more heat with rises in corn prices in 2008 and 2009, besides the fact that (for the case of U.S.) there won't be enough corn to support the expectations of liquid biofuel production in the country. Cellulosic biomass (from forestry and agriculture) is seem to be a potential key player in liquid biofuel production, due to attributes such as renewable, abundant raw material (mostly found elsewhere), and possible to produce at low cost.

Research groups are strongly focusing in increasing biomass to ethanol yield and lower conversion costs, in order to make cellulosic ethanol production more feasible. Despite that a myriad of technologies have been developed with many other currently under development;

and with sufficient biomass available, so far there is not operational production of cellulosic ethanol in the U.S.

As previously mentioned, major barriers for profitable cellulosic ethanol production have been identified as raw material cost, capital expenditure investment (CAPEX), technology efficiency (and maturity) and market ethanol selling price itself.

Biomass affects conversion process economy mainly in two ways: the cost of biomass per se and through the chemical composition of the biomass. The chemical composition of the biomass, for example carbohydrate content, determines the amount of carbohydrate available in the biomass that can be reduced into monomeric forms for further fermentation and alcohol production (i.e. in a biochemical process).

CAPEX, together with technology efficiency (and maturity) will impact the financial appreciation of the project as well as the financial expectations. Lower CAPEX, couple with reliable technology efficiency might reduce the risk of investment in this emerging industry. Ethanol selling price directly impact profitability of the industry, and is an area where government policies play an important role.

Providing information regarding the costs and profits associated with producing dedicated biomass for bioenergy, chemical composition of those biomass and biomass to ethanol yield in potential conversion process will give important decision makers in government and industry investors to picture and concentrate work in identified short term

routes for cellulosic ethanol production. Thus in this work we present three chapters developed to understand: i. biomass delivered cost of fast growing eucalyptus, ii. Cost of converting eucalyptus into ethanol through a dilute acid process and iii. Shorter rotation length, stand tree density and biomass delivered cost of loblolly pine in Southern U.S.

2 BACKGROUND

Cellulosic biomass has been identified as the most important and potential raw material for bioenergy production. Several attributes have contributed to such acclamation. Cellulose is the most abundant polymer on earth and has been used as energy source for heating since ancient times, as 2004 biomass contributed with ~13.4% of the global energy supply (Heinimö, 2007, Sims *et al.*, 2006). One of the main advantages of cellulosic biomass is its flexibility to be used for different forms of energy, as a solid raw material to generate heat, steam and electricity, but also can be processed to produce liquid biofuel used in transportation (Jackson, 2010). It is anticipated an increase in the global demand of biomass for bioenergy (Ericsson & Nilsson, 2004, Hillring, 2006, Junginger *et al.*, 2008, Parikka, 2004), mainly derived from the establishment of mandatory legislations in countries such as Netherlands, India, China, Thailand, New Zealand, Canada and U.S. (Sims *et al.*, 2006). The European Union (EU) has placed targets for bioenergy, for the whole region it is expected that at least 10% of the energy is to come from biomass by 2010 (Faaij, 2006). Moreover, EU countries have their own ambitions in bioenergy share, Sweden has formulated that 40% of its primary energy supply by 2020 should come from biomass (Faaij, 2006) while Finland has established a goal of 38% of energy coming from renewable sources (Tohka, 2009). As May 2010, the Swedish Bioenergy Association reported that bioenergy represented 31.7% of the final energy used in Sweden in 2009, displacing oil to second position with 30.8% of energy share (Focus, 2010). For the US, the Environmental Protection Agency has

announced ambitious goals in advanced biofuel and cellulosic biofuel production, with a target to produce cellulosic biofuel in magnitudes of 1 billion gallons by 2013 and 16 billion gallons by 2022, see figure 2.1 for the forecasted production mandate in cellulosic ethanol production (EPA, 2010).

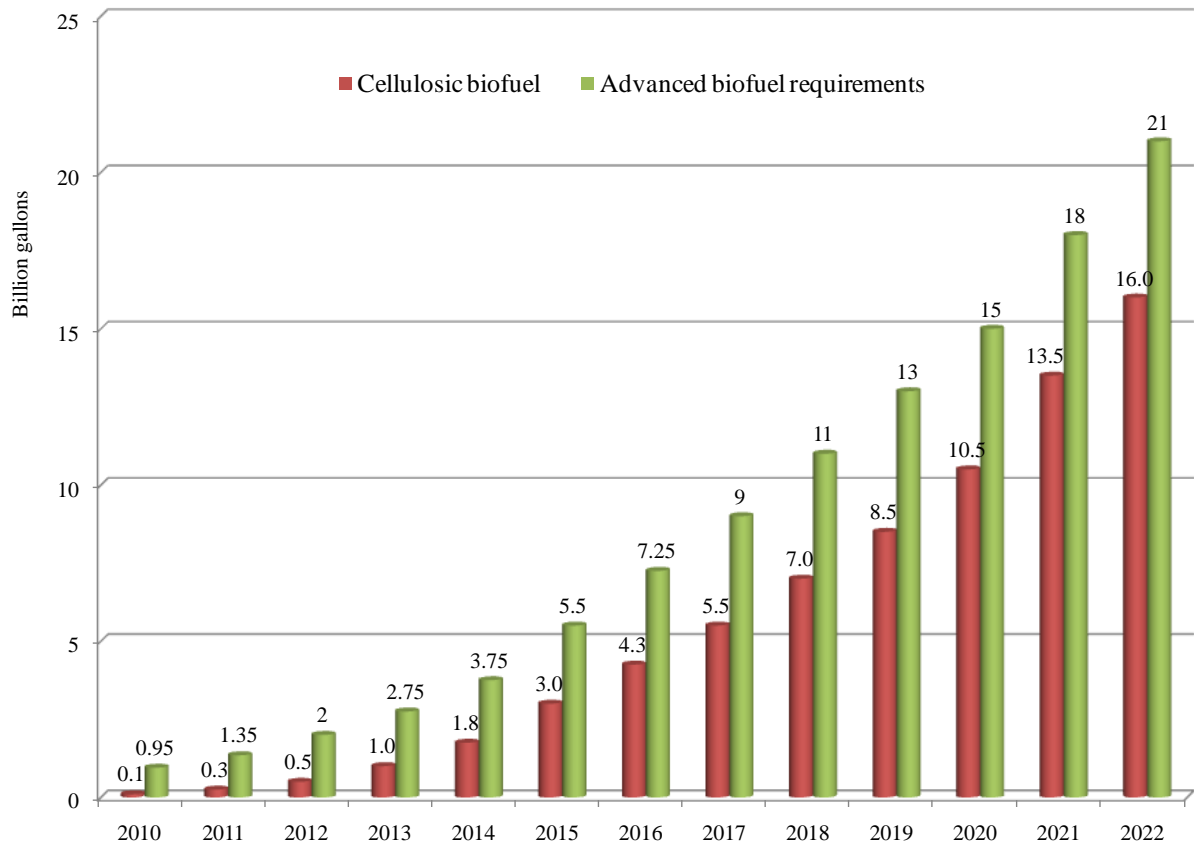


Figure 2-1 Cellulosic biofuel and advanced biofuel production requirements in the U.S. Source (EPA, 2010)

In the same manner individual States in the U.S. have established their own goals in bioenergy production. The State of North Carolina has created the Biofuel Center

Foundation, institution in charge of promoting the biofuel industry development within the State. The goal taken by the Biofuel Center is that by 2017, 10% of North Carolina's liquid fuels (~ 600 million gallons per year) will be produced in-state from locally-grown biomass (NCBC, 2010).

2.1 Biofuels from biomass

Production of liquid biofuel from biomass has been practiced for decades. Countries such as U.S. and Brazil have developed an important industry of bioethanol mainly from corn and sugar cane respectively (Goldemberg *et al.*, 2004, Shapouri *et al.*, 2004). As 2009 the US produced near 10.6 billion gallons of ethanol (mainly from corn), six year before (2003) this number roughly reached 2.8 billion gallons. Figure 2.2 presents the remarkable increase in US ethanol production between the years 1980 and 2009 (RFA, 2010). Such outcomes in ethanol production are the result of production incentives, biomass availability and technology development, all encouraging a profitable and growing business. For 2009 the world produced nearly ~20 billion gallons of bioethanol, with US (53% production share) and Brazil (33%) as the top two producers (figure 2.3), followed by EU countries (5%), China (3%) and others.

2.2 Ethanol

Ethanol is also known as ethyl alcohol, grain alcohol, and EtOH. Its molecular formula is represented as follows $\text{CH}_3\text{-CH}_2\text{-OH}$ (DOE, 2010a). Ethanol is a clear and odorless liquid

that works well internal combustion engines, and has been identified as a potential source of liquid fuel energy to replace gasoline (Von Blottnitz & Curran, 2007, Wheals *et al.*, 1999). Ethanol contains around 65% to 69% of energy content, compared to gasoline (Lynd, 1996, Sinor & Bailey, 1993). Ethanol has been used as a gasoline additive (Niven, 2005), but also can be utilized as a blend in a number of forms: low level blends ($\leq 22\%$ ethanol in gasoline), high level blends ($\geq 85\%$ ethanol in gasoline) or as a pure anhydrous ethanol, this last known as E100 (Lynd, 1996). Depending on ratio ethanol to gasoline, ethanol blend fuel is classified as E100 (100% ethanol in the blend), E85 (85% ethanol in the blend), E15 (15% ethanol in the blend) (Agbogbo & Coward-Kelly, 2008).

Ethanol can be obtained mainly by two broad pathways: synthetically from petroleum or by microbial conversion of biomass material through fermentation (Badger, 2002). In 1995 near 93% of ethanol produced worldwide came from fermentation pathways, while the rest came from synthetic methods.

2.3 Why cellulosic ethanol

The increase in bioethanol production based on the use of corn and sugar cane have brought the attention on the use of food based raw material for fuel production with an international debate on food versus fuel, with diverse points of views, with a wide selection of environmental, social, economical, energy dependence facts, pros and cons (Brown, 1981, Erickson & Saket, 2007, Runge *et al.*, 2007, Tenenbaum, 2008). Accentuated increase prices in corn in 2007 and 2008 in U.S. provided more heat to the already intense discussion (Baker

& Zahniser, 2006, Leibtag, 2008), and the concern was not only related to the increase in food prices, it also considered the fact that farmers would switch their current production of others agriculture goods for corn which may give them better profitability (Leibtag, 2008).

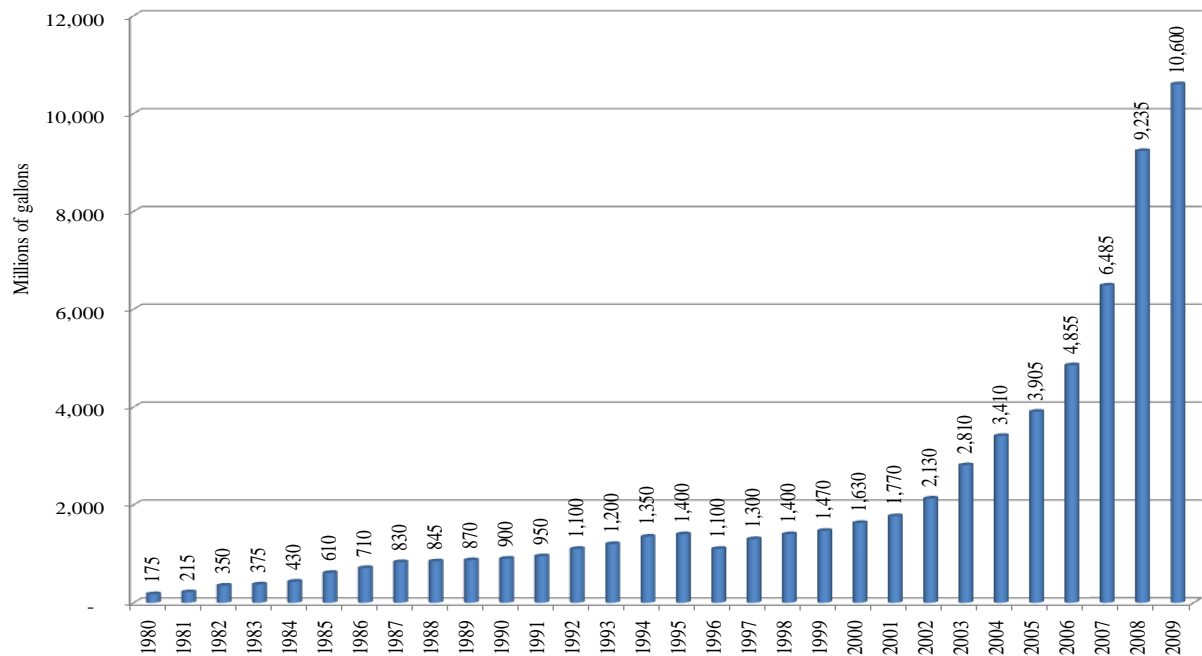


Figure 2-2 Cellulosic biofuel and advanced biofuel production requirements in the U.S. Source (RFA, 2010)

The use of cellulosic biomass has been considered as a potential raw material to offset the food versus fuel situation, lower future production cost of bioethanol as well as to increase production of this commodity (DiPardo, 2004, Erickson & Saket, 2007, Lynd, 1996, Lynd *et al.*, 1991).

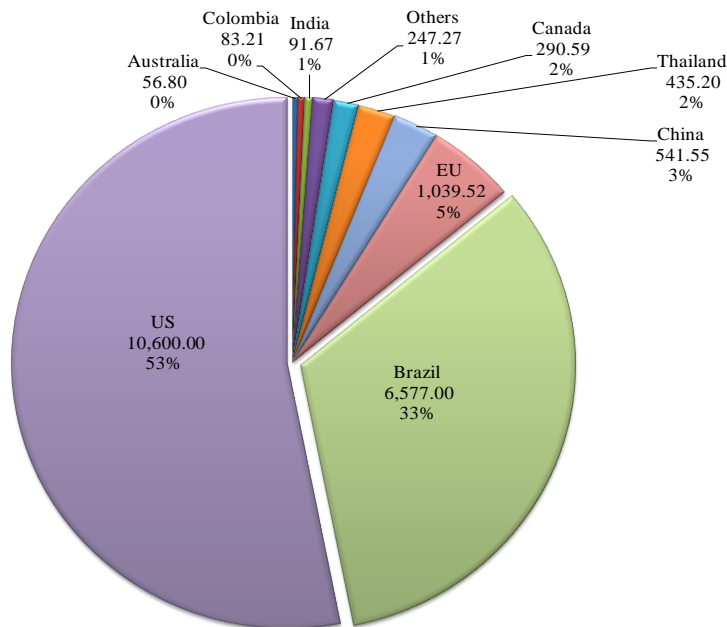


Figure 2-3 World production share of bioethanol in 2009. Source (RFA, 2010)

2.4 Conversion of cellulosic biomass into ethanol

The conversion process to produce ethanol from cellulosic biomass (compared to corn) are differentiated primarily on the pathways to achieve hydrolysis and fermentation, with significant higher costs in pretreatments, which are required to expose cellulose out of the lignocellulosic matrix for further conversion into monomeric reactable sugars, based on a biochemical conversion (Lynd, 1996, Mabee *et al.*, 2007). Technological developments have been targeted in a world wide effort to increase efficiencies in production yield and lower capital investment to produce ethanol from biomass. Cellulosic ethanol technologies can be divided into two main branches: biochemical and thermochemical conversion. Biochemical conversion requires biomass to be pretreated in order to increase the accessibility of

enzymes, responsible of reducing polymeric chain of carbohydrates into monomeric reactable sugars for subsequent fermentation and conversion to ethanol. Some of the most known chemical pretreatments are listed as follows (Sun & Cheng, 2002):

2.4.1 Physico-chemical pretreatment

2.4.1.1 Steam explosion (auto hydrolysis)

Steam explosion is one of the most used pretreatments to treat lignocellulosic materials (McMillan, 1994, Sun & Cheng, 2002). In this pretreatment the biomass is exposed to high pressure saturated steam and the suddenly exposed to atmospheric pressure. Steam explosion commonly starts at 160C to 260C (Sun & Cheng, 2002). The process significantly increases surface area, removers hemicelluloses and alter lignin structure in some degree, without removing lignin from the lignocellulosic matrix (Mosier *et al.*, 2005). This process has been used commercially to hydrolyze hemicelluloses for fiberboard and other products (DeLong, 1981, Mosier *et al.*, 2005).

2.4.1.2 Ammonia fiber explosion (AFEX)

This process treats lignocellulosic materials with high-pressure liquid ammonia for a period of time, and then pressure is explosively released (Holtzaple *et al.*, 1991, Sun & Cheng, 2002). The process reduce cellulose crystallization, increases surface area, partially remove hemicelluloses as well as alter and remove lignin from the lignocellulosic structure

(Holtzapple *et al.*, 1991, Mosier *et al.*, 2005, Sun & Cheng, 2002), it has been reported that AFEX pretreated biomass can have better yield in enzymatic hydrolysis when compared to steam explosion (Weil *et al.*, 1994). AFEX has been used to pre-treat switchgrass (Alizadeh *et al.*, 2005), miscanthus (Murnen *et al.*, 2007), corn stover (Sousa *et al.*, 2007).

2.4.1.3 CO₂ explosion

This process pre-treat the biomass with super critical carbon dioxide at a low temperature compared to steam explosion and with possible reduced expenses compared to AFEX (Zheng *et al.*, 1998). This process has been used to pre-treat aspen (hardwood) and southern yellow pine with sugars yield after enzymatic hydrolysis of 84.7 ± 2.6 and $27 \pm 3.8\%$ respectively (Kim & Hong, 2001).

2.4.2 Chemical pretreatment

2.4.2.1 Ozonolysis

Ozone pretreatment effectively removes lignin, no toxic contaminants are produced in the process and reactions undergo at room temperature and pressure (Sun & Cheng, 2002), with previous studies reported in wheat straw, cotton straw, eucalyptus, pine and poplar (Sun & Cheng, 2002, Vidal & Molinier, 1988).

2.4.2.2 Acid hydrolysis

Acid hydrolysis has been widely used to pre-treat biomass for ethanol production (Aden *et al.*, 2002, Sun & Cheng, 2002, Wooley *et al.*, 1999). Main acids used have been

H₂SO₄ and HCl. Dilute sulfuric acid has been used to commercially manufacture furfural from cellulosic materials (Mosier *et al.*, 2005). Dilute acid pretreatment increase accessible surface area, removes hemicelluloses, alter lignin structure and with practical no removal of lignin (Mosier *et al.*, 2005). Hemicelluloses removal during dilute acid pretreatment enhances digestibility of cellulose in the residual solids. The downside of these pretreatments include: concentrated acids are toxic, corrosive and hazardous, requiring reactor resistant to corrossions (Sun & Cheng, 2002). Advances in this process allow high xylan to xylose conversion with the use of less severe conditions (Mosier *et al.*, 2005). Acid hydrolysis pretreatment has been carried out in wheat straw (Delgenes *et al.*, 1990), rye straw and bermuda grass (Sun & Cheng, 2005) as well as in softwoods (Frederick *et al.*, 2008, Nguyen *et al.*, 1999).

2.4.2.3 Alkaline hydrolysis

Alkali pretreatment process is being carried out at lower temperature and pressures when compared to other technologies. The process increases accessible surface area, partially removes hemicelluloses and breakdown and removes lignin (Mosier *et al.*, 2005). Some of the reagents used in alkali hydrolysis include lime, green liquor (Na₂CO₃ and Na₂S), ammonia, sodium hydroxide and others (Jin *et al.*, 2010, Mosier *et al.*, 2005, Sun & Cheng, 2002). Pretreatments with dilute NaOH causes swelling, decrease degree of polymerization,

decrease in crystallinity and separation of structural linkages between lignin and carbohydrate (Sun & Cheng, 2002).

2.4.2.4 Oxidative delignification

Oxygen delignification is an existing technology in the pulp and paper industry, and has enjoyed steady growth worldwide since its introduction in 1970 (Chakar *et al.*, 2000, McDonough, 1996). This technology was introduced into pulp bleaching operations in order to address environmental concerns (Yang *et al.*, 2003). Lignin degradation in alkaline-oxygen medium arises from the reaction of hydroxide and oxygen with the phenoxy hydroxyl group (Johansson & Ljunggren, 1994, Yang *et al.*, 2003). Commercial oxygen delignification are capable of removing approximately 50% of lignin remaining after Kraft pulping, pretreated pulp removed up to 67% of the lignin and substantially increase yield from enzymatic hydrolysis (Draude *et al.*, 2001).

2.4.2.5 Organosolv process:

Organosolv was developed by the University of Pennsylvania and the General Electric Company in 1970 with the goal to produce clean biofuel for turbine generators (Aziz & Sarkanen, 1989). One of the main interesting features of this pretreatment process is the possibility to generate co-products as high-quality lignin (Lora & Glasser, 2002) that might increase biorefinery profitability. New companies as Lignol are exploring the use of organosolv to produce ethanol and lignin (Lignol, 2010). Organosolv process uses a blend of

ethanol and water at a ratio of 50:50 (w/w) at a temperature of 200C and pressure of 400 psi, in order to extract most of the lignin from wood chips, then (Pan *et al.*, 2005). Pine pulp samples treated with organosolv showed to be susceptible to hydrolyze by commercial enzymes (Pan *et al.*, 2005). In general terms, it has been reported that in organosolv pulping process hardwoods are delignified faster and more selectively than softwoods (McDonough, 1992).

Thermochemical process is based on the production of synthetic gas from biomass; gasses produced are then reformed and passed through catalytic materials to produced alcohol (Phillips, 2007, Phillips *et al.*, 2007b, Schmidt & Dauenhauer, 2007).

2.5 Enzymatic hydrolysis

The susceptibility of native cellulose to hydrolytic enzyme attack mainly depends on its structural features as surface area and cellulose crystallinity (Fan *et al.*, 1982). Also the relationship between the extent of delignification and hydrolyzes have been studied with clear higher hydrolysis conversion in materials with lower lignin content.

Enzymes are biological catalyst (proteins) designed to catalyze the hydrolysis of polymeric carbohydrate into monomeric sugars (Wright, 1988). Enzymatic hydrolysis of cellulose is performed by highly specific cellulose enzymes (Béguin & Aubert, 1994, Sun & Cheng, 2002), with lower utility cost compared to acid or alkaline hydrolysis, because enzyme hydrolysis are carried out at mild conditions (pH ~ 4.8, with temperatures 45 -50C)

avoiding corrosion problems and thus higher CAPEX and operative costs (Duff & Murray, 1996).

Cellulase cocktails are mixture of several enzymes, with 3 major groups clearly identified in the hydrolysis process:

2.5.1 Endoglucanase

Responsible of attacking low cristallinity regions in the cellulose fiber creating free chain ends (Beguin, 1990, Coughlan, 1992, Galway, 1988, Sun & Cheng, 2002).

2.5.2 Exoglucanase

Responsible for degrading the molecules by removing cellulose units from the free chain ends (Beguin, 1990, Coughlan, 1992, Galway, 1988, Sun & Cheng, 2002).

2.5.3 Betaglucosidase

Responsible for hydrolyzing cellulose units into glucose (Beguin, 1990, Coughlan, 1992, Galway, 1988, Sun & Cheng, 2002).

Besides these three major groups that specifically hydrolyze cellulose, there are specific enzymes that attack the hemicelluloses as:

- a. Glucuronidase
- b. Acetylerase

- c. Xylanase
- d. β -xylosidase
- e. Galactomannanase
- f. Glucomannanase

Enzyme costs is an important cost driver in biochemical cellulosic ethanol production (Gregg & Saddler, 1996, Hahn-Hägerdal *et al.*, 2006, Wingren *et al.*, 2003), several approaches have been deployed to reduce overall cost of enzymatic process and increase its efficiency. Main factors affecting enzymatic hydrolysis efficiency include substrates, cellulase activity as well as reaction conditions (temperature, pH, consistency, incubation time) and others (Sun & Cheng, 2002).

2.6 Biomass composition

Cellulosic biomass is mainly composed of cellulose, hemicelluloses, lignin, ash and extractives. The percentage of each component varies between species and among genotypes of the same species. Main components are described in the next lines; table 2.1 shows a comparison of the chemical composition in several hardwood, softwood and grasses.

Cellulose is a polymer of glucose, a six carbon sugars joined by glycosidic bonds. Cellulose polymer chains are joined by hydrogen bonds, resulting in a highly ordered crystalline material. Commonly cellulose comprises 60% of carbohydrate content in woody biomass and around 50% in herbaceous plants (Lynd, 1996, O'Sullivan, 1997).

Hemicelluloses is the second most common polysaccharides found in nature, is a polymer associated with cellulose and represent between 20% to 35% of dry mass of cellulosic biomass. Xylan, a five carbon sugar polymer, is the most abundant in hemicelluloses. Hemicelluloses are heterogeneous polymers of pentoses (xylose, arabinose), hexoses (mannose, glucose, galactose), and sugar acids (Lynd, 1996, Saha, 2003).

Lignin is a complex natural polymer built up of different inter-unit linkages and is covalently linked to carbohydrates forming a lignin-carbohydrate network (Fengel & Wegener, 1984, Guerra *et al.*, 2007, Jeffries, 1990). Mass fraction in plant material varies from 7% to 30%. Herbaceous plants have lower lignin content compared to hardwoods and softwoods respectively (Lynd, 1996, Mabee *et al.*, 2007). In the context of ethanol production, lignin cannot be fermented into ethanol, in fact higher conversion cost of cellulosic ethanol (compared to corn ethanol) is due to the need to pre-treat the biomass in order to breakdown the lignin complex to make cellulose more accessible to enzymes for further hydrolysis.

Table 2-1 Average biomass composition for several cellulosic feedstocks

Biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)
^a Softwood	35-40	25-30	27-30
^a Hardwood	45-50	20-25	20-25
^a Wheat straw	33-40	20-25	15-20
^a Switch grass	30-50	10-40	5-20
^b Corn stover	38	26	23
^b Soybean	33	14	14
^b Wheat straw	38	29	24
^b Miscanthus	43	24	19
^b Sweet sorghum	23	14	11

Source: ^a (McKendry, 2002) and ^b (Lee *et al.*, 2007)

2.7 Why biomass composition is important

The reason to understand chemical composition in biomass relies on its effect in the conversion process yield. Ethanol production under biochemical pathway is highly affected by the amount of carbohydrates available in the biomass for further hydrolysis and fermentation (Badger, 2002, Frederick *et al.*, 2008, Lynd *et al.*, 1991, Mielenz, 2001).

While in a thermochemical process the amount of carbohydrate is relevant, the components that drives alcohol production yield are carbon (C) and hydrogen (H), so lignin, carbohydrates and extractives contributes to higher alcohol yield (McKendry, 2002, Phillips *et al.*, 2007a, Schmidt & Dauenhauer, 2007). In contrast higher ash content in the biomass

lowers ethanol yield. Figure 2.4 depicts the relation between higher ash content in biomass and lower alcohol yield (gallon of alcohol per dry ton of biomass) in a thermochemical process (Phillips *et al.*, 2007b). Table 2.2 depicts ultimate composition analysis for several cellulosic feedstock with different carbon (C), hydrogen (H), oxygen (O) and nitrogen (N) content.

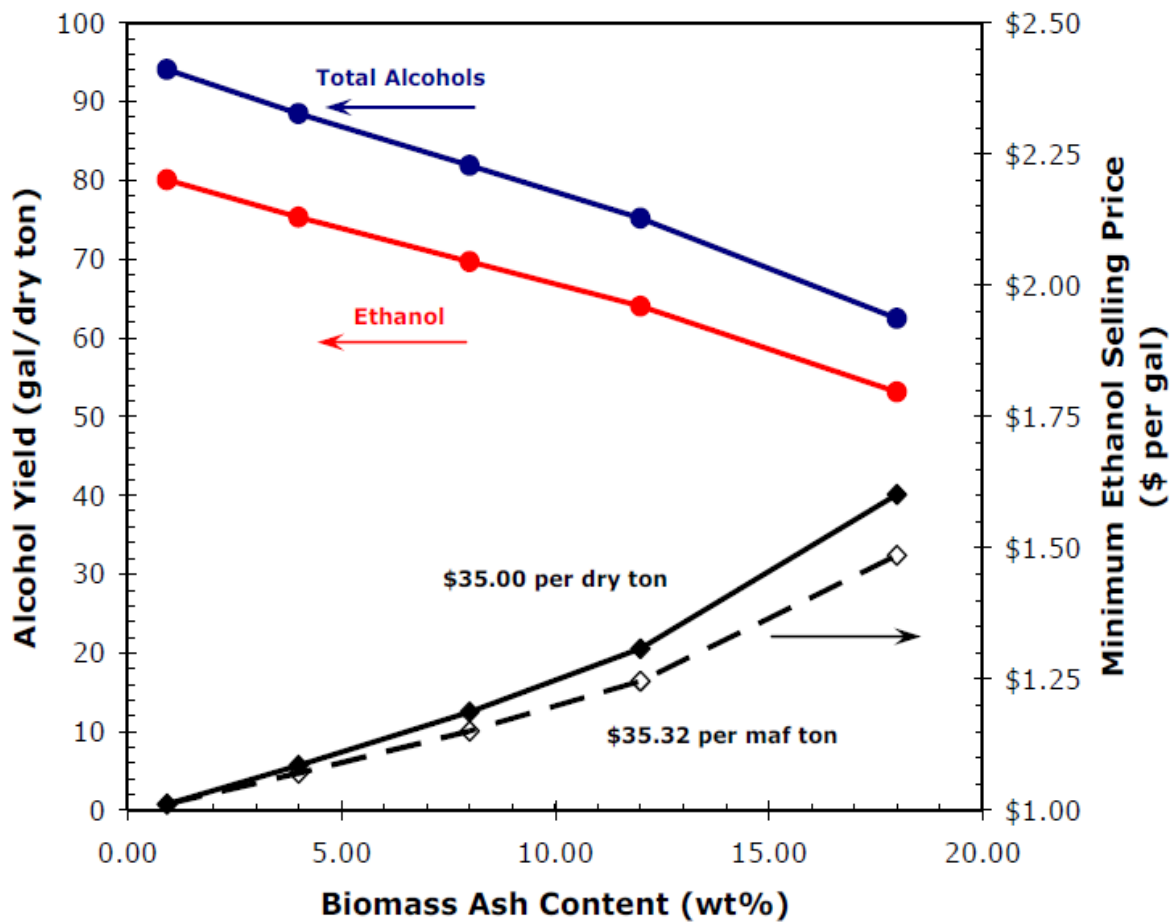


Figure 2-4 Sensitivity analysis of ash content in a thermochemical process

Source (Phillips *et al.*, 2007b)

Table 2-2 Ultimate composition analysis for several cellulosic biomass

Biomass	C	H	O	N	Ash
^a Softwood, average	52.1	6.1	41	0.2	1.7
^a Hardwood	48.6	6.2	41.1	0.4	2.7
^a Wheat straw	45.5	5.1	34.1	1.8	13.5
^a Wood bark	53.1	6.1	40.6	0.2	1.6
^b Miscanthus	48.1	5.4	42.2	0.5	2.8
^c Hybrid poplar	50.2	5.8	40.3	0.2	1.9
^c Switchgrass	47.3	5.6	40.6	0.6	5.8
^c Corn stover	46.6	5.7	39.4	0.7	11.9

Source: ^a (Demirba, 1997), ^b (McKendry, 2002) and ^c (DOE, 2010b)

2.8 Types of cellulosic biomass and availability in US

Cellulosic biomass can be broadly divided in two main types: woody plants (mainly from natural and plantation forestry) and herbaceous plant/ grasses (mainly from agriculture crops). Biomass from each type can be obtained from 1) residues from harvesting or industrial operations, 2) byproducts from the crop (or natural and planted forests) or 3) as a main product from energy crops/plantations established with main objective to feed the bioenergy industry. It is expected that in the short term, cellulosic biomass used for energy production may come from wastes and residues, due to the lower costs when compared to dedicated energy crops (Lynd, 1996, Wyman & Goodman, 1993) but in the long term bioenergy crop/plantations are expected to supply the biomass required by the emerging

bioenergy industry. Perlack, et al. 2005, estimated that U.S. can produce nearly 1 billion dry tons of biomass annually, out of this number, around 368 million dry tons of sustainable removable biomass could be produced on forestlands and about 998 millions dry tons may come from agricultural lands (Perlack *et al.*, 2005). This enormous biomass availability does not translate into free or low cost biomass, these biomasses are spread across the country and harvesting, collection, transportation and storage of the biomass increases biomass delivered costs, putting it as an important cost driver for energy production.

2.9 Biomass an important cost driver in conversion

The cost of biomass represents an important cost share for different types of energy production, for example for pellet production has been estimated to range from 38% to 53% in Austria and Sweden (Thek & Obernberger, 2004) and around 39% to 59% in the United States and Canada (Mani *et al.*, 2006). Cellulosic biomass has been identified as the largest cost for cellulosic ethanol (Galbe & Zacchi, 2002, Wyman, 2007). The approach to lower biomass delivered cost may include the use of fast growing species, highly productive perennial grasses and the development of specific biomass grown for bioenergy. In a manner similar to the pulp and paper industry with specific standards for feedstock, it may be necessary to grow specifically biomass for bioenergy. This would increase efficiency and yield in the selected conversion pathway. For example, fermentation yield pathways are very sensitive to carbohydrate content in biomass due to the available amount of carbohydrate to be converted into monomeric reactable sugars and further conversion to alcohol species

(Mielenz, 2001, Wyman, 2007). In the case for solid fuel, as pellets and briquettes, an important property in biomass is the content of carbon and the BTU per unit of biomass. Desired biomass properties (such as carbohydrate content) can be genetically improved and biomass delivery cost can be optimized when growing specific biomass sources for energy. And as expressed in previous studies “without the development of biomass resources (e.g. through energy crops) and a well-functioning biomass market that can assure a reliable and long lasting supply, the existing high ambitions for bioenergy may not be met” (Faaij, 2008). The importance of cost of biomass in bioenergy production has motivated studies in the area of biomass economics, delivered cost and supply chain. Most studies found in the literature do not undertake a complete economic analysis when determining biomass delivered or production costs. The profitability for growing biomass is sometimes not included which limits the analysis to production costs. The approach for a continuous and reliable supply chain of biomass for bioenergy should involve the study of the profitability on each step of the supply chain.

Grasses such as switchgrass and miscanthus have been researched for bioenergy purposes. The cost of producing switchgrass has been found to range from \$59 to \$66 per dry metric ton at farm gate for the U.S. Midwest (Duffy & Nanhou, 2001) though this does not include freight or storage costs. Other studies for the same region estimated switchgrass delivered cost to vary from \$37 to \$48 per dry ton (harvesting and freight costs only) while the cost of growing the crop may range from \$30 to \$36 per dry metric ton (Kumar &

Sokhansanj, 2007). Minimum selling price of switch grass in Italy has been estimated to be higher than €55 per dry metric ton at farm gate in order to be profitability cultivated. These numbers in production costs indicate that one dry metric ton of switchgrass delivered at mill gate varies from \$67 to \$84. A recent study predicted an average price of \$105-115 to deliver 500,000 dry short tons of switchgrass (Conable & Volk, 2010). These costs are, of course, very influenced by the assumption in biomass growing rate and establishment considered, and still there are other costs to consider such as storage, biomass handling and logistics (McDermott, 2010). In the case of grasses and other agriculture biomass, storage is required due to the reduced harvesting window (3-4 months), this cost driver besides other logistic concerns is still being researched. In terms of logistics and supply chain, forest biomass has several competitive advantages over agriculture biomass. Forest biomass can provide year round supply with no requirement for storage or insurance and with lower working capital when compared to agriculture biomass. In the forest biomass supply, there is worldwide availability of experienced contractors and supply chain stakeholders with proven expertise in harvesting and material handling. Understanding biomass delivered cost from the so called energy crops and their performance in different conversion process is fundamental to identify near short term routes for cellulosic ethanol production.

2.10 Financial indicators

Financial indicators commonly used to evaluate the performance or feasibility of a project are as follows:

2.11 Net present value

Net present value is a very well known financial indicator used to evaluate the financial performance of a project; it can be determined subtracting the cost of the investment (cash outflows at the beginning of the project) from the present value of the future cash inflows (when the investment become to produce positive cash flows (Edmonds *et al.*, 2007).

The present value of a future cash flow is the today's value of that cash flow after considering the appropriate market interest. If the net present value of a project is positive, then the project can be a good opportunity as it worth more than it cost (Ross *et al.*, 2004). The expected future payoffs are discounted by the rate return offered by comparable investment alternatives, this rate of return is also called: discount rate, hurdle rate or opportunity cost of capital (Brealey & Myers, 1996).

2.12 Internal rate of return

The internal rate of return is that rate where the net present value of a series of cash outflows and inflows is zero (Brealey & Myers, 1996). This number (IRR) does not depend on the interest rate that prevails in the capital market, this is where the name of internal rate of return comes from, this number is “internal or intrinsic to the project and does not depend on anything except the cash flow of the project” (Ross *et al.*, 2004).

2.13 EBITDA

EBITDA is the acronym for Earnings before interest taxes, depreciation and amortization. This financial indicators is used by companies in order to understand the earnings before taxes and interests and before non cash costs (depreciation, amortization and depletion) (Finnerty & Emery, 2004). This is a non-GAAP (general accepted accounting principles), and it can be used to analyze and compare profitability between companies and industries as it eliminates the effects of financing and accounting strategies (Investopedia, 2010a).

2.14 Free cash flow

Total cash flow of a firm includes adjustment for capital spending and additions to net working capital (Ross *et al.*, 2004). The free cash flow is a measure of financial performance; it is the result of operating cash flows minus capital expenditure (or new fixed capital). The free cash flow is nothing else than the cash that a company is able to generate after laying out the money required to maintain or expand its asset base (Investopedia, 2010b) .

2.15 REFERENCE

- Aden A, Ruth M, Ibsen K *et al.* (2002) Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. NREL.
- Agbogbo F, Coward-Kelly G (2008) Cellulosic ethanol production using the naturally occurring xylose-fermenting yeast, *Pichia stipitis*. *Biotechnology letters*, **30. 9**, 1515-1524.
- Alizadeh H, Teymouri F, Gilbert T, Dale B (2005) Pretreatment of switchgrass by ammonia fiber explosion (AFEX). *Applied Biochemistry and Biotechnology*, **124. 1**, 1133-1141.
- Aziz S, Sarkanen K (1989) Organosolv pulping (a review). *Tappi journal*, **72. 3**, 169-175.
- Badger P (2002) Ethanol from cellulose: A general review. *Trends in new crops and new uses*, 17-21.
- Baker A, Zahniser S (2006) Ethanol reshapes the corn market. Amber Waves. Economic Research Service. USDA 4. (2) 6
- Béguin P (1990) Molecular biology of cellulose degradation. *Annual Reviews in Microbiology*, **44. 1**, 219-248.
- Béguin P, Aubert J (1994) The biological degradation of cellulose. *FEMS Microbiology Reviews*, **13. 1**, 25-58.
- Brealey R, Myers S (1996) *Principles of Corporate Finance* McGraw-Hill.846. 2nd
- Brown L (1981) World Population Growth, Soil Erosion, and Food Security. *Science(Washington)*, **214. 4524**, 995-1002.

- Chakar F, Lucia L, Ragauskas A (2000) Extending the limits of oxygen delignification. International Pulp Bleaching Conference
- Conable D, Volk T (2010) Projecting Cropped Biomass Supplies: The Landowner Factor. Biomass Magazine. BBI (May 2010)
- Coughlan M (1992) Enzymic hydrolysis of cellulose: An overview. *Bioresource technology*, **39. 2**, 107-115.
- Delgenes J, Moletta R, Navarro J (1990) Acid hydrolysis of wheat straw and process considerations for ethanol fermentation by *Pichia stipitis* Y 7124. *PROCESS BIOCHEM. INT.*, **25. 4**, 132-135.
- Delong E (1981) Method of rendering lignin separable from cellulose and hemicellulose in lignocellulosic material and the productsoff produced. *Canadian Patent*, **1096374**.
- Demirba A (1997) Calculation of higher heating values of biomass fuels. *Fuel*, **76. 5**, 431-434.
- Dipardo J (2004) Outlook for biomass ethanol production and demand. *Washington, DC: Energy Information Administration*.
- Doe (2010a) What is ethanol? 2010. http://www.afdc.energy.gov/afdc/ethanol/what_is.html.
- Doe U (2010b) Biomass Feedstock Composition and Property Database. 2010. http://www1.eere.energy.gov/biomass/feedstock_databases.html.
- Draude K, Kurniawan C, Duff S (2001) Effect of oxygen delignification on the rate and extent of enzymatic hydrolysis of lignocellulosic material. *Bioresource technology*, **79. 2**, 113-120.
- Duff S, Murray W (1996) Bioconversion of forest products industry waste cellulose to fuel ethanol: a review. *Bioresource technology*, **55. 1**, 1-33.

- Duffy M, Nanhou V (2001) Costs of producing switchgrass for biomass in southern Iowa. 2010. <http://www.extension.iastate.edu/publications/pm1866.pdf>.
- Edmonds P, Edmonds C, Mcnair F, Olds P, Tsay B, Milam E (2007) *Survey of Accounting*, New York, McGraw-Hill Irwin.560-565.
- Epa (2010) EPA Finalizes Regulation for the National Renewable Fuel Standard Program for 2010 and Beyond. In: *EPA-420-F-10-007*. pp, United States Environmental Protection Agency
- Erickson L, Saket G (2007) Food vs. Fuel. http://www.uoguelph.ca/plant/courses/plnt-6250/pdf/G_Samii-Saket.pdf.
- Ericsson K, Nilsson L (2004) International biofuel trade--A study of the Swedish import. *Biomass and Bioenergy*, **26. 3**, 205-220.
- Faaij A (2006) Bio-energy in Europe: changing technology choices. *Energy Policy*, **34. 3**, 322-342.
- Faaij A (2008) Developments in international bio-energy markets and trade. *Biomass and Bioenergy*, **32. 2008**, 657.
- Fan L, Lee Y, Gharpuray M (1982) The nature of lignocellulosics and their pretreatments for enzymatic hydrolysis. *Microbial reactions*, 157-187.
- Fengel D, Wegener G (1984) Wood: chemistry, ultrastructure, reactions. *Berlin, New York*.
- Finnerty J, Emery D (2004) The value of corporate control and the comparable company method of valuation. *Financial Management*, **33. 1**, 91-99.
- Focus Re (2010) More bioenergy than oil in Sweden. 2010. <http://www.renewableenergyfocus.com/view/9480/more-bioenergy-than-oil-in-sweden/>.

- Frederick W, Lien S, Courchene C, Demartini N, Ragauskas A, Iisa K (2008) Production of ethanol from carbohydrates from loblolly pine: A technical and economic assessment. *Bioresource technology*, **99. 11**, 5051-5057.
- Galbe M, Zacchi G (2002) A review of the production of ethanol from softwood. *Applied microbiology and biotechnology*, **59. 6**, 618-628.
- Galway I (1988) Comparative biochemistry of fungal and bacterial cellulolytic enzyme systems. *Biochemistry and genetics of cellulose degradation*, 11.
- Goldemberg J, Coelho S, Nastari P, Lucon O (2004) Ethanol learning curve--the Brazilian experience. *Biomass and Bioenergy*, **26. 3**, 301-304.
- Gregg D, Saddler J (1996) Factors affecting cellulose hydrolysis and the potential of enzyme recycle to enhance the efficiency of an integrated wood to ethanol process. *Biotechnology and bioengineering*, **51. 4**, 375-383.
- Guerra A, Gaspar A, Contreras S, Lucia L, Crestini C, Argyropoulos D (2007) On the propensity of lignin to associate: A size exclusion chromatography study with lignin derivatives isolated from different plant species. *Phytochemistry*, **68. 20**, 2570-2583.
- Hahn-Hägerdal B, Galbe M, Gorwa-Grauslund M, Lidén G, Zacchi G (2006) Bio-ethanol-the fuel of tomorrow from the residues of today. *TRENDS in Biotechnology*, **24. 12**, 549-556.
- Heinimö Jp, V.; Ojanen, V. And Kässi, T. (2007) Intrnational Bioenergy Trade- scenario study on international biomass market in 2020. LAPPEENRANTA UNIVERSITY OF TECHNOLOGY DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT. Research report 181.
- Hillring B (2006) World trade in forest products and wood fuel. *Biomass and Bioenergy*, **30. 10**, 815-825.
- Holtzapple M, Jun J, Ashok G, Patibandla S, Dale B (1991) The ammonia freeze explosion (AFEX) process. *Applied Biochemistry and Biotechnology*, **28. 1**, 59-74.

Investopedia (2010a) Earnings Before Interest, Taxes, Depreciation and Amortization. 2010. <http://www.investopedia.com/terms/e/ebitda.asp>.

Investopedia (2010b) Free cash flow. 2010. <http://www.investopedia.com/terms/f/freecashflow.asp>.

Jackson Sr, T.; Taylor, A.; Bozell, J. And Norris, K. (2010) Wood2Energy. A State of the Science and Technology Report. The University of Tennessee. Institute of Agriculture.

Jeffries T (1990) Biodegradation of lignin-carbohydrate complexes. *Biodegradation*, **1. 2**, 163-176.

Jin Y, Jameel H, Chang H, Phillips R (2010) Green Liquor Pretreatment of Mixed Hardwood for Ethanol Production in a Repurposed Kraft Pulp Mill. *Journal of Wood Chemistry and Technology*, **30. 1**, 86-104.

Johansson E, Ljunggren S (1994) The Kinetics of Lignin Reactions During Oxygen Bleaching. IV. The Reactivities of Different Lignin Model Compounds and the Influence of Metal Ions on the Rate of Degradation. *Journal of Wood Chemistry and Technology*, **14. 4**, 507-525.

Junginger M, Bolkesjø T, Bradley D *et al.* (2008) Developments in international bioenergy trade. *Biomass and Bioenergy*, **32. 8**, 717-729.

Kim K, Hong J (2001) Supercritical CO₂ pretreatment of lignocellulose enhances enzymatic cellulose hydrolysis. *Bioresource technology*, **77. 2**, 139-144.

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

Lee D, Owens V, Boe A, Jeranyama P (2007) Composition of herbaceous biomass feedstocks. *Brookings, SD: North Central Sun Grant Center*, **16**.

- Leibtag E (2008) Corn Prices Near Record High, But What About Food Costs? *Amber Waves*, **6. 1**, 10-15.
- Lignol (2010) Lignol's organosolv process. 2010. <http://www.lignol.ca/about.html>.
- Lora J, Glasser W (2002) Recent industrial applications of lignin: A sustainable alternative to nonrenewable materials. *Journal of Polymers and the Environment*, **10. 1**, 39-48.
- Lynd L (1996) Overview and evaluation of fuel ethanol from cellulosic biomass: technology, economics, the environment, and policy. *Annual review of energy and the environment*, **21. 1**, 403-465.
- Lynd L, Cushman J, Nichols R, Wyman C (1991) Fuel ethanol from cellulosic biomass. *Science(Washington)*, **251. 4999**, 1318-1323.
- Mabee W, Gregg D, Arato C *et al.* (2007) Updates on softwood-to-ethanol process development. *Applied Biochemistry and Biotechnology*, **129. 1-3**, 55-70.
- Mani S, Sokhansanj S, Bi X, Turhollow A (2006) Economics of producing fuel pellets from biomass. *Applied Engineering in Agriculture*, **22. 3**, 421-426.
- Mcdermott S (2010) Understanding the Economic Drivers of Originating Biomass for Biomass for Power Projects. Biomass Magazine. BBI (May 2010)
- McDonough T (1992) The chemistry of organosolv delignification.
- McDonough T (1996) Oxygen delignification. *DENCE, CW, REEVE, DW Pulp Bleaching. Principles and Practice, TAPPI PRESS, Atlanta*, 215-239.
- Mckendry P (2002) Energy production from biomass (part 1): overview of biomass. *Bioresource technology*, **83. 1**, 37-46.
- Mcmillan J (1994) Pretreatment of lignocellulosic biomass.

- Mielenz J (2001) Ethanol production from biomass: technology and commercialization status. *Current Opinion in microbiology*, **4. 3**, 324-329.
- Mosier N, Wyman C, Dale B, Elander R, Lee Y, Holtzapple M, Ladisch M (2005) Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource technology*, **96. 6**, 673-686.
- Murnen H, Balan V, Chundawat S, Bals B, Da Costa Sousa L, Dale B (2007) Optimization of ammonia fiber expansion (AFEX) pretreatment and enzymatic hydrolysis of miscanthus x giganteus to fermentable sugars. *Biotechnology progress*, **23. 4**, 846-850.
- Ncbc (2010) Biofuels Center of North Carolina. Building a biofuel roadmap to the future. 2010.
<http://www.biofuelscenter.org/index.cfm?page=content&scid1=10&CategoryID=10>.
- Nguyen Q, Tucker M, Keller F, Beaty D, Connors K, Eddy F (1999) Dilute acid hydrolysis of softwoods. *Applied Biochemistry and Biotechnology*, **77. 1**, 133-142.
- Niven R (2005) Ethanol in gasoline: environmental impacts and sustainability review article. *Renewable and Sustainable Energy Reviews*, **9. 6**, 535-555.
- O'sullivan A (1997) Cellulose: the structure slowly unravels. *Cellulose*, **4. 3**, 173-207.
- Pan X, Arato C, Gilkes N *et al.* (2005) Biorefining of softwoods using ethanol organosolv pulping: Preliminary evaluation of process streams for manufacture of fuel-grade ethanol and co-products. *Biotechnology and bioengineering*, **90. 4**, 473-481.
- Parikka M (2004) Global biomass fuel resources. *Biomass and Bioenergy*, **27. 6**, 613-620.
- Perlack R, Wright L, Turhollow A, Graham R, Stokes B, Erbach D (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge National Lab.

- Phillips S (2007) Technoeconomic analysis of a lignocellulosic biomass indirect gasification process to make ethanol via mixed alcohols synthesis. *Ind. Eng. Chem. Res*, **46. 26**, 8887-8897.
- Phillips S, Aden A, Jechura J, Dayton D, Eggeman T (2007a) Thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass. *US Department of Energy, National Renewable Energy Laboratory, NREL/TP-510-41168*, 1-58.
- Phillips S, Aden A, Jechura J, Dayton D, Eggeman T (2007b) Thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass. *NREL: Golden, CO*.
- Rfa (2010) 2010 Ethanol industry outlook. Climate of opportunity. 2010. http://www.ethanolrfa.org/page/-/objects/pdf/outlook/RFAoutlook2010_fin.pdf?nocdn=1.
- Ross S, Westerfield R, Jaffe J (2004) *Corporate finance*, McGraw-Hill. 871. 6th
- Runge C, Senauer B, Romm J, Lovins A, Wirth T, Gray C, Podesta J (2007) Food for Fuel? *Foreign Affairs*. (September/October 2007)
- Saha B (2003) Hemicellulose bioconversion. *Journal of Industrial Microbiology and Biotechnology*, **30. 5**, 279-291.
- Schmidt L, Dauenhauer P (2007) Chemical engineering: hybrid routes to biofuels. *Nature*, **447. 7147**, 914-915.
- Shapouri H, Duffield J, Mcaloon A, Wang M (2004) The 2001 net energy balance of corn-ethanol. *US Department of Agriculture, Washington, DC*.
- Sims R, Hastings A, Schlamadinger B, Taylor G, Smith P (2006) Energy crops: current status and future prospects. *Global Change Biology*, **12. 11**, 2054-2076.

- Sinor J, Bailey B (1993) Current and potential future performance of ethanol fuels.
- Sousa L, Balan V, Chundawat S, Dale B (2007) Enzymatic hydrolysis of AFEX treated corn stover and Miscanthus at high solid loadings.
- Sun Y, Cheng J (2002) Hydrolysis of lignocellulosic materials for ethanol production: a review* 1. *Bioresource technology*, **83. 1**, 1-11.
- Sun Y, Cheng J (2005) Dilute acid pretreatment of rye straw and bermudagrass for ethanol production. *Bioresource technology*, **96. 14**, 1599-1606.
- Tenenbaum D (2008) Food vs. fuel: Diversion of crops could cause more hunger. *Environmental Health Perspectives*, **116. 6**, A254.
- Thek G, Obernberger I (2004) Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. *Biomass and Bioenergy*, **27. 6**, 671-693.
- Tohka Ak, N.; Savolahti, M. And Kupiainen, K. (2009) Finland's Long Term Climate and Energy Strategy-Emission Projections. 2010. http://www.unece.org/env/lrtap/TaskForce/tfiam/35/tfiam35_Tohka_NationalFinland.pdf.
- Vidal P, Molinier J (1988) Ozonolysis of lignin--Improvement of in vitro digestibility of poplar sawdust. *Biomass*, **16. 1**, 1-17.
- Von Blottnitz H, Curran M (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.
- Weil J, Westgate P, Kohlmann K, Ladisch M (1994) Cellulose pretreatments of lignocellulosic substrates. *Enzyme and microbial technology*, **16. 11**, 1002-1004.

- Wheals A, Basso L, Alves D, Amorim H (1999) Fuel ethanol after 25 years. *TRENDS in Biotechnology*, **17. 12**, 482-487.
- Wingren A, Galbe M, Zacchi G (2003) Techno-economic evaluation of producing ethanol from softwood: Comparison of SSF and SHF and identification of bottlenecks. *Biotechnology progress*, **19. 4**, 1109-1117.
- Wooley R, Ruth M, Sheehan J, Ibsen K, Majdeski H, Galvez A (1999) Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis current and futuristic scenarios. NREL
- Wright J (1988) Ethanol from biomass by enzymatic hydrolysis. *Chemical Engineering Progress*, **84. 8**, 62-74.
- Wyman C (2007) What is (and is not) vital to advancing cellulosic ethanol. *TRENDS in Biotechnology*, **25. 4**, 153-157.
- Wyman C, Goodman B (1993) Near term application of biotechnology to fuel ethanol production from lignocellulosic biomass. National Institute of Standard and Technologies. 93.
- Yang R, Lucia L, Ragauskas A, Jameel H (2003) Oxygen delignification chemistry and its impact on pulp fibers. *Journal of Wood Chemistry and Technology*, **23. 1**, 13-29.
- Zheng Y, Lin H, Tsao G (1998) Pretreatment for cellulose hydrolysis by carbon dioxide explosion. *Biotechnology progress*, **14. 6**, 890-896.

3 RESEARCH OBJECTIVES

Biomass delivered cost; features affecting ethanol conversion yield and conversion profitability have been studied. At the first stage this study deals with the simulation of biomass delivered cost of fast growing and high productive *Eucalyptus sp.* in Southern U.S. looking at possible biomass productivities, acres required to supply specific annual volumes, chemical composition in the biomass and costs to establish and grow Eucalyptus biomass. Harvesting and freight costs are considered in this formula to understand biomass delivered cost at different annual supply, percentage of covered area and site productivities. In a second stage the performance of *Eucalyptus* biomass is simulated in a co-current dilute acid process followed by enzymatic hydrolysis to understand possible conversion costs, effect of carbohydrate and lignin content in biomass in the conversion yield, as well as to identify key cost driver. In a third stage loblolly pine, one of the most important softwood species in Southern U.S. traditionally managed for long rotation length, is simulated with a silviculture model in order to understand biomass productivity related to short rotation length and high initial stand tree densities, the analysis includes biomass delivered costs, effect of covered area in biomass supply costs and delivered cost of carbohydrate. In a fourth study, a evaluation of seven different feedstocks (loblolly pine, natural mixed hardwood, Eucalyptus, switchgrass, miscanthus, corn stover and sweet sorghum) is made in terms of supply chain, biomass delivered costs, \$ per ton of carbohydrate and \$ per million BTU delivered to a biorefinery. Forest feedstocks present better advantages in terms of a well established

supply chain, year round supply and no need for biomass storage. In the same context biomass delivered costs, as well as cost to delivered one ton of carbohydrate and one million BTU is lower in forest feedstock. In a fifth study, conversion costs, profitability and sensitivity analysis for a novel pretreatment process, green liquor, are modeled for ethanol production with loblolly pine, natural mixed hardwood and Eucalyptus as feedstock, evaluated in two investment scenarios green field and repurposing of an old kraft pulp mill. Better financial returns are perceived in the repurposing scenario, mainly due to lower CAPEX, and in terms of feedstock natural hardwood and Eucalyptus outperform because of lower enzyme charge and cost. Finally, In the sixth study, conversion cost, CAPEX, ethanol yield and profitability for the thermochemical process (indirect gasification and production of mixed alcohol) is simulated for loblolly pine, natural hardwood, eucalyptus, corn stover and switchgrass. Higher ethanol yield in the forest feedstock, due to its higher content of %C and %H result in better economic performance.

Therefore, the main objectives of the present study are going to be addressed in the form of chapter as follow: Eucalyptus biomass delivered cost (exploring potential of this species for biomass to energy (chapter 4); Process simulation and conversion costs of eucalyptus for cellulosic ethanol production (chapter 5); Biomass supply and silviculture of loblolly pine; Biomass to cellulosic ethanol in southern us: supply chain and delivered cost of seven different feedstock (chapter 6), Economics of cellulosic ethanol production: green liquor pretreatment for softwood and hardwood - greenfield and repurpose scenarios, and as a final section (chapter 7) it is studied the Economics of cellulosic ethanol production in a

thermochemical pathway for softwood, natural hardwood, eucalyptus, corn stover and switchgrass.

4 Exploring the Potential of *Eucalyptus* for Energy Production in the Southern United States: Financial Analysis of Delivered Biomass

4.1 Abstract

Eucalyptus plantations in the Southern United States offer a viable feedstock for renewable bioenergy. Delivered cost of eucalypt biomass to a bioenergy facility was simulated in order to understand how key variables affect biomass delivered cost. Three production rates (16.8, 22.4 and 28.0 Mg ha⁻¹ y⁻¹, dry weight basis) in two investment scenarios were compared in terms of financial analysis, to evaluate the effect of productivity and land investment on the financial indicators of the project. Delivered cost of biomass was simulated to range from \$55.1 to \$66.1 per delivered Mg (with freight distance of 48.3 km from plantation to biorefinery) depending on site productivity (without considering land investment) at 6% IRR. When land investment was included in the analysis, delivered biomass cost increased to range from \$65.0 to \$79.4 per delivered Mg depending on site productivity at 6% IRR. Conversion into cellulosic ethanol might be promising with biomass delivered cost lower than \$66 Mg⁻¹. These delivered costs and investment analysis show that *Eucalyptus* plantations are a potential biomass source for bioenergy production for Southern U.S.

4.2 Introduction

The United States is in need of alternative energy sources to reduce the dependence on foreign suppliers of petroleum. The development of an alternative energy industry will also improve the cash flow balance of the country. The U.S. Energy Policy Act of 2005 calls for an increase production from 17 thousand million liters of ethanol in 2005 to 28.4 thousand million liters by 2012 by providing unprecedented federal support via research grants (Somerville, 2006). Several States in the U.S. are also creating centers to promote and support research in the areas of biofuel and biomass utilization (NCBC, 2009). Moreover, the U.S. Energy Secretary proposed the replacement of almost 30% of ground transportation fuel by alternative clean energy (an equivalent to 227 thousand million liters of ethanol) by 2030. Effects of the 2005 Energy Policy Act can be seen in both ethanol production and raw material prices (for ethanol production). In 2008 the total production of ethanol was almost 34.1 thousand million liters with a total of 139 biorefineries online across the country. This remarkable increase compares to ~14.8 thousand million liters and 81 biorefineries online in 2005; ~18.5 thousand million liters and 95 biorefineries in 2006; ~24.6 thousand million liters of ethanol and 110 biorefineries in 2007 and with forecasts of ~39.7 thousand million liters of ethanol and 170 biorefineries for 2010 (RFA, 2009). There was also a clear effect on raw material prices, mainly corn, with rising prices until mid 2008 (Hofstrand, 2008, Hofstrand, 2009, USDA, 2009) and with falling prices after late 2008 (RFA, 2009, USDA, 2009). The price drop may be explained by the derived low demand of ethanol-gasoline

during the accentuated financial crisis in the U.S. These episodes stimulated the debate of food versus fuel, bringing in the need for non food base lingo-cellulosic raw materials.

Additionally, a United States Forest Service (USFS) report suggests the possibility to sustainably produce ~1.2 thousand million dry tons of cellulosic biomass across the nation (Perlack *et al.*, 2005). The report's emphasis is mainly in biomass production and availability with little information regarding the delivered cost of the biomass. Understanding that biomass delivered cost is a key variable driving the profitability of the overall process, intensive research has been done to determine optimum conditions around biomass management, production, chemical and physical properties of the biomass as well as delivered costs (Desmond, 2009, Eaton, 2009, Eggeman, 2009, Gonzalez *et al.*, 2009b, Jackson, 2009, Perlack *et al.*, 2005, Schmer *et al.*, 2008, Scott & Tiarks, 2008, Swayze, 2009).

The hypothesis that biomass would be free or at low cost is no longer accepted even for forest waste collection or agriculture residues. For the case of dedicated bioenergy crops such as switchgrass, coastal bermuda grass, pine as well as hardwood plantations, cost drivers include crop establishment, maintenance, harvesting, freight and storage (this last when required). Studies in switchgrass have reported production costs ranging from \$72 to \$84 Mg⁻¹ (dry weight basis) (Kumar & Sokhansanj, 2007). For the same biomass, delivered costs including harvesting, storage and freight range from \$37 to \$47 per Mg, while farming costs range from \$30 to \$36 Mg⁻¹ (Bransby *et al.*, 2005, Kumar & Sokhansanj, 2007). In the case

of forest biomass, the cost of clean hardwood chips at mill gate for the Southern United States in 2007 ranged from \$35.6 to \$49.6 per green Mg (green weight basis), equivalent to ~\$65-\$90.2 Mg⁻¹; while clean softwood chips ranged from \$33.62 to \$49.6 green Mg⁻¹ (~\$61.2 to \$90.4 Mg⁻¹) (Timber-Mart-South, 2007) .

An ideal bioenergy crop would have the following features: high productivity per hectare (to decrease the amount of hectares needed to supply a specific demand), low establishment, maintenance and harvesting costs that together with higher bulk density would permit lower delivered costs, year round supply from the farm (to avoid storage), and competitive content of chemical components such as carbohydrates and lignin that influence conversion to energy efficiencies, and competitive amounts of key elements such as percent of carbon, hydrogen, oxygen and nitrogen that are important for thermochemical and pyrolysis process yields.

4.2.1 An alternative

Eucalyptus is among the fastest growing hardwood plantation genus in the world. In addition, eucalypts have been used for plantation grown bioenergy production in numerous countries (as well as for fiber supply), with practical studies in Australia, Hawaii (USA), Ireland, South Africa, Brazil, Uruguay, Venezuela (Forrest & Moore, 2008, Gonzalez *et al.*, 2008, González *et al.*, 2004, Keffer *et al.*, 2009, Liu *et al.*, 1993, Surles *et al.*, 2007, Turn *et al.*, 2005) . The native range of *Eucalyptus* is primarily Australia with a few species also native from Indonesia and Papua New Guinea. While there are more than 700 species, less

than 20 of these species have been widely planted outside their native range. Seed movement of *Eucalyptus* became important in the mid 1800's due to the need for timber in the gold mines of South Africa as well as a wood source to fuel steam locomotives in Brazil. Species introductions were taking place in other parts of the world at about the same time including the United States (Turnbull, 1999, Wright, 1997b, Zobel *et al.*, 1987).

Seed introductions of *Eucalyptus* species in the United States were focused primarily in Florida (Zon & Briscoe, 1911) and California (Moore, 1983) due to climatic similarities with Australia. The Australian government, as well as private seed collectors and dealers, have been the providers for seed from the native range of *Eucalyptus* for many years. *Eucalyptus* species from Indonesia and Papua New Guinea are largely too tropical for use in the United States, except for Hawaii, and access in these remote areas makes seed collection difficult.

In most instances, initial introductions focused on finding species that would produce seedlings in a nursery and survive typical field planting conditions. The next steps were to select species for provenance testing followed by wider testing that would lead to wood utilization studies. In addition to conventional genetic improvement, clonal forest plantations of various eucalypt species were developed in a number of countries (Wright, 1992, Wright, 1995, Wright, 1997a, Wright & Rosales, 2001). There was very little if any attention given to silviculture in the early days (pre-1970) of testing. Expertise in silviculture has developed

successful *Eucalyptus* plantations in several countries (Gonçalves *et al.*, 2004, Schönau, 1984).

4.2.2 Silviculture for Eucalyptus Bioenergy Plantations in the Southern US:

Eucalyptus plantations in Southern U.S. can be successfully established using freeze tolerant improved seedlings in some specific regions as shown in Figure 4.1. The best plantation growth will be realized with timely and adequate silvicultural management. One of the key success elements is an early start in the process. Site selection should be done in late winter or early spring to allow a fall planting. For pulpwood planting densities of 1,000 to 1,500 trees per hectare and for bioenergy 2,965 trees per hectare are suggested. Harvest systems must be considered before site preparation commences. Eucalypts prefer moderately well drained soils with some degree of clay content for water retention (Wright, 1992, Wright, 1997b, Wright & Rosales, 2001).

Site preparation should consist of chemical and mechanical methods. Chemical site preparation will depend on post-harvest re-growth but generally will include a summer broadcast application. Mechanical site preparation will consist of bedding or sub-soiling. Old-field sites will need to be ripped and sub-soiled. Planting season will vary depending on use of irrigation and historical timing of early and late frosts (Wright, 1992, Wright, 1997b, Wright & Rosales, 2001).



Figure 4-1 Regions where freeze tolerant eucalypt species can grow

Near the date of planting, a broadcast application of 168-224 kg ha⁻¹ of triple super phosphate on phosphorous-deficient sites is suggested. After crown closure at age 2-3 years, broadcast application of 180-224 k ha⁻¹ of urea is suggested. Weed control must be adequate before any nitrogen application. Complete weed control in the 1st year should be the objective and this will include herbaceous weed control. Currently, the only practical means to accomplish this is with a directed spray. In the second year, a directed-spray may be required.

Rotation length and yields for pulpwood can be 7 to 8 years with a mean annual increment (MAI) of 18 to 36 green Mg ha⁻¹ y⁻¹ (10 to 20 Mg ha⁻¹ y⁻¹, dry weight basis), while

biomass for bioenergy can be 3 to 4 years with a MAI of 22 to 40 green Mg ha⁻¹ y⁻¹ (12.3 to 22.4 Mg ha⁻¹ y⁻¹) (Gonzalez *et al.*, 2009a). Variability in these predictions is due to soil, climate and management variance. Coppice management is suggested on many eucalypt stands worldwide. This involves allowing the stump to coppice and at the end of the first growing season to mechanically thin to the single best coppice sprout per stump. Coppice management greatly reduces re-establishment costs.

In Southern United States, a large effort to test *Eucalyptus* species and provenances was undertaken by companies and universities in the 1970's. Few, if any, of these plantings still exist but the information gathered on species adaptability is important. Identified as having potential to grow in the Southern United States were *Eucalyptus camaldulensis*, *E. benthamii*, *E. viminalis*, *E. macarhturii*, *E. grandis*, *E. robusta*, *E. saligna* and the hybrid *E. urograndis*. Current field trials with freeze tolerant eucalypt species growing in Southern U.S. show that it is possible to grow eucalypt bioenergy plantations in the area inside the circle in Figure 2.6. *Eucalyptus* is climate limited to some region in Southern U.S. (Gonzalez *et al.*, 2009a, Gonzalez *et al.*, 2009b).

This paper focuses on the potential of *Eucalyptus* plantations in the Southern United States as a bioenergy raw material evaluating simulated delivered costs and investment scenarios for biomass supply.

4.3 Material and methods

A series of steps were followed in order to obtain the most reliable and accurate information to develop the financial models. The first step was a literature review to gather information regarding eucalypt species, harvesting practices, costs, as well as other relevant information. A group of experts from industry and universities were contacted to collect and verify the information that supports the models.

Once all the information was collected and processed, establishment and maintenance spreadsheet models were developed and connected with harvesting and freight models to determine delivered costs. Information about updated costs was obtained from current loggers and forest managers in business in the Southern U.S (Dougherty, 2008, Mark, 2009). Maintenance and establishment costs were simulated based on yearly cash flow and modeled in an income statement to determine net present value (NPV) and internal rate of return (IRR).

Productivity sensitivity scenarios were measured in three levels: low (0.75), medium (1.0) and high (1.25), relative to a central assumption of 22.4 Mg ha⁻¹ y⁻¹ (dry weight basis).

4.3.1 General assumptions

Several assumptions were defined in order to create the models and estimated biomass delivered costs. These assumptions are described next:

4.3.1.1 Investment scenarios

Two investment scenarios were analyzed, one including land purchase called investor supply chain (ISC) scenario and another without land purchase called biomass division supply chain (BDSC) scenario. For both scenarios freight cost per kilometer is the same and is charged as current market price from outsourcing companies. Harvesting cost has a fixed dollar per green Mg, using prices consistent with the information obtained from loggers and forest managers currently in business. The analysis was performed for 6, 8 and 10% rate of return with the delivered price ($\$ \text{Mg}^{-1}$) back calculated using Goal Seek, a Microsoft Excel ® tool (prices were back calculated to achieve each of the internal rate of returns).

4.3.1.2 Moisture content

For all scenarios and growing rates, moisture content is kept constant at 45%. This moisture content value is representative of fresh harvested *Eucalyptus* logs.

4.3.1.3 Rotation length

A rotation length of five years for bioenergy production is considered. Following harvest the stands are replanted. Five years is a common rotation length for *Eucalyptus*

pulpwood production in South America. Nevertheless, for bioenergy it is expected to have lower rotation length which would make this genus more attractive as raw material for this industry.

4.3.1.4 Productivity

An average productivity (medium scenario) of 22.4 Mg ha⁻¹ y⁻¹ is the main assumption with low scenario of 16.8 Mg ha⁻¹ y⁻¹ and high scenario of 28.0 Mg ha⁻¹ y⁻¹. The total volume considers the entire tree including limbs, bark, branches and leaves. These values of production are taken from current trials in Florida (Gonzalez *et al.*, 2009a, Gonzalez *et al.*, 2009b, Hinchee *et al.*, 2009).

4.3.1.5 Tree density

For this analysis, 1483 trees per hectare is used. Current trials in Florida and Georgia are established with this initial tree stand density. Nevertheless, there are pilot plantations looking to understand the tradeoff between biomass productivity and establishment costs at higher stand tree densities.

4.3.1.6 Supply production per year

The annual supply considered for this analysis is 453,592 Mg y⁻¹ of delivered biomass from the *Eucalyptus* plantations (the annual volume was originally calculated in dry short ton per year to an equivalent of 500,000 dry short tons), which could be a representative size for biorefinery ethanol plants.

4.3.1.7 Chemical composition

The chemical composition used for this analysis is an average based on nine different genotypes of *Eucalyptus x urograndis* (Gomides *et al.*, 2006), presented in Table 4.1.

Table 4-1 Average chemical components for eucalypts (Gomides *et al.*, 2006)

Chemical component	% *
Glucans	44.6
Xylans	12.8
Galactans	0.5
Mannans	0.5
Arabinans	0.3
Uronic acid	4.4
Acetyl	2.9
Lignin	30.1
Resins	3.6
Ash	0.3

*Based on dry mass

The information regarding the amount of carbohydrate (Table 1) will be used along with the delivered cost to determine the dollar per Mg (dry weight basis) of delivered carbohydrate.

4.3.2 Financial analysis assumptions

4.3.2.1 *Life time of the project:* 30 years.

4.3.2.2 Discount rate: A discount rate for evaluation of net present value is used at 6% per year.

4.3.2.3 Land value: In the case of investor analysis, a fixed price of \$2,471 per hectare is charged; this represents a cash outflow in the free cash flow section at the beginning of the project. This investment in land is assumed to appreciate at a rate of 1% per year for the life time of the project. In year 30, the capitalized value of the land is assumed to be sold and contributes to the terminal value of the project.

4.3.2.4 Terminal value: For the Investor Supply Chain scenario, the terminal value of the project is composed of the capitalized value of the land and the deferred charges for plantations still standing in year 30 of the project. For the Biomass Division Supply Chain scenario, the terminal value is related only to the deferred charges of the standing plantations at year 30.

4.3.2.5 Deferred charges: Deferred charges are the cash outflows per year invested in plantation establishment and maintenance. These amounts are not represented in the income statement at the time of plantation establishment; instead, these investments are considered assets and would appear in the balance sheet without affecting the income statement. When the plantation is sold or harvested the deferred charges are converted into costs through depletion. This depletion is consistent with the Internal Revenue Service (IRS) (IRS, 2007).

4.3.2.6 **Rate of return:** For most of the analysis a rate of return of 6% is used to back calculate biomass delivered costs. Sensitivity analysis is then performed at 8% and 10%.

4.3.2.7 **Equity:** An equity of 100% was assumed, therefore there is no finance charge.

4.3.2.8 **Depletion:** Depletion is the deferred charge invested in the plantation establishment and maintenance represented in the income statement at the moment that the forest is harvested or sold. Depletion rate is the ratio of the total deferred charges amount for that specific plantation track divided by the total volume of biomass extracted. This is consistent with the definition used by the IRS (IRS, 2007).

4.3.2.9 **Currency:** All currency amounts are in U.S. dollars.

4.4 Results and discussion

4.4.1 Establishment and maintenance costs

In this section a complete analysis of the results obtained are discussed and evaluated. Average establishment and maintenance costs are estimated at \$1341 ha⁻¹. Cost drivers for this average are presented in Figure 4.2. Higher costs are represented by seedlings (at \$0.25 seedling⁻¹), land preparation, weed control (pre-planting and post-planting), fertilization and plantation establishment. Total establishment and maintenance cost will vary depending on the type of forestland, drainage, and land preparation, amongst others. A cost of \$1341 ha⁻¹

might represent average plantation establishment conditions. Research efforts are underway by companies and universities to reduce this cost.

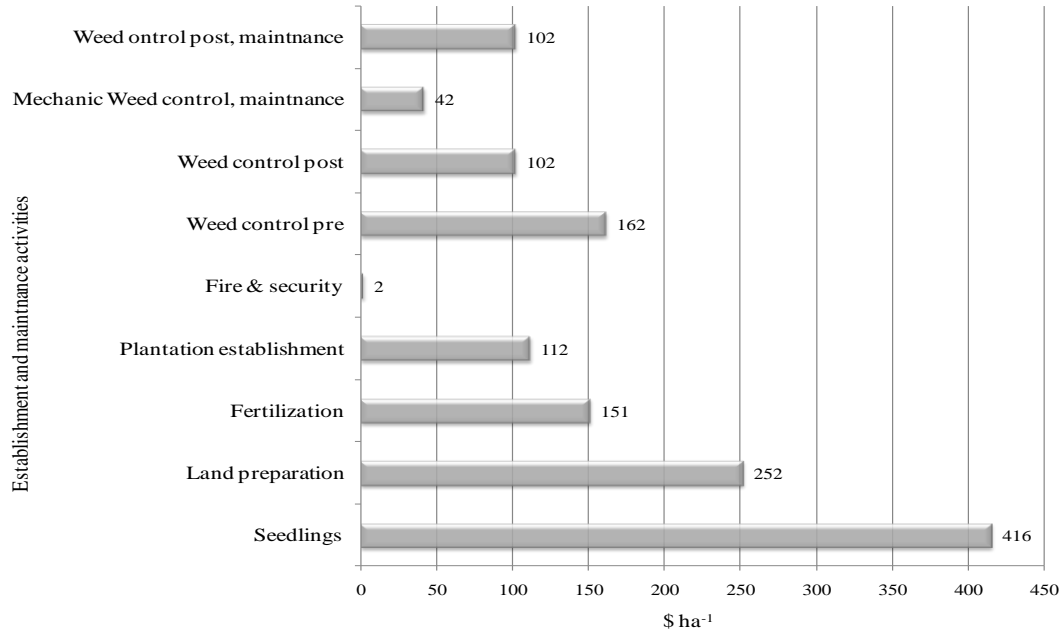


Figure 4-2 Establishment and maintenance cost per hectare for eucalypt plantations in the Southern U.S.

4.4.2 Harvesting and freight

Harvesting cost is assumed to be \$16.7 per green Mg (or ~ \$30.4 Mg⁻¹ dry weight basis). Freight cost is estimated to be \$6.36 green Mg⁻¹ (or \$11.6 Mg⁻¹), for an average distance of 48.3 km (freight distance plantation site to biorefinery). Freight is composed of two components: fixed and variable. The fixed rate is the charge per hour for loading and unloading waiting time. The variable component is based on a charge per mile of loaded truck.

4.4.3 Biomass delivered costs

Delivered costs of eucalypt biomass ($\$ \text{Mg}^{-1}$ dry weight basis) for a 48.3 km of distance was back calculated for three biomass productivity rates per hectare to achieve internal rate of returns of 6%, 8% and 10% IRR. Figure 4.3 shows the delivered cost of eucalypt biomass and component costs (in 48.3 miles of distance) for the three biomass productivity rates of 16.8, 22.4 and 28 $\text{Mg ha}^{-1} \text{y}^{-1}$ back calculated to achieve at 6% IRR in the Biomass Division Supply Chain Scenario.

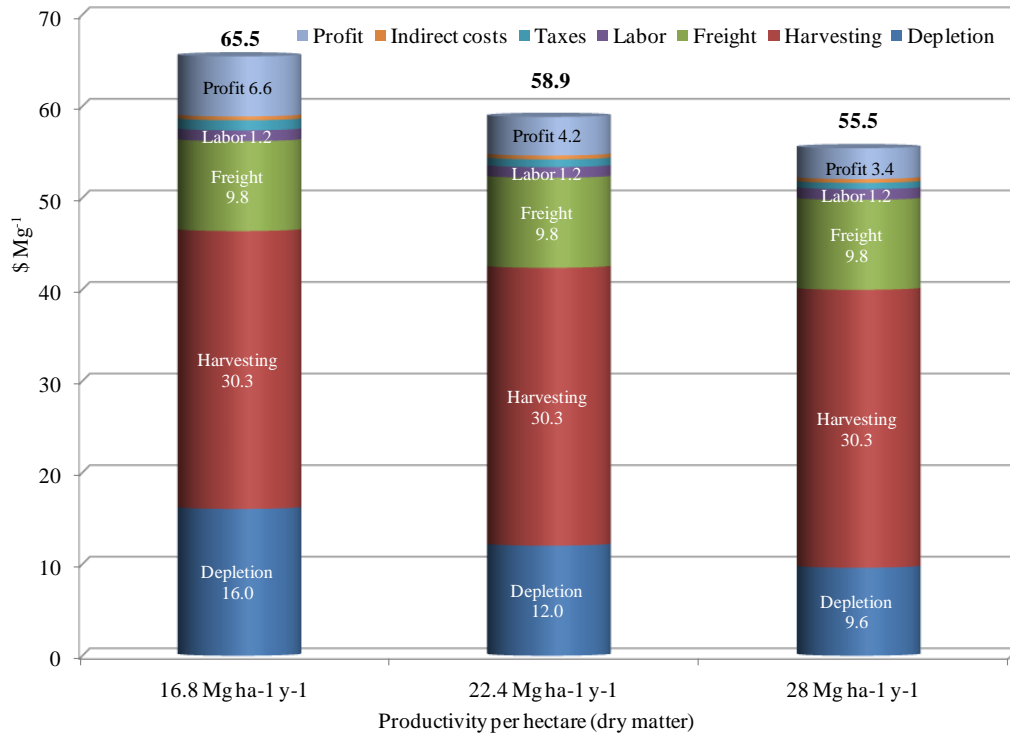


Figure 4-3 Eucalypt biomass delivered costs and component costs ($\$ \text{Mg}^{-1}$) back calculated to achieve 6% IRR in Southern U.S. Biomass Division Supply Chain scenario

4.4.4 Biomass division supply chain scenario

From figure 2.8, delivered cost ranged from ~ \$55.5 Mg⁻¹ (at a site productivity of 28 Mg ha⁻¹ y⁻¹) to \$65.5 Mg⁻¹ (at a site productivity of 16.8 Mg ha⁻¹ y⁻¹). In terms of delivered cost in green weight basis, the range was from \$30.5 to \$36 per green Mg. A lower productivity per hectare requires a higher quantity of hectares to supply a specific volume per year. Thus, the cash outflow in deferred charges (plantation establishment and maintenance) is higher and there is a higher cost of depletion per Mg (see depletion cost in figure 4.3). Higher productivity would decrease the amount of hectares to plant and harvest thus reducing the depletion rate per Mg. The after tax profit-margin is lower at higher productivity as prices are back calculated to achieve a specific rate of return, in this case 6% IRR.

Higher expected internal rate of returns will result in higher delivered cost of biomass (keeping constant the freight sourcing distance 48.3 km). Figure 4.4 shows the back calculated delivered cost of eucalypt biomass at three different productivity rates of 16.8, 22.4 and 28.0 Mg ha⁻¹ y⁻¹ to achieve three different internal rates of return (6%, 8% and 10%). The lowest delivered cost resulted in the least costly option at 28.0 Mg ha⁻¹ y⁻¹ and 6% IRR (at \$55.5 Mg⁻¹), while the highest cost is for site productivity of 16.8 Mg ha⁻¹ y⁻¹ at 10% IRR, with biomass delivered costs at \$69.8 Mg⁻¹.

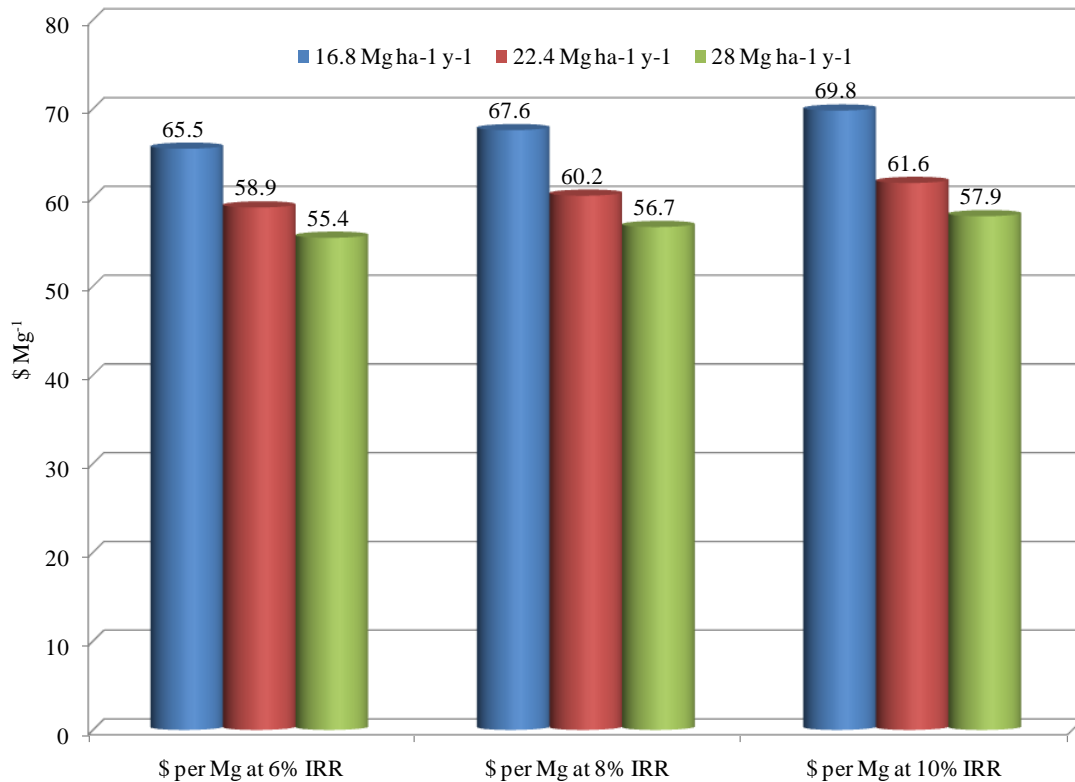


Figure 4-4 Biomass delivered cost (\$ Mg⁻¹) at 6%, 8% and 10% IRR and at 16.8, 22.4 and 28 Mg ha⁻¹ y⁻¹ for eucalypt plantations in the Southern U.S.

4.4.5 Investor supply chain scenario

To better understand the delivered cost of eucalypt biomass in the Investor Supply Chain scenario, it is important to consider the effect of biomass productivity per hectare (Mg ha⁻¹ y⁻¹) on the total amount of hectares required to supply a specific amount of biomass. Figure 4.5 shows the amount of plantable (net) hectares required to supply 453,592 Mg y⁻¹. In site productivity of 16.8 Mg ha⁻¹ y⁻¹, the area required to supply that annual volume is

5,422 ha y⁻¹ for a total of ~27,114 ha⁻¹ given the five years rotation, while for a site productivity of 28 Mg ha⁻¹ y⁻¹, the annual net harvesting area and total area for continuous production are 3,254 hectares and 16,268 hectares respectively . The investment in net land for production may be as high as \$67 million (at 16.8 Mg ha⁻¹y⁻¹), while for higher productivities, an area of 3,254 ha to harvest each year for a total area of ~16,268 ha (for a five years rotation) decreases the land investment to \$40.2 million. This difference in land investment considerably impacts the delivered cost to achieve a specific rate of return, as the values used to calculate the internal rate of return are based on the free cash flow of the project. The consideration of land investment in the Investor Supply Chain scenario provides useful information for a more complete financial evaluation of the project.

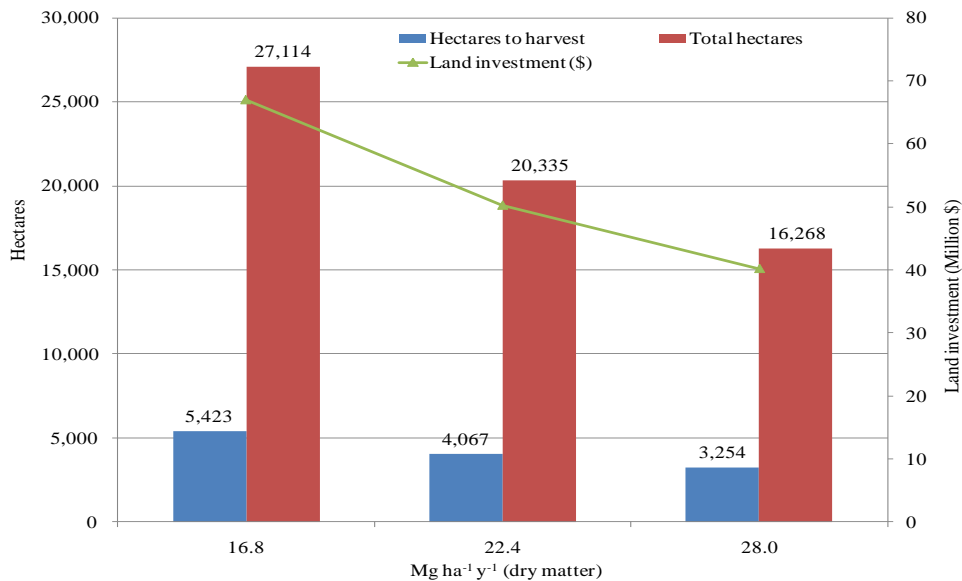


Figure 4-5 Effect of productivity (Mg ha⁻¹ y⁻¹) on net plantable area and land investment for eucalypt plantations in Southern U.S.

Eucalyptus biomass delivered cost for the Investor Supply Chain scenario is highly impacted when land investment is taken into consideration. Figure 4.6 displays *Eucalyptus* delivered cost and component costs at three different levels of productivity: 16.8, 22.4 and 28.0 Mg ha⁻¹ y⁻¹ back calculated to achieve 6% IRR. The lowest delivered cost in this scenario is \$64 Mg⁻¹ for a site productivity of 28 Mg ha⁻¹ y⁻¹. Depending on site productivity delivered cost can be as high as \$79.6 Mg⁻¹. Certainly the investment in land for production does not affect the income statement or the costs per se, as the land investment affects the asset in the balance sheet, yet in terms of financial analysis, a higher cash outflow means a higher \$ Mg⁻¹ in order to achieve targeted levels in IRR. Depletion cost goes from \$16.0 Mg⁻¹ (for a site productivity of 16.8 Mg ha⁻¹ y⁻¹) to \$9.6 Mg⁻¹ (for a site productivity of 28.0 Mg ha⁻¹ y⁻¹). Profit per Mg is larger compared to the Biomass Division Supply Chain scenario as the delivered cost of the biomass in the Investor Supply Chain scenario is higher to compensate the cash outflows in land investment.

4.4.6 Carbohydrate delivered costs

Based on the information provided in Table 1 regarding the amount of chemical components in dry mass basis, the total average percentage of carbohydrate is 66%. This includes the following components: glucan, xylan, galactan, mannan, arabinan, uronic acid and acetyl. Average lignin value is ~ 30.1%, resin ~3.6% and ash ~0.3%.

Average delivered carbohydrate cost is obtained by dividing the delivered cost of *Eucalyptus* biomass by the average percentage of carbohydrate. Figure 4.7 shows the average delivered

cost of carbohydrate for both Investor Supply Chain and Biomass Division Supply Chain scenarios for a productivity of 22.4 Mg ha⁻¹ y⁻¹, freight distance of 48.3 km and annual supply of 453,592 Mg y⁻¹, with biomass delivered costs back calculated to achieve 6%, 8% and 10% IRR. The cost per Mg of carbohydrate ranges from \$93.7 Mg⁻¹ (BDSC scenario) to \$121.3 Mg⁻¹ (ISC scenario) for a 10% IRR; with lower carbohydrate delivered costs of \$89.3 to \$103.6 Mg⁻¹ of carbohydrate for a 6% IRR. The difference in delivered cost is due to different levels of IRR for each of the cases and the land investment for the Investor Supply Chain scenario. This reference value of dollars per Mg of carbohydrate is extremely important to the biorefinery industry to compare different types of biomass. This is especially true in those cases where biomass chemical components in the form of carbohydrate determine the efficiency of conversion processes such as fermentation

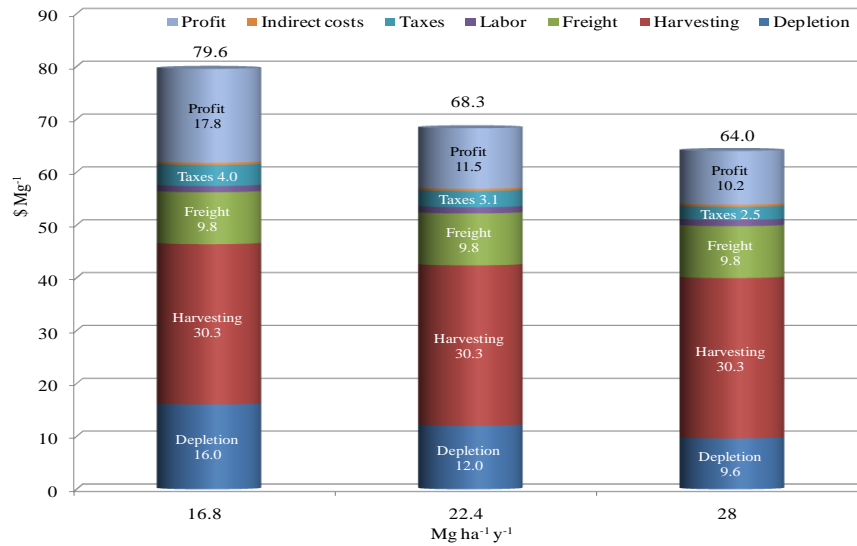


Figure 4-6 Eucalypt biomass delivered cost and component costs, Investor Supply Chain Scenario, \$ Mg⁻¹ back calculated to achieve 6% IRR at 16.8, 22.4 and 28 Mg ha⁻¹ year⁻¹.

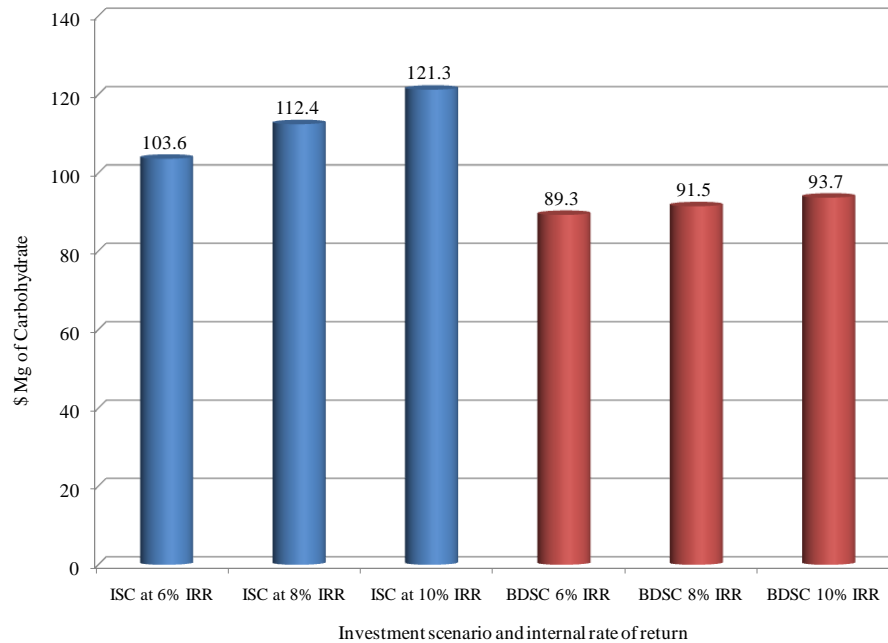


Figure 4-7 Eucalyptus carbohydrate delivered costs in the Investor Supply Chain and Biomass Division Supply Chain Scenarios, back calculated to achieve 6%, 8% and 10% IRR, at a productivity of 16.8 Mg ha⁻¹ y⁻¹.

4.4.7 Depletion, revenue, EBITDA, new fixed capital and deferred charges and free cash flow trends

Figure 4.8 shows the trends of revenue, depletion, EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization), new fixed capital and deferred charges and free cash flow for the Investor Supply Chain scenario for a 6% IRR and supply of 453,592 Mg y⁻¹ of *Eucalyptus* biomass (with a freight distance 48.3 km and annual productivity of 22.4 Mg ha⁻¹ y⁻¹). Revenue occurs after year five and is positive for the rest of the project

life, in the same way depletion occurs after year five when plantations begin to be harvested. The new fixed capital and deferred charges line is negative from year zero through year 29, representing cash outflows in land investment as well as establishment and maintenance cost. New fixed capital and deferred charges in become positive in year 30 as a result of the assumption that forestland is sold. EBITDA is positive after year five as a result of after tax profit (positive trends) and depletion which is a tax incentive. Free cash flow used to measure the IRR and NPV of the project is negative from year zero to year six, and then positive for the rest of the project life. Free cash flow is an important indicator as more free cash flow could make it possible to reinvest in the business as well as to pay debts or distribute dividends.

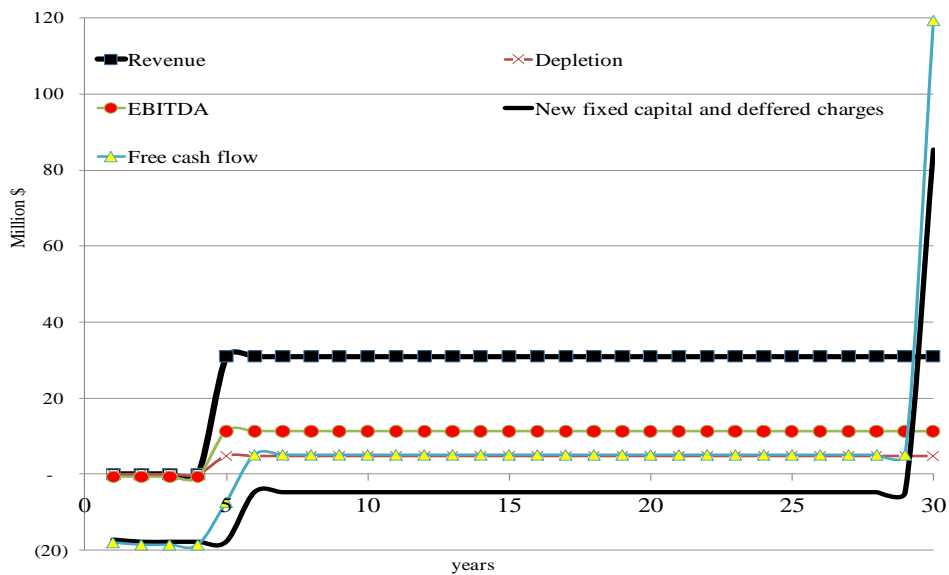


Figure 4-8 Revenue, Depletion, EBITDA, New fixed capital and Deferred charges at 6% IRR and supply of 453,592 Mg y-1 of eucalypt biomass for the ISC scenario considering productivity of 22.4 Mg ha-1 y-1.

4.4.8 Effect of forest covered area and annual demand on biomass delivered cost

There are specific variables in the supply chain logistic that greatly affect biomass delivered cost. For example, freight distance and thus freight cost varies depending on: annual supply, productivity of the crop ($\text{Mg ha}^{-1} \text{ y}^{-1}$), rotation length and the percentage of covered area with that specific plantation around the biomass facility (CERES, 2009).

The percentage of covered area is determined based on the actual percentage of area under that specific biomass taking in consideration biomass productivity per hectare ($\text{Mg ha}^{-1} \text{ y}^{-1}$) and rotation length. The percentage of covered area together with biomass productivity, and rotation length, determine the maximum sourcing freight distance to achieve the targeted supply per year. To consider this percentage, it is important to understand that this fraction of area is not the amount of hectares of *Eucalyptus* plantation around the biorefinery but instead it refers to the amount of hectares with *Eucalyptus* around the biorefinery with a supply agreement between the biorefinery and the forestland owner(s) or biomass division(s). Figure 4.9 shows the effect of percentage of cover area around the biomass facility on freight ($\text{\$ Mg}^{-1}$) and delivered cost ($\text{\$ Mg}^{-1}$ delivered), assuming a productivity of $22.4 \text{ Mg ha}^{-1} \text{ y}^{-1}$ and annual supply of $453,592 \text{ Mg y}^{-1}$.

As presented in Figure 4.10 when the forest cover area increases from 2% to 25% there is a dramatic drop in freight cost, from $\text{\$}11.3 \text{ Mg}^{-1}$ to $\text{\$}4.4 \text{ Mg}^{-1}$. A direct consequence is observed in delivered cost per Mg, ranging from $\text{\$}69.9 \text{ Mg}^{-1}$ to $\text{\$}62.7 \text{ Mg}^{-1}$ in the Investor Supply Chain Scenario (ISC) scenario, and from $\text{\$}59.9 \text{ Mg}^{-1}$ to $\text{\$}53 \text{ Mg}^{-1}$ in the Biomass

Division Supply Chain Scenario (BDSC) scenario. Increasing the percentage of covered area of the desired biomass around the biorefinery is possible through agreements with local producers; this is a strategic way to reduce biomass delivered cost. As mentioned earlier, other key variables affecting freight and total delivered cost are annual biomass supply (Mg y^{-1}) and productivity ($\text{Mg ha}^{-1} \text{y}^{-1}$). Figure 4.10 shows the effect of four annual supply volumes (226,796 Mg y^{-1} ; 453,592 Mg y^{-1} ; 680,389 Mg y^{-1} and 907,185 Mg y^{-1}) and two site productivities (11.2 and 22.4 $\text{Mg ha}^{-1} \text{y}^{-1}$) on freight distance (km) and delivered cost, assuming *Eucalyptus* plantation covered area of 5% around the biorefinery facility and with delivered costs back calculated to achieve 6% IRR. All analysis in this section are performed assuming the Biomass Division Supply Chain (BDSC) scenario. In general, a higher biomass supply volume per year demand results in higher freight distance. In addition, higher freight distance is related to lower site productivity (11.2 $\text{Mg ha}^{-1} \text{y}^{-1}$), with delivered cost ranging from \$74.6 to \$77.6 Mg^{-1} (BDSC scenario). For a site productivity of 22.4 $\text{Mg ha}^{-1} \text{y}^{-1}$, delivered costs range from \$56.4 Mg^{-1} to \$57.8 Mg^{-1} .

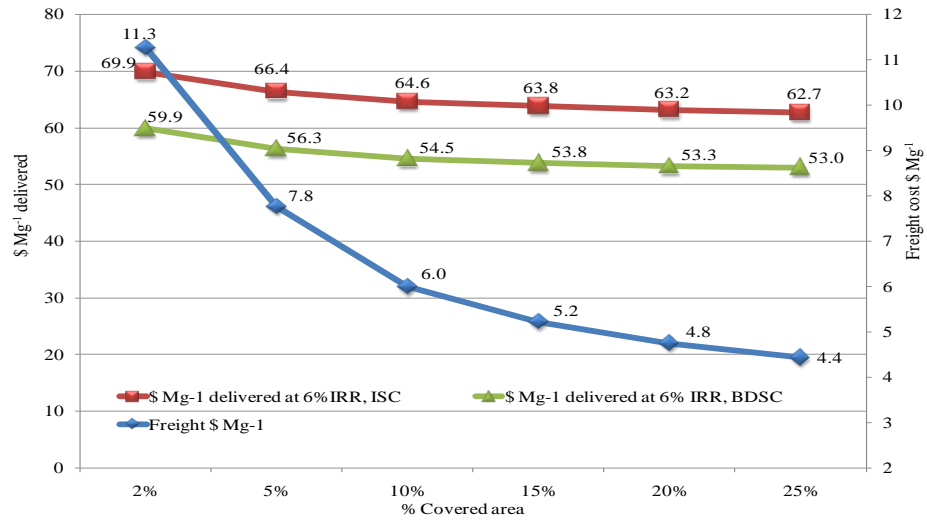


Figure 4-9 Effect of percentage of covered area on freight costs ($\$ \text{Mg}^{-1}$) and delivered cost ($\$ \text{Mg}^{-1}$) in two investment scenarios ISC and BDSC, evaluated at $22.4 \text{ Mg ha}^{-1} \text{ y}^{-1}$ and back calculated at 6% IRR.

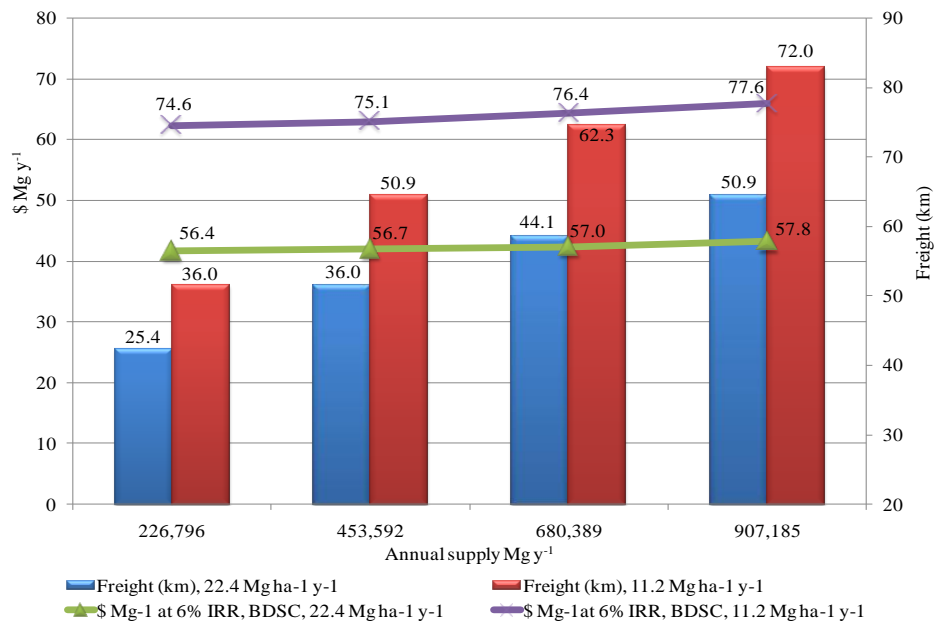


Figure 4-10 Effect of annual biomass supply and site productivity (Mg ha y) in freight distance (km) and delivered cost ($\$ \text{Mg}^{-1}$) in the BDSC scenario.

4.5 Conclusions

Eucalyptus biomass can be produced and delivered in Southern United States at a competitive cost when compared to reported biomass delivered cost of grasses and other hardwoods. Simulated delivered cost of *Eucalyptus* biomass range from \$55.5 to \$65.5 Mg⁻¹ (within 48.3 km of distance forest to biorefinery) depending on site productivity (without considering land investment) at 6% IRR. When land investment was included in the analysis, delivered biomass cost rises to a range from \$64 .0 to \$79.6 Mg⁻¹ depending on site productivity at the same IRR.

Site productivity greatly affects delivered cost, which is why a high productive plantation would reduce delivered cost with fewer hectares to plant and harvest. Delivered cost of *Eucalyptus* biomass growing at 16.8 Mg ha⁻¹ y⁻¹ (in a freight distance of 48.3 km and 6% IRR, BSC scenario) is around ~\$65.5 Mg⁻¹ while for site growing at 22.4 Mg ha⁻¹ y⁻¹ with the same 6% IRR, the biomass delivered cost drops \$6.6 Mg⁻¹.

The effect of land cost in a biomass supply investment analysis raises back calculated delivered costs to achieve a 6% IRR (from \$65.5 Mg⁻¹ to \$79.6 Mg⁻¹), thus emphasizing the objective to decrease the amount of hectares to supply a required amount of biomass per year. The percentage of covered area together with site productivity greatly affects freight distance and delivered cost. Still there are enough opportunities to reduce the delivered cost of eucalyptus biomass while achieving adequate financial returns. Shorter rotation length, development of more freeze tolerant seedlings, higher stand tree density along with other

silviculture practices are being currently developed in order to improve plantation productivity. These results indicate that *Eucalyptus* is a promising biomass for energy production in Southern U.S.

4.6 Reference

- Bransby D, Smith H, Taylor C, Duffy P (2005) Switchgrass budget model: An interactive budget model for producing & delivering switchgrass to a bioprocessing plant. *Industrial Biotechnology*, **1. 2**, 122-125.
- Ceres (2009) Radius calculator. 2009. <http://www.ceres.net/Products/Products-Ovw-Econ.asp>.
- Desmond M (2009) Financial modeling to determine the net present value and internal rate of return for conversion of annual rye grass to renewable energy. International Biomass Conference Portland, OR
- Dougherty D (2008) Forest plantations establishment and maintenance costs. Personal information
- Eaton J (2009) Bioenergy from sustainable poplar tree farms. International Biomass Conference Portland, OR
- Eggeman T (2009) Dedicated energy crops: Advanced biorefinery perspectives. Biomass Conference. Portland, OR.
- Forrest M, Moore T (2008) Eucalyptus gunnii: A possible source of bioenergy? *Biomass and Bioenergy*, **32. 10**, 978-980.
- Gomides J, Colodotte J, Chaves R, Mudado C (2006) Os clones de excelencia de Eucalyptus no Brasil para producao de Celulose. In: *39th Pulp and Paper International Congress and Exhibition*. pp, São Paulo, Brazil.
- Gonçalves J, Stape J, Laclau J, Smethurst P, Gava J (2004) Silvicultural effects on the productivity and wood quality of eucalypt plantations. *Forest Ecology and Management*, **193. 1-2**, 45-61.

- Gonzalez R, Saloni D, Dasmohapatra S, Cubbage F (2008) South America: industrial roundwood supply potential. *BioResources*, **3. 1**, 255-269.
- González R, Stock J, Plonczak A (2004) Plantaciones forestales e industrias asociadas en Venezuela. Aspectos socio-económicos. *Revista Forestal Venezolana*, **2**. 048.
- Gonzalez R, Wright J, Saloni D (2009a) Filling a need: Forest Plantation for Bioenergy in the Southern U.S. . *Biomass Magazine* 8. 44-47
- Gonzalez R, Wright J, Saloni D (2009b) An overview of growing Eucalyptus in the Southern United States: Profitability, production and bio-energy raw material. In: *International Biomass Conference* pp, Portland, OR.
- Hinchee M, Rottmann W, Mullinax L *et al.* (2009) Short-rotation woody crops for bioenergy and biofuels applications. *In Vitro Cellular & Developmental Biology-Plant*, 1-11.
- Hofstrand D (2008) Who profits from the corn ethanol boom. Iowa State University.
- Hofstrand D (2009) Profitability prospects for the corn ethanol industry. Iowa State University.
- Irs (2007) Business expenses. Department of Treasury. Internal Revenue Service. Publication 535, Cat. N. 15065Z.
- Jackson S (2009) Establishing a switchgrass biomass supply chain for energy production in Tennessee. International Biomass Conference Portland, OR
- Keffer V, Turn S, Kinoshita C, Evans D (2009) Ethanol technical potential in Hawaii based on sugarcane, banagrass, Eucalyptus, and Leucaena. *Biomass and Bioenergy*, **33. 2**, 247-254.
- Kumar A, Sokhansanj S (2007) Switchgrass (*Panicum virgatum*, L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. *Bioresource technology*, **98. 5**, 1033-1044.

- Liu W, Merriam R, Phillips V, Singh D (1993) Estimating short-rotation *Eucalyptus saligna* production in Hawaii: An integrated yield and economic model. *Bioresource technology*, **45. 3**, 167-176.
- Mark M (2009) Harvesting costs. Personal communication
- Moore P (1983) Southern California trial plantings of *Eucalyptus*. Proceedings of a workshop on *Eucalyptus* in California. Sacramento, California
- Ncbc (2009) Biofuels from farm to fuel tank. 2009. [www. Biofuelscenter.org](http://www.Biofuelscenter.org).
- Perlack R, Wright L, Turhollow A, Graham R, Stokes B, Erbach D (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge National Lab.
- Rfa (2009) Annual Industry Outlook. 2009. <http://www.ethanolrfa.org/pages/annual-industry-outlook>.
- Schmer M, Vogel K, Mitchell R, Perrin R (2008) Net energy of cellulosic ethanol from switchgrass. *Proceedings of the National Academy of Sciences*, **105. 2**, 464.
- Schönau A (1984) Silvicultural considerations for high productivity of *Eucalyptus grandis*. *Forest Ecology and Management*, **9. 4**, 295-314.
- Scott D, Tiarks A (2008) Dual-cropping loblolly pine for biomass energy and conventional wood products. *Southern Journal of Applied Forestry*, **32. 1**, 33-37.
- Somerville C (2006) The billion-ton biofuels vision (editorial). *Science*, **312. 5558**, 1277.
- Surles T, Foley M, Turn S, Staackman M (2007) A Scenario for Accelerated Use of Renewable Resources for Transportation Fuel in Hawaii. School of Ocean and Earth Science and Technology. Hawaii Natural Energy Institute. University of Hawaii.

- Swayze S (2009) Dedicated energy crops as a feedstock strategy. International Biomass Conference. Portland, OR
- Timber-Mart-South (2007) Logging rates No. 4th Quarter. Warnell School of Forestry and Natural Resources. University of Georgia.
- Turn S, Keffer V, Dalla S, Evans D, Wang W (2005) Preliminary Gasification Testing of Eucalyptus Fuels. University of Hawaii.
- Turnbull J (1999) Eucalypt plantations. *New Forests*, **17. 1**, 37-52.
- Usda (2009) Illinois ethanol corn and co-products processing values. USDA.
- Wright J (1992) Vegetative propagation of pines and Eucalyptus at Smurfit Carton de Colombia. IUFRO Symposium, Mass production technology for genetically improved forest tree species. Bordeaux, France
- Wright J (1995) Operational gains and constraints with clonal Eucalyptus grandis in Colombia. in CRC/IUFRO Conference. CRC/IUFRO Conference. Hobart, Australia
- Wright J (1997a) Realized operational gains from clonal eucalypt forestry in Colombia and current methods to increase them. Tappi Biological Sciences Symposium. San Francisco, CA
- Wright J (1997b) A review of the worldwide activities in tree improvement with Eucalyptus grandis, Eucalyptus urophylla and the hybrid urograndis. Southern Forest Tree Improvement Conference. Orlando, FL
- Wright J, Rosales L (2001) Developing clonal eucalypt forest plantations in Venezuela. *Asian Timber* 20. (1) 8-10
- Zobel B, Van Wyk G, Stahl P (1987) *Growing exotic forests*, New York, John Wiley and Sons

Zon R, Briscoe J (1911) Eucalyptus in Florida. U.S. Department of Agriculture. Forest Service Bulletin 87.

5 Converting *Eucalyptus* Biomass into Ethanol: Financial and Sensitivity analysis in a Co-Current Dilute Acid Process.

5.1 Abstract

The technical and financial performance of high yield *Eucalyptus* biomass in a co-current dilute acid pretreatment followed by enzymatic hydrolysis process was simulated using WinGEMS® and Excel®. Average ethanol yield per dry Mg of *Eucalyptus* Biomass was approximately 347.6 liters of ethanol (with average carbohydrate content in the biomass around 66.1%) at a cost of \$0.49 L⁻¹ of ethanol, cash cost of ~ \$0.46 L⁻¹ and CAPEX of \$1.03 L⁻¹ of ethanol. The main cost drivers are: biomass, enzyme, tax, fuel (gasoline), depreciation and labor. Profitability of the process is very sensitive to biomass cost, carbohydrate content (%) in biomass and enzyme cost. Biomass delivered cost was simulated and financially evaluated in Part I; here in Part II the conversion of this raw material into cellulosic ethanol using the dilute acid process is evaluated.

5.2 Introduction

Eucalyptus is a fast growing genus, managed and studied worldwide due to its importance as fiber raw material and biomass production (Campinhos, 1999, Gonzalez *et al.*, 2008, Gonzalez *et al.*, 2009, Guo *et al.*, 2002, Sims *et al.*, 1999, Wright, 1995b, Wright, 1997a). Part I of this paper discussed in detail the potential of *Eucalyptus* for biomass for energy production in the Southern United States, looking at the financial analysis of different investment scenarios and their respective impact on biomass delivered costs. Delivered cost of *Eucalyptus* was found to range from \$55.5 to \$65.5 Mg⁻¹ (dry weight basis) for the Biomass Division Supply Chain scenario (BDSC), where land investment is excluded from the calculations, with 6% IRR (internal rate of return) and site productivities at 16.8, 22.4 and 28.0 Mg ha⁻¹ y⁻¹ (Gonzalez *et al.*, 2010).

The main driver to explore the potential for biofuels production from *Eucalyptus* is the need for a biomass that is highly productive, fast growing, and relatively low cost. These elements are necessary to make the cellulosic ethanol production business more profitable and competitive so that more investors will invest in this emerging industry. Additionally, *Eucalyptus* is a lingo-cellulosic feedstock that is not used as a food source for humans or livestock. As discussed in Part I, U.S. ethanol production reached almost 34.1 thousand million liters as of 2008 with a total of 139 biorefineries (RFA, 2009). Representing a remarkable increase from ~14.8 thousand million liters and 81 biorefineries in 2005; with forecasts for ~39.7 thousand million liters of ethanol and 170 biorefineries by 2010 (RFA,

2009). In addition, the debate on how the rise in production of ethanol might have affected raw material prices (mainly corn) (Hofstrand, 2008, Hofstrand, 2009, USDA, 2009) setting up the basis for discussion of the food versus fuel debate was presented in Part I.

Several studies have been presented in order to understand the performance of *Eucalyptus* biomass being converted into energy through different pathways (Rockwood *et al.*, 2008) such as gasification (Turn, 2005) and fermentation (Ferrari *et al.*, 1992). However, there are no previous published studies on the performance of this biomass in the dilute sulfuric acid process developed by NREL (National Renewable Energy Laboratory) (Aden 2002). Part II of this paper presents a financial and sensitivity analysis pertaining to the conversion of *Eucalyptus* biomass into ethanol in a co-current dilute acid prehydrolysis followed by enzymatic hydrolysis process.

5.3 Materials and methods

The co-current dilute acid prehydrolysis followed by enzymatic hydrolysis process model was simulated using WinGEMS® v5.3 (Metso, 2009) and is based upon the model developed by the National Renewable Energy Laboratory (Aden *et al.*, 2002). The NREL Aspen® model is based on dilute sulfuric acid prehydrolysis followed by enzymatic hydrolysis for corn stover. The WinGEMS® process model was validated by comparing output data while examining the same feedstock NREL processed in the Aspen® model. In addition, other parameters were cross checked; the critical values of ethanol production

efficiency ($L\ Mg^{-1}$ biomass) and power production (MW) are compared in Table 5.1. A summary of the process is presented in figure 5.1.

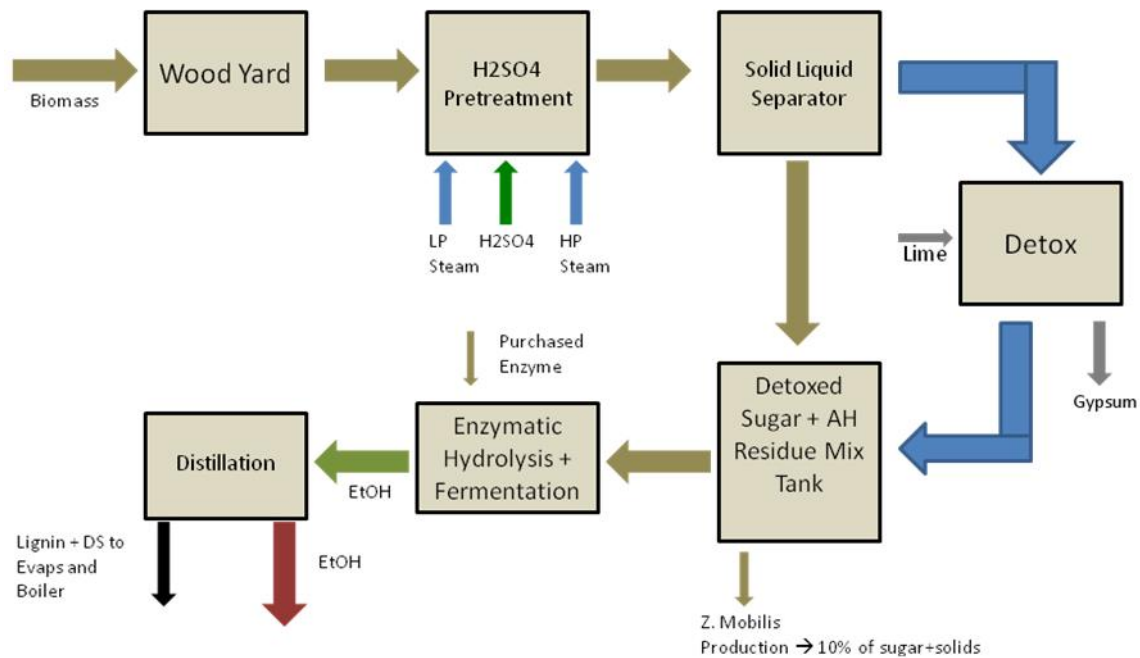


Figure 5-1 Summary of the dilute acid prehydrolysis followed by enzymatic hydrolysis process for ethanol production

The *Eucalyptus* biomass is first reacted with steam and sulfuric acid in the prehydrolysis section which is designed to liberate sugars from the hemicellulosic polymers. The pretreated biomass is then processed through a solid-liquid separator so that the liquid stream can be detoxified via overliming to neutralize the sulfuric acid. The sulfuric acid is removed so that it does not inhibit the subsequent enzymatic hydrolysis and fermentation reactions. Following detoxification, the liquid stream is mixed back with the solid stream

from prehydrolysis and processed in a series of SSCF (simultaneous saccharification and co-fermentation) reactors. A portion of the sugar and solid stream from prehydrolysis is used to produce the ethanologen (*Z. mobilis*) on site. Enzymes are purchased and added to the SSCF reactors along with the ethanologen. Following the SSCF reactors, the biomass beer is processed through distillation and dehydration to produce the final ethanol product. Solids and non-volatile dissolved solids are recovered in the bottom of the first distillation column, dehydrated using evaporators and presses, and are sent to a boiler for steam production and power generation.

Table 5-1 Model validation results

Feedstock	Ethanol Produced (L Mg ⁻¹ of biomass)	NREL's Prediction (L Mg ⁻¹ of biomass)	Power Produced (MW)	NREL's Prediction (MW)
Corn Stover	369.3	371.8	30.9	30.4

5.3.1 Reactions yields

Reaction yields are key to determine mass balance and ethanol yield. The reaction yields modeled for this analysis were taken directly from NREL and therefore details of each process area can be reviewed in the 2002 NREL report (Aden *et al.*, 2002). In general, the main reaction yields by process area are presented in Table 5.2. It is assumed that reactant components in *Eucalyptus* yields are generally equivalent to those in corn stover. This assumption is based on a comparison of the pretreatment reaction yields reported by NREL

for yellow poplar (Wooley, 1999) and corn stover. The reaction yields differ only in the amount of hemicellulose hydrolysis. The hemicelluloses hydrolysis for poplar was reported to be 75% compared to 90% for corn stover. The use of 90% hydrolysis for *Eucalyptus* is not unreasonable and reflects the possible hydrolysis efficiency in a nth generation facility.

Table 5-2 WinGEMS modeled reactions

Reactions	Reactant	Fractional Conversion
Acid Pre-Treatment		
$(\text{Glucan})_n + n \text{H}_2\text{O} \rightarrow n \text{Glucose}$	Glucan	0.07
$(\text{Glucan})_n + m \text{H}_2\text{O} \rightarrow m \text{Glucose Oligomer}$	Glucan	0.007
$(\text{Glucan})_n + \frac{1}{2}n \text{H}_2\text{O} \rightarrow \frac{1}{2}n \text{Cellobiose}$	Glucan	0.007
$(\text{Hemicellulose})_n + n \text{H}_2\text{O} \rightarrow n \text{Hemicellulose}$	Hemicellulose	0.90
$(\text{Hemicellulose})_n + m \text{H}_2\text{O} \rightarrow m \text{Hemicellulose Oligomer}$	Hemicellulose	0.025
$(\text{Hemicellulose})_n \rightarrow n \text{Furfural HMF} + 2n \text{H}_2\text{O}$	Hemicellulose	0.05
Acetate \rightarrow Acetic Acid	Acetate	1.0
$(\text{Lignin})_n \rightarrow n \text{Soluble Lignin}$	Lignin	0.05
Enzymatic Hydrolysis		
$(\text{Glucan})_n + n \text{H}_2\text{O} \rightarrow n \text{Glucose}$	Glucan	0.90
Fermentation		
6 carbon sugar fermentation	6 C sugar	0.95
5 carbon sugar fermentation	5 C sugar	0.85

5.3.2 Chemical composition

The chemical composition used for this analysis is an average based on nine different genotypes of *Eucalyptus x urograndis* (Gomides, 2006), presented in Table 5.3 The value of

chemical composition for the nine clones is used to perform sensitivity analysis of ethanol yield and process economics around biomass components.

Table 5-3 Average chemical components for eucalypts (Gomides *et al.* 2006)

Chemical component	% *
Glucans	44.6
Xylans	12.8
Galactans	0.5
Mannans	0.5
Arabinans	0.3
Uronic acid	4.4
Acetyl	2.9
Lignin	30.1
Resins	3.6
Ash	0.3

*Based on dry mass

5.3.3 Financial model assumptions

A discounted free cash flow financial model was created to determine the NPV (Net Present Value) and the IRR (Internal Rate of Return) of a facility processing *Eucalyptus* feedstock at a plant capacity of 453,592 Mg y⁻¹. Key assumptions pertaining to the financial model are listed below:

- Plant startup: December 2009
- Capital spending schedule
 - 20% in 2007, 40% in 2008, and 40% in 2009

- 2009 Ethanol revenue: \$0.66 L⁻¹ (no escalation)
- Biomass cost (delivered at mill): \$66.1 Mg⁻¹
- Excess electricity sold at: \$50 MWh⁻¹
- Operating days per year: 350 days
- Land Cost: \$5 million
- Installed Capital Cost based on NREL report (Aden *et al.*, 2002).
 - Feedstock handling modified for roundwood operation with no debarking
 - Total installed cost scaled for year and plant capacity
 - Capital cost (CAPEX) per annual liter of ethanol ~\$1.03 L⁻¹
- 10 year project life
 - Terminal year value of 5 x year 9 EBITDA (Earnings before interest taxes and depreciation).
 - Discount rate 12%
 - Depreciation takes into consideration a 50% capital investment depreciation for year 1 (IRS 2008) and 7-year modified accelerated cost recovery system (MACRS)
- Operating costs: Table 5.4 shows the cost values of operating material

Table 5-4 Operative material cost assumed in the simulation

Operating material	Modeled Cost	Basis for Cost
Gasoline	\$0.66 L ⁻¹	\$0.66 L ⁻¹ (EIA-DOE, 2009)
Di-ammonium phosphate	\$0.50 kg ⁻¹	\$0.23 kg ⁻¹ (Chang, 2009b)
Sulfuric acid	\$0.09 kg ⁻¹	\$0.07 kg ⁻¹ (Chang, 2009a)
Propane cost	\$0.04 kg ⁻¹	\$0.005 kg ⁻¹ (Aden <i>et al.</i> , 2002)
Lime	\$0.20 kg ⁻¹	\$0.08 kg ⁻¹ (Chang, 2009a)
Corn steep liquor	\$0.03 L ⁻¹	\$0.18 kg ⁻¹ (Aden <i>et al.</i> , 2002)
Enzyme	\$0.09 L ⁻¹ of ethanol	\$0.03 L ⁻¹ of ethanol (Aden <i>et al.</i> , 2002)

- Currency: All currency amounts are in U.S. dollars. Values of 2009.

5.4 Results and discussions

5.4.1 Ethanol production cost drivers

Based on the simulated income statement for ethanol production (in the co-current dilute acid prehydrolysis followed by enzymatic hydrolysis process), all costs were considered to evaluate the major cost drivers in this process. This information is used to analyze the financial sensitivity of the project to these key cost drivers. It can be observed in Figure 5.2 that main cost drivers are biomass (33%), followed by enzyme (16%), taxes (14%), gasoline (7%) as well as depreciation and labor (5% and 6% respectively). Other

important material costs were sulfuric acid and lime. Total capital expenditure (CAPEX) for a facility processing 453,592 dry Mg y⁻¹ is around \$160 million with a CAPEX around \$1.03 L⁻¹ of ethanol.

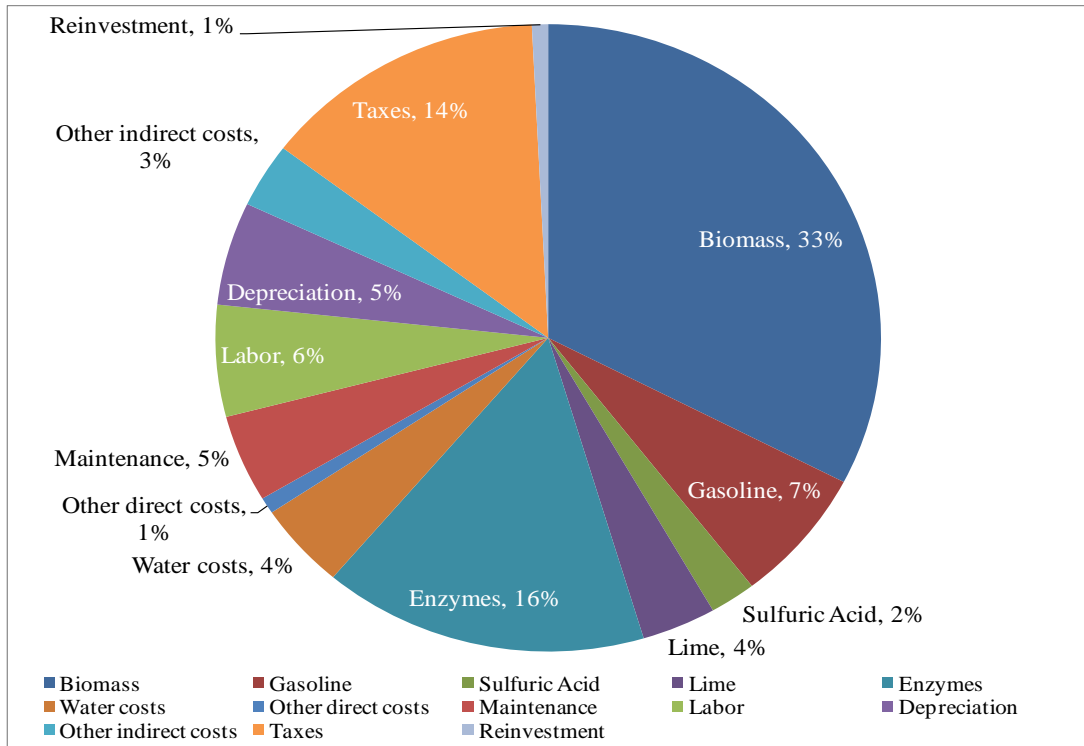


Figure 5-2 Cost drivers in ethanol production in the co-current dilute acid prehydrolysis model (year 2009).

The main financial analysis evaluation of the profitability of this process was performed based on the assumptions presented in the methodology section. The financial situation for the facility was determined based on biomass delivered cost at \$66.1 Mg⁻¹ (dry basis), enzyme cost per liter of ethanol of \$0.09, discount rate of 12% and an assumed ethanol price at the plant of \$0.66 L⁻¹. Under this analysis the operation has a NPV of -\$6 million and IRR of 11.4%. Current ethanol price as of 4th Quarter of 2009 was on average

\$0.48 L⁻¹ of ethanol (DTN, 2009). Under this current price, this process and with this biomass the conversion into ethanol is not profitable based on the assumptions previously discussed. But profitability of the conversion process can be improved based on lower biomass delivered costs as well higher amount of carbohydrate content in the biomass. Sensitivity analysis of *Eucalyptus* biomass in this ethanol conversion pathway was undertaken and is presented below.

5.4.2 Sensitivity of biomass delivery cost

Figure 5.3 illustrates the financial sensitivity of a biorefinery with biomass costs ranging from \$49.6 to \$99.2 Mg⁻¹ biomass. Note that the 12% IRR is achieved when delivered biomass cost is around ~\$64 Mg⁻¹. NPV values are negative and IRR decreases when delivered biomass costs increase. When biomass delivered cost is \$99.2 Mg⁻¹ the IRR is a meager 5%. Based on the previous information regarding biomass delivered cost, *Eucalyptus* plantations as simulated in Part I growing at 16.8, 22.4 and 28.0 Mg ha⁻¹ y⁻¹ and with delivered price ranging from \$55.5 to \$65.5 Mg⁻¹ (Gonzalez *et al.*, 2010), would result in a biorefinery capable of achieving an IRR ranging from 10% to 12% (with ethanol selling price at \$0.66 per liter). Additionally, it is possible to deliver biomass in the cost range of \$55.5 to \$60.3 Mg⁻¹ when the productivity of the plantation goes from 22.4 to 28.0 Mg ha⁻¹ y⁻¹ with an IRR (for the producer) ranging from 6% to 10% respectively (with 48.3 km freight distance in all cases).

The percentage of covered area analysis presented in Part I (Gonzalez *et al.*, 2010) plays an important role since a higher percentage of covered area allows lower distance freight and lower delivered cost. Delivered cost of biomass growing at 22.4 Mg ha⁻¹ y⁻¹ for the Biomass Division Supply Chain scenario ranges from \$52.9 to \$59.5 Mg⁻¹ (with biomass covered area ranging from 5% to 25%), which fit into the range required to secure a minimum of 12%.

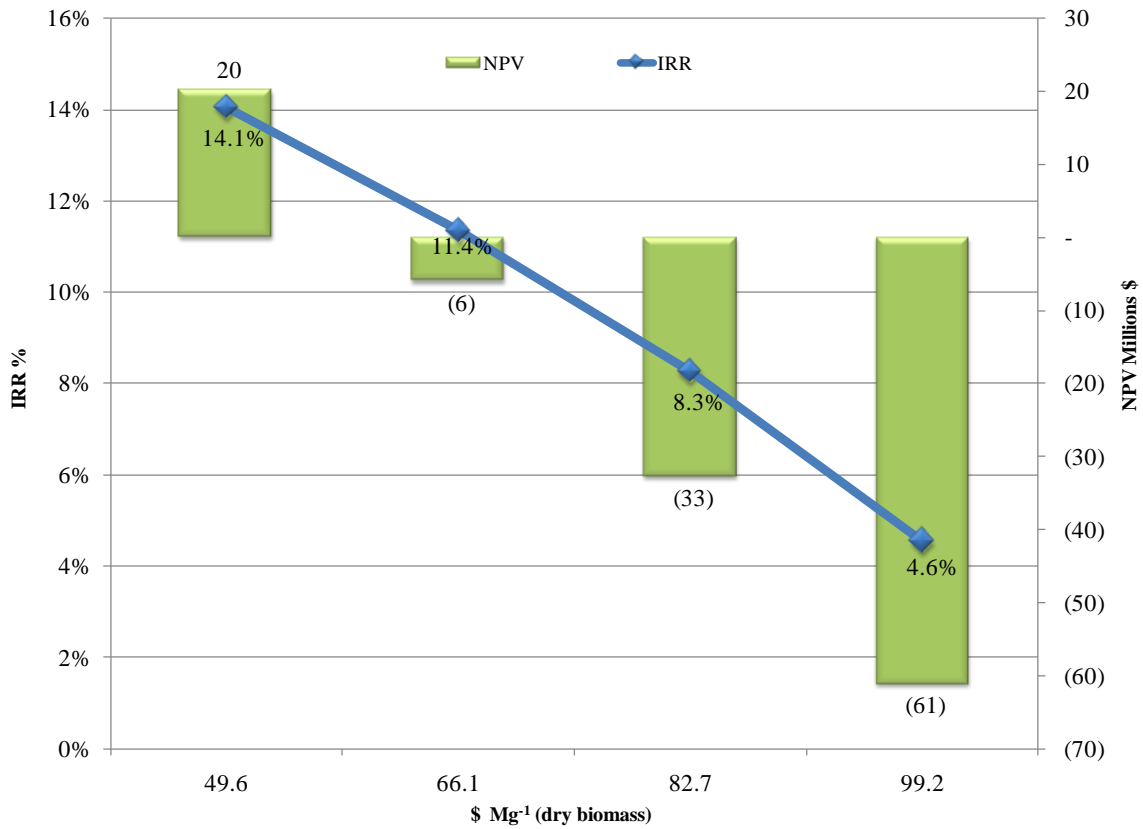


Figure 5-3 Biorefinery sensitivity to biomass delivered cost

5.4.3 Sensitivity analysis of carbohydrate composition

Figure 5.4 shows the financial sensitivity of a biorefinery facility with variations in the chemical composition of *Eucalyptus* biomass (at \$66.1 Mg⁻¹ delivered cost for all cases of carbohydrate composition), the chemical composition data is taken from different *Eucalyptus urograndis* genotypes previously reported (Gomides *et al.*, 2006). Higher percentage of carbohydrate in biomass increases the profitability of the overall process, as more polymeric carbohydrates can be reduced into the monomeric forms for further fermentation into ethanol. A minimum of 66.1% carbohydrate is required to achieve ~ 11.9% IRR. A composition of 64.4% carbohydrate results in 10.9 % IRR, while 70.3% carbohydrate content increase IRR values almost 3 points (13.6%).

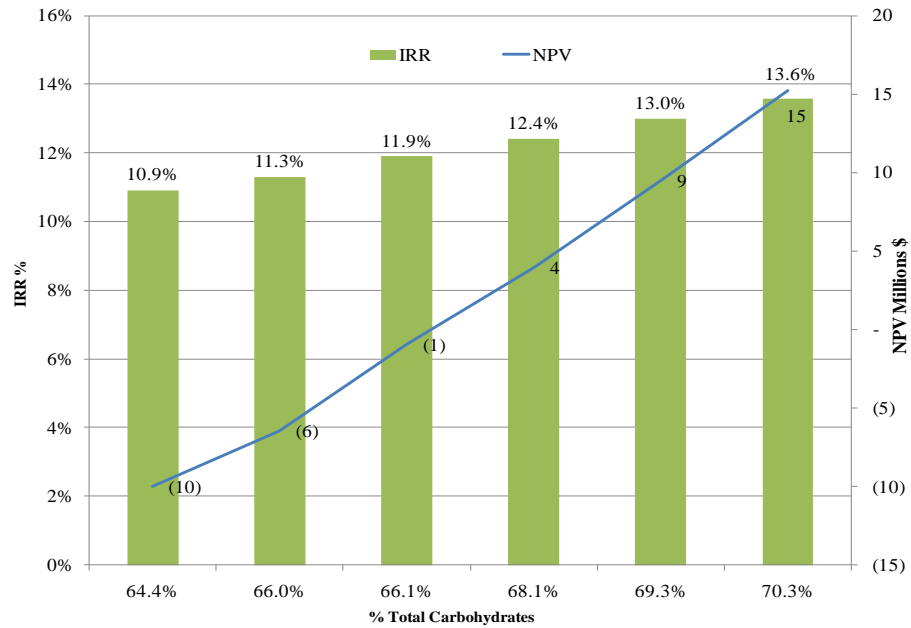


Figure 5-4 Biorefinery sensitivity to total carbohydrate in biomass

The effect of carbohydrate content in the biomass on ethanol yield can be observed in Figure 5.5 The lower carbohydrate content (64.4%) yields fewer liters of ethanol (335 liters) per Mg of biomass (dry weight basis); while higher carbohydrate content (70.3%) results in higher ethanol yield (372.2 liters of ethanol). It can also be observed in Figure 5 that power production is lower at higher carbohydrate percentages, as the lignin content is lower. Thus higher carbohydrate percentage might result in higher ethanol yield but lower power production.

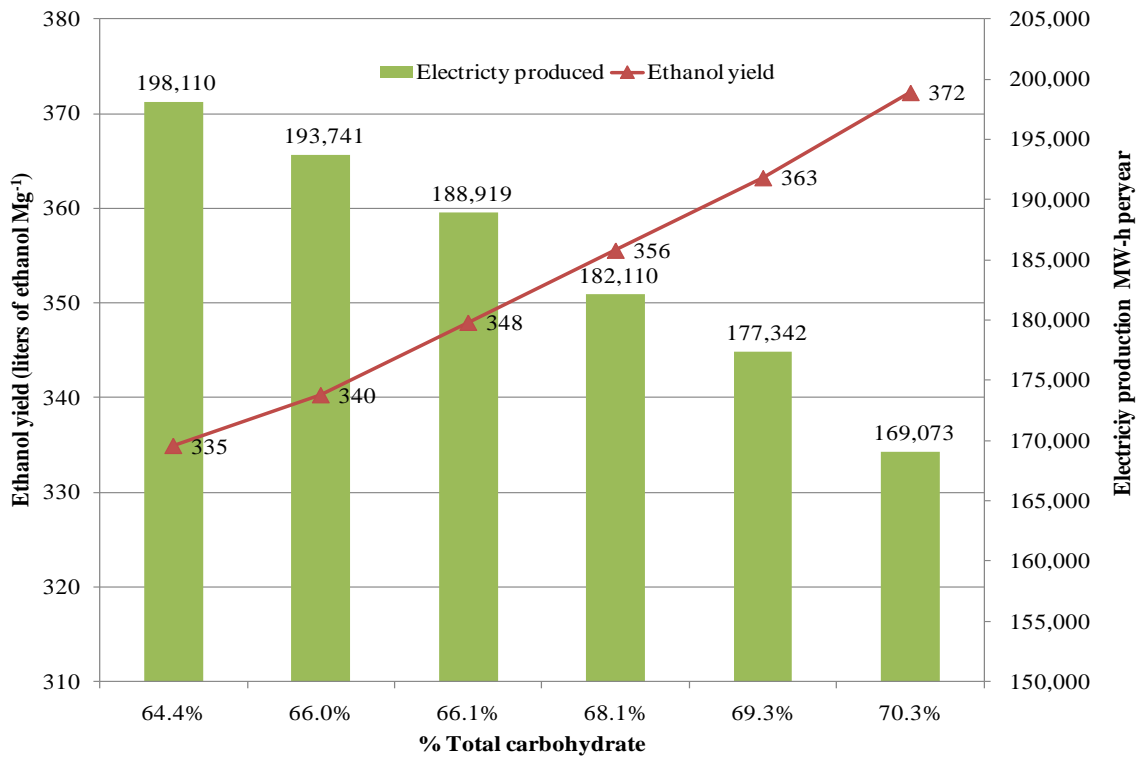


Figure 5-5 Effect of chemical composition on ethanol yield (liter Mg⁻¹) and power production

The relationship between carbohydrate content, lignin content and electricity production can be observed in Figure 5.6. Lignin content tends to be lower when the carbohydrate content is higher, although deviations in this trend can be observed due to variations in individual clones. A decrease of only 4% in lignin content (from 31.7% to 27.5%) decreases the electricity available to sell per year (from 134,000 to 105,000 MW-h per year) by 29,000 MW-h per year; this excess in electricity (after internal electricity consumption is met) is assumed to be sold.

Certainly the amount of carbohydrate and lignin content are very important in the conversion of any ligno-cellulosic biomass to ethanol. The manipulation of the chemical components of the biomass is possible through genetic modification. This creates research opportunities aimed at inventing specific bioenergy plantations or crops with ideal characteristics designed to minimize biomass delivered costs and enhance chemical properties. Furthermore, short rotation forest biomass plantations such as *Eucalyptus* allow for rapid tree improvement resulting in plantations producing biomass with optimal properties for specific locations and conversion technologies.

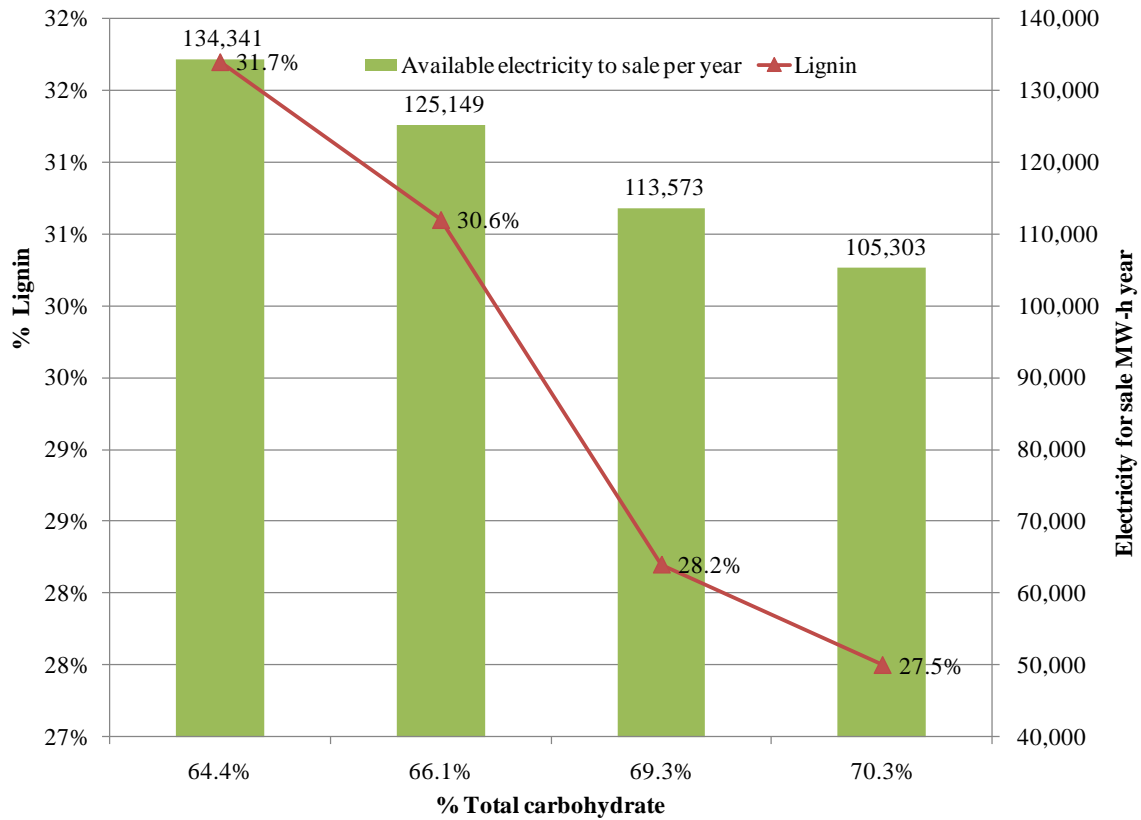


Figure 5-6 Lignin and carbohydrate content in biomass and electricity available to sell per year

5.4.4 Sensitivity analysis of enzyme costs

Another key cost driver in ethanol production in this conversion process is enzyme cost. Figure 5.7 highlights how sensitive the profitability of the process is with respect to enzyme cost. At \$0.09 enzyme cost per liter of ethanol, the NPV is ~ -\$6 million with an IRR of ~11.4%. In addition, a high enzyme cost (\$0.13 per liter of ethanol) adversely affects the

profitability of the conversion process (-30 million NPV and 8.5% IRR), while lower enzyme cost at \$0.04 L⁻¹ result in NPV of \$17 million and 13.8% IRR.

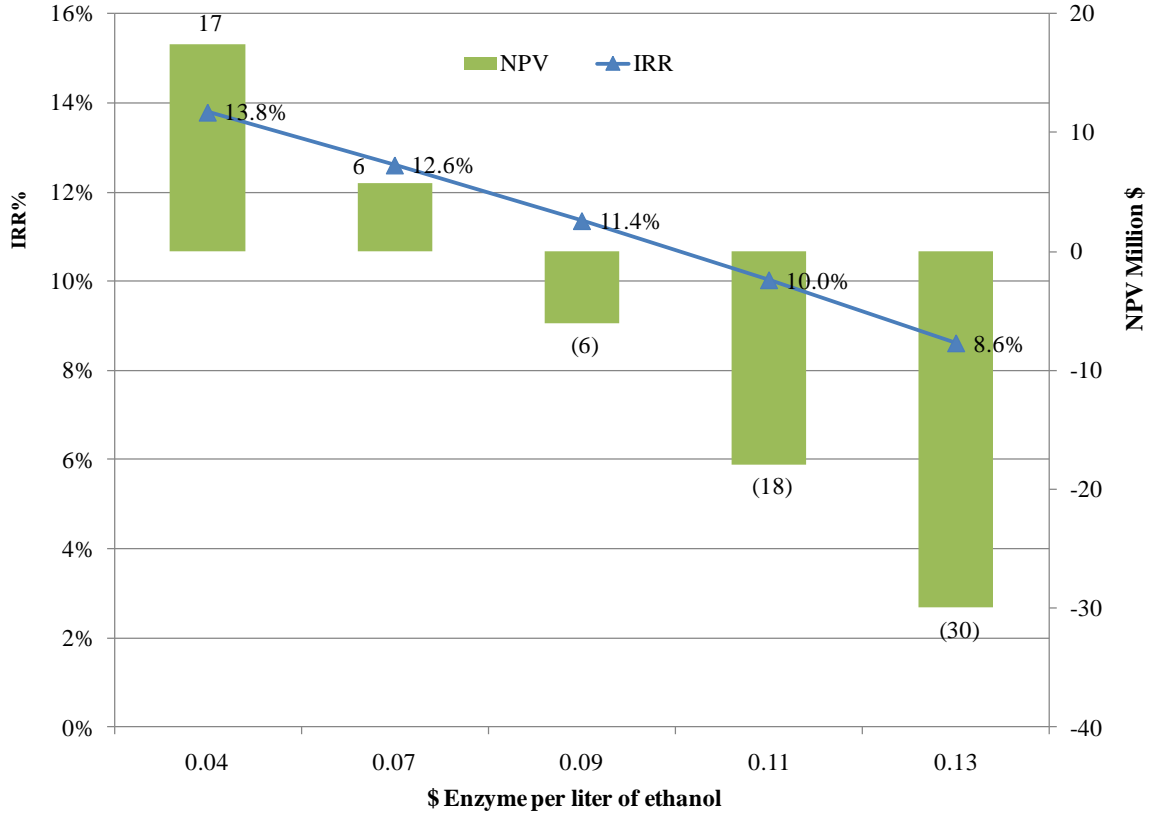


Figure 5-7 Effect of enzyme cost on NPV and IRR values of the conversion process

5.5 Conclusions

Eucalyptus biomass has potential for ethanol conversion due to a variety of characteristics. *Eucalyptus* is a fast growing species with desirable chemical properties that can be grown in some places in Southern U.S., at competitive costs and without the need for

extra supply chain costs such as storage (also avoiding biomass and sugar degradation). Being a very easy species for cloning allows *Eucalyptus* the possibility for genetic manipulation and massive reproduction in order to control chemical components in the biomass to favor the profitability of the process (Wright, 1995a, Wright, 1997b). Average simulated ethanol yield per Mg of dry *Eucalyptus* Biomass was approximately 347.6 liters of ethanol (with average carbohydrate content in the biomass ~66.1%) at a cost of \$0.49 L⁻¹, cash cost of ~ \$0.46 L⁻¹ and CAPEX of \$1.03 L⁻¹ of ethanol.

Ethanol yield and power production in the facility greatly depend on the chemical composition of the biomass. Higher carbohydrate content results in higher ethanol yield but generally results in decrease power production (depending on lignin content). There is still room for improvement in delivered cost for *Eucalyptus* biomass with respect to growing, harvesting, and freight. In addition, lower biomass delivered cost along with higher carbohydrate content in the biomass greatly benefits the profitability of the process.

5.6 References

- Aden A, Ruth M, Ibsen K *et al.* (2002) Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. NREL.
- Campinhos E (1999) Sustainable plantations of high-yield shape Eucalyptus trees for production of fiber: the Aracruz case. *New Forests*, **17. 1**, 129-143.
- Chang J (2009a) Indicative Chemical Prices A-Z. 2009. <http://www.icis.com/StaticPages/a-e.htm#A>.
- Chang J (2009b) INDICATIVE CHEMICAL PRICES A-Z. Retrieved Nov. 1, 2009, from ICIS. <http://www.icis.com/StaticPages/a-e.htm#A>.
- Dtn (2009) Ethanol Price. 2009. <http://www.ethanolmarket.com/fuelethanol.html>.
- Eia-Doe (2009) Weekly U.S. Retail Gasoline Prices, Regular Grade. Retrieved Nov. 1, 2009, from Energy Information Administration, DOE, na. http://www.eia.doe.gov/oil_gas/petroleum/data_publications/wrgp/mogas_home_page.html.
- Ferrari Md, Neirotti E, Albornoz C, Saucedo E (1992) Ethanol production from eucalyptus wood hemicellulose hydrolysate by *Pichia stipitis*. *Biotechnology and bioengineering*, **40. 7**.
- Gomides J, Colodotte J, Chaves R, Mudado C (2006) Os clones de excelencia de Eucalyptus no Brasil para producao de Celulose. In: *39th Pulp and Paper International Congress and Exhibition*. pp, São Paulo, Brazil.
- Gomides J, Colodotte, J., Chaves, R. And Mudado, C (2006) Os clones de excelencia de Eucalyptus no Brasil para producao de Celulose. *39th Pulp and Paper International Congress and Exhibition*. São Paulo, Brazil

- Gonzalez R, Saloni D, Dasmohapatra S, Cubbage F (2008) South America: industrial roundwood supply potential. *BioResources*, **3. 1**, 255-269.
- Gonzalez R, Treasure T, Wright J, Phillips R, Saloni D, Abt R, Hasan J (2010) Exploring the Potential of Eucalyptus for Energy Production in the Southern United States: Financial Analysis of Delivered Biomass. Part I. *Biomass and Bioenergy*, **In review process**.
- Gonzalez R, Wright J, Saloni D (2009) An overview of growing Eucalyptus in the Southern United States: Profitability, production and bio-energy raw material. In: *International Biomass Conference* pp, Portland, OR.
- Guo L, Sims R, Horne D (2002) Biomass production and nutrient cycling in Eucalyptus short rotation energy forests in New Zealand: biomass and nutrient accumulation. *Bioresource technology*, **85. 3**, 273-283.
- Hofstrand D (2008) Who profits from the corn ethanol boom. Iowa State University. Jan 2008.
- Hofstrand D (2009) Profitability prospects for the corn ethanol industry. Iowa State University. Jan 2009.
- Metso (2009) WinGem software. Metso Corporation Automation.
- Rfa (2009) Ethanol industry outlook. pp, Renewable Fuel Association.
- Rockwood Dl, Rudie Aw, Ralph Sa, Zhu Jy, Winandy Je (2008) Energy product options for Eucalyptus species grown as short rotation woody crops. *International Journal of Molecular Sciences*, **9. 8**, 1361.
- Sims R, Senelwa K, Maiava T, Bullock B (1999) Eucalyptus species for biomass energy in New Zealand--I: Growth screening trials at first harvest. *Biomass and Bioenergy*, **16. 3**, 199-205.

Turn S, Keffer, V., Dalla, S., Evans, D. And Wang, W. (2005) Preliminary Gasification Testing of Eucalyptus Fuels. School of Ocean and Earth Science and Technology. Hawaii Natural Energy Institute. University of Hawaii.

Usda (2009) Illinois ethanol corn and co-products processing values. USDA Department of Ag. Market News.

Wooley R, Ruth, M., Sheehan, J., Kajdeski, H., Galvez, A (1999) Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis Current and Futuristic Scenarios. National Renewable Energy Laboratory. 1617 Cole Boulevard Golden, Colorado 80401-3393.

Wright J (1995a) Operational gains and constraints with clonal Eucalyptus grandis in Colombia. CRC/IUFRO Conference. Hobart, Australia

Wright J (1995b) Operational gains and constraints with clonal Eucalyptus grandis in Colombia. in CRC/IUFRO Conference. CRC/IUFRO Conference. Hobart, Australia

Wright J (1997a) Realized operational gains from clonal eucalypt forestry in Colombia and current methods to increase them. Tappi Biological Sciences Symposium. San Francisco, CA

Wright J (1997b) Realized operational gains from clonal eucalypt forestry in Colombia and current methods to increase them. Tappi Biological Sciences Symposium. San Francisco, CA

6 Loblolly Pine for Biomass-Bioenergy: Silviculture and Delivered Costs

6.1 Abstract

Production and delivered of Loblolly pine (*Pinus taeda*) biomass for bioenergy was simulated using FASTLOB2 and financial spreadsheets prepared to determine optimum rotation length and trees per hectare at the lower dollar per dry metric ton of biomass delivered. The financial simulations were designed to find lower biomass delivered prices, to achieve an 8% internal rate of return, using six different stand tree densities and with rotation lengths ranging from 7 to 15 years. Sensitivity analysis of seedling cost indicates optimum stand tree densities between 2,965 to 3,459 trees per hectare for seedling costs lower than \$0.12 per seedling. For seedling costs between \$0.18 and \$0.24, optimum stand tree densities vary from 1,977 to 2,471 trees per hectare (based on the six stand tree densities studied). Two investment scenarios were considered evaluating the effect of land investment on biomass delivered cost. The effects of annual biomass supply, the percentage of covered area producing biomass and site productivity on the economics of growing biomass for bioenergy were analyzed. The potential of pine biomass for bioenergy, its effects on the working capital of the biorefinery, carbohydrate content as well as supply chain competitive advantages were examined and compared with other potential bioenergy crop. Pine biomass can be profitably produced and delivered with prices ranging from \$57 to \$69 per dry metric ton.

6.2 Introduction

U.S. and Brazil have developed an important industry of bioethanol mainly from corn and sugar cane respectively (Goldemberg *et al.*, 2004, Shapouri *et al.*, 2004), for 2009 both countries shared nearly 86% of world's ethanol production. For that same year U.S. produced near 10.6 billion gallons of ethanol (mainly from corn), six year before (2003) this number roughly reached 2.8 billion gallons of ethanol, this increase in production and industry development can be partially attributed to intensive governments funds and policy acts. There was also a clear effect on raw material cost used for ethanol production, mainly corn, with corn prices rising until mid 2008 (Hofstrand, 2008, Hofstrand, 2009, USDA, 2009), and falling after late 2008. The price drop may be explained by the low demand of ethanol for gasoline during the accentuated financial crisis in the U.S. (RFA, 2009, USDA, 2009). These events inspired the debate of food versus fuel, highlighting the need for non-food base ligno-cellulosic raw materials. In addition, it is estimated that there would not be enough corn to supply the biofuel industry to meet liquid biofuel production quantities as mandated by the U.S. federal government standards. The "One Billion Ton Study" suggests the possibility to sustainably produce 1.3 billion dry tons of cellulosic biomass across the nation (Perlack *et al.*, 2005). The report provides useful information mainly in biomass availability though it does not provide information regarding the delivered cost of the biomass. Cellulose biomass is relatively abundant but the costs of production and delivered need more comprehensive analysis.

Cellulosic biomass is seen to be the major source for bioenergy and it is an important cost driver for bioenergy production. The cost of biomass for pellet production has been estimated to range from 38% to 53% in Austria and Sweden (Thek & Obernberger, 2004) and around 39% to 59% in the United States and Canada (Mani *et al.*, 2006). Cellulosic biomass has also been identified as the largest cost for cellulosic ethanol production (Galbe & Zacchi, 2002, Wyman, 2007). The approach to lower biomass delivered cost may include the use of fast growing species, highly productive perennial grasses and the development of specific biomass grown for bioenergy. In a manner similar to the pulp and paper industry with specific standards for feedstock, it may be necessary to grow biomass for bioenergy. This would increase efficiency and yield in the selected conversion pathway. For example, fermentation yield pathways are very sensitive to carbohydrate content in biomass due to the available amount of carbohydrate to be converted into monomeric reactable sugars and further conversion to alcohol species (Mielenz, 2001, Wyman, 2007). In the case for solid fuel, as pellets and briquettes, an important property in biomass is the content of carbon and the BTU per unit of biomass. Desired biomass properties (such as carbohydrate content) can be genetically improved and biomass delivered cost can be optimized when growing specific biomass sources for energy. As expressed in previous studies “without the development of biomass resources (e.g. through energy crops) and a well-functioning biomass market that can assure a reliable and long lasting supply, the existing high ambitions for bioenergy may not be met” (Faaij, 2008).

The importance of biomass cost in bioenergy production has motivated studies in the area of biomass economics, delivered cost and supply chain. Most studies found in the literature do not undertake a complete economic analysis when determining biomass delivered or production costs. The profitability for growing biomass is sometimes not included which limits the analysis to production costs. The approach for a continuous and reliable supply chain of biomass for bioenergy should involve the study of the profitability of each step in the supply chain. Though biomass delivered cost in the literature may not include the entire financial and economic analysis, these values are useful to benchmark different biomass sources in order to understand the cost impact of a specific biomass in the economics of the conversion process into bioenergy.

Grasses such as switchgrass and miscanthus have been researched for bioenergy purposes. The cost of producing switchgrass has been found to range from \$59 to \$66 per dry metric ton (Dt) at farm gate for the U.S. Midwest (Duffy & Nanhou, 2001b) though this does not include freight or storage costs. Other studies for the same region estimated switchgrass delivered cost to vary from \$37 to \$48 per dry ton (harvesting and freight costs only) while the cost of growing the crop may range from \$30 to \$36 per dry metric ton (Kumar & Sokhansanj, 2007). Minimum selling price of switch grass in Italy has been estimated to be higher than €55 per dry metric ton at farm gate in order to be profitability cultivated. These numbers indicate that one dry metric ton of switchgrass delivered at mill gate varies from \$67 to \$84. A recent study developed in New York, USA, predicted an average price of \$105-115 to deliver 500,000 dry short tons of switchgrass (453,592 Dt)

(Conable & Volk, 2010). But still, there are other costs to consider such as storage, biomass handling and logistics (McDermott, 2010). For the case of grasses and other agriculture biomass storage is required, due to reduced harvesting window (2-4 months), this cost driver besides other logistic concerns are still being researched. In terms of logistics and supply chain, forest biomass has several competitive advantages over agriculture biomass. Forest biomass can provide year round supply with no requirement for storage or insurance and with lower working capital when compared to agriculture biomass. In the forest biomass supply there is worldwide availability of experienced contractors and supply chain stakeholders with proven expertise in harvesting and material handling. These references values and logistic issues will be considered in the next pages to benchmark our simulated pine biomass with other biomass such as switchgrass.

Loblolly pine (*Pinus taeda*) is an abundant softwood species in the Southern U.S. with almost 29 million acres (11.7 million ha) making up 20% of standing pine volume in 2007 (Baker & Langdon, 2010). Loblolly pine is also an important source for saw timber and pulp wood. In 2002 this species provided nearly 73% of total roundwood softwood volume in the Southern U.S. (Johnson *et al.*, 2003). This species grows naturally from central Florida, northward to Delaware and New Jersey, and westward to east Texas and southeast Oklahoma (Schultz, 1999).

Loblolly pine yield has been widely studied for pulp (Wright & Sluis-Cremer, 1992) and solid wood purposes, but very few studies on the profitability, sensitivity and investment

of producing exclusively biomass for energy are available. Andre and Scott (2008) (Scott & Tiarks, 2008) presented results on trials related to dual-cropping loblolly pine for both biomass and conventional products over a 22 years rotation. The authors reported biomass production over 10 ton ha⁻¹ of pine biomass for energy and up to an additional 633 m³ ha⁻¹ of wood that could be used for either biomass energy or for various solid wood products (roughly 14.4 Dt ha⁻¹ y⁻¹), with stand tree density from 588 to 620 trees per acre (1,433-1,532 trees per hectare). Intensively managed short rotation (10 to 12 years) loblolly pine in Georgia has been reported to produce around 26.6 m³ ha⁻¹ y⁻¹ (~12.8 dry tons⁻¹ ha y⁻¹) for pulpwood with stand tree density between 608 to 652 trees per acre (1502 to 1611 trees ha⁻¹) (Borders & Bailey, 2001a). In 2007, the cost of clean hardwood chips at mill gate for the southern United States ranged from \$32.25 per green short ton to \$45 per green short ton (roughly \$65-\$101 per dry ton); while clean softwood chips ranged from \$30.5 per green short ton to \$45 per green short ton (\$61.2-\$90.38 per dry ton) (Timber-Mart-South, 2007). For the first quarter of 2010, softwood pulpwood delivered price at mill gate range from \$22 to \$29 per green short ton (around \$44 to \$58 per dry metric ton) in Tennessee, USA (Anonymous, 2010).

Loblolly pine has been studied for ethanol production; results show that ethanol production from this species can be economically competitive in comparison with ethanol from corn and other lignocellulosic materials, yet improvement in enzymatic hydrolysis and conversion of pentoses into monomeric reactable sugars still need more research though (Frederick *et al.*, 2008). Southern Pines (a mixture of different pines including loblolly pine)

has been clearly identified as a sustainable and suitable source of biomass for cellulosic ethanol, pellets and briquette production (Bradfield & Levi, 1984, Hinchee *et al.*, 2009).

This paper presents financial profitability, sensitivity analysis and delivered cost of simulated loblolly pine plantation grown exclusively for biomass energy purposes at short rotation length and different stand tree densities (trees per hectare), using the Silviculture Support System for loblolly plantations developed by the Forest Nutrition Cooperative at North Carolina State University and Virginia Tech (version 3.0 beta). Two main financial investments are evaluated. One includes land investment and the other does not include land investment, at different site productivities.

6.3 Materials and methods

A series of steps were followed in order to obtain reliable and accurate information to develop the financial models. The first step was a literature review to gather information regarding loblolly pine species, plantation establishment and maintenance, harvesting practices and costs, as well as other relevant information. A group of experts from industry and universities were contacted to collect and verify the information that supports the models.

Once all the information was collected and processed, establishment and maintenance cost spreadsheet models were developed and linked to harvesting and freight costs to determine biomass delivered costs. Information regarding updated costs was obtained from

current loggers and forest managers in the Southern U.S. as well as from published references (Bradfield & Levi, 1984, De La Torre & Abt, 2010, Dougherty, 2009, Duncan, 2009, Mark, 2009). It is important to note that most of the cost data presented in this paper came from first hand information from current key players in the biomass supply arena. This brings more accuracy, an updated data set and a more realistic financial analysis, which will allow us to provide current data from 2009 to the biomass and bioenergy community.

Maintenance and establishment costs were simulated based on yearly free cash flow for 30 years. This cost center contains the following activities for the first year of the plantation: land preparation, chemical weed control, seedling cost, plantation establishment, fertilization and mechanical weed control. Maintenance for the second year included mechanical and chemical weed control. Originally all data was gathered and the financial analysis was performed based on short tons and acres, though for this paper most of these data were converted into dry metric tons (Dt). In some cases data is presented in both English and metric units.

The structure of the income statement, core of our financial analysis, includes:

1. Revenue resulting from the selling of the biomass produced and delivered;
2. Back calculated biomass delivered price to achieve 8% IRR;
3. Direct cost which includes: payroll, depletion, harvesting and freight costs;

4. Indirect cost, including: research and development, depreciation, water and electricity and other fixed costs;
5. EBIT (earnings before interest and taxes), resulting from the difference between revenue and total costs;
6. Taxes: state and federal taxes, including tax carry forward;
7. After tax income, obtained by subtracting EBIT less taxes;
8. EBITDA (Earnings before interest, taxes, depreciation, depletion and amortization), which is a financial indicator that measures the earnings excluding non cash costs;
9. New fixed capital and deferred charges that are accounts of balance sheet nature that impact the financial evaluation of the project but do not impact the profitability of the operations and include investment in new plantation (that do not account as a cost for that current taxable period) and other outflows investment such as purchase of land;
10. Cash flow, which reports the EBIT plus non cash costs as depreciation and amortization;
11. Free cash flow derived from the difference between cash flow and deferred charges which is the net cash flow available per year for new investments, to pay debts or to pay dividend. Free cash flow is obtained from the difference between cash flow and deferred charges, this is the net cash flow available per year for new investments, pay debts or pay dividends, we use the free cash flow to measure NPV and IRR as it is the real available cash

per year in the project. Sensitivity analysis for different productivity scenarios were measured in three levels: low (0.75), medium (1.0) and high (1.25), relative to a central assumption of 16.8 Dt per hectare per year ($7.5 \text{ BDTacre}^{-1} \text{ y}^{-1}$).

The financial and economic indicators that were used to compare growing and investment scenarios were US dollar (\$) per dry metric ton delivered ($\$ \text{ Dt}^{-1}$ delivered), internal rate of return (IRR) and net present value (NPV). These two last financial indicators were determined based on the free cash flow of the project. The \$ per Dt delivered includes the cost of growing the biomass (also called depletion), profit for the farmer, harvesting cost and freight cost, in our case the \$ per Dt delivered is back calculated to achieve a specific IRR % which implies a profit to the farmer. The internal rate of return (IRR) is the rate at which the present value of inflows equals the cash outflows, in other words it is the rate that will produce a zero net present value (Edmonds *et al.*, 2007), for our analysis we will be using an IRR of 8%. The net present value is the difference between the cost of investment and the present value of future cash inflows at a specific discount rate (Edmonds *et al.*, 2007), the discount rate in our analysis will be 6%. As the price per Dt (which will drive the revenues together with the Dt produced) have been back calculated so that the project achieve an 8% of IRR, we should expect all NPV values to be positive, in this way a combination of lower \$ per Dt of biomass delivered along with higher NPV value will represent the most profitable scenarios for biomass production under the assumptions presented and scenarios evaluated. The base year for the analysis, prices and costs is 2009.

6.3.1 General assumptions

Several assumptions were defined in order to create the models which are the goal of this research.

6.3.2 Investment scenarios

Two investment scenarios were analyzed, one including land purchase called investor supply chain (ISC) and another without land purchase called biomass division supply chain (BDSC). For both scenarios freight cost per mile is the same and is assumed as the current market price from transport outsourcing companies. Harvesting and in-field chipping have a fixed dollar per bone dry short ton (BDT) converted into dry metric tonne (Dt), using prices based on the information obtained from loggers and forest managers currently in business. Prices were back calculated using Goal Seek (Microsoft Excel ® tool) and the model calculates the price of biomass delivered (\$ per Dt delivered) so that the project can achieve an 8% of IRR.

6.3.3 Moisture content

For all scenarios and growing rates, moisture content is kept constant at 45%. This moisture content value is representative of fresh delivered pine logs.

6.3.4 Rotation length

Rotation lengths simulated ranged from 7 to 15 years old. Then further analysis is performed based on a 10 years rotation length.

6.3.5 Productivity

An average productivity (medium scenario) of $16.8 \text{ Dt ha}^{-1} \text{ y}^{-1}$ (or 7.5 bone dry short ton per acre per year –BDT $\text{acre}^{-1} \text{ y}^{-1}$) is the central assumption, with a low productivity scenario at $12.6 \text{ Dt ha}^{-1} \text{ y}^{-1}$ (or 5.6 BDT $\text{acre}^{-1} \text{ y}^{-1}$) and a high productivity scenario at $21.1 \text{ Dt ha}^{-1} \text{ y}^{-1}$ (or 9.4 BDT $\text{acre}^{-1} \text{ y}^{-1}$). The total volume considers the entire tree including limbs, bark, branches and leaves. Central productivity assumptions were very similar to those productivity values found in the literature (Borders & Bailey, 2001a, Scott & Tiarks, 2008) .

6.3.6 Stand tree density

For this analysis, six initial stand tree densities were studied: 988, 1483, 1977, 2471, 2965 and 3459 trees per hectare (400, 600, 800, 1000, 1200 and 1400 trees per acre respectively). Further sensitivity analyses in this paper will be performed on a 2965 trees per hectare basis (1200 trees per acre). The analysis was limited up to 1400 trees per acre as it is a limitation of the simulation software.

6.3.7 Supply production per year

The annual supply considered for this analysis is 500,000 BDT y^{-1} (453,592 Dt y^{-1}), which could be a representative size for biorefinery ethanol plants. Other supply volumes at 750,000 and 1 million BDT y^{-1} (680, 389 and 907,185 Dt $year^{-1}$) are studied for sensitivity analysis.

6.3.8 Chemical composition

The chemical composition used for this analysis was: Glucans 41.7%, xylans 5.9%, galactans 2.4%, mannans 10.7%, arabinans 1.5%, uronic acid 2.5%, acetyl 2.9%, lignin (soluble and insoluble lignin) 25.9%, resins 2.7% and ash 0.3%. Total carbohydrate is around 67.6%. Composition analysis came from laboratory tests for carbohydrate and lignin determination carried out in the Department of Forest Biomaterials at North Carolina State University, and those are very similar to values found in the literature (Frederick *et al.*, 2008).

6.3.9 Financial analysis assumptions

6.3.10 Life time of the project for financial evaluation:

30 years.

6.3.11 Discount rate and internal rate of return

A discount rate of 6% per year for the evaluation of net present value was used. A rate of return of 8% was used as reference to back calculated biomass delivered price and 8% is considered to be very good in the forestry business.

6.3.12 Equity

An equity of 100% is assumed. Therefore there is no finance charge in the costs.

6.3.13 Land value

In the case of the investor analysis scenario, a fixed price of \$1,000 acre⁻¹ (3,040 ha⁻¹) of plantable area is charged. This represents a cash outflow in the free cash flow section at the beginning of the project. This investment in land is assumed to appreciate at a rate of 1 % per year for the life time of the project. In year 30, the capitalized value of the land is assumed to be sold and forms part of the terminal value of the project, a cash inflow.

6.3.14 Terminal value

For the Investor Supply Chain scenario, the terminal value of the project is composed of the capitalized value of the land and the deferred charges for plantations still standing in the year 30 of the project. For the Biomass Division Supply Chain scenario, the terminal value is related only to the deferred charges of the standing plantations at year 30.

6.3.15 Deferred charges

Deferred charges are the cash outflows (investments) in plantation establishment and maintenance. These amounts are not represented in the income statement at the time of plantation establishment; instead, these investments are considered assets and would appear in the balance sheet without affecting the income statement. When the plantation is sold or harvested, deferred charges are converted into costs through depletion.

6.3.16 Depletion

Depletion is the deferred charge invested in plantation establishment and maintenance represented in the income statement at the moment that the forest is harvested or sold. Depletion rate is the ratio of the total deferred charges amount for that specific plantation tract divided by the total volume of biomass extracted, consistent with the IRS (IRS, 2007).

6.3.17 Currency

All currency amounts are in U.S. dollars.

6.3.18 After tax analysis

Our analysis includes state tax (assumed as 6%) and federal tax (assumed as 15%). Tax incentives as tax carried forward and the use of depletion are included.

6.3.19 Biomass delivered price

Biomass delivered price in our analysis is composed of depletion, profit (for the farmer), harvesting fee and freight fee (these last two fees includes the profit for each activities and represents current market values). What we define as biomass delivered price, source of revenue for our project, is in fact the biomass delivered cost from the point of view of the buyer (biorefinery).

6.3.20 Working capital

Working capital is technically defined as current assets minus current liabilities. Current assets include assets most likely to be converted into cash or consumed in the current operating period (Edmonds *et al.*, 2007). Our interest in working capital is that it includes the cost of raw material. In fact accounts receivable and raw-materials inventories have been identified as the two most volatile components of working capital affecting finance constraints on investments (Fazzari & Petersen, 1993). This conceptual frame work will be used to understand the impact of stored biomass in working capital and the cash flow of the project.

6.3.21 Silviculture support system for loblolly plantation FASTLOB2

The Forest Nutrition Cooperative's (FNC) Decision Support System (DSS) utilizes an expert system approach to model the effects of site conditions, site preparation, and first year silvicultural treatments on plantation survival and growth. At the core of the expert system is

the FASTLOB2 growth and yield system (Amateis *et al.*, 2001) which is a complete stand growth and yield model that includes options to evaluate thinning and (or) established stand fertilization. FASTLOB2 is the further evolution and development of several widely used models developed by the Virginia Tech Growth and Yield Cooperative. The DSS system was originally published as: “A Silvicultural Decision Support System for Loblolly Pine Plantations” (FNC, 2007, Montes, 2001).

6.4 Results

6.4.1 Plantation establishment and maintenance costs

The cost to establish one acre of loblolly pine was simulated to be around \$622 per acre (\$1537 per hectare) in the first year and an additional \$61 per acre (\$151 per hectare) for maintenance allocated in the second year. The cost per acre is based on personal communication with active forest managers and are similar to those found in the literature (Borders & Bailey, 2001b, De La Torre, 2010, Dougherty, 2008b). The share cost between plantation establishment and maintenance activities, based on 1,000 trees per acre (2741 trees per hectare) is presented in Figure 6.1. The main cost drivers are fertilization, seedlings, land preparation and weed control.

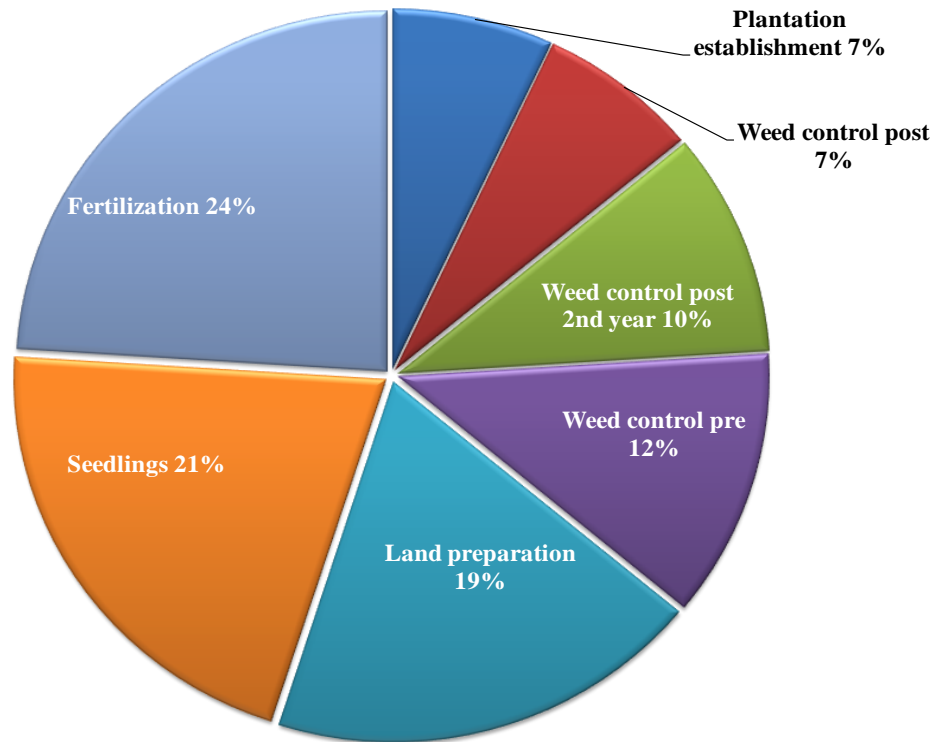


Figure 6-1 Structure cost of plantation establishment and maintenance for loblolly pine (based on 1,000 trees per acre or 2,471 trees per hectare)

6.4.2 Harvesting costs

Harvesting and in-field chipping costs were assumed at \$15.12 per green short ton (or \$16.7 per green metric tonne) considering all cost drivers in harvesting from loggers and harvesting companies currently in operation (Dougherty, 2008a, Duncan, 2009, Mark, 2009). This cost includes the profit for the harvesting business unit.

6.4.3 Freight

Freight cost is estimated to be \$4.9 per green ton or \$9.8 BDT⁻¹ (\$5.40 per green ton or \$10.8 Dt⁻¹), for an average distance of 30 miles (plantation site to biorefinery). Freight is composed of two components: fixed and variable. The fixed rate is the charge per hour for loading and unloading waiting time. The variable component is based on a charge of loaded truck per mile. This fee included profit for the freight service business unit.

6.4.4 Financial optimum rotation length and stand tree density, Biomass Division Supply Chain Scenario:

In order to identify optimum financial rotation lengths and stand tree densities for loblolly pine biomass production, six initial stand tree densities were simulated at 988, 1483, 1977, 2471, 2965 and 3459 trees per hectare (400 , 600, 800, 1000, 1200 and 1400 trees per acre respectively) with rotation lengths in a range from 7 to 15 years, using FASTLOB2 and financial spreadsheets (land value was not included in this analysis). We define financial optimum as the lowest dollars per Dt of biomass delivered at a specific IRR %. This lower price (back calculated to achieve a specific IRR %) is in fact the most profitable scenario at any price given by the market. Figure 6.2 shows the dollar per Dt of delivered biomass to achieve 8% IRR (freight distance 30 miles to the biorefinery). Lower delivered prices occur in rotation lengths from 9 to 11 years, with year 10th as the lowest delivered price. For the period from 9 to 12 years, the optimum stand tree density take place around 2695 and 3459 trees per hectare (1,200 to 1,400 trees per acre respectively). Biomass delivered prices back

calculated to achieve 8% IRR per stand tree density, in 30 miles freight distance and for a rotation length of 10 years, are displayed in table 6.1. Seedling cost for this analysis was simulated at \$0.12 per seedling.

Table 6-1 Biomass delivered price (\$ Dt-1) back calculated to achieve 8% IRR, Biomass Division Supply Chain Scenario

Trees per hectare	988	1483	1977	2471	2965	3459
Trees per acre	400	600	800	1000	1200	1400
\$/Dt (delivered)	66.0	61.3	60.6	60.2	60.0	59.9

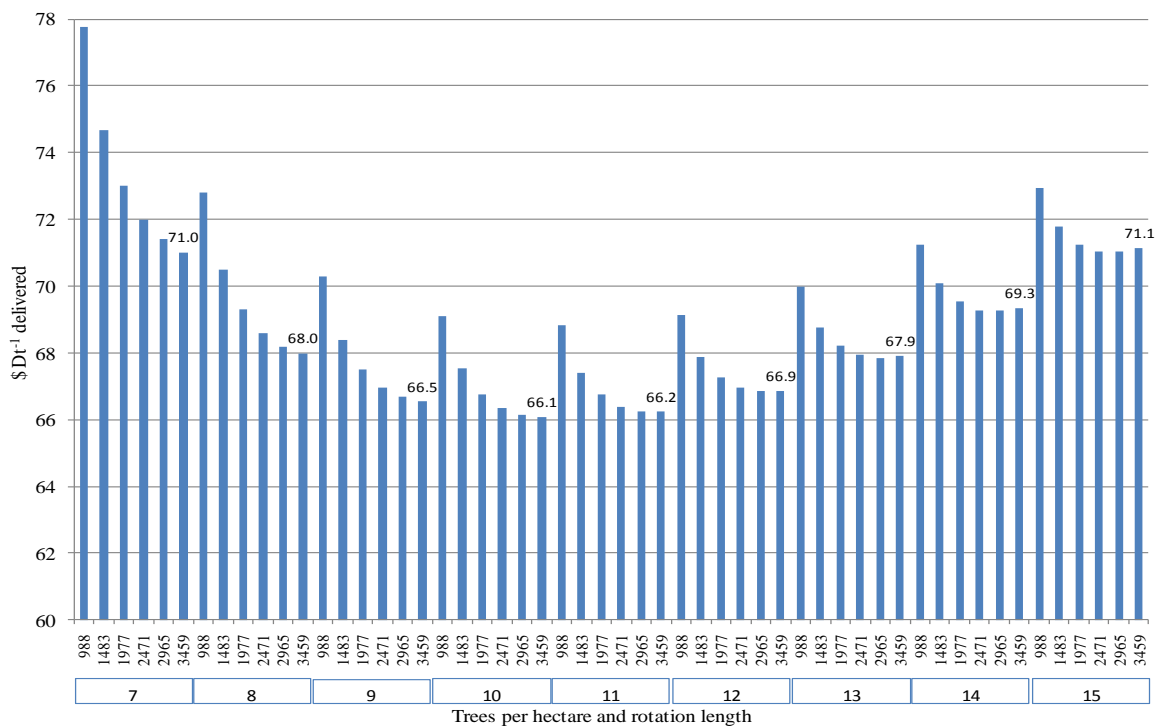


Figure 6-2 Biomass delivered price (\$ Dt-1) for loblolly pine at 988, 1483, 1977, 2471, 2695 and 3459 trees ha-1 with rotation length from 7 to 15 years, freight distance 30 miles, 8% IRR

There are several options in terms of lower delivered price leading to increased flexibility for the management of the loblolly pine plantation for biomass production (Figure 6.2). For trees per hectare in a specific rotation length (10 years), Figure 6.3 shows the effect on NPV values with biomass delivered price back calculated to achieve 8% IRR and with a hypothetical biomass delivered price of \$69.5 Dt⁻¹. There is an increase in the production of biomass per hectare (Dt ha⁻¹year⁻¹) when the initial stand tree density increases from 988 to 3459 trees per hectare, with biomass productivity going from 12.5 to 17.5 Dt ha⁻¹ year⁻¹. Total NPV with biomass delivered price adjusted to achieve 8% IRR decreases, because the \$ Dt⁻¹ delivered is lower at higher stand tree densities (Figure 6.2). Just to validate that the lower \$ Dt⁻¹ in delivered price is the most profitable option, in Figure 6.3, the NPV trend at a discount rate of 6% and fixed delivered priced of \$69.5 Dt⁻¹ shows the highest NPV at the highest stand tree densities (2965 and 3459 trees per hectare or 1,200 to 1,400 trees per acre). Site index (SI) for this analysis is based on an SI = 85. Site index is a number related to the productivity of the site, in the case of loblolly pine, SI 85, means that the average height of dominant and co-dominant trees in a plantation at age 25 is 85 feet (Clutter, 1963, Doolittle, 1958). In the southern U.S. most site productivities range from SI 65-75, nevertheless an 85 SI may be reached with adequate land preparation, improved genetic material, fertilization and weed control.

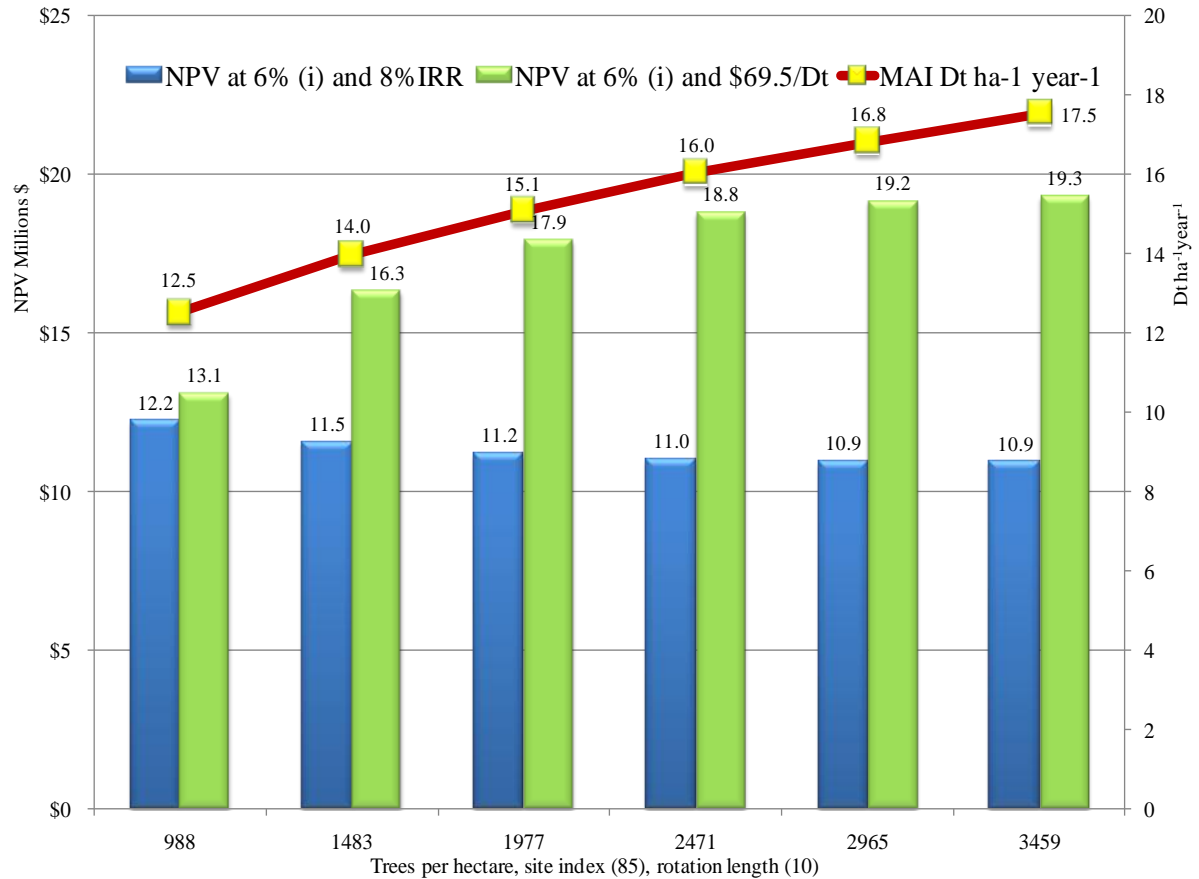


Figure 6-3 Effect of stand tree density (trees per hectare) on NPV of the project and productivity (Dt ha⁻¹year⁻¹)

6.4.5 Financial optimum rotation length and stand tree density, Investor Supply Chain (ISC) scenario

The same simulation under the same initial stand tree densities (988, 1483, 1977, 2471, 2965 and 3459 trees per hectare or 400, 600, 800, 1000, 1200 and 1400 trees per acre respectively) and rotation lengths (7 to 15 years) were evaluated for the ISC scenario, where

land investment was included in the financial analysis. The investment in land does not affect the income statement of the business unit. This is an operation between asset accounts, so it does modify the accounts in the assets section of the balance sheet, there is a cash outflow from the bank account (or an increase in liability is originated if funds are borrowed) and there is an increase in the asset account of land and properties. The way that we evaluate the investment in land is through the impact on the free cash flow of the project. Since IRR and NPV values are measured based on the free cash flow of the business unit, it will impact the back calculated price to achieve specific values of IRR. In this ISC scenario it is expected that when land investment is included in the free cash flow analysis, the price of delivered biomass (in the same 30 miles of freight distance) to achieve the same 8% IRR should be higher when compared to the Biomass Division Supply Chain (BDSC) scenario. In this scenario (ISC) lower prices occurred at the highest stand tree density (3459 trees ha⁻¹ or 1400 trees acre) at a 9 year rotation length (one year earlier compared to BDSC). For the 9th year, the delivered price back calculated to achieve 8% IRR is presented in Table 6.2 using seedling costs of \$0.12 per seedling.

Table 6-2 Biomass delivered cost (\$ Dt-1) to achieve 8%IRR, Investment Supply Chain scenario

Trees per hectare	988	1483	1977	2471	2965	3459
Trees per acre	400	600	800	1000	1200	1400
\$/Dt (delivered)	105.3	99.5	96.2	93.9	92.3	91.1

In the investor supply chain scenario, there are several options to reach the same 8% IRR at lower delivered prices (ranging from \$91.1 to \$92.6 per Dt) at high stand tree

densities (3459 trees ha⁻¹ or 1,400 trees acre⁻¹) with rotation length from 8 to 11 years. The main difference with the Biomass Division Supply Chain Scenario is that in the ISC scenario lower delivered prices occurred at an earlier rotation length, as the cost of land entails a shorter production period to reach the same IRR at lower delivered price.

The delivered prices obtained from the Biomass Division Supply Chain (BDSC) scenario are used in operational profitability analysis. The delivered prices obtained from the Investor Supply Chain (ISC) scenario are useful for investment analysis, as the land investment will greatly impact the cash flow of the project, and of course its financial indicators.

6.4.6 Biomass and carbohydrate delivered price to achieve 6%, 8% and 10% IRR (BDSC)

Biomass and carbohydrate delivered prices back calculated to achieve 6%, 8% and 10% IRR for the Biomass Division Supply Chain (BDSC) scenario at 10 years rotation length and 2,965 trees per hectare (1,200 trees acre⁻¹) were simulated to understand variation in delivered prices at different investment expectations. Biomass and carbohydrate delivered prices back calculated at 6% IRR are \$60.3 and \$89.2 per Dt respectively. When a higher expectation in IRR is evaluated (10%) delivered prices of biomass and carbohydrate jump to ~\$69.2 and ~\$102.3 per Dt as expected. Carbohydrate price is obtained by dividing \$ per Dt of delivered biomass by the percentage of total carbohydrate (figure 6.4).

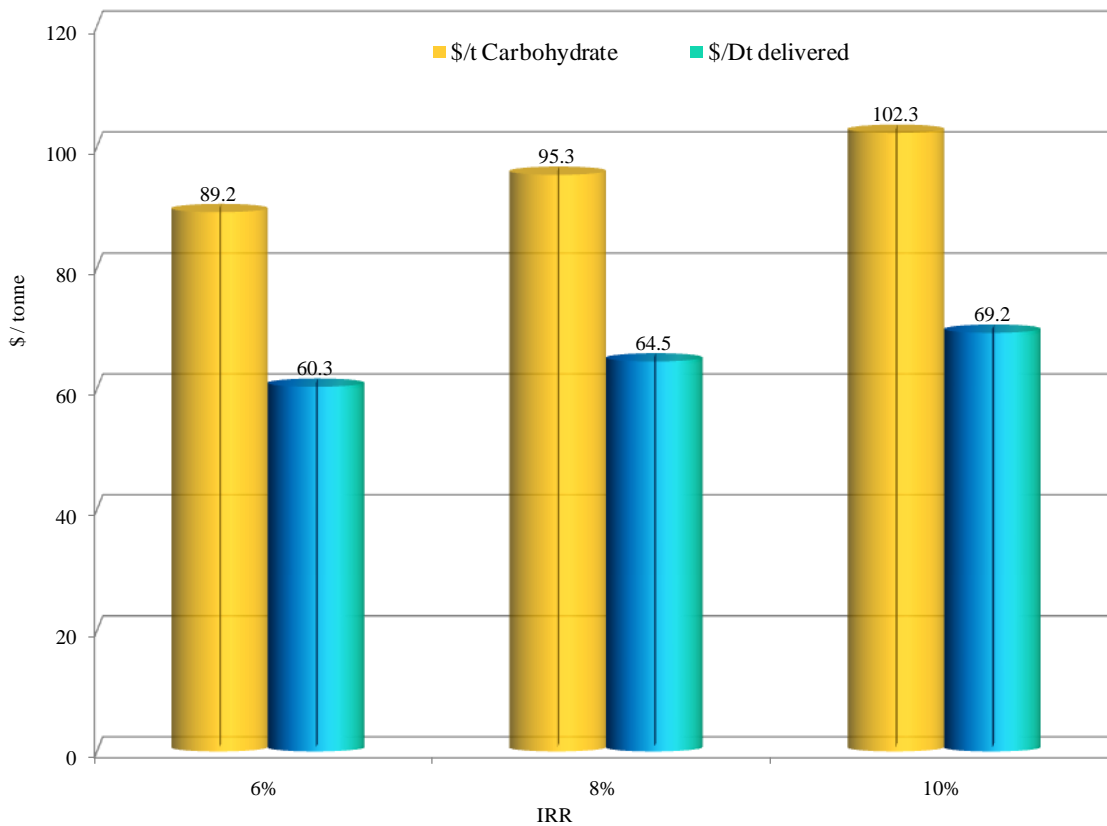


Figure 6-4 Effect of IRR on biomass and carbohydrate delivered prices

6.4.7 Sensitivity analysis

In order to understand how key variables may affect biomass delivered cost and the operational profitability in the business of producing pine biomass; sensitivity analyses are performed in the Biomass Division Supply Chain (BDSC) scenario with the following variables: seedling cost, productivity per hectare ($\text{Dt ha}^{-1} \text{ year}^{-1}$), percent of covered area around the biorefinery facility and annual volume supply to the biorefinery facility.

6.4.8 Seedling cost

Seedling cost impacts establishment cost per hectare, increases deferred charges and the cash outflow of the project and affects the delivered cost of the biomass through depletion. For several seedling costs (\$0.06, \$0.12, \$0.18 and \$0.24 per seedlings), the lower delivered price (back calculated to achieve 8% IRR) was estimated around year 10th (rotation length) though the optimum stand tree density (trees per hectares) changes. Figure 6.5 shows the effect of seedling cost at \$0.06, \$0.12, \$0.18 and \$0.24 per seedlings on biomass delivered prices back calculated to achieve 8% IRR (rotation length = 10 year, BDSC scenario). Observe that at \$0.06 and \$0.08 per seedling, biomass delivered price decreases when stand tree density increases since productivity ($Dt \text{ hectare}^{-1} \text{ year}^{-1}$) increases. Lower biomasses delivered prices are seen around 3459 trees ha^{-1} (1,400 trees per acre). Biomass delivered prices ($\$ Dt^{-1}$) at seedling costs of \$0.18 and \$0.24 per seedling do not follow the previous trends, with lower delivered prices are found between 1977 and 2471 trees ha^{-1} (800 and 1000 trees per acre respectively). The extra increment in productivity per year (due to a higher stand tree density) does not pay off the higher costs in seedlings. For this analysis, freight distance is kept constant at 30 miles (forest to biorefinery facility). Biotech companies provide seedlings with prices ranging from \$0.06 to \$0.45 each and this methodology can be used to know the maximum price to be paid per seedling based on the extra increments of biomass productivity ($Dt \text{ ha}^{-1} \text{ year}^{-1}$).

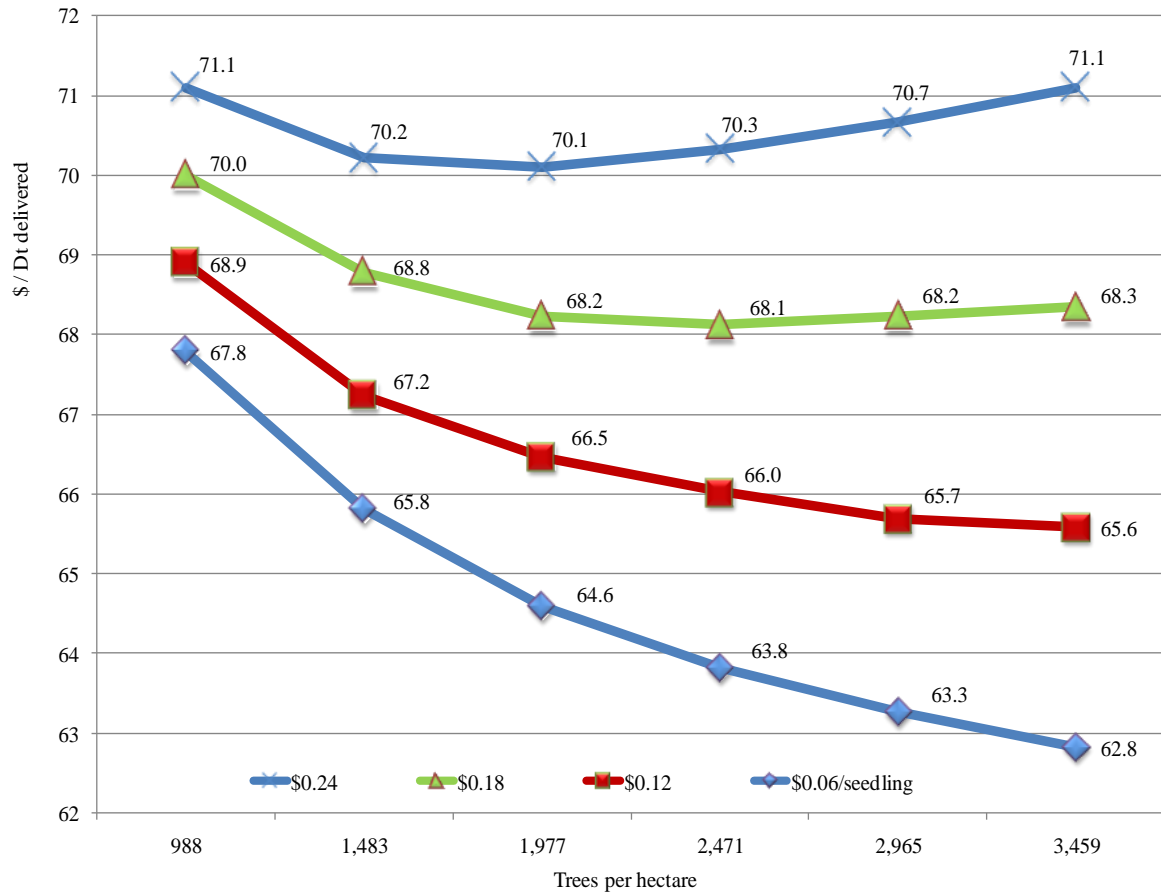


Figure 6-5 Effect of seedling cost on biomass delivered price

6.4.9 Productivity

Productivity ($\text{Dt ha}^{-1}\text{y}^{-1}$) impacts the number of hectares required to supply certain volume per year and also affects biomass delivered price (price back calculated to achieve a specific IRR%). Figure 6.6 illustrates how site productivity at 12.6, 16.8 and 21.1 $\text{Dt ha}^{-1}\text{y}^{-1}$ (5.6, 7.5 and 9.4 $\text{BDT acre}^{-1}\text{y}^{-1}$ respectively) affect the hectares required to supply ~454K Dt

per year (500K BDT per year); with hectares ranging from 36,000 hectares for a site productivity of 12.6 Dt ha⁻¹y⁻¹ to 21,000 hectares for a productivity of 21.1 Dt ha⁻¹y⁻¹ (assuming 20% of covered area around the biomass facility with loblolly pine and with supply agreements). A higher number of hectares to produce the same amount of Dt per year increases the \$ per Dt of biomass delivered due to an increase in deferred charges and depletion. Observe that biomass delivered price back calculated to achieve 8% IRR drops from \$69.1 Dt⁻¹ (BDSC scenario) and \$104.1 Dt⁻¹ (ISC scenario) at a site productivity of 12.6 Dt ha⁻¹year⁻¹ to \$57 Dt⁻¹ (BDSC scenario) and \$78 Dt⁻¹ (ISC scenario) at a site productivity of 21.1 Dt ha⁻¹y⁻¹.

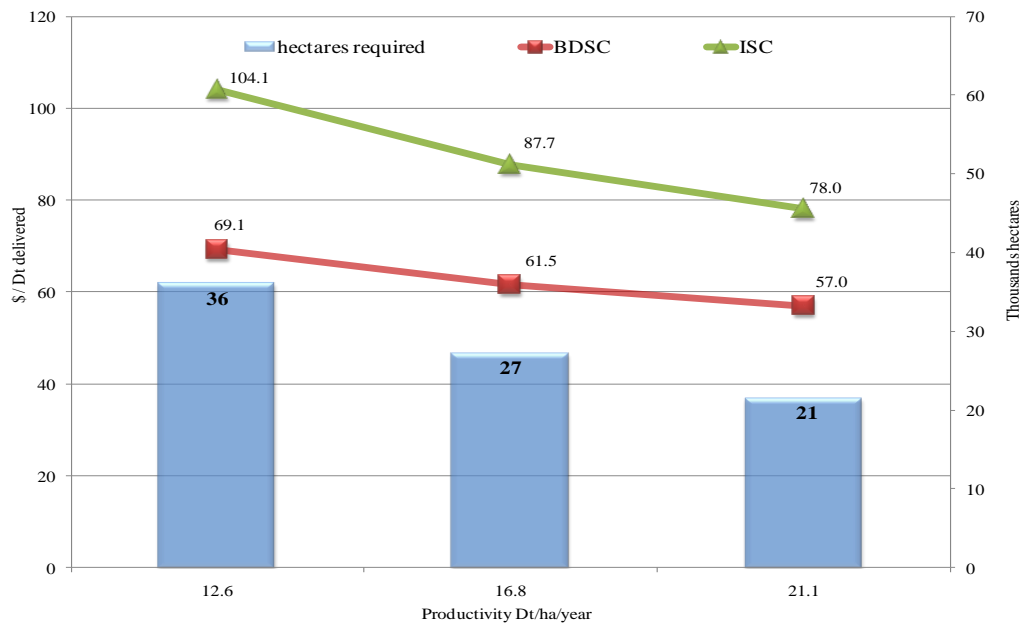


Figure 6-6 Effect of productivity on biomass delivered price and acres required to supply 453,592 Dt (500,000 BDT per year)

6.4.10 Percent of covered area

The percent of covered area around the biomass refinery facility impacts the freight distance and indeed freight cost and delivered price to achieve a specific IRR. The percent of covered area indicates the proportion of land around the biorefinery facility that is currently planted with loblolly pine and assumes that a supply agreement between forest biomass suppliers and the biorefinery has been established. For example, a 20% covered area means that 20% of the land around the facility is dedicated to grow loblolly pine to exclusively supply the biorefinery. This 20% of land producing biomass at a specific productivity ($\text{Dt ha}^{-1}\text{y}^{-1}$) will determine the maximum freight distance to source enough raw materials to achieve the targeted supply. In order to understand the importance of the percent of covered area, Figure 6.7 illustrates the impact of covered area on biomass delivered price (back calculated to achieve 8% IRR), freight distance and freight cost. Assumption for this analyses are based on productivity of $16.8 \text{ Dt ha}^{-1}\text{y}^{-1}$, an annual supply of $\sim 454\text{K Dt year}^{-1}$ ($500\text{K BDT year}^{-1}$), stand tree density of 2,956 trees per hectare in the Biomass Division Supply Chain (BDSC) scenario. It can be seen that lower biomass delivered price occurs at the higher covered area (55%) with biomass delivered price at \$60.2 per Dt, freight distance of 7.8 miles and freight cost at \$3.9 per Dt. A covered area of 5% results in biomass delivered price at \$65.1 per Dt, ~ 26 miles of freight distance and freight cost at \$8.7 per Dt. This difference in covered area affects the profitability of the biorefinery and farmer in $\sim \$2.2$ million per year (freight costs), hence the importance of strategic location but also indicates the importance to

establish supply agreements with local farmers in order to lower delivered price and get a more continuous, reliable and sustainable supply of raw material.

Establishing strategic supply agreements with local farmers has several advantages:

- a. Freight distance and freight costs are reduced when suppliers are located close to the biorefinery facility, as an effect of increasing the percent of covered area with that specific biomass.
- b. Lower carbon foot print in the supply chain can be achieved with shorter freight distance.
- c. Supply agreements give farmers the sensation of market security to establish specific bioenergy crops.
- d. The biorefinery can get more uniform raw material, as well as feedstock genetically modified that might help to enhance conversion yield.

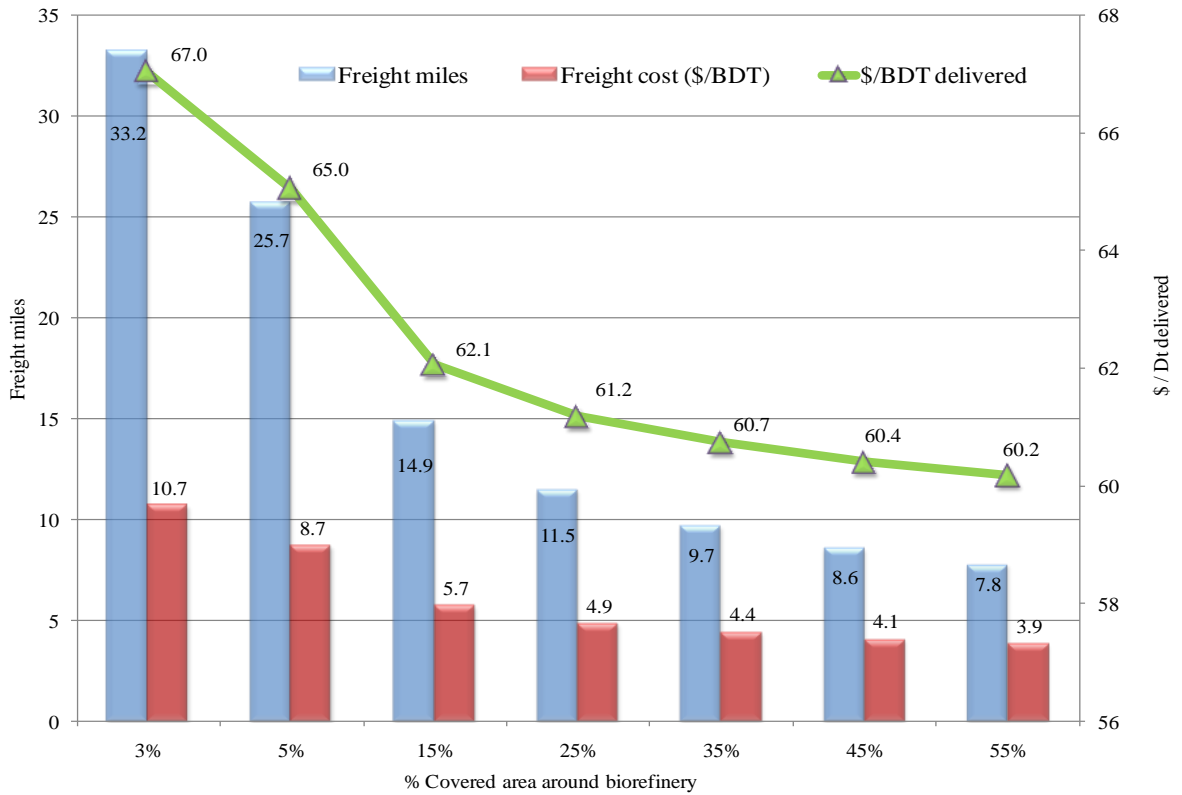


Figure 6-7 Effect of covered area on biomass delivered price ($\$ \text{Dt}^{-1}$), freight cost ($\$ \text{Dt}^{-1}$) and freight miles for a supply of $\sim 454\text{K Dt}$ per year (500K BDT per year)

6.4.11 Annual supply

The annual supply drives delivered price in terms of the amount of hectares to establish, plant, harvest and biomass to transport, $\$ \text{ per Dt}$ as a function of annual supply is sensitive to productivity and covered area. Higher covered area (with supply agreements) might reduce freight miles and delivered price. Figure 6.8 shows the effect of annual supply on $\$ \text{ per Dt}$ delivered, freight costs ($\$ \text{ Dt}^{-1}$) and freight miles. Assumptions for this analysis

are: \$ Dt⁻¹ is back calculated to achieve 8% IRR, 5% covered area, 2,965 trees per hectare and 10 years of rotation length in Biomass Division Supply Chain scenario. A supply of ~ 454K Dt y⁻¹ (500K BDT y⁻¹) indicates a delivered price of \$65 Dt⁻¹, freight distance equivalent to 25.7 miles and freight costs at \$7.8 Dt⁻¹. While a supply of ~907K Dt y⁻¹ (1 million BDT y⁻¹) indicates a delivered price of \$66 Dt⁻¹, freight distance equivalent to 36.4 miles and freight costs at \$11.6 Dt⁻¹. More attention should be paid to the difference in freight miles and freight costs, as \$ per Dt of biomass delivered is back calculated from the free cash flow to achieve a specific IRR.

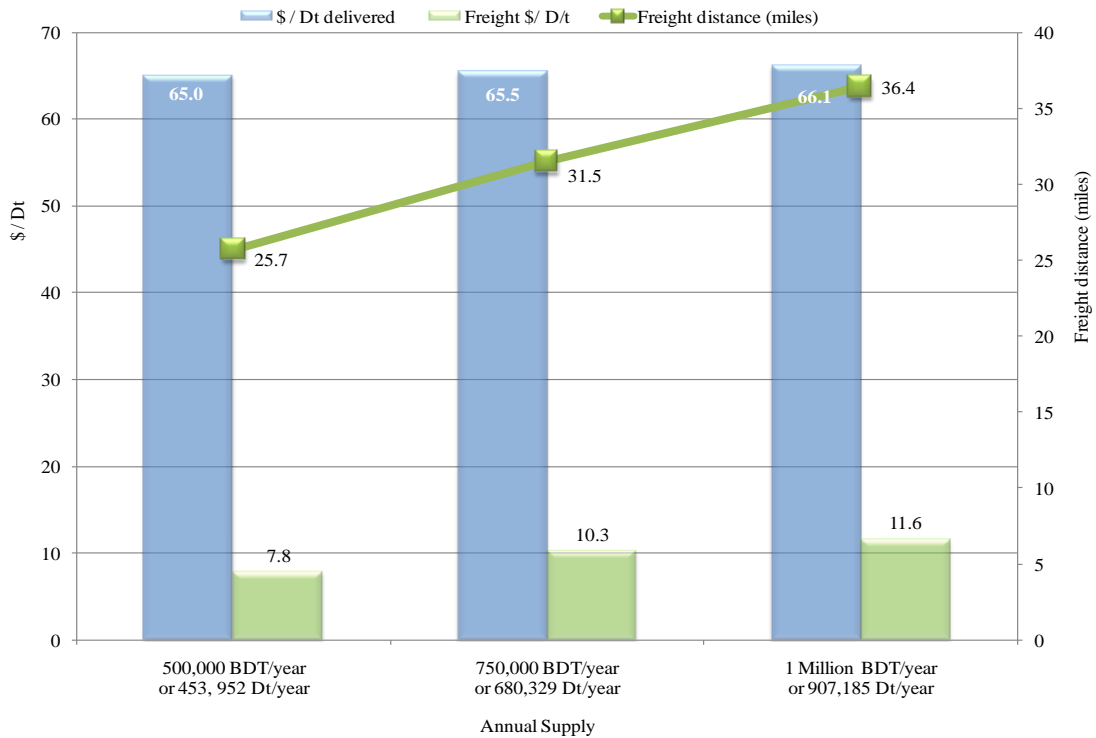


Figure 6-8 Effect of annual supply on \$ BDT⁻¹ delivered, freight costs (\$ BDT⁻¹) and freight miles

6.4.12 Raw material cost, benchmarking loblolly pine

In order to compare our results with other potential energy crops such as switchgrass, Table 3 shows a comparative cost analysis of raw material from the perspective of the biorefinery. Some underestimated but important cost drivers including storage cost, biomass loss during storage and working capital are included in the analysis. The comparison is set for two raw materials with two scenarios for each:

1. Loblolly pine at current delivered market prices, at $\$58 \text{ Dt}^{-1}$ (Anonymous, 2010);
2. Loblolly pine biomass for biomass and bioenergy with delivered price from our simulations at $\$67 \text{ Dt}^{-1}$;
3. Switchgrass biomass delivered price from literature reference value at $\$75.5 \text{ Dt}^{-1}$ (Duffy & Nanhou, 2001a, Kumar & Sokhansanj, 2007);
4. Switchgrass biomass delivered price from a most recent reference, at $\$115 \text{ Dt}^{-1}$ (Conable, 2010).

For all comparisons an annual supply of 500,000 Dt is assumed. With the aim of estimating storage cost and biomass loss during storage, we assume that 70% of the total supply would be stored, resulting in an initial storage quantity of $350,000 \text{ Dt y}^{-1}$. Storage cost was assumed to be around $\$11.9 \text{ Dt}^{-1}$, based on our financial storage models and references found in the literature (Cundiff & Marsh, 1996, Duffy, 2007). Biomass loss during storage was assumed as 4% (Cundiff & Marsh, 1996, Duffy, 2008). A 4% biomass loss storage

represent a biomass loss of around 12,000 Dt, representing a cost in biomass loss ranging from \$900,000 to \$1.4 million (see biomass storage loss cost in Table 3), which is the result of the total biomass loss multiplied by the biomass delivered price and this would charge an additional \$1.8 to \$2.8 per Dt of raw material.

One very important financial issue regarding biomass being stored is the amount of working capital for the biorefinery and the financial cost. Raw material cost while being stored either in biorefinery or in a storage facility near the biorefinery forms part of the working capital. From Table 3, it can be seen that the amount of working capital for switchgrass, under the assumptions used, may range from \$26 million to \$40.2 million, with a large impact on the cash flow of the biorefineries processing these type of biomass. The financial cost of working capital has been estimated multiplying the total value amount of raw material in working capital by an alternative interest rate, in this case 6%, the financial cost of working capital (mainly from raw material) might range from \$1.6 million to \$2.5 million, representing an additional charge of \$3.2 to \$4.8 per Dt.

Comparing the overall raw material cost from the biorefinery perspective from table 3, it can be observed the difference in raw material cost between pine biomass ranging from \$58.0 to \$67.0 Dt⁻¹ with the cost from sourcing with switchgrass, ranging from \$92.7 to \$135.0 Dt⁻¹. The overall incremental cost of using switchgrass instead of loblolly pine would rise to ~\$25.6 million per year, in terms of raw material per se, the economic quantification of the ease of each biomass for conversion into ethanol (i.e. enzymatic hydrolysis) will

provide a more comprehensive understanding. Considerations for risk of potential fire, as well as insurance cost of the switchgrass raw material need to be quantified.

Table 6-3 Raw material costs analyses since the perspective of the biorefinery

		Pine roundwood-Market	Pined chips-simulated	Swtichgrass # 1	Swtichgrass # 2
Annual supply	Dt	500,000	500,000	500,000	500,000
Biomass in storage , 70% of annual supply	Dt			350,000	350,000
Delivered price at mill's gate	\$ Dt ⁻¹	58	67	75.5	115
Storage cost	\$ Dt ⁻¹			11.9	11.9
Biomass storage loss	%			4%	4%
Biomass storage loss	Dt			14,000	14,000
Biomass storage loss costs	\$			1,057,000	1,610,000
Biomass storage loss costs	\$ Dt ⁻¹			2.1	3.2
Working capital	\$			26,425,000	40,250,000
Working capital financial cost per year	\$			1,585,500	2,415,000
Working capital financial cost per Dt	\$ Dt ⁻¹			3.2	4.8
Total raw material cost for biorefinery	\$ Dt ⁻¹	58.0	67.0	92.7	135.0
Total raw material cost for biorefinery	\$MM	29.0	33.5	46.3	67.5

6.4.13 Carbohydrate delivered price

Delivered price per Dt of carbohydrate, is directly influenced by biomass delivered price and the total carbohydrate content in the biomass. The price per Dt of carbohydrate of loblolly pine biomass in the Biomass Division Supply Chain (BDSC) and Investor Supply Chain (ISC) scenarios are presented in Figure 6.9. The \$ per Dt of carbohydrate for the BDSC scenario are represented with a biomass delivered price of \$66.1 per Dt at 65%, 67.5% and 70% carbohydrate content (carbohydrate content at different percent for sensitivity analysis purposes), with delivered carbohydrate prices ranging from \$94.5 to \$101.8 Dt⁻¹ of carbohydrate delivered. In the ISC scenario, the carbohydrate delivered price (at 67.6%

carbohydrate) is around $\$138.6 \text{ Dt}^{-1}$ of carbohydrate. Just for comparison, as of November 2009, one Dt at farm gate of corn carbohydrate (starch) was an equivalent of $\$230 \text{ Dt}^{-1}$ (May, 2009, Murphy, 2010, USDA, 2009).

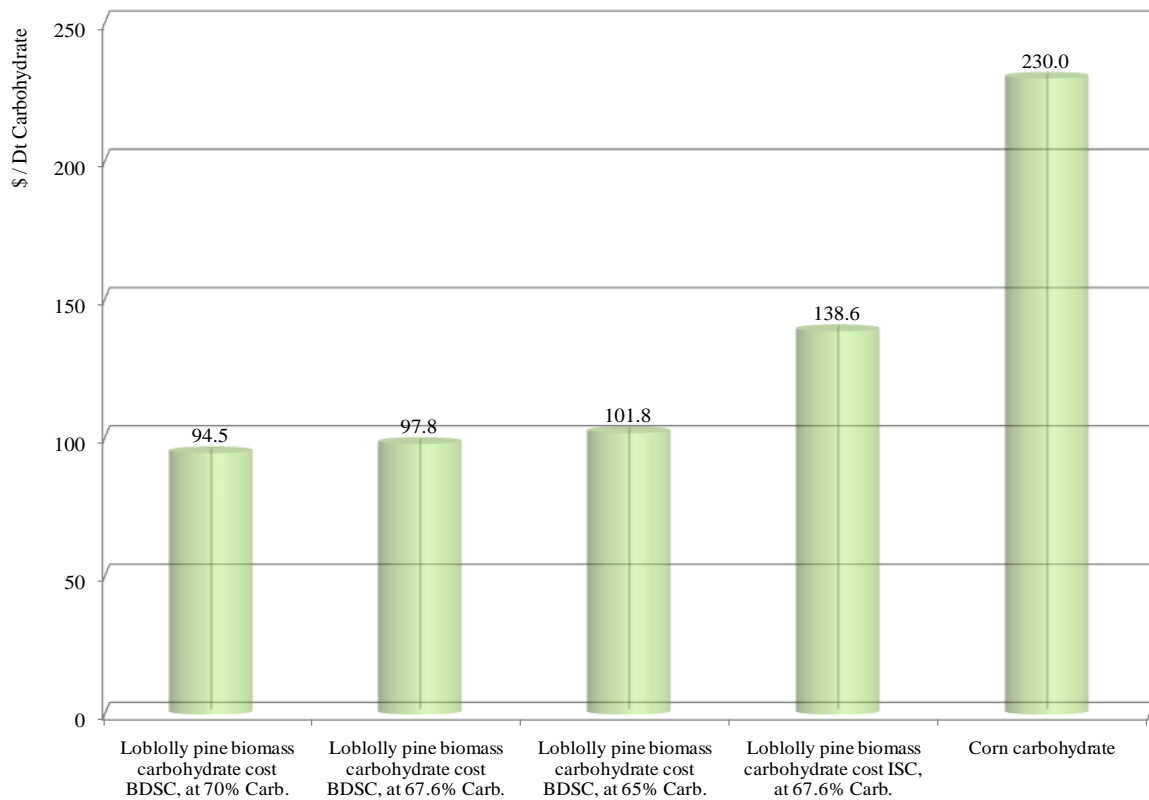


Figure 6-9 Equivalent carbohydrate cost in corn and loblolly pine biomass

6.5 Conclusion

Numerous attributes found in loblolly pine (*Pinus taeda*) such as fast growth, carbohydrate content comparable with other sound bioenergy crops, year round supply with

no need of storage, and the current availability of experienced people with the knowhow of growing, harvesting and delivered, makes loblolly pine a potential biomass to feed the emerging bioenergy industry. The potential of this species in cellulosic ethanol and pellet production has been previously studied and is equally comparable with other bioenergy crops. Our finding show that loblolly pine biomass can be profitably grown with attractive financial return and with the potential to solve many of the underestimated cost drivers presented with agriculture biomass. The comparison of loblolly pine biomass with current costs in switchgrass and its impact in the working capital of the biorefinery is considerable.

Our results indicate that short rotation lengths (9 to 12 years) and high stand tree densities (2,965 to 3,459 trees per hectare) are the best options for biomass production under the costs assumed. The financial simulation identified how key drivers as seedling costs, productivity ($\text{Dt ha}^{-1} \text{ year}^{-1}$) and percentage of covered area growing a specific biomass greatly affect the economics of biomass production.

The flexibility in forest management to achieve similar financial returns in a wide range of rotation lengths at several stand tree densities (trees per hectare) help to reduce the risk associated with growing a new “forest product” such as biomass for bioenergy. The competitive advantage of loblolly pine can be enhanced with genetic improvement and reducing operating costs such as freight which can be reduced with the establishment of supply agreements with local suppliers. The models and supply chain analysis show that loblolly pine is a viable biomass for energy production.

6.6 References

- Amateis R, Burkhart H, Allen H, Montes C (2001) FASTLOB: Fertilized and Selectively Thinned Loblolly Pine Plantations (A Stand-Level Growth and Yield Model for Fertilized and Thinned Loblolly Pine Plantations). *Loblolly Pine Growth and Yield Cooperative*. VPI&SU. Blacksburg, VA. 32pp.
- Anonymous (2010) Market report. Tennessee Forest Products Bulletin. 34-2.
- Baker J, Langdon G (2010) Loblolly Pine. 2010. http://www.na.fs.fed.us/pubs/silvics_manual/Volume_1/pinus/taeda.htm.
- Borders B, Bailey R (2001a) Loblolly pine-pushing the limits of growth. *Southern Journal of Applied Forestry*, **25**, 2, 69-74.
- Borders Be, Bailey RI (2001b) Loblolly pine-pushing the limits of growth. *Southern Journal of Applied Forestry*, **25**, 2, 69-74.
- Bradfield J, Levi M (1984) Effect of species and wood to bark ratio on pelleting of southern woods. *Forest Products Journal*, **34**, 1.
- Clutter J (1963) Compatible growth and yield models for loblolly pine. *Forest Science*, **9**, 3, 354-371.
- Conable D, Volk T (2010) Projecting Cropped Biomass Supplies: The Landowner Factor. Biomass Magazine. BBI (May 2010)
- Conable Dav, T. (2010) Projecting cropped biomass supplies: The landowner factor. Biomass Magazine. BBI International 4. (05) 100
- Cundiff J, Marsh L (1996) Harvest and storage costs for bales of switchgrass in the southeastern United States. *Bioresource technology*, **56**, 1, 95-101.

- De La Torre R, Abt R (2010) Forest Management Options in a Biomass Market. Forest Landowner Magazine. Forest Landowner (April 2010)
- De La Torre Raa, R. (2010) Forest Management Options in a Biomass Market. Forest Landowner Magazine. Forest Landowner Association (April)
- Doolittle W (1958) Site index comparisons for several forest species in the southern Appalachians. *Soil Science Society of America Journal*, **22. 5**, 455.
- Dougherty D (2008a) Forest plantations establishment and maintenance costs. Personal information
- Dougherty D (2008b) President Dougherty & Dougherty.
- Dougherty D (2009) Establishment and maintenance costs of forest plantations. Dougherty & Dougherty Forest Manager. Personal communication
- Duffy M (2007) Estimated costs for production, storage, and transportation of switchgrass. *Staff General Research Papers*.
- Duffy M (2008) Estimated costs for production, storage, and transportation of switchgrass. Iowa State University, Department of Economics.
- Duffy M, Nanhou V (2001a) Costs of producing switchgrass for biomass in southern Iowa. *Iowa State University, University Extension, PM1866*. Available at <http://www.extension.iastate.edu/publications/pm1866.pdf>.
- Duffy M, Nanhou V (2001b) Costs of producing switchgrass for biomass in southern Iowa. 2010. <http://www.extension.iastate.edu/publications/pm1866.pdf>.
- Duncan D (2009) Logging and freight rates, NC Association of Professional Loggers. Personal communication

- Edmonds P, Edmonds C, Mcnair F, Olds P, Tsay B, Milam E (2007) *Survey of Accounting*, New York, McGraw-Hill Irwin.560-565.
- Faaij A (2008) Developments in international bio-energy markets and trade. *Biomass and Bioenergy*, **32**. **2008**, 657.
- Fazzari S, Petersen B (1993) Working capital and fixed investment: new evidence on financing constraints. *RAND Journal of Economics*, **24**. **3**, 328-342.
- Fnc (2007) Silviculture Decision Support System. North Carolina State University and Virginia Tech. 3.0 Beta
- Frederick W, Lien S, Courchene C, Demartini N, Ragauskas A, Iisa K (2008) Production of ethanol from carbohydrates from loblolly pine: A technical and economic assessment. *Bioresource technology*, **99**. **11**, 5051-5057.
- Galbe M, Zacchi G (2002) A review of the production of ethanol from softwood. *Applied microbiology and biotechnology*, **59**. **6**, 618-628.
- Goldemberg J, Coelho S, Nastari P, Lucon O (2004) Ethanol learning curve--the Brazilian experience. *Biomass and Bioenergy*, **26**. **3**, 301-304.
- Hinchee M, Rottmann W, Mullinax L *et al.* (2009) Short-rotation woody crops for bioenergy and biofuels applications. *In Vitro Cellular & Developmental Biology-Plant*, 1-11.
- Hofstrand D (2008) Who profits from the corn ethanol boom. Iowa State University.
- Hofstrand D (2009) Profitability prospects for the corn ethanol industry. Iowa State University.
- Irs (2007) Business expenses. Department of Treasury. Internal Revenue Service. Publication 535, Cat. N. 15065Z.

- Johnson T, Bentley J, Howell M (2003) The South's Timber Industry—An Assessment of Timber Product Output and Use. United States Department of Agriculture Forest Service. Southern Research Station Resource. Bulletin SRS-114.
- Kumar A, Sokhansanj S (2007) Switchgrass (*Panicum virgatum*, L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. *Bioresource technology*, **98. 5**, 1033-1044.
- Mani S, Sokhansanj S, Bi X, Turhollow A (2006) Economics of producing fuel pellets from biomass. *Applied Engineering in Agriculture*, **22. 3**, 421-426.
- Mark M (2009) Harvesting costs. Personal communication
- May A (2009) Corn Market Review. 2010. <http://www4-auth.sdstate.edu/econ/extension/corn/index.cfm>.
- Mcdermott S (2010) Understanding the Economic Drivers of Originating Biomass for Biomass for Power Projects. Biomass Magazine. BBI (May 2010)
- Mielenz J (2001) Ethanol production from biomass: technology and commercialization status. *Current Opinion in microbiology*, **4. 3**, 324-329.
- Montes C (2001) A silvicultural decision support system for loblolly pine plantations. Tesis MSc Forestry. North Carolina State University, 2001, 151 p.
- Murphy W (2010) Tables for weight and measurements: crops. 2010. <http://extension.missouri.edu/publications/DisplayPub.aspx?P=G4020>.
- Perlack R, Wright L, Turhollow A, Graham R, Stokes B, Erbach D (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge National Lab.
- Rfa (2009) Ethanol Industry Outlook. 2010. <http://www.ethanolrfa.org/pages/annual-industry-outlook>.

Schultz R (1999) Loblolly--the pine for the twenty-first century. *New Forests*, **17. 1**, 71-88.

Scott D, Tiarks A (2008) Dual-cropping loblolly pine for biomass energy and conventional wood products. *Southern Journal of Applied Forestry*, **32. 1**, 33-37.

Shapouri H, Duffield J, Mcaloon A, Wang M (2004) The 2001 net energy balance of corn-ethanol. *US Department of Agriculture, Washington, DC*.

Thek G, Obernberger I (2004) Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. *Biomass and Bioenergy*, **27. 6**, 671-693.

Timber-Mart-South (2007) Logging rates No. 4th Quarter. Warnell School of Forestry and Natural Resources. University of Georgia.

Usda (2009) Illinois ethanol corn and co-products processing values. USDA.

Wright J, Sluis-Cremer H (1992) Tracheid morphology and pulp and paper strength traits of *Pinus taeda* and *P. patula* at age 17 years in South Africa. *Tappi journal*, **75. 5**, 183-187.

Wyman C (2007) What is (and is not) vital to advancing cellulosic ethanol. *TRENDS in Biotechnology*, **25. 4**, 153-157.

7 Biomass to Cellulosic Ethanol in Southern U.S.: Supply Chain and Delivered Cost

7.1 Abstract

Supply chain and delivered cost models for seven feedstocks (loblolly pine, Eucalyptus, natural hardwood, switchgrass, miscanthus, sweet sorghum and corn stover) were built simulated the supply of 453,597 dry ton per year to a biorefinery. Biomass delivered cost in forestry feedstock is found to range from \$69 to \$71 per dry ton. Agriculture biomass delivered costs range from \$77.6 to \$102.5 per dry ton. Total production area in fast growing feedstocks was estimated between 22,500 to 27,000 hectares, while total net area for feedstocks with lower biomass productivity ranged from 101,200 to 202,300 hectares (corn stover and natural hardwood respectively). Lower delivered cost per ton of carbohydrate and million BTU are found in loblolly pine, Eucalyptus and natural hardwood. Agriculture biomass showed the higher carbohydrate and BTU delivered costs.

7.2 Introduction

Bioethanol production has been gradually increasing, with Brazil and U.S. as the major producers, with a combined share of ~86% of world bioethanol output for 2009 (RFA, 2010). United States alone has dramatically increased its production by 210% since 2005 (RFA, 2010). This achievement in bioethanol production scale up in U.S. and Brazil, based on the use of corn and sugar cane (respectively) as main feedstocks (Goldemberg, 2007, Goldemberg *et al.*, 2004), has come with concerns on the use of food based raw material for fuel production, with an international debate on food versus fuel, with a wide selection of environmental, social, economical and political pros and cons (Erickson & Sackett, 2007, Foust *et al.*, 2009, Mitchell, 2008, Runge *et al.*, 2007, Tenenbaum, 2008, Wu *et al.*, 2010). The distress was not only related to the increase in food and feed prices, it also considered the fact that farmers would switch their production of current agriculture goods for corn which may give them better profitability (Leibtag, 2008), in addition it is well known that there would not be enough corn in the U.S. to feed the growing ethanol industry. These scenarios have made clear the need for non feed/food based raw material.

Cellulose is the most abundant polymer on earth and has been used as energy source for heating since ancient times, as 2004 biomass contributed with ~13.4% of the global energy supply (Heinimö, 2007, Sims *et al.*, 2006). One of the main advantages of cellulosic biomass is its flexibility to be used to produce different forms of energy, as a solid raw material to generate heat, steam and electricity, but also can be processed to produce liquid

biofuels used in transportation (Jackson, 2010). It is anticipated an increase in the global demand of biomass for bioenergy (Ericsson & Nilsson, 2004, Hillring, 2006, Junginger *et al.*, 2008, Parikka, 2004), mainly derived from the establishment of mandatory legislations in countries such as Netherlands, India, China, Thailand, New Zealand, Canada and U.S (Sims *et al.*, 2006). Just to mention some few examples, the European Union (EU) has placed targets for bioenergy, for the whole region, it is expected that at least 10% of the energy is to come from biomass by 2010 (Faaij, 2006). Moreover, specific EU countries have their own ambitions in bioenergy share, Sweden has formulated that 40% of its primary energy supply by 2020 should come from biomass (Faaij, 2006) while Finland has established a goal of 38% of energy coming from renewable sources (Tohka, 2009). As May 2010, the Swedish Bioenergy Association reported that bioenergy provided 31.7% of the final energy used in Sweden in 2009, displacing oil to second position with 30.8% of energy share (Focus, 2010, Gibson, 2010). For the U.S., the Environmental Protection Agency has announced ambitious goals in advanced biofuels and cellulosic biofuels production, with a target of 1 billion gallons of cellulosic biofuels by 2013 and 16 billion gallons by 2022 (EPA, 2010). Taking into consideration that i) cellulosic feedstock is the single major cost in biomass to bioenergy production (Gonzalez *et al.*, 2010a, Pirraglia *et al.*, 2010b, Tao & Aden, 2009), ii) market place economics, which include type of biomass and availability, should be considered to decide which conversion approach would be used (Blaschek & Boateng, 2009, Faaij, 2008, Mu *et al.*, 2010), and iii) projects that are not endorsed with sufficient feedstock supply are likely to have difficult time obtaining external funding (Johnson, 2010); all of these justify

the special attention that feedstock deserves. The approach to lower biomass delivered cost may include the use of fast growing species, highly productive perennial grasses and the development of specific biomass grown for bioenergy (Gonzalez *et al.*, 2010b, Wu *et al.*, 2010). Recently, a good number of publications on biomass are being produced, mostly based on productivities, chemical composition, and species adaptation to different sites, though there is an increasing number of papers dealing with economics, it is not an easy task to compare supply chain characteristics and biomass delivered cost between different feedstock relying in different publications, mainly because of the different assumptions and financial indicators used. Our paper presents the supply chain and biomass delivered cost of five dedicated energy crops and one agriculture residue, comparing productivities, delivered cost, sourcing freight distance and land area required for an annual supply of 500,000 BDT (bone short dry ton) per year (453,597 dry tons equivalent) to a specific biorefinery.

7.3 Material and methods

7.3.1 Feedstock selection

The basis for the selection of potential agricultural and forestry energy crops plantation was based on extensive literature review and interaction with specialist in the biomass and bioenergy arena, the main parameters to select the potential feedstock are listed as follows:

- i. High biomass productivity per unit of area, measured in dry ton (metric ton) per hectare per year.

- ii. Lignocellulosic biomass not used for food or feed.
- iii. High carbohydrate content in dry biomass basis, suitable for biochemical and thermochemical conversion into ethanol.
- iv. Current availability of that biomass growing in Southern-east U.S.
- v. Available published information on the species as: biomass productivity, carbohydrate content, establishment and maintenance costs, harvesting costs as well as other biomass properties as bulk density and moisture content when harvested, that may allow developing more accurate economic analysis.
- vi. Information on the performance of the biomass in existing and proposed conversion technologies for cellulosic ethanol production.

Based on the review and consultation with specialists, the following feedstocks were selected for further study: fast growing loblolly pine, Eucalyptus, mixed natural hardwood, switchgrass, miscanthus, corn stover and sweet sorghum.

7.3.2 Feedstock description

7.3.2.1 Loblolly pine

Loblolly pine (*Pinus taeda*) is an abundant softwood species in the Southern U.S. with almost 29 million acres (11.7 million ha) making up 20% of standing pine volume in 2007 (Baker, 2008). Loblolly pine is also an important source for saw timber and pulp wood.

In 2002 this species provided nearly 73% of total roundwood softwood volume in the Southern U.S. (Johnson et al. 2003). It grows naturally from central Florida, northward to Delaware and New Jersey, and westward to east Texas and southeast Oklahoma (Schultz, 1999). Intensively managed short rotation (10 to 12 years) loblolly pine in Georgia has been reported to produce around 26.6 m³/ha/year (~12.8 dry tons⁻¹ ha year⁻¹) for pulpwood with stand tree density between 608 to 652 trees per acre. Loblolly pine has been studied for alcohol production; results showed that ethanol production from this species can be economically competitive in comparison to ethanol from corn and other lignocellulosic materials, yet improvement in enzymatic hydrolysis and conversion of pentoses into monomeric reactable sugars still need more research (Frederick et al., 2008).

7.3.2.2 *Eucalyptus*

Eucalyptus (*Eucalyptus sp*) is among the fastest growing hardwood plantation genus in the world. In addition, eucalypts have been used for plantation grown bioenergy and fiber production in numerous countries, as Australia, USA (Hawaii), Ireland, South Africa, Brazil, Uruguay, Venezuela (Gonzalez *et al.*, 2008, Gonzalez *et al.*, 2009, Hinchee *et al.*, 2009, Keffer *et al.*, 2009). The native range of *Eucalyptus* is primarily Australia with a few species also native from Indonesia and Papua New Guinea. *Eucalyptus* plantation in Southern U.S. can be successfully established using freeze tolerant improved seedlings in some specific regions as Florida, Georgia, Alabama, Texas and South Carolina. In 2010 the Forest Nutrition Cooperative at North Carolina State University established freeze tolerant

Eucalyptus trials in order to understand biomass productivity and survival for several regions in U.S. including North Carolina. Rotation length and yields for pulpwood can be 5-8 years with a mean annual increment (MAI) of 8-16 green tons acre⁻¹ year⁻¹ (10 to 20 dry ton ha⁻¹ year⁻¹), while biomass for bioenergy can be 3 to 4 years with MAI of 10 to 18 green tons per acre per year (12.3 to 22.4 dry ton ha⁻¹ year⁻¹) (Gonzalez, 2009). This species is currently being widely researched for pellets and ethanol production (Ferrari *et al.*, 2004, Gonzalez *et al.*, 2008, Gonzalez *et al.*, 2010a, Gonzalez *et al.*, 2010b).

7.3.2.3 Mixed hardwood - natural regeneration

Mixed natural hardwood represents cellulosic biomass current available for conversion across Southern U.S. As 2007 only in the State of North Carolina there were a total of 10.2 million acres of natural hardwood forests and nearly 2.3 million acres of mixed hardwood and pine natural forests as well. Natural hardwood rotation length management may range from 30 to 50 years (Cassidy, 2005). Growth rate and species composition varies according to soil types, climatic conditions and age of the forest. Based on data obtained from the Forest Inventory Data Online (USDA, 2010a) as 2007 the growth per year of natural hardwood forest in the State of North Carolina was close to ~ 0.9 dry ton ha⁻¹ year⁻¹ including only trees with more than 5 inches of diameter at breast height. For transportation costs and distance calculations, it is assumed total biomass growth per year around 2.2 dry ton ha⁻¹ year⁻¹, it is estimated that native forest grows at a rate of ~2.5 dry ton ha⁻¹ year⁻¹ (SunGrant-BioWeb, 2010a), though this will depend on soil and climate characteristics, as well as

species composition. Species composition of natural hardwood forests in North Carolina may include: white and red oaks, hard and soft maples, hickory, yellow birch, beech, sweetgum, tupelo, cottonwood, aspen and yellow poplar (USDA, 2010a).

7.3.2.4 Switchgrass

Switchgrass (*Panicum virgatum* L.) is a perennial grass native to North America. This species has been identified as potential biomass feedstock for bioenergy and is being studied across the U.S. to understand growing conditions and production costs (Austin, 2010a, Austin, 2010b, Cundiff & Marsh, 1996, Epplin, 1996, Kumar & Sokhansanj, 2007, McLaughlin & Kszos, 2005, Wiseloge *et al.*, 1996). Best commercial varieties have been managed successfully with a rotation of 10 years with growth yields ranging from 5.6 to ~22.4 dry ton ha⁻¹ year⁻¹ (Austin, 2010a, Austin, 2010b, McLaughlin & Kszos, 2005, Perrin *et al.*, 2008). Harvesting time of switchgrass is reduced ranging from three to four months per year. Currently studies are being developed to expand the harvesting windows and so reduce storage costs. Switchgrass can be harvested in different seasons of the year, though studies are looking to understand the tradeoff of harvesting switchgrass in different seasons on its long term productivity (Adler *et al.*, 2006), moisture content of switchgrass when harvested after the first freeze and early spring ~ 16% (Haq, 2002).

7.3.2.5 *Miscanthus*

Miscanthus (*Miscanthus sp.*) is a perennial plant native to tropical, subtropical, and warm temperate parts of Southeast Asia and is related to sugar cane. Very limited research has been conducted on this species in the United States. In Europe this species has been studied for bioenergy production (SunGrant-BioWeb, 2010b). In the case of Europe productivity per acre has been estimated between 4.5 and 31.4 dry tons ha⁻¹ year⁻¹ (Clifton-Brown *et al.*, 2001, Lewandowski *et al.*, 2000). Biotech companies in the USA are developing material with better genetics, and with expected productivity between 8 to 16 dry tons per acre per year (White-Technology, 2010). Rotation length may vary from 10 to 25 years, though the tradeoff between productivity and rotation length must be studied in the U.S. Experience from Denmark suggests that harvesting can be done in the Fall or Spring, at different moisture content, if harvested in April/May moisture content range between 12 and 15% (Kristensen, 1998). Delay harvest in late spring may reduce dry biomass per yields, but improves biomass quality, as moisture content is drastically reduced with resulting advantages in handling with no need to dry (Dopazo *et al.*, 2010). Rotation length management for U.S. has been suggested for 10 years with average productivities ranging from 22.4 to 36 dry ton ha⁻¹ year⁻¹ (Heaton *et al.*, 2004).

7.3.2.6 *Sweet sorghum*

Sweet sorghum (*Sorghum sp.*) is a crop close to sugar cane in respect to its sugar content. The plant has high sucrose content and also offers additional carbohydrate material

in the bagasse. The sucrose contained in its juice are fermentable sugars that require minimum pretreatment for ethanol production (Prasad et al., 2007a). Sweet sorghum has also been identified as a possible ethanol feedstock because of its biomass productivity but also for the concentration of readily fermentable sugars as previously mentioned, yet due to short harvest window and poor post harvest storage characteristics its use has been limited (Bennett & Anex, 2008, Bennett & Anex, 2009). The crop has rotation of ~ 4 month with a harvesting windows of ~ 3months (Rajvanshi, 1996, Stotts, 2008). When harvested, sweet sorghum cane moisture content is around ~70 to 75% (Jasberg *et al.*, 1983, Prasad *et al.*, 2007a). Due to its short growing time it is possible to grow two cycle of sweet sorghum per year depending on climate conditions (Brekke, 2005, Matthews, 2009, Veal, 2009), with an expected reduction in biomass production per crop/cycle. For Southern U.S., typical dry matter production varies from ~13.5 to 22.4 dry ton ha⁻¹ year⁻¹, data for one crop per year (Bennett & Anex, 2008, Irvin *et al.*, 2001a). The production of sugar per acre in a sweet sorghum plantation has been found to be positively correlated with dry biomass production (Bennett & Anex, 2008, Bennett & Anex, 2009).

7.3.2.7 Corn stover

Corn stover is the residue left after the corn grain has been harvested. When late harvested, corn stover has low moisture content (16%-20%) with a low bulk density (8.1 lb per f³) (Glassner *et al.*, 1998, Womac *et al.*, 2005). Corn stover supply economics has been studied to understand its potential as a biomass feedstock for bioenergy production (Kadam

& McMillan, 2003, Petroliia, 2008), corn stover's pretreatments and enzymatic hydrolysis for ethanol production have been studied as well (Aden *et al.*, 2002, Kim & Lee, 2005, Öhgren *et al.*, 2007, Wilhelm *et al.*, 2007). The amount of corn stover available per acre is related to the production per acre of corn grain, thus in order to estimate the amount of corn stover available, a ratio of grain corn to corn stover in dry basis has been established and is commonly used to be 1:1 (Lee *et al.*, 2007, Perlack & Turhollow, 2003). In North Carolina, an average productivity of 5.9 dry ton ha⁻¹ year⁻¹ for corn grain was estimated from data available in the National Agricultural Statistics Service for 2009 (USDA, 2010b). Using a conservative scenario of grain to stover ratio of 1:0.8, then an average of 4.6 dry ton ha⁻¹ year⁻¹ of corn stover might be available per acre, with minimum and maximum values between 1.8 to 7.9 dry ton ha⁻¹ year⁻¹.

7.3.2.8 Chemical composition

Chemical composition for each feedstock is illustrated in table 7-1. Carbohydrate content was obtained from average values found in the literature. Forest feedstocks as loblolly pine, Eucalyptus and natural mix hardwood show higher carbohydrate content compared to those found in corn stover, miscanthus and switchgrass. Sweet sorghum is the only feedstock, of those listed here, that provides readily monomeric sugars for fermentation. These sugars, accounting ~48% of total dry biomass, can be sent directly to fermentation without additional costs in pretreatment. This monomeric rich stream can be obtained in a squeeze operation, the resulting solid residues, called sweet sorghum bagasse, can provide

heat (through burning) or can be pretreated for further hydrolysis and fermentation. This source of readily available sugars provide competitive advantage in the conversion process, though due to the reduced harvesting windows and high moisture content, supply chain issues arise when handling this type of raw material. Data regarding the energy content for each of the feedstock (in BTU/lb) were obtained from (DOE, 2010, Ghetti *et al.*, 1996, Pirraglia *et al.*, 2010a).

Table 7-1 Chemical composition for the forest and agriculture feedstock

Components	Loblolly		Natural			Sweet	Corn
	Pine ¹	Eucalyptus ²	hardwood ³	Switchgrass ⁴	Miscanthus ⁵	sorghum ⁶	stover ⁷
Glucose						48%	
Glucans	43.6%	46.7%	42.6%	33.3%	44.0%	20.0%	35.5%
Xylans	6.6%	12.3%	15.1%	21.9%	19.0%	12.0%	19.2%
Galactans	2.2%	0.7%	1.0%	1.1%	0.0%	0.4%	0.9%
Mannans	10.8%	0.6%	2.1%	0.3%	0.0%	0.1%	0.5%
Arabinans	1.6%	0.2%	0.5%	2.9%	0.0%		2.3%
Uronic acid	3.7%	4.4%	4.7%	1.7%	0.0%		3.2%
Acetyl	1.1%	2.8%	2.7%	0.0%	0.0%		0.0%
Lignin	26.8%	29.4%	28.3%	18.1%	17.0%	10.0%	18.7%
Resins							
Extractives	3.2%	3.1%	2.5%	13.2%	2.5%	7.7%	5.4%
Ash	0.4%	0.1%	0.3%	5.5%	2.5%	0.9%	11.6%
Total Carb.	69.6%	67.7%	68.7%	61.2%	63.0%	80.5%	61.5%

Source: ¹ (Frederick et al., 2008), ² (Gomides et al., 2006), ³ (Tunc & van Heiningen, 2008), ⁴ (DOE, 2010), ⁵ (Murnen et al., 2007), ⁶ (Prasad et al., 2007b), ⁷ (DOE, 2010).

7.3.3 Basis for evaluation

The basis for evaluation is biomass delivered cost for a biorefinery with an annual capacity to process 453,597 dry metric tons per year (500,000 dry short ton). For all feedstock a covered area of 5% was assumed, this percentage reflects the portion of area around the biorefinery growing that specific biomass. Economic spreadsheet for each feedstock considering biomass growing costs, harvesting, freight, storage (where applicable) and storage loss (where applicable) were developed and integrated to supply chain models, assuming biomass productivity ($\text{dry ton ha}^{-1} \text{ year}^{-1}$), rotation length and harvesting windows for each of the feedstock as illustrated in table 7-2. Delivered cost for each of the biomass was assumed to vary according to its nature; for dedicated energy crop and plantations as loblolly pine, Eucalyptus, switchgrass, miscanthus and sweet sorghum, total delivered cost is composed of biomass payment to the farmer (stumpage), harvesting cost (paid to a harvesting contractor) and freight cost (paid to a freight service company). For natural hardwood biomass, delivered cost is similar, except for biomass cost which consider a value of 80% of the market price of pulp wood stumpage. For corn stover biomass cost was assumed as most recent reported market values, while other costs for harvesting and freight were estimated similar using the same methodology for switchgrass and corn stover. In the case of agriculture biomass as switchgrass, miscanthus, corn stover and sweet sorghum additional cost in storage and biomass loss during storage were considered. Biomass payment to the farmer was estimated assuming a 6% IRR, harvesting cost estimated assuming 8% IRR,

freight cost were estimated assuming market values, storage cost assuming 6% IRR profit for business unit plus 3% extra cost for biomass loss during storage. For all cases, dollar values are expressed as the first quarter of 2010. For the estimation of the IRR, a 30 years financial evaluation was considered. In the case of switchgrass, miscanthus and sweet sorghum, it was assumed the land was leased by a farmer, who was attracted to grow the bioenergy crop for a financial return, leasing per hectare was assumed at \$135 ha⁻¹. No inflation neither increases in biomass price was considered. For further detail on the methodology see (Gonzalez et al., 2010b). Delivered costs were estimated based on biomass productivity values listed in table 7-2 and establishment and maintenance costs illustrated in table 7-3.

Table 7-2 Biomass productivity, rotation length and harvesting window

Feedstock	*ton ha ⁻¹ yr ⁻¹	Rotation length (moths)	Harvesting window
¹ Loblolly pine	17.1	132	Year round
² Eucalyptus	20.2	48	Year round
³ Natural hardwood	2.2	480	Year round
⁴ Switchgrass	15.7	12	3 months
⁵ Miscanthus	20.2	12	3 months
⁶ Sweet sorghum cane	16.8	4	3 months
⁷ Corn stover	4.5	4	3 months

Based on: ¹simulation using Loblolly pine decision support system (Amateis *et al.*, 2001, Montes, 2001), ²(Gonzalez *et al.*, 2010b, Hinchee *et al.*, 2009), ³(USDA, 2010a), ⁴(Austin, 2010a, Conable & Volk, 2010, George *et al.*, 2008, McLaughlin & Kszos, 2005, Perrin *et al.*, 2008), ⁵(Clifton-Brown *et al.*, 2001, Lewandowski *et al.*, 2000, White-Technology, 2010), ⁶(Bennett & Anex, 2009, Irvin *et al.*, 2001b), ⁷(Kadam & McMillan, 2003, Perlack & Turhollow, 2003, USDA, 2009)

7.3.4 Establishment, maintenance cost and harvesting cost

Establishment costs were estimated based on available publications and through consultation with forestry and agriculture specialist. Harvesting cost were estimated based on harvesting model developed for forestry biomass, grasses and agriculture residues. Harvesting costs were estimated including an 8% IRR for the harvesting contractor. Values in establishment and maintenance and harvesting costs are illustrated in table 7-3. In the case of forestry feedstock, the biomass is delivered in form of chips with moisture content assumed at ~45%. In the case of corn stover, switchgrass and miscanthus, biomass is delivered in form of square bales with a moisture content assumed at ~16%. For sweet sorghum bagasse biomass is delivered in the form of chopped cane with assumed moisture content at ~74%.

7.3.5 Freight

Freight distance was estimated using the average value of biomass productivity listed in table 7-3 and a covered of 5%, this is assumes that 5% of the area around the facility is dedicated to grow that specific energy crop or plantation. Based on the annual supply, biomass productivity (dry ton ha⁻¹ yr⁻¹) and percentage of covered area; the maximum freight distance to achieve that biomass supply was estimated, the methodology is the same as used by (CERES, 2009, Gonzalez *et al.*, 2010b). Freight cost was estimated based on the sourcing distance and with market fees as 2010, those were estimated at \$3.5 per mile of loaded truck (considering one way), plus additional \$30 per hour of loading and unloading. It was

assuming that forestry biomass was weight limited by 26 green tons per truck, while agriculture biomass was volume limited, using a bulk density ~ 8.11 lb per f³ (Edwards, 2007, Kaliyan *et al.*, 2009, Scurlock, 2005, Sokhansanj *et al.*, 2002).

Table 7-3 Trees per hectare, establishment and maintenance cost and harvesting cost for the different feedstocks

Feedstock	Trees per ha	Establishment cost \$ per ha	Maintenance cost \$ per ha	Harvesting cost \$ per dry ton ^f
^a Loblolly pine	2,690	^a 1459	130	34.3
^b Eucalyptus	1,271	^b 1244	135	34.3
Natural hardwood	n/a	n/a	n/a	34.3
^c Switchgrass	n/a	^c 531	242	13.2
^d Miscanthus	n/a	^d 746	242	13.2
^e Sweet sorghum cane	n/a	^e 408	n/a	13.3
Corn stover	n/a	n/a	n/a	26.2

Source: ^{a, b} (ArborGen, 2010, De La Torre & Abt, 2010, Dougherty, 2009, Gonzalez *et al.*, 2010b), ^{c, d} (Conable & Volk, 2010, Duffy, 2008a, Kumar & Sokhansanj, 2007, Lewandowski *et al.*, 2000, Rizzon, 2009, Veal, 2010, White-Technology, 2010), ^e (Bennett & Anex, 2009, Rizzon, 2009, Veal, 2010), ^f based on harvesting models develop at NC State University 2010.

7.3.6 Storage and biomass loss

Storage cost was considered for agriculture energy crops and residues as switchgrass, miscanthus, corn stover and sweet sorghum. Storage cost was calculated at \$13.3 per dry ton, this was estimated as a separate business unit to achieve 6% IRR based on annual supply of

453,597 dry ton year⁻¹ and with the assumption that 60% of the biomass will be stored, this value of biomass storage cost is similar to previous reported storage costs and followed similar methodology used by (Cundiff & Marsh, 1996, Duffy, 2008b). Storage biomass loss cost was estimated assuming an average of 3% biomass loss per year considering a covered storage (Cundiff & Marsh, 1996, Sanderson *et al.*, 1997, Shinnors *et al.*, 2003, Sokhansanj *et al.*, 2006), biomass loss cost was obtained multiplying biomass loss percentage by the cost of the delivered biomass, the overall costs was then divided by the total volume per year.

7.4 Results and Discussion

7.4.1 Annual productivity and total required area for production

Total production area required to supply an annual volume equivalent to 453,597 dry ton, directly depend on the biomass productivity of the feedstock, measure in dry ton (metric) per hectare per year. As listed in figure 7-1, in the case of loblolly pine the annual area to harvest, assuming an average biomass productivity of 17.1 dry ton hectare year, and rotation length of 11 years, would be ~2, 416 hectares (2,416 hectares x 11 years rotation length x 17.07 dry ton ha⁻¹ year⁻¹ \approx 453,597 dry ton). Yet, this is the net area require to supply the targeted volume in a specific year, for a continuous production year after year production, the total net area required is ~ 26,576 hectares (2,416 hectares year⁻¹ x 11 years rotation length). Based on this, it is expected that high productive biomass as Eucalyptus, switchgrass and loblolly pine would required less area, when compared to low productivity biomass as natural

hardwood and corn stover. It is emphasize that these calculation consider net area of production, commonly total area would be 25% to 30% bigger due to areas belonging to natural forests, roads and facilities. In this respect, it can be observed how total production net areas can vary around 22,500 to 28,900 hectares for the fast growing species, to more extensive production surface between 101,200 to 202,300 hectares for corn stover and natural mixed hardwood respectively. More acres in production to achieve the same annual supply imply more land mechanization, increasing CO₂ emission of the plantation-crop establishment and harvesting, plus a greater sourcing distance to achieve that annual supply.

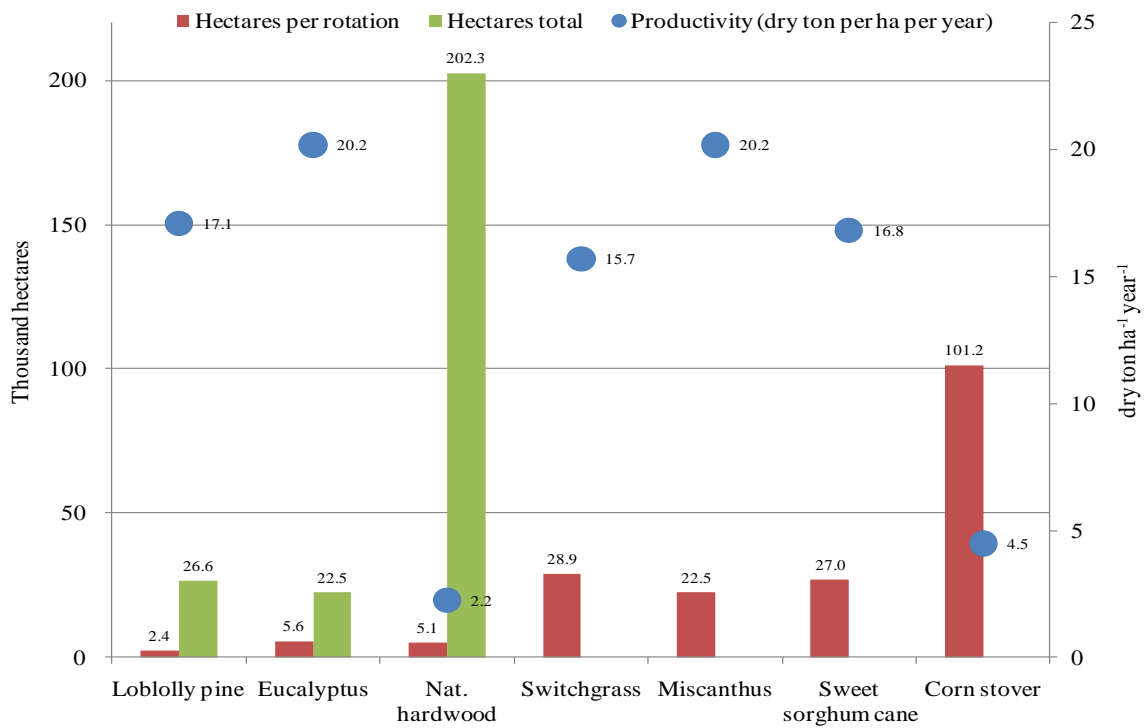


Figure 7-1 Biomass productivity and hectares required for production to supply 453,597 dry ton yr-1

7.4.2 Sourcing freight distance

As previously mentioned, sourcing freight distance depends on biomass productivity and percentage of area growing that specific biomass. Changes in either biomass productivity (dry ton ha⁻¹ yr⁻¹), percentage of covered area (%) and annual biomass supply (dry tons per year) will affect feedstock sourcing radius distance. Taking as example loblolly pine, with a biomass productivity of 17.1 dry ton ha⁻¹ yr⁻¹, assuming 5% of covered area around the facility growing loblolly pine exclusively to supply 453,597 dry tons per year to the biorefinery, a maximum radius distance of 41.1 km is needed to source the targeted biomass supply. Thus, from figure 7-2 it can be observed how high productive feedstocks as eucalyptus, miscanthus and loblolly pine have lower sourcing radius with freight distance ranging from ~38 to 41 km. In the other hand, feedstock with lower biomass productivity such as corn stover and natural mixed hardwood lead to higher sourcing freight distance, ranging from ~80 to ~114 km. As higher freight distance will result in higher freight costs, this can level off biomass delivered costs of agriculture residues to delivered costs of dedicated energy crops, as an example, in the case of corn stover biomass payment to the farmer might be lower compared to those payments required to compensate investment to grow dedicated energy crops as switchgrass, miscanthus and eucalyptus, considering that agriculture residues as corn stover having low biomass availability per hectare would result in higher freight costs to supply specific biomass volume.

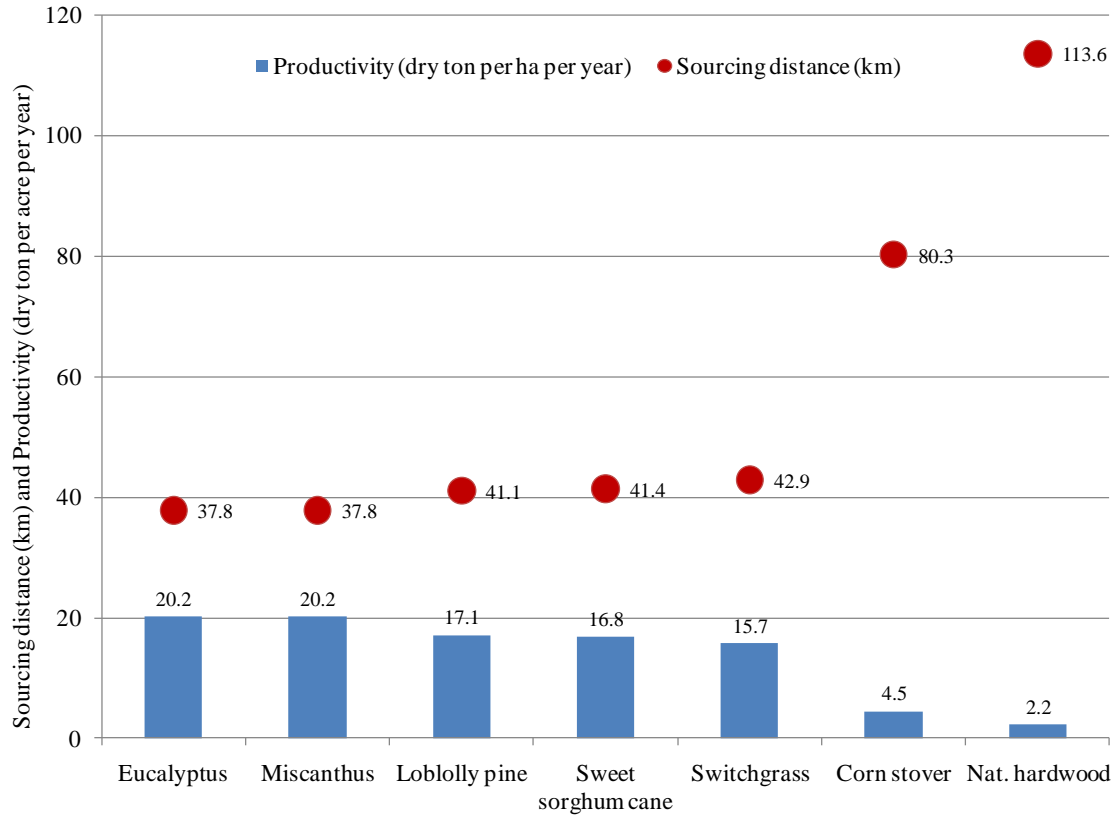


Figure 7-2 Sourcing distance (km) and productivity (dry ton ha⁻¹ yr⁻¹) for the different feedstocks

7.4.3 Delivered cost

Though there are huge expectations to achieve lower biomass delivered costs below \$40 per dry ton, studies so far show that the target is not yet around the corner. Based on the assumption listed in the methodology section, using average establishment, maintenance, harvesting and freight costs, as well as average reported biomass productivity; biomass delivered cost for the seven feedstocks considered in this manuscripts do not even fall below \$65 per dry ton. For forestry feedstock, the main cost driver is harvesting, follow by

stumpage (payment to the farmer), with exception to natural hardwood where the second more important cost driver is freight cost (due to higher sourcing distance). Reduction in delivered costs for forestry feedstock includes the establishment of plantations at high strand tree density (exclusively for biomass production) and with harvesting equipments specifically developed for forest biomass. Biomass delivered cost for the modeled energy plantation feedstock range from \$69.4 to \$71 per dry ton, figure 7-3. Biomass delivered cost for switchgrass; miscanthus, sweet sorghum and corn stover include additional costs in storage and biomass loss during storage. Lower delivered cost might be found in miscanthus followed by switchgrass and corn stover (\$77.6, \$85.9 and \$87 per dry ton respectively). Though delivered cost of sweet sorghum cane is higher compared to the other feedstock considered in this analysis, there is an important advantage derived from the availability of readily monomeric sugars for fermentation no requiring additional costs in pretreatments (for this fractions of the biomass), this cost saving can be better appreciated in a complete conversion model into alcohol comparing each of the feedstocks. Increases in biomass productivity and ensuring a higher percent of covered with the desired feedstock will reduce harvesting and freight costs, with a favorable impact to the delivered into the biorefinery.

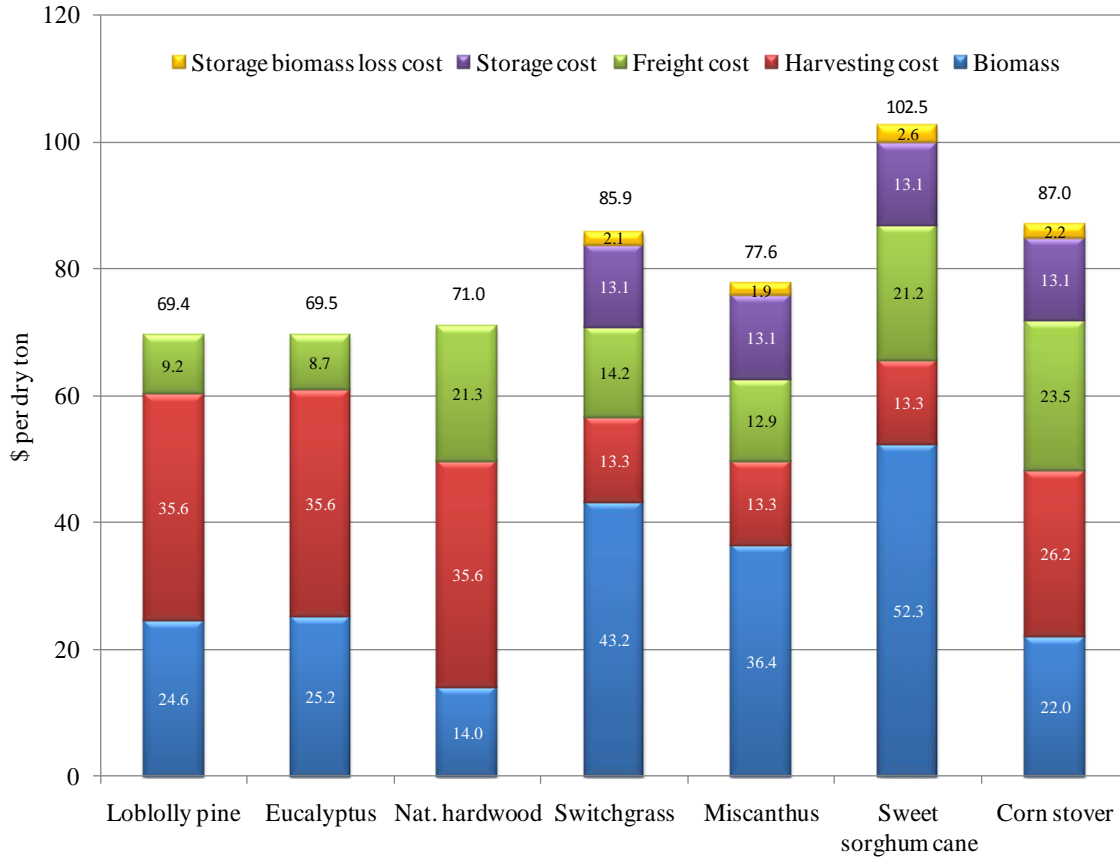


Figure 7-3 Biomass delivered cost for each of the feedstock, considering 5% covered area and annual supply of 453,597 dry ton year-1

7.4.4 Carbohydrate and BTU delivered cost

Biomass delivered cost is an important indicator to understand raw material cost and compare between different alternative feedstock available in a region. More over there are two indicators that provides more useful information, taking into consideration carbohydrate and energy content, those are carbohydrate delivered cost (\$ per ton of carbohydrate) and

BTU delivered cost (\$ per million BTU), illustrated in figure 7-4. Carbohydrate delivered cost is lower in more recalcitrant biomass as loblolly pine and Eucalyptus (resulting from a combination of lower biomass delivered cost and high carbohydrate content). Carbohydrate cost in dedicated energy crops and agriculture residues, range from \$123.1 to \$141.4 per dry ton. In terms of heating content, lower delivered cost are found in loblolly pine (\$3.7 per million BTU) and Miscanthus (\$4.4 per million BTU), while higher delivered costs are found in sweet sorghum and corn stover (\$6.3 and \$5 per million BTU respectively).

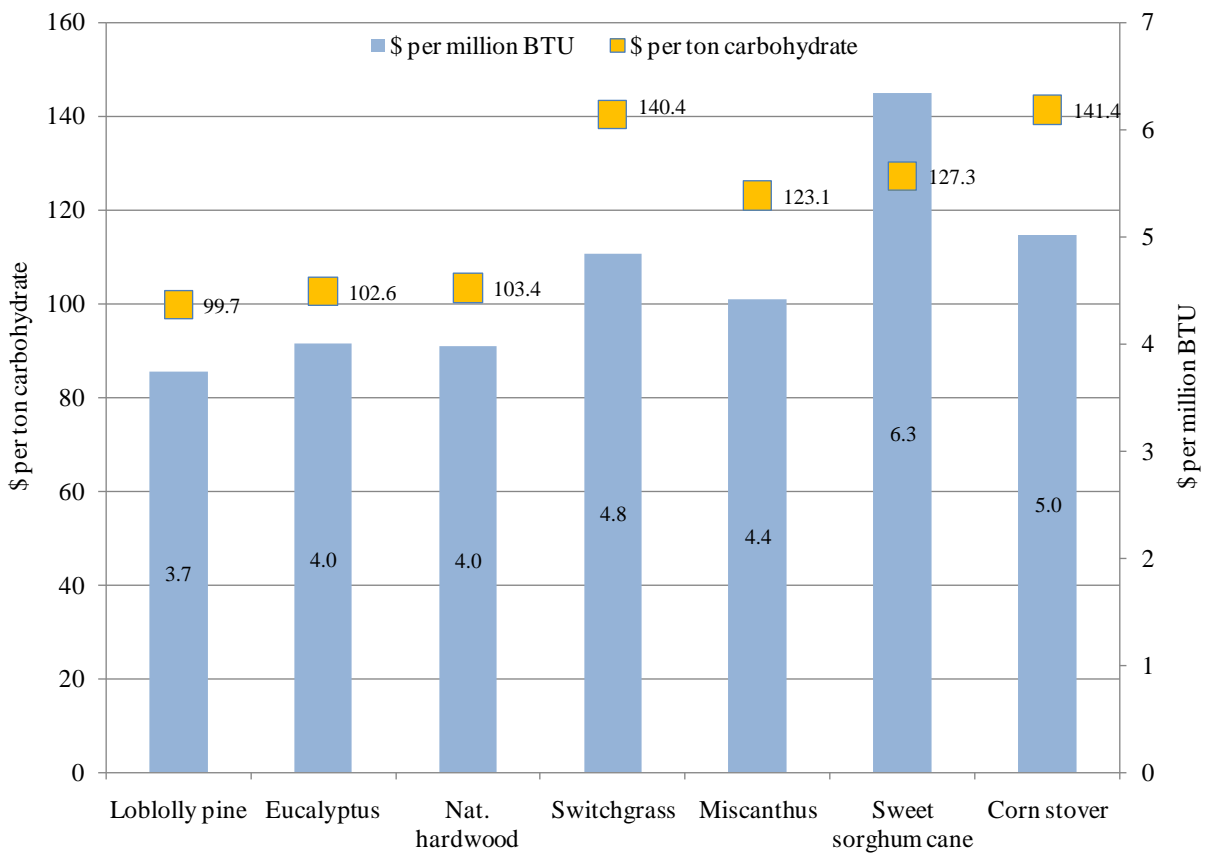


Figure 7-4 Delivered cost per ton of carbohydrate and \$ per million BTU

7.4.5 Supply chain

Woody biomass offers many advantages over agricultural crops and harvest residues, because: (a) efficient and well developed machinery for harvest; (b) storage in the field is not an issue, since the trees continue to grow until ready for harvest; and (3) wood is dense enough to load trucks to a weight limit, thus minimizing transportation costs. Wood chips store well at a plant site, and are not subject to degradation and loss of chemical value at the processing plant. Almost none of those advantages exist for non-wood crops:

- a. Harvesting equipment is typically adapted from other commercially available designs;
- b. In the case of corn stover and switchgrass, baling is required. Bale storage location can be in the field or at the plant site, but in either case, insurance and ownership must be addressed.
- c. Storage is problematic. Though we assumed 3% loss in storage, other issues include accelerated degradation dependent on local weather, and means of storage. Some plant design concerns arise when considering accumulating a year's volume of raw material supply in the short (3-4 months) harvest window period. The land requirement for storage at a central location is prohibitive, so decentralized storage is often specified.
- d. Crop failure, at least for corn and sweet sorghum, are well known; switchgrass experience is not extensive enough at present to assess.
- e. Following harvest and baling most reports suggest compaction prior to transport to plant site. In most cases, trucks are filled only to a volume limit – rather than the more economic

weight limit due to low < 10 bone dry pounds per cubic foot, a value approximately 3 x the bulk density of wood chips.

7.5 Conclusions

Biomass delivered cost for seven feedstock (loblolly pine, Eucalyptus, natural hardwood, switchgrass, miscanthus, sweet sorghum and corn stover) were modeled in supply chain and economic models to deliver 453,597 dry ton per year to a biorefinery, considering most recent published costs and biomass productivity. Lower freight distance can be achieved by establishing high yield energy crops as loblolly pine, Eucalyptus, switchgrass, miscanthus and sweet sorghum. Biomass delivered cost in forestry feedstock is found to range from \$69 to \$71 per dry ton, agriculture biomass delivered costs range from \$77.6 to \$102.5 per dry ton. Total production area in fast growing biomass was estimated between 22,500 to 27,000 hectares, while total net area for feedstock with lower biomass productivity ranged from 101,200 to 202,300 hectares (corn stover and natural hardwood respectively). Lower delivered cost per ton of carbohydrate and million BTU are found in loblolly pine, Eucalyptus and natural hardwood. Agriculture biomass showed the higher carbohydrate and BTU delivered costs.

7.6 References

- Aden A, Ruth M, Ibsen K *et al.* (2002) Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. NREL.
- Adler P, Sanderson M, Boateng A, Weimer P, Jung H (2006) Biomass yield and biofuel quality of switchgrass harvested in fall or spring. *Agronomy Journal*, **98. 6**, 1518.
- Amateis R, Burkhart H, Allen H, Montes C (2001) FASTLOB: Fertilized and Selectively Thinned Loblolly Pine Plantations (A Stand-Level Growth and Yield Model for Fertilized and Thinned Loblolly Pine Plantations). *Loblolly Pine Growth and Yield Cooperative. VPI&SU. Blacksburg, VA. 32pp.*
- Arborgen (2010) Product Catalog. In: *2010-2011 Planting Season.* (ed Arborgen) pp, Summerville, SC, ArborGen.
- Austin A (2010a) Scientists evaluate switchgrass yields across the US. Biomass Magazine. BBI International 2010. (9) 18-19
- Austin A (2010b) Studying switchgrass. Biomass Power and Thermal. BBI International 2010. (11) 46-51
- Baker Jal, G. (2008) Loblolly Pine. pp, USDA Forest Service.
- Bennett A, Anex R (2008) Farm-gate production costs of sweet sorghum as a bioethanol feedstock. *American Society of Agricultural and Biological Engineers*, **51. 2**.
- Bennett A, Anex R (2009) Production, transportation and milling costs of sweet sorghum as a feedstock for centralized bioethanol production in the upper Midwest. *Bioresource technology*, **100. 4**, 1595-1607.
- Blaschek H, Boateng A (2009) Introduction to Session 4: New Biofuels and Biomass Chemicals. *Applied Biochemistry and Biotechnology*, **154. 1**, 1-2.

- Brekke K (2005) Beyond Corn, Alternative feedstocks for ethanol production *Ethanol Today* April. 31-33
- Cassidy D (2005) A Southern Pine Management Guide for Tennessee Landowners. University of Tennessee. Extension PB1751. Extension PB1751.
- Clifton-Brown J, Lewandowski I, Andersson B *et al.* (2001) Performance of 15 Miscanthus genotypes at five sites in Europe. *Agronomy Journal*, **93. 5**, 1013.
- Conable D, Volk T (2010) Projecting Cropped Biomass Supplies: The landowner factor. *Biomass Magazine*. BBI International 2010. (5) 78-81
- Cundiff J, Marsh L (1996) Harvest and storage costs for bales of switchgrass in the southeastern United States. *Bioresource technology*, **56. 1**, 95-102.
- De La Torre R, Abt R (2010) Forest Management Options in a Biomass Market. *Forest Landowner Magazine*. 2010. (4)
- Doe U (2010) Biomass Feedstock Composition and Property Database. 2010. http://www1.eere.energy.gov/biomass/feedstock_databases.html.
- Dopazo R, Vega-Nieva D, Ortiz L (2010) Herbaceous energy crops: reviewing their productivity for bioenergy production. 2010. http://193.146.36.56/ence/publicaciones/Valencia_OC7.3.pdf.
- Dougherty D (2009) Establishment and maintenance costs of forest plantations. Dougherty & Dougherty Forest Manager. Personal communication
- Duffy M (2008a) Estimated costs for production, storage, and transportation of switchgrass. Iowa State University, Department of Economics.
- Duffy M (2008b) Estimated costs for production, storage, and transportation of switchgrass. *Staff General Research Papers*.

- Epa (2010) EPA Finalizes Regulation for the National Renewable Fuel Standard Program for 2010 and Beyond. In: *EPA-420-F-10-007*. pp, United States Environmental Protection Agency
- Eppin F (1996) Cost to produce and deliver switchgrass biomass to an ethanol-conversion facility in the southern plains of the United States. *Biomass and Bioenergy*, **11. 6**, 459-467.
- Erickson L, Saket G (2007) Food vs. Fuel. http://www.uoguelph.ca/plant/courses/plnt-6250/pdf/G_Samii-Saket.pdf.
- Ericsson K, Nilsson L (2004) International biofuel trade--A study of the Swedish import. *Biomass and Bioenergy*, **26. 3**, 205-220.
- Faaij A (2006) Bio-energy in Europe: changing technology choices. *Energy Policy*, **34. 3**, 322-342.
- Faaij A (2008) Developments in international bio-energy markets and trade. *Biomass and Bioenergy*, **32. 2008**, 657.
- Ferrari M, Neirotti E, Alborno C, Saucedo E (2004) Ethanol production from eucalyptus wood hemicellulose hydrolysate by *Pichia stipitis*. *Biotechnology and bioengineering*, **40. 7**, 753-759.
- Focus Re (2010) More bioenergy than oil in Sweden. 2010. <http://www.renewableenergyfocus.com/view/9480/more-bioenergy-than-oil-in-sweden/>.
- Foust T, Aden A, Dutta A, Phillips S (2009) An economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion processes. *Cellulose*, **16. 4**, 547-565.
- Frederick W, Lien S, Courchene C, Demartini N, Ragauskas A, Iisa K (2008) Production of ethanol from carbohydrates from loblolly pine: A technical and economic assessment. *Bioresource Technology*, **99. 11**, 5051-5057.

- George N, Tungate K, Hobbs A (2008) A guide for growing swithgrass in North Carolina. North Carolina Solar Center, NC State University. 1.
- Ghetti P, Ricca L, Angelini L (1996) Thermal analysis of biomass and corresponding pyrolysis products. *Fuel*, **75. 5**, 565-573.
- Gibson L (2010) Biomass Sweet Spot. Biomass Power and Thermal. BBI International 2010. (12) 34-39
- Glassner D, Hettenhaus J, Schechinger T (1998) Corn stover collection project.
- Goldemberg J (2007) Ethanol for a sustainable energy future. *Science*, **315. 5813**, 808.
- Goldemberg J, Coelho S, Nastari P, Lucon O (2004) Ethanol learning curve--the Brazilian experience. *Biomass and Bioenergy*, **26. 3**, 301-304.
- Gomides J, Colodotte J, Chaves R, Mudado C (2006) Os clones de excelencia de Eucalyptus no Brasil para producao de Celulose. In: *39th Pulp and Paper International Congress and Exhibition*. pp, São Paulo, Brazil.
- Gonzalez R, Saloni D, Dasmohapatra S, Cubbage F (2008) South America: industrial roundwood supply potential. *BioResources*, **3. 1**, 255-269.
- Gonzalez R, Treasure T, Phillips R, Jameel H, Saloni D, Abt R, Wright J (2010a) Converting Eucalyptus biomass into ethanol: Financial and sensitivity analysis in a co-current dilute acid process. Part II. *Biomass and Bioenergy*, **35. 2**, 767-772.
- Gonzalez R, Treasure T, Wright J, Saloni D, Phillips R, Abt R, Jameel H (2010b) Exploring the potential of Eucalyptus for energy production in the Southern United States: Financial analysis of delivered biomass. Part I. *Biomass and Bioenergy*, **35. 2**, 755-766.
- Gonzalez R, Wright J, Saloni D (2009) Filling a need: Forest Plantation for Bioenergy in the Southern US Biomass Magazine BBI 2009. (8) 44-47

- Gonzalez R, Wright, J. And Saloni, D (2009) Filling a need: Forest Plantation for Bioenergy in the Southern U.S. . *Biomass Magazine* 8. 44-47
- Haq Z (2002) Biomass for electricity generation. *Energy Information Administration, US Dept. of Energy Washington, DC: Available at <http://www.eia.doe.gov/oiaf/analysispaper/biomass/pdf/biomass.pdf>*.
- Heaton E, Long S, Voigt T, Jones M, Clifton-Brown J (2004) Miscanthus for renewable energy generation: European Union experience and projections for Illinois. *Mitigation and adaptation strategies for global change*, **9. 4**, 433-451.
- Heinimö Jp, V.; Ojanen, V. And Kässi, T. (2007) INTERNATIONAL BIOENERGY TRADE- scenario study on international biomass market in 2020. LAPPEENRANTA UNIVERSITY OF TECHNOLOGY DEPARTMENT OF INDUSTRIAL ENGINEERING AND MANAGEMENT. Research report 181.
- Hillring B (2006) World trade in forest products and wood fuel. *Biomass and Bioenergy*, **30. 10**, 815-825.
- Hinchee M, Rottmann W, Mullinax L *et al.* (2009) Short-rotation woody crops for bioenergy and biofuels applications. *In Vitro Cellular & Developmental Biology-Plant*, 1-11.
- Irvin C, Dwayne R, Hallam A, Hunter E (2001a) Biomass Production and Ethanol Potential from Sweet Sorghum. Iowa State University. 91-46.
- Irvin C, Dwayne R, Hunter E (2001b) Biomass Production and Ethanol Potential from Sweet Sorghum. Iowa State University.
- Jackson Sr, T.; Taylor, A.; Bozell, J. And Norris, K. (2010) Wood2Energy. A State of the Science and Technology Report. The University of Tennessee. Institute of Agriculture.
- Jasberg B, Montgomery R, Anderson R (1983) Preservation of sweet sorghum biomass.

- Johnson R (2010) Event tackles controversial topics. *Biomass Magazine*. BBI International 2010. (9) 4
- Junginger M, Bolkesjø T, Bradley D *et al.* (2008) Developments in international bioenergy trade. *Biomass and Bioenergy*, **32. 8**, 717-729.
- Kadam K, Mcmillan J (2003) Availability of corn stover as a sustainable feedstock for bioethanol production. *Bioresource technology*, **88. 1**, 17-25.
- Keffer V, Turn S, Kinoshita C, Evans D (2009) Ethanol technical potential in Hawaii based on sugarcane, banagrass, Eucalyptus, and Leucaena. *Biomass and Bioenergy*, **33. 2**, 247-254.
- Kim T, Lee Y (2005) Pretreatment and fractionation of corn stover by ammonia recycle percolation process. *Bioresource Technology*, **96. 18**, 2007-2013.
- Kristensen E (1998) Harvesting and handling of Miscanthus—Danish experiences.
- Kumar A, Sokhansanj S (2007) Switchgrass (*Panicum virgatum*, L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. *Bioresource technology*, **98. 5**, 1033-1044.
- Lee D, Owens V, Boe A, Jeranyama P (2007) Composition of herbaceous biomass feedstocks. No. *SGINCI-07*. Brookings, SD: North Central Sun Grant Center.
- Leibtag E (2008) Corn Prices Near Record High, But What About Food Costs? *Amber Waves*, **6. 1**, 10-15.
- Lewandowski I, Clifton-Brown J, Scurlock J, Huisman W (2000) Miscanthus: European experience with a novel energy crop. *Biomass and Bioenergy*, **19. 4**, 209-228.
- Mattews J (2009) Sweet sorghum two crops per year.

- Mclaughlin S, Kszos A (2005) Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. *Biomass and Bioenergy*, **28. 6**, 515-535.
- Mitchell D (2008) A note on rising food prices. The World Bank Development Prospects Group. Policy Research Working Paper 4682.
- Montes C (2001) A silvicultural decision support system for loblolly pine plantations. Thesis MSc Forestry. North Carolina State University, 2001, 151 p.
- Mu D, Seager T, Rao P, Zhao F (2010) Comparative Life Cycle Assessment of Lignocellulosic Ethanol Production: Biochemical Versus Thermochemical Conversion. *Environmental Management*, **46**. 565-578.
- Murnen H, Balan V, Chundawat S, Bals B, Da Costa Sousa L, Dale B (2007) Optimization of ammonia fiber expansion (AFEX) pretreatment and enzymatic hydrolysis of miscanthus x giganteus to fermentable sugars. *Biotechnology progress*, **23. 4**, 846-850.
- Öhgren K, Bura R, Saddler J, Zacchi G (2007) Effect of hemicellulose and lignin removal on enzymatic hydrolysis of steam pretreated corn stover. *Bioresource Technology*, **98. 13**, 2503-2510.
- Parikka M (2004) Global biomass fuel resources. *Biomass and Bioenergy*, **27. 6**, 613-620.
- Perlack R, Turhollow A (2003) Feedstock cost analysis of corn stover residues for further processing. *Energy*, **28. 14**, 1395-1403.
- Perrin R, Vogel K, Schmer M, Mitchell R (2008) Farm-scale production cost of switchgrass for biomass. *BioEnergy Research*, **1. 1**, 91-97.
- Petrolia D (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.

- Pirraglia A, Gonzalez R, Saloni D (2010a) Energy properties of two the cold-resistant Eucalyptus (*E. Benthamii* and *E. Macarthurii*) North Carolina State University. First Quater Report 2010.
- Pirraglia A, Gonzalez R, Saloni D (2010b) Techno-economical analysis of wood pellets production for US manufacturers. *BioResources*, **5. 4**, 2374-2390.
- Prasad S, Singh A, Jain N, Joshi H (2007a) Ethanol production from sweet sorghum syrup for utilization as automotive fuel in India. *Energy Fuels*, **21. 4**, 2415-2420.
- Prasad S, Singh A, Jain N, Joshi Hc (2007b) Ethanol production from sweet sorghum syrup for utilization as automotive fuel in India. *Energy Fuels*, **21. 4**, 2415-2420.
- Rajvanshi A (1996) Sweet Sorghum R&D at the Nimbkar Agricultural Research Institute (NARI).
- Rfa (2010) 2010 Ethanol industry outlook. Climate of opportunity. 2010. http://www.ethanolrfa.org/page/-/objects/pdf/outlook/RFAoutlook2010_fin.pdf?nocdn=1.
- Rizzon (2009) Forecasting Profits and Production Feasibility of Emerging North Carolina Energy Crops. Unpublished Master North Carolina State University, Raleigh, 219 pp.
- Runge C, Senauer B, Romm J, Lovins A, Wirth T, Gray C, Podesta J (2007) Food for Fuel? Foreign Affairs. (September/October 2007)
- Sanderson M, Egg R, Wiselogel A (1997) Biomass losses during harvest and storage of switchgrass. *Biomass and Bioenergy*, **12. 2**, 107-114.
- Schultz Rp (1999) Loblolly--the pine for the twenty-first century. *New Forests*, **17. 1**, 71-88.
- Shinners K, Binversie B, Savoie P (2003) Harvest and storage of wet and dry corn stover as a biomass feedstock. 2003 ASAE Annual International Meeting Las Vegas, Nevada, USA

- Sims R, Hastings A, Schlamadinger B, Taylor G, Smith P (2006) Energy crops: current status and future prospects. *Global Change Biology*, **12. 11**, 2054-2076.
- Sokhansanj S, Kumar A, Turhollow A (2006) Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). *Biomass and Bioenergy*, **30. 10**, 838-847.
- Stotts D (2008) Oklahoma's Biofuels Initiative Transforming Energy Industry. 2010. <http://www.vpr.okstate.edu/publications/Vanguard%2008.pdf#page=1>.
- Sungrant-Bioweb (2010a) Hybrid Poplar. 2010. <http://bioweb.sungrant.org/Technical/Biomass+Resources/Agricultural+Resources/New+Crops/Short+Rotation+Woody+Crops/Hybrid+Poplar/Default.htm>.
- Sungrant-Bioweb (2010b) Miscanthus. 2010. <http://bioweb.sungrant.org/>.
- Tao L, Aden A (2009) The economics of current and future biofuels. *In Vitro Cellular & Developmental Biology-Plant*, **45. 3**, 199-217.
- Tenenbaum D (2008) Food vs. fuel: Diversion of crops could cause more hunger. *Environmental Health Perspectives*, **116. 6**, A254.
- Tohka Ak, N.; Savolahti, M. And Kupiainen, K. (2009) Finland's Long Term Climate and Energy Strategy-Emission Projections. 2010. http://www.unece.org/env/lrtap/TaskForce/tfiam/35/tfiam35_Tohka_NationalFinland.pdf.
- Tunc M, Van Heiningen A (2008) Hemicellulose extraction of mixed southern hardwood with water at 150 C: Effect of time. *Ind. Eng. Chem. Res*, **47. 18**, 7031-7037.
- Usda (2009) 2007 Census of Agriculture. 1. http://www.agcensus.usda.gov/Publications/2007/Full_Report/usv1.pdf.
- Usda (2010a) Forest Inventory and Analysis National Program. 2010. <http://fia.fs.fed.us/>.

Usda (2010b) National Agricultural Statistics Service. 2010. <http://www.nass.usda.gov/>.

Veal M (2009) Sweet sorghum production.

Veal M (2010) Establishment and harvesting costs of switchgrass. Personal communication

White-Technology (2010) Miscanthus. 2010.
<http://www.whitetechnologyllc.com/miscanthus.htm>.

Wilhelm W, Johnson J, Karlen D, Lightle D (2007) Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy Journal*, **99. 6**, 1665.

Wiseloge A, Agblevor F, Johnson D, Deutch S, Fennell J, Sanderson M (1996) Compositional changes during storage of large round switchgrass bales. *Bioresource technology*, **56. 1**, 103-109.

Womac A, Igathinathane C, Sokhansanj S, Pordesimo L (2005) Biomass moisture relations of an agricultural field residue: corn stover. *Transactions of the ASAE*, **48. 6**, 2073-2083.

Wu X, McLaren J, Madl R, Wang D (2010) Biofuels from Lignocellulosic Biomass. *Sustainable Biotechnology*, 19-41.

8 Economics of cellulosic ethanol production: green liquor pretreatment for softwood and hardwood, greenfield and repurpose scenarios

8.1 Abstract

Green liquor pulping takes advantage of a technology used worldwide in hundreds of kraft pulp mills and is proposed here as a potential pretreatment pathway for efficient conversion of lignocellulosic biomass into ethanol. Mixed southern hardwood, Eucalyptus and loblolly pine were evaluated through process simulation in two investment scenarios: greenfield and repurposing of existing kraft pulp mill assets to cellulosic ethanol production. Several advantages come with this concept: i) proven technology (both process and equipment); ii) chemical and energy recovery in place, iii) existing fiber supply chain, and iv) experienced labor force around the mill. Ethanol yields by enzymatic hydrolysis of pretreated fibers were higher in natural mixed hardwood and eucalyptus (280-285 liters per dry ton of biomass) and lower in loblolly pine (273). Natural hardwood and Eucalyptus in the repurposing scenario are the most profitable combinations with IRR ~19%, mainly due to low CAPEX, low enzyme costs (compared to loblolly pine) and higher ethanol yield. Production cost was estimated at \$2.51 per gallon of ethanol, (or \$0.66 per liter), cash cost of \$2.14/gallon (or \$0.57 per liter) and CAPEX of \$3.15/gallon (or \$0.83 per liter). Due to high CAPEX, a greenfield green liquor pretreatment scenario does not produce financeable returns under the current assumptions.

8.2 Introduction

Despite unprecedented incentives and investments by both private and government entities there is not a single commercial facility producing cellulosic ethanol in the U.S. as of the 4th quarter 2010. The Environmental Protection Agency (EPA) has set ambitious cellulosic biofuel production targets of 0.25 billion gallons (BBG) for 2011, 1 BBG for 2013 and 16 BBG for 2022 (EPA, 2010). Several barriers across the entire supply chain have been identified as the major hurdles to profitably produce cellulosic ethanol (Figure 8-1). These obstacles are mainly related to lignocellulosic feedstock costs and availability (Bohlmann, 2006, Gonzalez *et al.*, 2010c, Jackson, 2010), high pretreatment costs required to lower recalcitrant nature of cellulosic biomass (Gonzalez *et al.*, 2010b, Lynd *et al.*, 2008, Mosier *et al.*, 2003, Mosier *et al.*, 2005, Overend *et al.*, 1987), high enzyme costs (Wyman, 2007), high capital investment required (Bohlmann, 2006, Solomon *et al.*, 2007) and low market ethanol selling price requiring incentive and subsidy (PEW-CENTER, 2010) to achieve competitive financial returns.

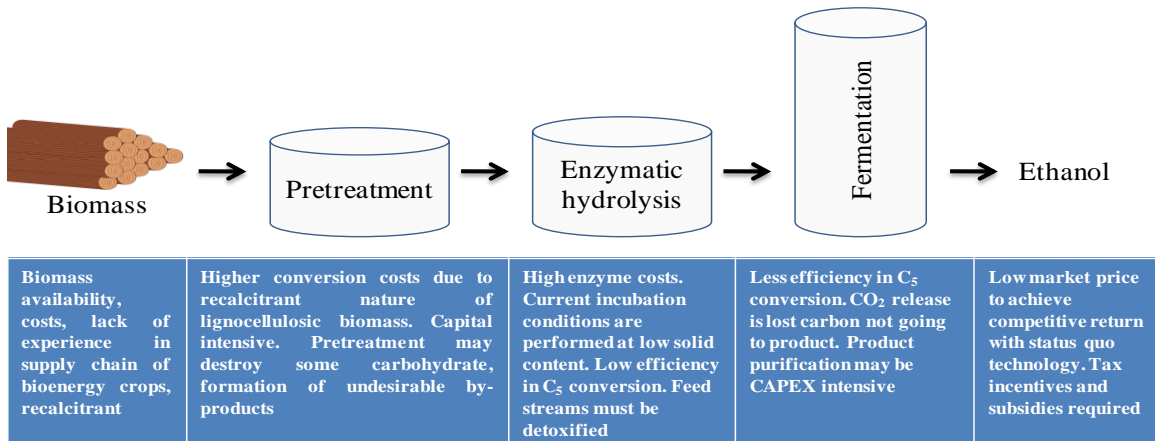


Figure 8-1 Brief description of major barriers identified in cellulosic ethanol production

When comparing the success in bioethanol production in the U.S. and Brazil (mainly using corn grain and sugar cane as feedstocks) versus cellulosic ethanol (using mainly lignocellulosic feedstocks such as grasses, agriculture residues and forest biomass), major differences exist with respect to byproduct value, and manufacturing and pretreatment/conversion costs. Corn ethanol conversion processes produce several byproducts such as protein, oil, corn steep liquid, gluten and dry distilled grains with an existing and increasing market (RFA, 2010, Wu *et al.*, 2010b). On the other hand, though technical/economic analyses of cellulosic ethanol have highlighted the importance of recovering all major lignocellulosic components to offset high feedstock cost (Gregg & Saddler, 1996), commercial byproducts of cellulosic ethanol processes are so far minimal. Researchers are working to find possible uses of hemicelluloses for polymer manufacturing and identifying more profitable uses of lignin other than heat-steam-power generation (Janssen *et al.*, 2008, Janssen & Stuart, 2010, Pan *et al.*, 2005a). The production of marketable byproducts is indeed of great importance for the economy of the biorefinery. In addition, conversion costs are higher in lignocellulosic biomass (compared to corn and sugar cane ethanol) mainly due to its natural resistance to enzymatic hydrolysis (Mosier *et al.*, 2005, Pan *et al.*, 2005b, Wyman *et al.*, 2005). Features in biomass affecting enzymatic digestibility have been the subject of intense research with special interest on: cellulose crystallinity, degree of polymerization, specific surface area, carbohydrate-lignin complexes and degree of hemicelluloses acetylation (Zheng *et al.*, 2009). Significant resources have been committed to understanding the recalcitrance of lignocellulosic biomass, as well as in

designing low CAPEX (Capital expenditure) and low OPEX (operational expenditure) pretreatment process. Although many pretreatment methods have been developed and are in pilot demonstration (Wu et al., 2010b), this required stage in conversion still represents one of the major technological challenge for ethanol commercialization.

Pretreatments might be broadly divided into three major groups: physical, chemical and biological. Physical pretreatments include chipping, grinding and milling the biomass to reduce particle size but some have argued that the energy requirement for such a process would be unfeasible (Jin et al., 2010). Biological pretreatments include the use of lignin degrading microorganisms. This type of pretreatment is considered environmentally friendly and consumes small amounts of energy relative to physical pretreatments. However, biological pretreatments are not practical at industrial scale because of long residence times and loss of C₅ and C₆ sugars along with lignin (Jin *et al.*, 2010, Lee, 1997, Walton, 2009). Chemical pathways include pretreatments under alkaline and/or acidic media used to increase accessibility to the cellulose (Mosier *et al.*, 2005, Wu *et al.*, 2010b, Yang *et al.*, 2002). Chemical pretreatments are believed to be the most promising pathway for commercial application, but still barriers persist as uncertainty in equipment scale up (Boerrigter, 2006) and the need for additional CAPEX for chemical recovery (required for both economical and environmental reasons) (Zheng et al., 2009).

This paper focuses on the economics of producing cellulosic ethanol using green liquor, a novel pretreatment process based on proven technology currently used in hundreds of Kraft pulp mills around the world. Green liquor is an alkaline intermediate in Kraft

pulping; it is composed of ~75% Na_2CO_3 and 25% Na_2S , its recovery process in the mill is proven and practiced. Green liquor pretreatment has been shown to achieve competitive carbohydrate recovery (% of carbohydrates in wood that are converted to monomeric sugars) in hardwood (>80%) (Jin et al., 2010) and softwood (>70%) (Wu et al., 2010a). Other attractive features of this pathway include technology already in place and available experience in equipment scale up and operations. Green liquor has also been reported to be used in hemicellulose extraction prior to pulping (Um & van Walsum, 2009, Um & van Walsum, 2010, Walton, 2009) and as a pretreatment prior pulping to improve kraft pulp yield (Ban & Lucia, 2003). The concept of green liquor pretreatment in a repurposed Kraft mill is based on the idea of converting existing shut down Kraft pulp mills (closed due to economic conditions) into biorefineries for ethanol production. The financial impact of considering the repurposing concept is analyzed in comparison to a greenfield scenario. Detailed financial analysis, CAPEX and sensitivity analysis is presented considering three biomass types: southern mixed hardwood, Loblolly Pine and Eucalyptus.

8.3 Material and methods

8.3.1 Green liquor pretreatment

As previously discussed, green liquor is a mixture of sodium carbonate and sodium hydroxide. It is inherently produced in the chemical recovery process in kraft pulp mills when spent cooking black liquor is burned in the recovery boiler, producing a water-soluble smelt of sodium carbonate and sodium sulfide. When dissolved, green liquor is produced.

Chemical recovery is proven and with technology already in place, a major advantage compared to other emerging technologies. The overall proposed pathway is illustrated in Figure 8-2. Biomass is chipped and fed into a pulp digester with conditions as described by (Jin *et al.*, 2010, Wu *et al.*, 2010a). After pulping, the slurry is washed in vacuum filters, with two streams coming out of this process unit: i) weak black liquor and ii) washed pulp. Weak black liquor contains dissolved organic material, lignin and cooking chemicals. Solids content of weak black liquor is increased by means of evaporators (using fresh steam from the recovery boiler) and the resulting black liquor is fed, together with lignin (coming from a downstream lignin filter), into the recovery boiler where it is burned to produce steam (for power and process steam) and begin the chemical recovery process. The smelt from the recovery boiler is dissolved in water producing green liquor. Following the pathway for ethanol production, the pulp (after washers) is fibrillated using refiners commonly found in pulp and paper mills (not shown). Following mechanical treatment in the refiners to increase accessible surface area, the pulp is further delignified using molecular oxygen and sodium hydroxide as a catalyst. Oxygen delignification is highly selective towards removing lignin without destroying carbohydrates. The pulp is then enzymatically hydrolyzed for 48 hours as described by (Jin *et al.*, 2010). After hydrolysis the remaining lignin is filtered (and sent to recovery boiler) and separated from the monomeric stream which is subsequently fermented and dehydrated to produce 99% ethanol as a final product.

8.3.2 Basis for evaluation

A total of six cases were evaluated (Table 8-1), and represent combinations of i) three biomasses (mixed natural hardwood, Eucalyptus and pine), ii) green liquor pretreatment for all cases, and iii) two scenarios regarding greenfield and repurposing. Additional sensitivity analyses are presented later.

Table 8-1 Basis for evaluation

Case\Combination	I	II	III	IV	V	VI
Technology	GL	GL	GL	GL	GL	GL
Raw material	N. Harwood	N. Harwood	Eucalyptus	Eucalyptus	Pine	Pine
Financial scenarios	Green field	Repurposing	Green field	Repurposing	Green field	Repurposing

GL = Green liquor; N. Harwood = natural hardwood

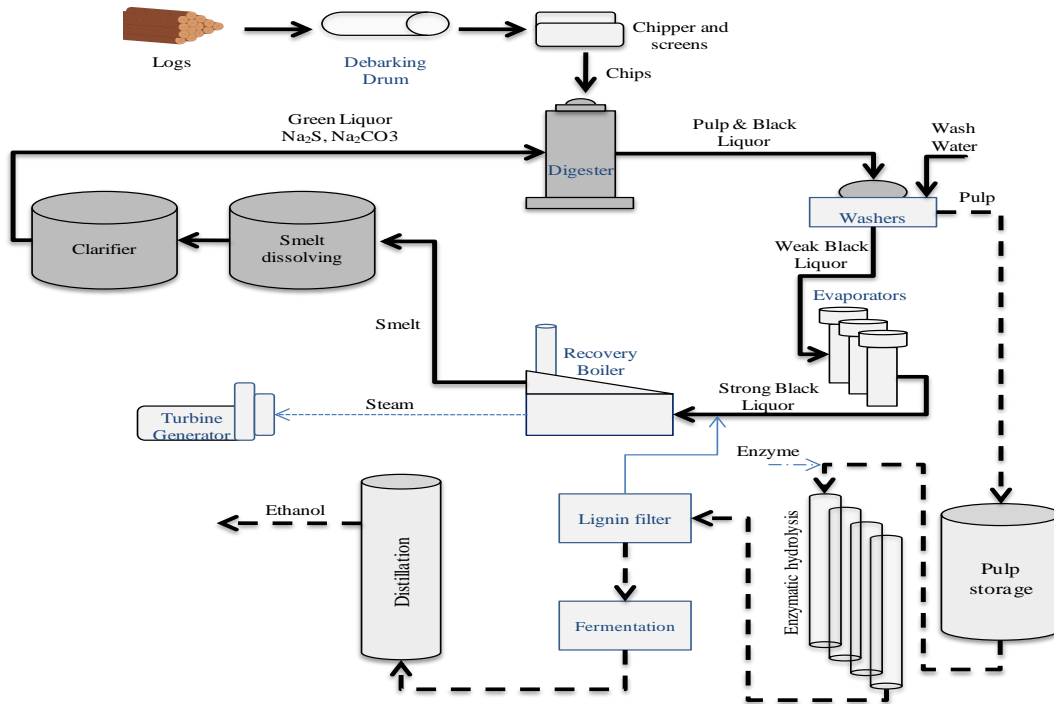


Figure 8-2 Illustration of green liquor recovery in a Kraft pulping process

8.3.3 Feedstock

Three forestry biomasses are used as feedstocks in this economic conversion analysis: southern mixed hardwood, Loblolly Pine and *Eucalyptus sp.* Chemical compositions assumed for each of the biomasses are presented in Table 8-2. Southern mixed hardwood and Loblolly Pine are abundant feedstocks naturally occurring in Southern U.S. These raw materials currently supply the wood product industry in the region and constitute a well established supply chain. Genetically improved, fast growing and cold resistant *Eucalyptus sp.*, has been recently introduced in Southern U.S. by ArborGen (Gonzalez *et al.*, 2008, Gonzalez *et al.*, 2010c, Hinchee *et al.*, 2009). These three biomasses represent current and potential forest biomass assets for conversion into liquid biofuel.

Feedstock cost for each biomass has been assumed and estimated as follows: mixed southern hardwood at \$71 per dry metric ton (dry ton), Loblolly Pine at \$69.4 per dry ton and *Eucalyptus* at \$69.4/dry ton. The estimated biomass delivered cost was based on the productivities, rotation length, moisture content, covered area and annual supply as presented on Table 8-3. The methodology implemented to estimate biomass delivered cost is similar to the methodology used by Gonzalez et al 2010 (Gonzalez et al., 2010c). For pine and eucalyptus the following items were considered when estimating biomass delivered cost: plantation establishment and maintenance cost (ensuring a 6% internal rate of return (IRR) to the farmer), harvesting cost (estimating an 8% IRR to the harvesting contractor) and freight

cost using market values. For natural mixed hardwood all analysis was the same except for the stumpage cost that was assumed at 80% of pulpwood stumpage market price.

Table 8-2 Chemical constituents of southern mixed hardwood, Loblolly Pine and Eucalyptus

Composition	¹ Southern mixed hardwood	² Loblolly Pine	³ Eucalyptus sp
Glucans	42.6%	43.6%	46.7%
Xylans	15.1%	6.6%	12.3%
Galactans	1.0%	2.2%	0.7%
Mannans	2.1%	10.8%	0.6%
Arabinans	0.5%	1.6%	0.2%
Uronic acid	4.7%	3.7%	4.4%
Acetyl	2.7%	1.1%	2.8%
Lignin	28.3%	26.8%	29.4%
Resins	2.5%	3.2%	3.1%
Ash	0.3%	0.4%	0.1%

Source: ¹(Tunc & van Heiningen, 2008), ²(Frederick et al., 2008), ³(Gomides et al., 2006).

Table 8-3 Delivered cost, rotation length, productivity, moisture content, covered area and annual supply assumed for natural mixed hardwood, Eucalyptus and Pine

Biomass	Natural hardwood	Eucalyptus	Pine
\$/dry ton *	71.0	69.4	69.4
Rotation length (years)	-	4	11
Productivity (dry ton/acre/yr)	2.2	20.2	17.0
Moisture content (%)	45%	45%	45%
Covered area (%)	5%	5%	5%
Supply (dry ton/year)	453,597	453,597	453,597

*metric ton

8.3.4 CAPEX

Capital expenditure (CAPEX), which represents all capital expending in equipments and structures is summarized in Table 8-4. All equipment costs have been up-dated to year 2012 and sized for an equivalent dry biomass flow of 453, 597 dry ton (or 500,000 dry short tons). Two investment scenarios are illustrated: greenfield and repurposing. Greenfield includes all investment associated with land purchase and preparation, equipment, and buildings for a brand new facility with a total CAPEX of ~ \$310 million. CAPEX for the greenfield cases are very similar for the three biomass considered, as is the case for repurposing. Total CAPEX in the repurposing scenario is estimated around ~ \$106 million. The lower CAPEX (compared to greenfield) for the repurposing scenario is mainly due to the fact that existing equipment and buildings in the closed kraft pulp mill resemble most of the equipment required in the greenfield facility. New investments in the repurpose scenario are required in chip receiving, mechanical and chemical post-treatments (refining and oxygen delignification respectively) and lignin filter. Investment in fermentation and dehydration assets is required in both scenarios.

Table 8-4 Capital expenditure for the biorefinery, greenfield and repurposing

Area	Scale factor	Green field (US\$)	Repurposing (US\$)	Source
Site preparation				
Land purchase	0.9	1,238,934		1
Land preparation	0.9	14,867,211		1
Raw water treatment	0.7	1,447,504		1
Waste water treatment	0.7	2,171,256		1
Roundwood receiving				
Chip receiving		17,745,379	17,745,379	1
Pretreatment				
Green liquor pretreatment	0.6	30,373,350		1
Post Treatment				
Mechanical post treatment	0.6	5,528,526	5,528,526	1
Oxygen post treatment	0.6	18,597,603	18,597,603	1
Enzyme post treatment	0.5	48,619,292		1
Lignin filter	0.6	12,525,287	12,525,287	2
Biorefinery				
Fermentation	0.8	22,074,022	22,074,022	3
Beer column	0.8	5,011,199	5,011,199	3
Rectification column	0.8	4,653,067	4,653,067	3
Dehydration	0.7	4,320,328	5,139,166	3
Product storage & shipment	0.6	4,718,604	4,718,604	3
Yeast preparation				
Recovery and power				
Evaporation	0.6	28,409,692		1
Recovery boiler	0.6	59,475,156		1
Turbine generator	0.5	28,100,034		1
Other			10,000,000	1
Total CAPEX		309,876,446	105,992,853	

Source: ¹(Anonymous, 2010a), ²(Anonymous, 2010b), ³(Aden et al., 2002)

8.3.5 General assumptions

Table 8-5 lists major assumptions used in the technical/economic analysis. Listed input data are related to: financial evaluation horizon of the project (15 years), CAPEX

spending schedule, working capital, tax rate, discount rate, revenue for ethanol selling, subsidies and other (see Table 8-5 for further detail). Most of the inputs assumed are standards for the three biomass considered, except for enzyme and chemical costs (both in \$ per liter of ethanol). Enzyme cost are assumed to be different mainly because of the enzyme charge required to achieve targeted polymer to monomer conversion. Differences in enzyme doses are due to varying recalcitrance of each biomass. Enzyme dosages are obtained from laboratory experiments and literature review (Jin *et al.*, 2010, Kazi *et al.*, 2010, Wu *et al.*, 2010a) (see enzyme dosage and cost section for further information). Costs are scale at 3% per year. Ethanol revenue (\$ per liter of ethanol) is assumed to increase 2% per year with the ethanol subsidy being held constant throughout the project life time.

Table 8-5 Modeled chemical and enzyme cost, and majors assumptions used in the economic analysis

Description	Value	Description	Value
Startup year	2012	Hourly and administrative staff	120
Terminal year	2026	Salaried staff, \$/hr	24
Plant & equipment scaleup exponent	0.70	Maintenance expense, including Labor,	2%
CAPEX spending		Capital reinvestment, % of replacement asset value	1%
% of spending in year -2	30%	Other fixed costs, % of sales	3%
% of spending in year -1	50%	Sales and other overhead, % of sales	3%
% of spending in year -0	20%	Gas cost, \$ per MMBTU	4.5
% of nominal capacity, project year 1	50%	Enzyme cost, \$ per liter ethanol, M. hardwood	0.15
% of nominal capacity, project year 2	80%	Enzyme cost, \$ per liter ethanol, Eucalyptus	0.16
Excess Material Use in Project year 1	0.3	Enzyme cost, \$ per liter ethanol, Loblolly pine	0.31
Working capital % of direct cost +	10%	Chemical cost, \$ per liter ethanol, M. hardwood	0.01
Years depreciation schedule, straight line	10	Chemical cost, \$ per liter ethanol, Eucalyptus	0.01
Tax rate, with tax loss carryforward	35%	Chemical cost, \$ per liter ethanol, Loblolly Pine	0.01
Discount rate	12%	Yeast cost, \$ per liter ethanol	0.02
Terminal value, year 15 EBITDA multiple X	5	Caustic Soda, \$ per Ton (100%)	441
Hours per year	8400	Sodium Carbonate, \$ per Ton (100%)	220
Revenue per liter of ethanol	0.528	Sodium Sulfate, \$ per Ton (100%)	441
Subsidy added to price, \$ per liter ethanol	0.267	Ammonia, \$ per Ton (100%)	220
Subsidy, tax credit	0.5	Sulfuric Acid, \$ per Ton (100%)	441
Power, \$ per MWH	50	Lime, \$ per Ton (100%)	220

8.3.6 Enzyme costs and dosage

Enzyme cost was assumed at \$1.85 per kg of enzyme (Bryant, 2010). Enzyme doses modeled for our analysis are presented in Table 8-6. The conversion between enzyme dose g/g of cellulose and FPU/g of cellulose was done following methodology used by (Kazi et al., 2010). Enzymatic charge was based on enzymatic hydrolysis lab results (Jin *et al.*, 2010, Wu *et al.*, 2010a). Enzyme activity is estimated to be 85 FPU per gram of enzyme. The

enzyme dose for Eucalyptus was assumed similar to mixed hardwood, while twice the dose is needed to achieve 80% of enzyme hydrolysis of loblolly pine.

Table 8-6 Enzyme doses for each of the biomass

Biomass	Enzyme dose (gm/g cellulose)	Relative dose charge, based on M. hardwood
M. hardwood	0.059	1
Eucalyptus	0.059	1
Loblolly pine	0.118	2

8.3.7 Reaction rates and yield

Reaction yield and conversion factors assumed for the economic analysis for the three biomasses are displayed in Table 8-7. As illustrated in table 8-7, #1 represent yield factor assumed for Loblolly Pine exclusively, #2 contains conversion factors for both mixed hardwood and Eucalyptus, and #3 list values for the three biomasses. Washing efficiency in the lignin filter is assumed to be 95% (meaning that 5% of monomeric sugars are lost with lignin and other dissolve organics). Consistency of cake solids after lignin filter is assumed to be 50%. Fermentation efficiency for C₆ and C₅ sugars was assumed to be 95%. Stoichiometry conversion of monomeric sugars to ethanol was assumed at 51% (see Table 8-5 for more details).

Table 8-7 Reaction yields and conversion factors

Process		Components					
		Lignin	Glucan	Hexan	Xylan	Extractives	Ash
1	Green liquor pretreatment	90%	90%	50%	80%	50%	50%
	Chemical post-treatment	80%	98%	96%	96%	50%	50%
2	Green liquor pretreatment	92%	91%	38%	80%	50%	50%
	Chemical post-treatment	80%	98%	98%	98%	50%	50%
3	Enzymatic hydrolysis		80%	80%	80%		100%
	Hydration factor		111%	111%	114%		
	Lignin filter efficiency		95%	95%	95%		
	Fermentation efficiency		95%	95%	80%		
	Fermentation stoichiometry		51%	51%	51%		

1 =Loblolly Pine; 2= Mixed hardwood and Eucalyptus; 3= Pine, mixed hardwood and Eucalyptus

8.3.8 Process Simulation

A complete process model for the green liquor pretreatment biorefinery was produced using WinGEMS v5.3. This process simulation software was originally developed for use in the pulp and paper industry and therefore has specialty blocks and units operations (such as chemical recovery equipment and reactions) commonly found in a pulp and paper mill. The process simulation model produced steady state mass and energy balances for the entire facility. This information was exported to a spreadsheet by interface with Microsoft Excel where it could easily be referenced during the financial evaluation of the project.

8.4 Results and Discussion

8.4.1 Production costs

Production cost, cost drivers and cash costs in \$ per gallon of ethanol are depicted for each combination in Table 8-8. Production costs are similar for all cases except for enzyme, energy and depreciation, which are different mainly because of enzyme dose, lignin content and CAPEX respectively. Enzyme cost is considerably higher for pine due to its recalcitrance (compared to more easily hydrolyzed raw materials such as natural hardwood). In the case of pine, enzyme cost represent one third of total production cost, while for hardwood it is around 17% to 22%. Lower CAPEX in the repurposing scenarios results in lower depreciation per gallon of ethanol. Natural hardwood and Eucalyptus in the repurposing scenarios have the lower production costs and cash costs. The most costly option is the greenfield investment scenario and more specifically with loblolly pine.

Table 8-8 Reaction yields and conversion factors

Cost drivers	N. harwood	N. harwood	Eucalyptus	Eucalyptus	Pine	Pine
	Green field	Repurposing	Green field	Repurposing	Green field	Repurposing
Ethanol revenue (\$/gallon)	2.08	2.08	2.08	2.08	2.08	2.08
Ethanol subsidy (\$/gallon)	1.01	1.01	1.01	1.01	1.01	1.01
Wood (\$/gallon)	-1.00	-1.00	-0.96	-0.96	-1.00	-1.00
Chemicals (\$/gallon)	-0.04	-0.04	-0.04	-0.04	-0.05	-0.05
Yeast (\$/gallon)	-0.07	-0.07	-0.07	-0.07	-0.07	-0.07
Enzymes (\$/gallon)	-0.55	-0.55	-0.59	-0.59	-1.14	-1.14
Energy (\$/gallon)	0.04	0.04	0.03	0.03	0.07	0.07
Depreciation (\$/gallon)	-0.91	-0.31	-0.90	-0.31	-0.94	-0.31
Labor, overhead, others (\$/gallon)	-0.63	-0.58	-0.62	-0.58	-0.64	-0.59
Production cost (\$/gallon)	-3.15	-2.51	-3.14	-2.51	-3.76	-3.09
Cash cost (\$/gallon)	-2.18	-2.14	2.19	-2.14	-2.76	-2.71

Total production cost for natural mixed hardwood in the repurposing green liquor scenario are illustrated in Figure 8-3. The four major cost drivers are: raw material (~40%), Enzyme (21.8%), labor & overhead (23.2%) and depreciation (12.3%). Raw material and enzyme together account for ~ 61.6% of cash cost. Chemicals are not an important cost share, mainly due to the chemical recovery feature of the green liquor process. All the combinations of biomass and pretreatment are auto-sufficient in energy; this is generated with steam coming from the recovery boiler.

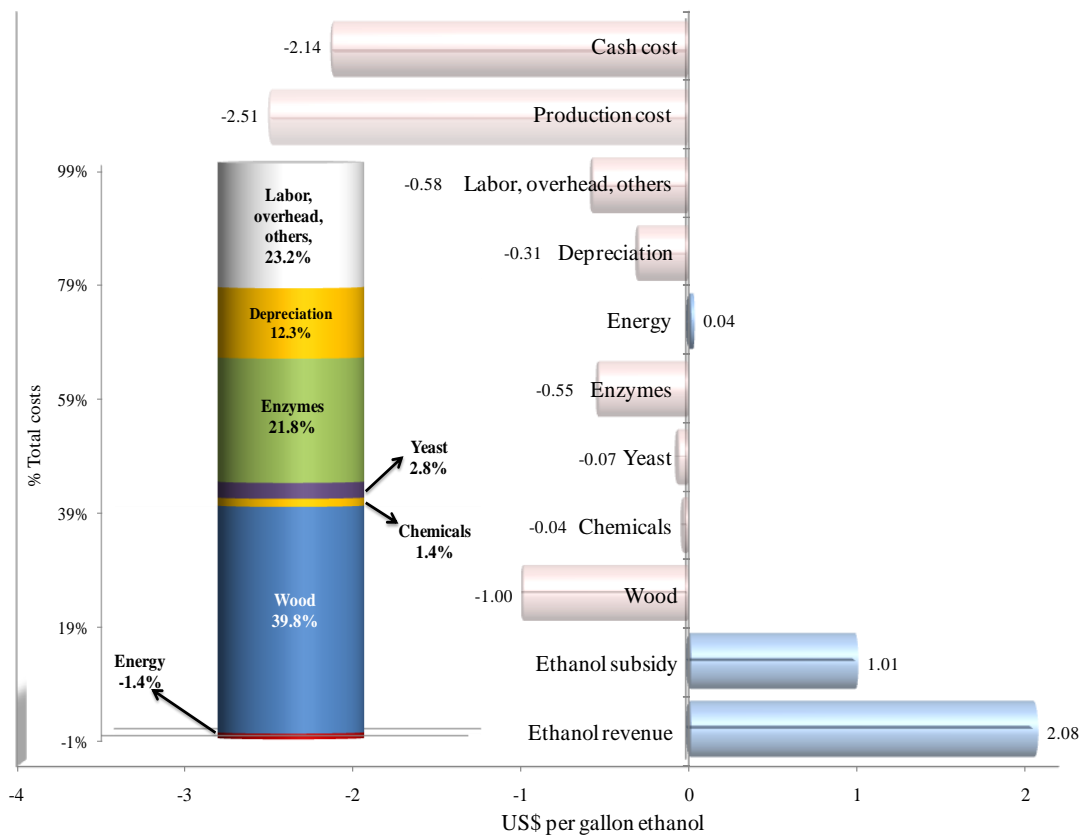


Figure 8-3 Production costs, cash cost and share cost for ethanol for natural mixed hardwood in the repurposing green liquor scenario

8.4.2 Financial indicators

Financial indicators (net present value and internal rate of return) for the three biomass and investment scenarios are illustrated in Figure 8-4. Only two combinations show positive returns, both in the repurposing scenarios, which are natural hardwood (NPV \$64 million, IRR 19.1%) and Eucalyptus (NPV \$66 million and IRR 19.2%). Loblolly Pine is the less attractive biomass in both greenfield (NPV -\$205 million) and repurposing (NPV -\$22 million and IRR 9.4%). For all cases the repurposing scenario is the most profitable.

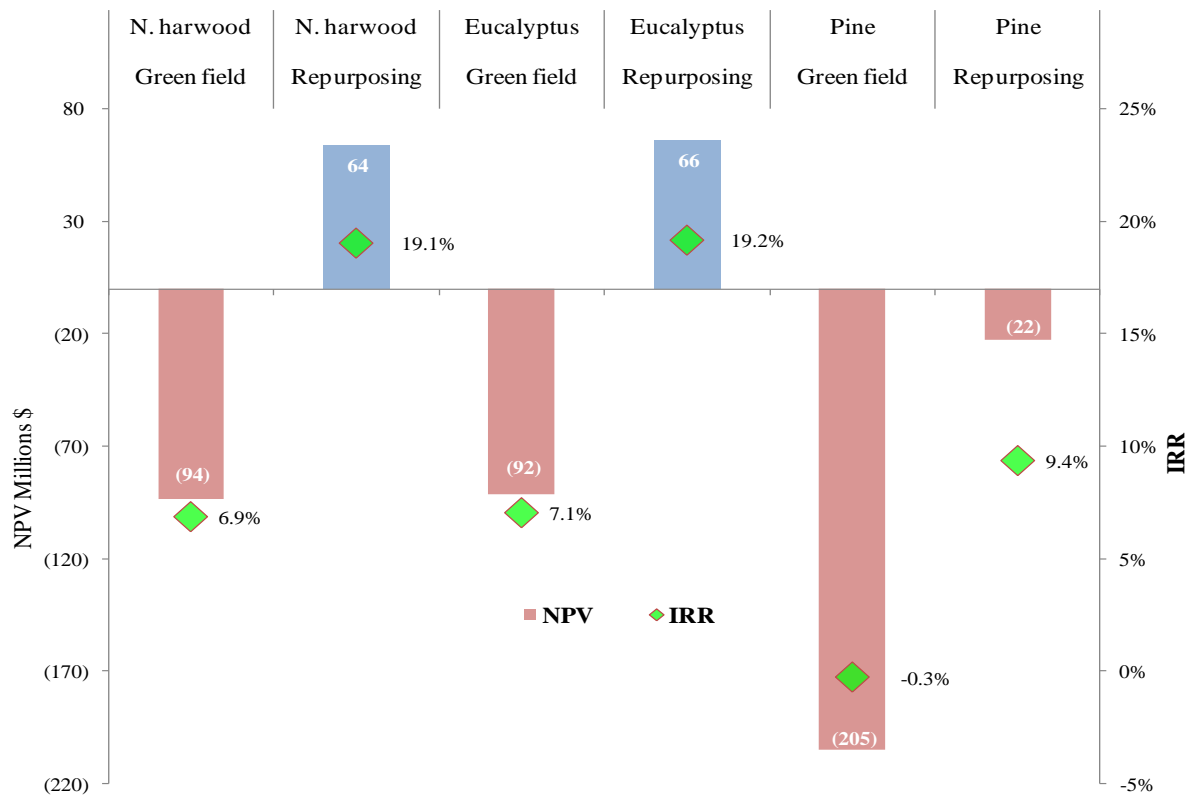


Figure 8-4 NPV and IRR for the six combinations of biomass and investment

The financial performance of the three biomass and investment scenarios is explained from Figure 8-5, where total CAPEX and CAPEX per liter of ethanol are depicted. As expected, higher CAPEX goes to the greenfield scenario, with total CAPEX ranging from \$310 million to \$312 million, resulting in CAPEX per liter of ethanol ranging from ~\$2.4 to \$2.5 per liter of ethanol. The repurposing scenarios show the lower CAPEX with values between \$104 million and \$106 million, resulting in CAPEX of \$0.8 per liter.

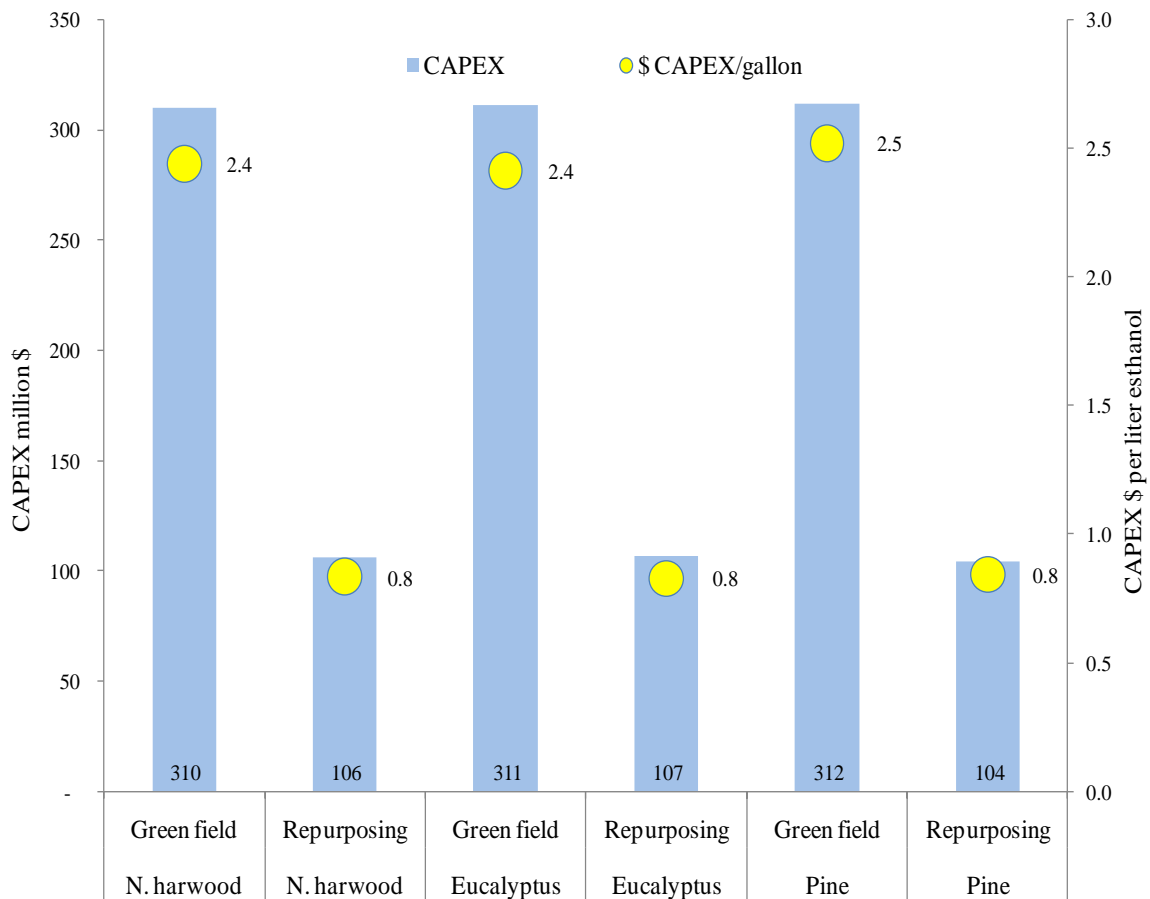


Figure 8-5 Total CAPEX and CAPEX per liter of ethanol for the six biomass and investment combinations

8.4.3 Ethanol yield

Ethanol yield, CAPEX per liter and the payback of the investment is presented for each biomass and investment scenario in Figure 8-6. Payback is the number of years required to offset the total investment, so that the accumulated free cash flow (at historical values) becomes positive (Ross et al., 2004). Lower payback is found in the repurposing scenarios, mainly in natural hardwood and eucalyptus, where ethanol yields are higher. Ethanol yield (liter of ethanol per dry metric ton of biomass) is higher in Eucalyptus (285 liter/dry ton), natural hardwood (280 liters/dry ton) and lower in Loblolly Pine (273 liter/dry ton). Ethanol yield depends on the carbohydrate content found in the biomass and pretreatment yield (Gonzalez et al., 2010a). Ease of biomass conversion (polymeric to monomeric sugars) will influence the severity of the pretreatment and finally the amount of monomeric sugars available for fermentation after enzymatic hydrolysis.

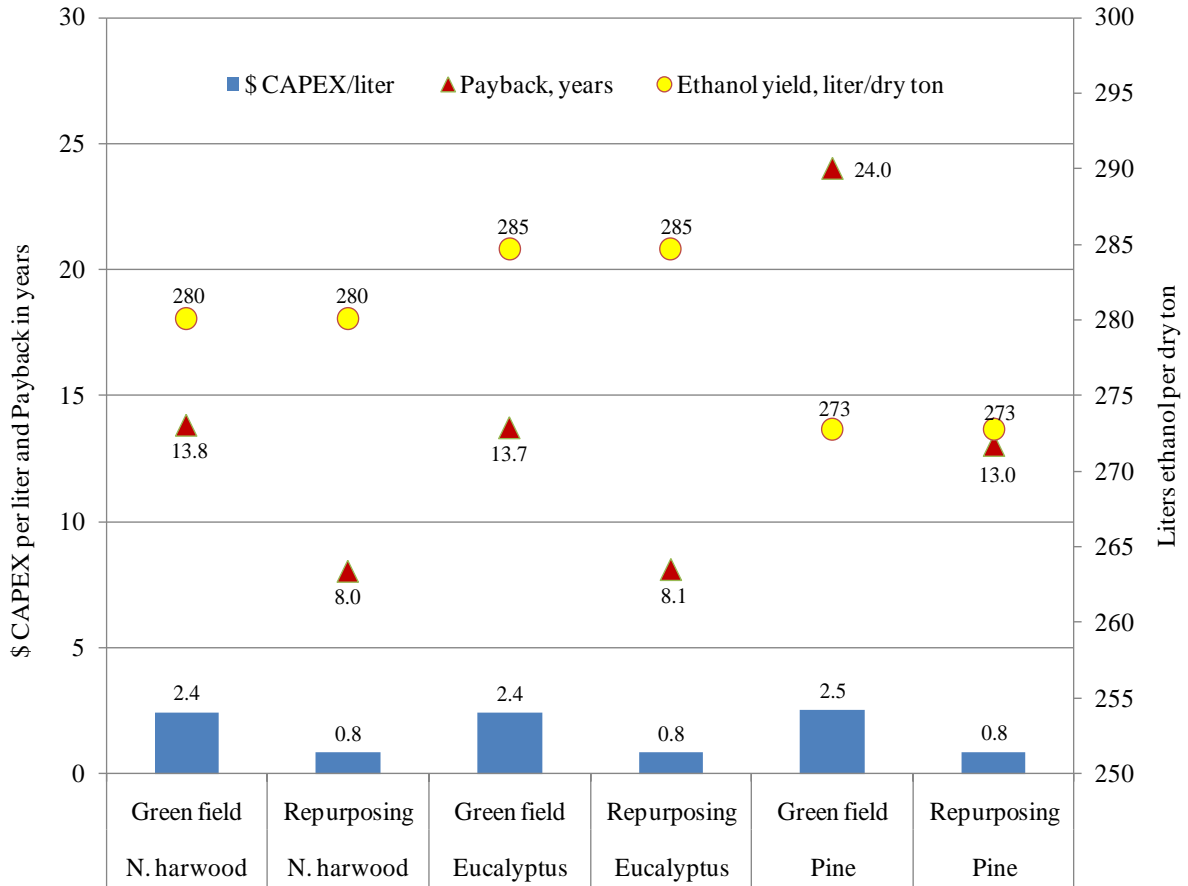


Figure 8-6 Ethanol yield, CAPEX per liter of ethanol and payback for each biomass and investment combination

8.4.4 Sensitivity analysis

Sensitivity analysis was performed for the most profitable scenario, mixed natural hardwood (Figure 8-7), to understand how changes in CAPEX, ethanol yield, biomass cost and enzyme cost affect the profitability of the project, specifically the net present value (NPV). This analysis includes a variation of +/- 25% of the central assumptions listed in methodology section. Ethanol yield has the highest impact on the NPV of the biorefinery.

Biomass and enzyme costs represent the second set of most significant sensitivities. A variation of +/- 25% in the CAPEX of the project affected NPV the least.

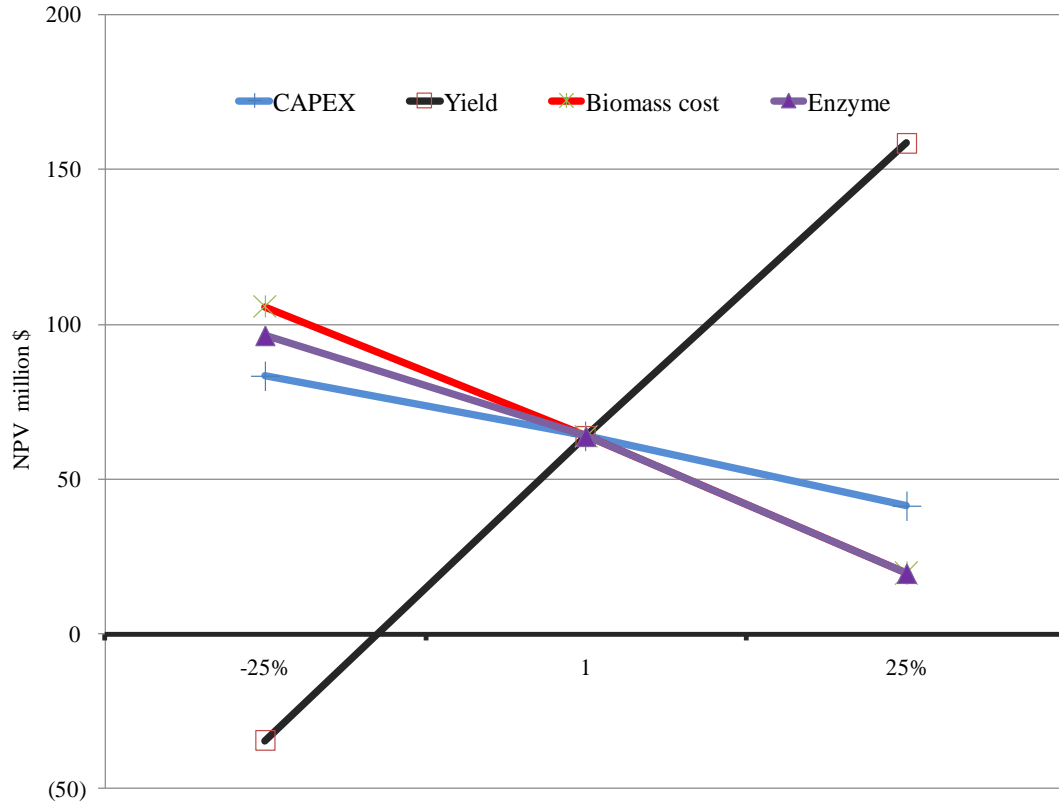


Figure 8-7 Sensitivity analysis +/- 25% of CAPEX, yield (liter ethanol/dry ton), biomass cost and enzyme cost

8.5 Conclusions

Green liquor repurposed pathway is a potential pretreatment for cellulosic ethanol conversion. This technology brings several advantages:

- Proven technology currently in operation in hundred of kraft pulp mills around the world
- Chemical recovery is very well known
- The repurposing concept, the most attractive scenarios, is an ideal solution to activate shut down operation in regions where the biorefinery can be an important source of employment and development for the economy. This repurposing concept will also take advantage of existing fiber supply chain and experienced work force
- Existing biomass assets such as natural hardwood and fast growing species of eucalyptus are potential biomasses available for conversion into ethanol. However, reduction in fiber supply cost is important to reduce sourcing risk and the economy of the biorefinery.

8.6 References

- Aden A, Ruth M, Ibsen K *et al.* (2002) Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. NREL.
- Anonymous (2010a) Kraft pulp mill CAPEX. Confidential
- Anonymous (2010b) Lignin filter. Factored vendor quote. Confidential
- Ban W, Lucia L (2003) Kraft green liquor pretreatment of softwood chips. 1. Chemical sorption profiles. *Ind. Eng. Chem. Res*, **42**, **3**, 646-652.
- Boerrigter H (2006) Economy of Biomass-to-Liquids (BTL) plants. 2010. www.ecn.nl/publications.
- Bohlmann G (2006) Process economic considerations for production of ethanol from biomass feedstocks. *Industrial Biotechnology*, **2**, **1**, 14-20.
- Bryant C (2010) New Cellic CTec2 Enzymes for More Efficient Commercial-Scale Cellulosic Ethanol Production. 2010. http://www.biofuelsjournal.com/articles/Novozymes_Introduces_New_Cellic_CTec2_Enzymes_for_More_Efficient_Commercial_Scale_Cellulosic_Ethanol_Production-89822.html.
- Epa (2010) EPA Finalizes Regulation for the National Renewable Fuel Standard Program for 2010 and Beyond. 2010. <http://www.epa.gov/oms/renewablefuels/420f10007.pdf>.
- Frederick W, Lien S, Courchene C, Demartini N, Ragauskas A, Iisa K (2008) Production of ethanol from carbohydrates from loblolly pine: A technical and economic assessment. *Bioresource Technology*, **99**, **11**, 5051-5057.

- Gomides J, Colodotte J, Chaves R, Mudado C (2006) Os clones de excelencia de Eucalyptus no Brasil para producao de Celulose. In: *39th Pulp and Paper International Congress and Exhibition*. pp, São Paulo, Brazil.
- Gonzalez R, Saloni D, Dasmohapatra S, Cubbage F (2008) South America: industrial roundwood supply potential. *BioResources*, **3. 1**, 255-269.
- Gonzalez R, Treasure T, Jameel H, Saloni D, Phillips R, Abt R, Wright J (2010a) Converting Eucalyptus Biomass Into Ethanol: Financial And Sensitivity Analysis In A Co-Current Dilute Acid Process. Part II. *Biomass and Bioenergy*, **10.1016/j.biombioe.2010.10.025**.
- Gonzalez R, Treasure T, Phillips R, Jameel H, Saloni D, Abt R, Wright J (2010b) Converting Eucalyptus biomass into ethanol: Financial and sensitivity analysis in a co-current dilute acid process. Part II. *Biomass and Bioenergy*, **35. 2**, 767-772.
- Gonzalez R, Treasure T, Wright J, Saloni D, Phillips R, Abt R, Jameel H (2010c) Exploring the potential of Eucalyptus for energy production in the Southern United States: Financial analysis of delivered biomass. Part I. *Biomass and Bioenergy*, **35. 2**, 755-766.
- Gregg D, Saddler J (1996) A techno-economic assessment of the pretreatment and fractionation steps of a biomass-to-ethanol process. *Applied biochemistry and biotechnology*, **57. 1**, 711-727.
- Hinchee M, Rottmann W, Mullinax L *et al.* (2009) Short-rotation woody crops for bioenergy and biofuels applications. *In Vitro Cellular & Developmental Biology-Plant*, 1-11.
- Jackson Sr, T.; Taylor, A.; Bozell, J. And Norris, K. (2010) Wood2Energy. A State of the Science and Technology Report. The University of Tennessee. Institute of Agriculture.
- Janssen M, Chambost V, Stuart P (2008) Successful partnerships for the forest biorefinery. *Industrial Biotechnology*, **4. 4**, 352-362.

- Janssen M, Stuart P (2010) Sustainable Product Portfolio And Process Design Of The Forest Biorefinery. *Proceedings of the Canadian Engineering Education Association*.
- Jin Y, Jameel H, Chang H, Phillips R (2010) Green Liquor Pretreatment of Mixed Hardwood for Ethanol Production in a Repurposed Kraft Pulp Mill. *Journal of Wood Chemistry and Technology*, **30. 1**, 86-104.
- Kazi F, Fortman J, Anex R, Hsu D, Aden A, Dutta A, Kothandaraman G (2010) Techno-economic comparison of process technologies for biochemical ethanol production from corn stover. *Fuel*, **89. 1**, 20-28.
- Lee J (1997) Biological conversion of lignocellulosic biomass to ethanol. *Journal of Biotechnology*, **56. 1**, 1-24.
- Lynd L, Laser M, Bransby D *et al.* (2008) How biotech can transform biofuels. *Nature biotechnology*, **26. 2**, 169-172.
- Mosier N, Hendrickson R, Dreschel R, Dien B, Bothast R, Welch G, Ladisch M (2003) Principles and Economics of Pretreating Cellulose in Water for Ethanol Production. American Chemical Society National Meeting
- Mosier N, Wyman C, Dale B, Elander R, Lee Y, Holtzapple M, Ladisch M (2005) Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource Technology*, **96. 6**, 673-686.
- Overend R, Chornet E, Gascoigne J (1987) Fractionation of Lignocellulosics by Steam-Aqueous Pretreatments [and Discussion]. *Philosophical Transactions for the Royal Society of London. Series A, Mathematical and Physical Sciences*, **321. 1561**, 523-536.
- Pan X, Arato C, Gilkes N *et al.* (2005a) Biorefining of softwoods using ethanol organosolv pulping: Preliminary evaluation of process streams for manufacture of fuel-grade ethanol and co-products. *Biotechnology and bioengineering*, **90. 4**, 473-481.

- Pan X, Xie D, Gilkes N, Gregg D, Saddler J (2005b) Strategies to enhance the enzymatic hydrolysis of pretreated softwood with high residual lignin content. *Applied biochemistry and biotechnology*, **124. 1**, 1069-1079.
- Pew-Center (2010) Cellulosic ethanol. 2010.
<http://www.pewclimate.org/technology/factsheet/CellulosicEthanol>.
- Rfa (2010) Ethanol, DDGS exports surge. 2010.
<http://www.ethanolrfa.org/news/entry/ethanol-ddgs-exports-surge/>.
- Ross S, Westerfield R, Jaffe J (2004) *Corporate finance*, Tata McGraw-Hill
- Solomon B, Barnes J, Halvorsen K (2007) Grain and cellulosic ethanol: History, economics, and energy policy. *Biomass and Bioenergy*, **31. 6**, 416-425.
- Tunc M, Van Heiningen A (2008) Hemicellulose extraction of mixed southern hardwood with water at 150 C: Effect of time. *Ind. Eng. Chem. Res*, **47. 18**, 7031-7037.
- Um B, Van Walsum G (2009) Acid hydrolysis of hemicellulose in green liquor pre-pulping extract of mixed northern hardwoods. *Applied biochemistry and biotechnology*, **153. 1**, 127-138.
- Um B, Van Walsum G (2010) Mass balance on green liquor pre-pulping extraction of northeast mixed hardwood. *Bioresource Technology*, **101. 2010**, 5978-5987.
- Walton S (2009) Biological Conversion of Hemicellulose Extract into Value-added Fuels and Chemicals. Unpublished PhD Dissertation, University of Maine Maine.
- Wu S, Chang H, Jameel H, Philips R (2010a) Novel Green Liquor Pretreatment of Loblolly Pine Chips to Facilitate Enzymatic Hydrolysis into Fermentable Sugars for Ethanol Production. *Journal of Wood Chemistry and Technology*, **30. 3**, 205-218.
- Wu X, McLaren J, Madl R, Wang D (2010b) Biofuels from Lignocellulosic Biomass. *Sustainable Biotechnology*, 19-41.

- Wyman C (2007) What is (and is not) vital to advancing cellulosic ethanol. *TRENDS in Biotechnology*, **25. 4**, 153-157.
- Wyman C, Dale B, Elander R, Holtzapple M, Ladisch M, Lee Y (2005) Coordinated development of leading biomass pretreatment technologies. *Bioresource Technology*, **96. 18**, 1959-1966.
- Yang B, Boussaid A, Mansfield S, Gregg D, Saddler J (2002) Fast and efficient alkaline peroxide treatment to enhance the enzymatic digestibility of steam-exploded softwood substrates. *Biotechnology and bioengineering*, **77. 6**, 678-684.
- Zheng Y, Pan Z, Zhang R (2009) Overview of biomass pretreatment for cellulosic ethanol production. *International Journal of Agricultural and Biological Engineering*, **2. 3**, 51.

9 Economics of Cellulosic Ethanol Production in a Thermochemical Pathway for Softwood, Hardwood, Corn Stover and Switchgrass.

9.1 Abstract

The economics of producing cellulosic ethanol using loblolly pine, natural mixed hardwood, Eucalyptus, corn stover and switchgrass as feedstock were simulated in Aspen using the thermochemical process via indirect gasification and mixed alcohol synthesis developed by NREL. Outputs from the simulation were linked to an economical analysis spreadsheet to estimate NPV, IRR, payback and run further sensitivity analysis of the different combinations of feedstock – process. Results indicate that forest feedstock as loblolly pine, natural hardwood and eucalyptus may present more attractive financial returns when compared to switchgrass and corn stover, mainly due to their composition (% C, % H, % ash) and alcohol yield. Alcohol yield in forest feedstock is comparable higher to those simulated with switchgrass and corn stover. Also these last two feedstocks show to be highly sensitive to changes in ethanol price, alcohol yield, CAPEX and biomass costs. Receiving feedstocks moisture content greatly affects the economics of the biorefinery. A difference of 10% in the moisture content of the receiving feedstock can affect the NPV of the project by US\$66 + million.

9.2 Introduction

Brazil and United States are the major producers of bioethanol (mainly from sugar cane and corn starch respectively), with a combined production representing ~86% of world's total output for 2009, approximately 75,571 thousand million gallons liters of ethanol in total (Goldemberg, 2007, RFA, 2010). United States alone has dramatically increased bioethanol production by 210% since 2005 (RFA, 2010). Despite the success in bioethanol production (first generation biofuels), special interest has been placed to increase, at industrial levels, the production of cellulosic ethanol and biodiesel (second generation biofuels), using cellulosic feedstocks as grasses (switchgrass, miscanthus) and forest biomass (forest residues, sawdust and industrial waste) as raw materials. The emphasis to increase the production of second generation biofuels, comes from major distresses related to bioethanol production, as food supply and rising prices frequently related to the use of corn to produce fuel (Foust *et al.*, 2009, Mitchell, 2008), heating on the debate of food versus fuel. In addition, it is estimated that there would not be enough corn to supply the biofuel industry to meet liquid biofuel production quantities as mandated by the U.S. federal government standards. Based on these facts, and with the pursue to alleviate U.S. commercial balance, enhance national security as well as establish the basis for a clean energy industry, the Environmental Protection Agency (EPA) has set ambitious cellulosic biofuel production targets of 0.25 billion gallons (bil gal) for 2011, 1 bil gal for 2013 and 16 bil gal for 2022 (EPA, 2010). These mandates have come together with unprecedented funding for research and pilot plant demonstrations; just to mention some examples, three USDOE funded centers (US\$ 125 million each), with

additional funding for research exceeding US\$ 786.5 million, and with private funding as well, just to mention the BP funded bioenergy center for US\$500 million (Baker & Keisler, 2009, Schuetzle *et al.*, 2007). Though great effort has been done by public and private entities to ramp up in second generation biofuels, there is not a single commercial facility producing cellulosic ethanol in the U.S. as of 4th quarter 2010. Current barriers to profitable produce cellulosic ethanol have been widely discussed, pointing out some of the most important as biomass cost and availability (Gonzalez *et al.*, 2008, Gonzalez *et al.*, 2010b, Wu *et al.*, 2010), pretreatment costs, high capital expenditure (CAPEX), equipments scale up and overall production costs (Aden *et al.*, 2002, Gonzalez *et al.*, 2010a, Mosier *et al.*, 2003, Mosier *et al.*, 2005, Tao & Aden, 2009, Wu *et al.*, 2010, Wyman, 2007, Wyman, 2008).

Two major pathways have been clearly identified as the most promising routes for cellulosic ethanol production; those are biochemical conversion, relying mainly in hydrolysis (acid and/or enzymatic hydrolysis) to reduce polymeric carbohydrate chains into fermentable monomeric sugars. The other approach is thermochemical conversion, with numerous versions and hybrid designs, the major concept behind thermochemical processes is the production of synthetic gas (syn gas) from cellulosic biomass, gasses are then reformed and passed through catalytic reactors to produce alcohol species (Mosier *et al.*, 2005, Mu *et al.*, 2010, Phillips *et al.*, 2007). Economic and life cycle analysis studies made to compare biochemical and thermochemical pathways do not clearly identify a winner technology for conversion (Foust

et al., 2009, Mu *et al.*, 2010), in fact there is a general and logic agreement that market place economics would be used to decide which conversion approach should be used (Blaschek & Boateng, 2009, Mu *et al.*, 2010), this is based on type of biomass available and delivered costs.

Biochemical technologies seems to be more feasible in regions where large volumes of consistent biomass are available, while thermochemical pathways can virtually process any type of raw material (Foust *et al.*, 2009, Mu *et al.*, 2010, Schuetzle *et al.*, 2007). More over some studies suggest that hardwood and herbaceous feedstock are more suitable for biochemical pathways, while more recalcitrant raw materials as softwood feedstock can better suit to thermochemical processes (Foust *et al.*, 2009, Gonzalez *et al.*, 2010a). Great emphasis is made on raw material choice, availability and cost as it represents the major single cost in biomass to bioenergy conversion (Gonzalez *et al.*, 2010a, Pirraglia *et al.*, 2010, Tao & Aden, 2009). Conversion pathways capable of processing several types of biomass may bring in strategic advantages to the economy of the biorefinery as it can use feedstocks with the lowest delivered cost across the year. Though the number of publications dealing with economic evaluations in cellulosic ethanol production has increased in recent years, a fair economical comparison between various technologies and biomasses is a difficult task, mainly because of the different assumptions and reaction yields used. Our paper present the economic evaluation and sensitivity analysis of producing cellulosic ethanol using the thermochemical process via indirect gasification and mixed alcohol synthesis develop by NREL (Phillips *et al.*, 2007), includes a revised and more complete estimation of CAPEX

and considers the use of five different feedstocks: loblolly pine, natural hardwood, Eucalyptus, corn stover and switchgrass, all those compared under the same economic conditions. This manuscript provides a practical piece of information that combines raw material, conversion process and profitability, with useful data for investors and academics.

9.3 Material and methods

9.3.1 Thermochemical process

Conversion process used in this paper for economic evaluation relies on the thermochemical ethanol process via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass developed by NREL (Phillips et al., 2007). The overall process is illustrated in figure 9-1. In brief the process considers biomass handling and drying, biomass is gasified and then gas is cleaned and conditioned. Passing through catalytic reactors alcohols are formed, followed by separation. More details in the process are presented in the next sections.

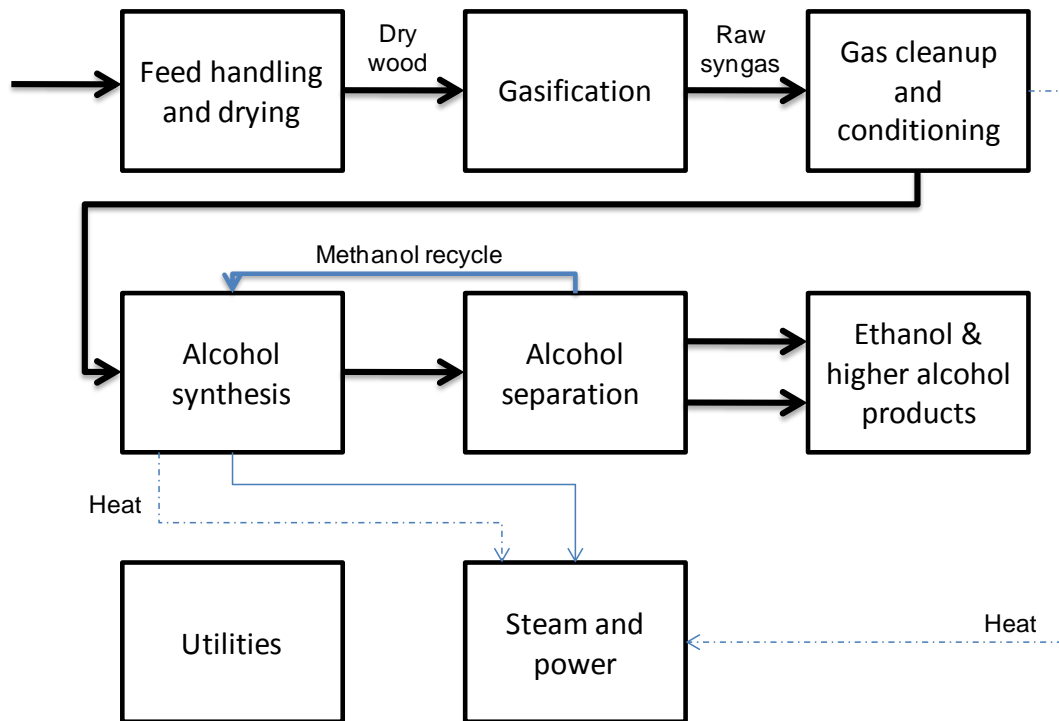


Figure 9-1 Gasification process for ethanol production

9.3.2 Gasification process simulation

Since there are no commercial cellulosic ethanol production processes currently in operation, process simulation was used to generate values used in the economic analysis. The thermochemical ethanol conversion process model developed by NREL (Phillips et al., 2007) was used. This model performs energy and a material balance based on the incoming biomass feed rate and composition. These balances are based on correlations and data

obtained from the Battelle coal gasifier. The simulation was operated in Aspen Plus version 2004.1 (Aspen-Tech, 2004), as newer versions of Aspen Plus were unable to run the model.

9.3.3 Major unit process description

Many unit processes are required to convert cellulosic materials into alcohols and biofuels. The hundreds of unit processes ranging from heating to reactions are grouped into seven hierarchy groupings within the Aspen Plus simulation. The following describes the unit processes within figure 9-1.

Handling and drying: The incoming feedstock is dried and screened to remove unusable biomass and contaminants. Flue gas from the char combustor and syn gas boiler is the primary source of heat for drying. Biomass moisture content is reduced to around 5%.

Gasification: Incoming biomass is further heated by olivine circulated from the char combustor. Endothermic reactions release syn gas, primarily CO and H₂ in the gasifier.

Gas cleanup and conditioning: Dirty syn gas is cleaned by removing catalyst poisons such as acids and sulfur compounds.

Alcohol syntheses: Cleaned syn gas is converted to a mixture of alcohols via catalyzed reaction. Ethanol and propanol are the major products.

Alcohol separation: Ethanol and higher alcohols are separated by distillation and molecular sieves. Process methanol is used to clean the molecular sieve and is recycled back to alcohol syntheses for further processing.

Power and steam: Process steam and electrical power are generated and supplied to other unit processes by burning dirty syn gas and capturing process heat. The power boiler is controlled to maintain energy self sufficiency, neither selling nor buying any outside power.

Utilities: Low quality steam from power production and other unit processes are condensed using cooling towers fed by well water. The condensate is recycled back to the process for further use.

This process description presents the basic unit processes of the thermochemical conversion pathway. A full process description is included in Phillips et al. 2007 technical feasibility study (Phillips et al., 2007).

9.3.4 Simulation modification

To meet the needs of this study, several modifications were made to the NREL thermochemical model. Several aspects of the model were not functional as received from the NREL website. One of these deactivated features was the input parameter calculator “SETFEED”. The Fortran code was updated and the calculator was modified to write the input parameters into the incoming biomass stream.

In addition to fixing the “SETFEED” calculator, the syn gas boiler temperature was manipulated to maintain energy equilibrium. Depending on the incoming feedstock flow rate, composition, and moisture content, the power production was adjusted to meet the needs of the process. This was done through manually changing the design specification

“REFTEMP”. This process was time consuming but unavoidable as the model would not converge using a traditional controller for this parameter.

9.3.5 Operation parameters

To demonstrate model characteristics, multiple input parameters were manipulated. The original feed rate of 772,000 dry tons per year (dry metric tons) of biomass was maintained while changing the biomass type and moisture content, for the economic analysis and CAPEX estimation a flow of 453,597 dry metric tons was used (500,000 dry short tons). In total, five biomass types were examined in addition to the original hybrid poplar feedstock (this last not included in the paper). The moisture content of the energy crops and agricultural residue (switchgrass and corn stover respectively) were set at 16%. Both the ultimate and proximate analyses for each biomass type are included in table 2.

The biomass gasification pathway to biofuels is very complex and requires many unit processes. As a result of this, the process requires a large capital investment and is generally less understood than the biochemical process. Despite this, a revised CAPEX is presented including other potential capital investment not considered initially in the NREL report.

9.3.6 Feed preparation

Similar to the biochemical process, incoming biomass must be chipped and screened to insure proper chip size. Additionally, the gasification step requires low biomass moisture

content (~17%) (Phillips et al., 2007). Moisture is removed from the incoming biomass by utilizing the heat from the char combustor flue gas. An immense amount of energy is required to dry this biomass and would be difficult to achieve without using recovered process energy.

9.3.7 Gasification

Direct gasification should be noted as another viable gasification method, although, indirect gasification is described here. Indirect gasification is defined by indirect heating often achieved through circulating heated olivine. This olivine leaves the char combustor at temperatures of around 1800°F and heats the biomass to a temperature of 1600°F in addition to supplying the energy for the endothermic gasification reactions. The products of these reactions include CO, H₂, CO₂, and CH₄ along with tars, and solid char. This solid tar, resulting from fixed carbon deposited on the olivine, is then separated using cyclone filters and sent to a char combustor to generate process energy.

9.3.8 Gas cleanup and conditioning

Within this conversion step, tars and other hydrocarbons are reformed into CO and H₂, syn gas is cooled/quenched, and acid gas is removed and reduced to sulfur. These actions can be achieved through use of fluidized bed reactors with online catalysis regenerators, heat exchangers and scrubbers, and an “amine” unit, respectively. This step is critical to preventing catalysis fouling in the alcohol synthesis step.

9.3.9 Alcohol Synthesis

Once the syngas is purified, it can then be converted to alcohols using a fixed bed reactor. This is done in the presence of catalysis such as Molybdenum-disulfide. The unconverted syngas can either be recycled back to the alcohol synthesis, or sent to the char combustor to avoid excess CO₂ accumulation and subsequent catalyst fouling.

9.3.10 Alcohol Separation

Within this processes, the alcohol stream is depressurized in preparation for the dehydration using a molecular sieve. Once water is removed from the alcohol stream, a distillation column is used to separate ethanol from other alcohols. The higher alcohols are sold as a co-product, while most of the methanol is recycled back to molecular sieve to flush the adsorbed water.

9.3.11 Heat and Power

Steam can be generated from integrated use of processes heat. Turbines can then create electricity as well as create process steam at varying pressures to meet the energy requirements of the rest of the process. A fuel combustor can be used to burn dirty syngas to provide additional heat and power, if needed, to avoid purchasing power or natural gas.

9.3.12 Feedstock

Five feedstocks are considered in this paper, those are loblolly pine, southern natural mixed hardwood, Eucalyptus, corn stover and switchgrass, major assumptions to estimate biomass delivered costs are illustrated table 9-1. Annual supply was estimated for 453,567 dry tons (metric tons) or 500,000 BDT (bone dry short tons). For Loblolly pine and Eucalyptus biomass delivered cost was estimated assuming a 6% IRR for the forest land owner (stumpage), assuming harvesting at 8% IRR to the harvesting contractor and freight cost at market values, both similar to current market values, the methodology to estimate delivered cost is similar to the one used by Gonzalez et al 2010 (Gonzalez et al., 2010b). For natural hardwood, all values: stumpage, harvesting and freight costs were estimated using market values. The approach for switchgrass considers biomass cost including 6% IRR to the farmer, harvesting cost assuming 8% IRR to the harvesting contractor and freight cost using market values. Corn stover cost was estimated based on reported market values and more recent published information. Chemical composition, % C, %H, %O, % N, % fixed carbon, % volatile mater and % ash assumed for each of the biomass is presented in table 9-2.

Table 9-1 Biomass delivered cost, rotation length, productivity, moisture content and annual supply

Biomass	Loblolly pine	N. hardwood	Eucalyptus	Corn stover	Switchgrass
\$/dry ton	69.4	71.0	69.4	80.3	79.3
Rotation length (years)	11	-	4	-	10
Productivity (dry ton/ha/yr)	17.0	2.2	20.2	4.5	15.7
Moisture content (%)	45%	45%	45%	16%	16%
Covered area (%)	5%	5%	5%	5%	5%
Supply (dry ton/year)	453,597	453,597	453,597	453,597	453,597

Table 9-2 Chemical composition of the feedstock

Feedstock type	% C	% H	% N	% O	% S	% Ash	% Fixed Carbon	% Volatile Matter	% Ash	Source #
Loblolly pine	51.9	6.5	0.0	41.3	0.0	0.4	14.2	85.3	0.5	1
N. hardwood	50.4	6.5	0.0	42.5	0.0	0.6	18.9	80.4	0.7	2
Eucalyptus	49.7	5.9	0.2	42.6	0.0	1.0	18.2	81.1	1.0	3
Corn stover	46.6	5.7	0.7	39.4	0.1	11.9	21.1	72.5	11.9	3
Switch grass	47.3	5.6	0.6	40.6	0.1	5.8	20.6	74.2	5.8	3

Source: 1= (Yan et al., 2009), 2 = (Adebayo et al., 2009), 3= (DOE, 2010)

9.3.13 CAPEX

Capital expenditure was estimated based on the NREL report (Phillips et al., 2007) and with consultation to experts in CAPEX estimation (Phillips, 2010). Capex was projected for a biorefinery with a capacity to process 453,597 dry tons per year (500,000 BDT). Total CAPEX, excluding land is estimated at ~ US\$ 290 million. Further details in equipments, scale factor, estimated green field cost and sources are illustrated in table 9-3.

Table 9-3 Capital expenditure for a green field biorefinery

Description	factor	US\$	S	Description	factor	US\$	S
Site preparation				<i>Continuation</i>			
Land purchase	0.9	923,012	1	Methanol/Ethanol Splitter Reboiler	0.68	162,330	2
Land preparation	0.9	18,328,324	1	Mol Sieve Flush Condenser (air cooled)	1	68,499	2
Biomass handling				Product Cooler / Mol Sieve preheater	0.6	4,649	2
Roundwood/chipping receiving	0.6	19,462,961	1	Ethanol Product Pump	1.79	3,992	2
Bark drying	0.6	16,591,727	2	ETHANOL Product Cooler / Mol Sieve preheater	0.6	11,408	2
Flue Gas Cooler/Steam Generator	0.6	1,280,203	2	Ethanol Product Pump	2.79	196,596	2
Flue Gas Cooler /Boiler Water Preheater	0.6	465,933	2	Ethanol/Propanol Splitter Bottoms Pump	0.79	24,151	2
Flue Gas Cooler / Steam Generator	0.65	233,016	2	Ethanol/Propanol Splitter Reflux Pump	0.79	4,172	2
Rotary Biomass Dryer	0.75	19,357,788	2	Methanol/Ethanol Splitter Bottoms Pump	0.79	38,475	2
A100				Methanol/Ethanol Splitter Reflux Pump	0.79	4,172	2
Indirectly-heated Biomass Gasifier	0.65	12,916,238	2	Mixed Alcohol Product Pump	0.79	6,661	2
A200				Ethanol Product Pump	0.79	25,773	2
Post-tar Reformer Cooler / Steam Generator	0.65	280,793	2	Syngas Separato	0.6	106,310	2
Reformer Flue Gas Cooler/Steam superheater	0.6	573,129	2	Molecular Sieve (9 pieces)	0.7	3,445,594	2
Reformed Syngas cooler / Synthesis Reactor Preheat	0.44	254,966	2	Ethanol/Propanol Splitter Reflux Drum	0.93	12,034	2
Water-cooled Aftercooler	0.44	79,254	2	Methanol/Ethanol Splitter Reflux Drum	0.93	12,034	2
LO-CAT Preheater	0.6	4,498	2	Mixed Alcohol Product Storage Tank	0.51	452,976	2
Recycle Syngas Cooler / Steam Generator	0.6	180,778	2	Ethanol Product Storage Tank	0.51	1,084,940	2
Recycle Syngas cooler #2 / Air preheat	0.6	32,214	2	A500			
Syngas Compressor	0.8	17,647,662	2	Blowdown Water-cooled Cooler	0.44	94,962	2
Regenerator Combustion Air Blower	0.59	98,824	2	Hot Process Water Softener System	0.82	3,044,885	2
Sludge Pump	0.33	9,795	2	Extraction Steam Turbine/Generator	0.71	11,801,498	2
Tar Reformer Catalyst Regenerator	0.65	9,719,926	2	Startup Boiler	0.6	579,837	2
Tar Reformer	0.65	8,670,224	2	Collection Pump	0.33	21,122	2
LO-CAT Oxidizer Vessel	0.65	2,378,057	2	Condensate Pump	0.33	30,304	2
Pre-compressor Knock-out	0.6	638,432	2	Deaerator Feed Pump	0.33	50,691	2
Post-compressor Knock-out	0.6	170,781	2	Boiler Feed Water Pump	0.33	558,718	2
L.P. Amine System	0.6	12,147,805	2	Blowdown Flash Drum	0.6	43,703	2
Sludge Settling Tank	0.65	759	2	Condensate Collection Tank	0.6	71,468	2
A300				Condensate Surge Drum	0.6	83,371	2
Flue Gas Cool / syngas rxn preheat	0.6	43,705	2	Deaerator	0.72	381,292	2
Air preheat #3 / post Reactor Syngas cooling	0.6	24,862	2	Steam Drum	0.72	27,467	2
Post synthesis cooler #2/Deaerator Water Preheater	0.6	52,558	2	A600			
C 1 Post Synthesis cooler	0.6	31,445	2	Plant Air Compressor	0.34	283,936	2
Post Synthesis cooler	0.6	37,295	2	Cooling Tower System	0.78	564,218	2
Post Synthesis Cooler	0.6	8,745	2	Hydraulic Truck Dump with Scale	0.6	237,526	2
Post Mixed Alcohol Cooler	0.44	214,230	2	Flue Gas Stack	1	46,530	2
Mixed Alcohol first Condenser	1	136,649	2	Cooling Water Pump	0.33	807,601	2
Mixed Alcohol Condenser	0.44	281,814	2	Firewater Pump	0.79	110,110	2
Recycle Syngas Heat #2 / Flue gas Cool	0.44	344,070	2	Diesel Pump	0.79	36,504	2
Mixed Alcohol Gas Compressor	0.8	2,262,251	2	Ammonia Pump	0.79	29,921	2
Purge Gas Expander	0.8	13,710,103	2	Hydrazine Pump	0.79	16,457	2
Mixed Alcohol Reactor	0.56	3,218,633	2	Instrument Air Dryer	0.6	48,813	2
Mixed Alcohols Condensation Knock-out	0.6	246,225	2	Plant Air Receiver	0.72	20,472	2
A400				Firewater Storage Tank	0.51	496,991	2
Ethanol/Propanol Splitter	1.32	478,460	2	Diesel Storage Tank	0.51	43,086	2
Methanol/Ethanol Splitter	1.32	531,228	2	Ammonia Storage Tank	0.72	859,635	2
Syngas Cooler #4 / Mol Sieve preheater	0.6	64,211	2	Hydrazine Storage Tank	0.93	37,102	2
Mol Sieve Superheater / reformed syngas cool	0.6	10,842	2	Others			
Condenser (air cooled)	1	127,442	2	Product storage and shipment	0.6	4,735,574	1
Ethanol/Propanol Splitter Reboiler	0.68	126,830	2	Power	0.6	23,807,177	1
Condenser (air cooled)	1	203,538	2	Water	0.6	5,106,802	1

S = Source; 1 = (Phillips, 2010); 2 = (Phillips et al., 2007)

9.3.14 General assumptions

Major assumptions used for the economic analysis are illustrated in table 9-4. In brief start up year is assumed for 2012, with construction beginning in 2010. All CAPEX and cost were updated to 2012. The economic analysis included an evaluation horizon of 15 years. CAPEX spending is illustrated in table 9-4. Revenue includes ethanol selling price at US\$ 2 per gallon, plus a subsidy of US\$ 1.01 per gallon (price of US\$ 0.53 per liter and subsidy of US\$ 0.27 per liter of ethanol). Ethanol selling price alone is assumed to increase at a rate of 2% per year. Biomass and other costs are assumed to increase at 3% per year, while chemicals are assumed to increase at 2% per year. Discount rate used is 12% and terminal value in year 15 is five times EBITDA of the same year (Earnings before interest, taxes, depreciation and amortization).

Table 9-4 Major assumptions used in the financial analysis

Description	Value	Description	Value
Startup year	2012	Tax rate, with tax loss carryforward	35%
Terminal year	2026	Discount rate	12%
CAPEX spending		Terminal value, year 15 EBITDA multiple X	5
% of spending in year -2	30%	Hours per year	8400
% of spending in year -1	50%	Revenue per liter of ethanol	2
% of spending in year -0	20%	Subsidy added to price, \$ per liter ethanol	1.01
% of nominal capacity, project year 1	50%	Maintenance expense, including Labor,	2%
% of nominal capacity, project year 2	80%	Other fixed costs, % of sales	3%
Working capital % of direct cost +		Capital reinvestment, % of	
presubsidy product revenue	10%	replacement asset value	1%
Years depreciation schedule, straight line	10	Sales and other overhead, % of sales	3%

9.3.15 Ethanol and propanol yield

Ethanol and propanol yield (liters of alcohol per dry ton of biomass) are obtained from the process simulation in ASPEN, those values are presented in the next sections (figures 9-4 and 9-5). In other to estimated revenues from the production of propanol, the energy content of this heavy alcohol was estimated based on literature review, and its equivalent ratio to ethanol was used to estimate its revenue, using same price assumed for ethanol.

9.4 Results and Discussion

9.4.1 Production costs

Production cost for alcohol production was estimated for each of the feedstocks, raw material cost, chemical consumption were used to feed the economic spread sheet to estimate net present value, internal rate of return and payback of the investment. Figure 9-2 illustrates two composed graphics for alcohol production costs using loblolly pine as feedstock for year 2014. The Bar figure represent estimated cost (negative) in US\$ per gallon of ethanol equivalent (ethanol plus propanol). Total production cost is estimated at US\$ 1.76 per gallon of ethanol, while cash cost (production cost minus non cash costs as depreciation) is around US\$ 1.21 per gallon of ethanol equivalent, with biomass and depreciation as the major cost drivers; the inner pie graph illustrates the share (%) of each cost, out of total production cost, with biomass and depreciation representing nearly ~67% of total costs.

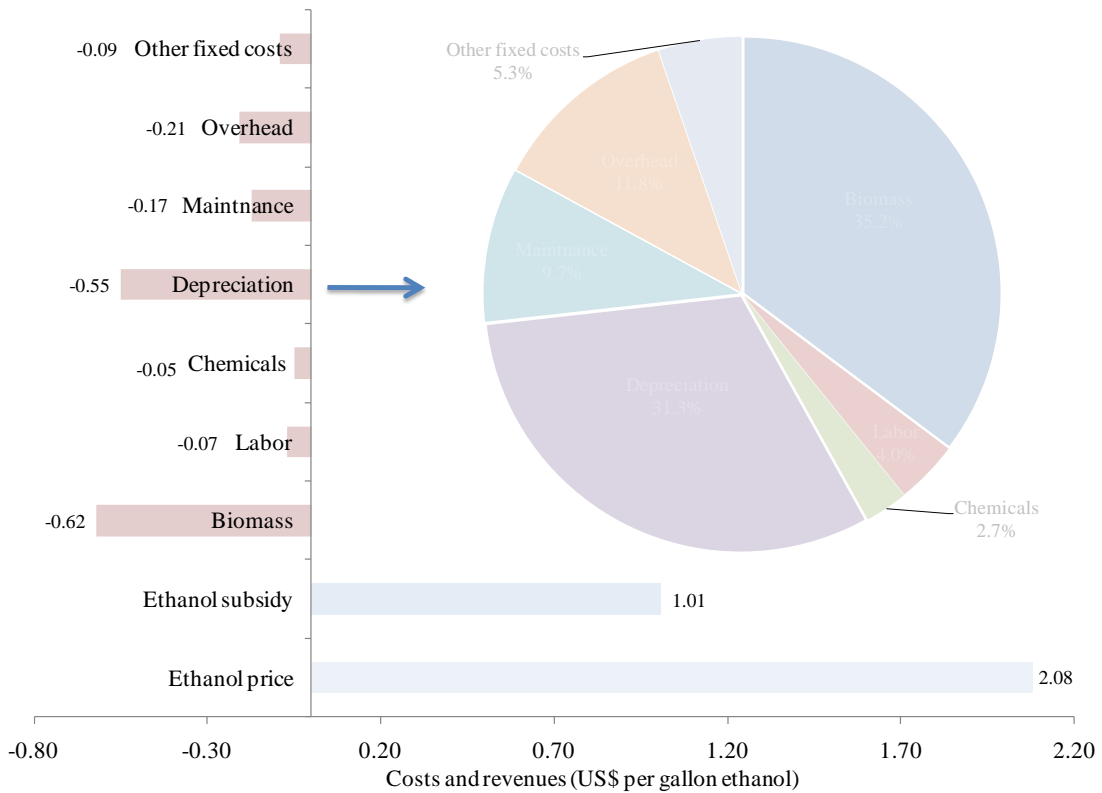


Figure 9-2 Ethanol production costs (US\$ per gallon ethanol) and cost share (%), using loblolly pine as feedstock. 1 gallon = 3.7854 liters

9.4.2 Financial indicators

Net present value (NPV) and internal rate of return (IRR) were estimated for each of the combinations of gasification and biomass. Higher NPV and IRR are observed in forest biomass (softwood and hardwoods) with NPV ranging from US\$ 135.5 million to US\$ 191.9 million and IRR ranging from 19% to 21.4%. Lower NPV and IRR are found in corn stover and switch grass. The performance of these financial indicators is explained by a combination of raw material costs (table 9-2) and alcohol yield (figure 9-4 and 9-5).

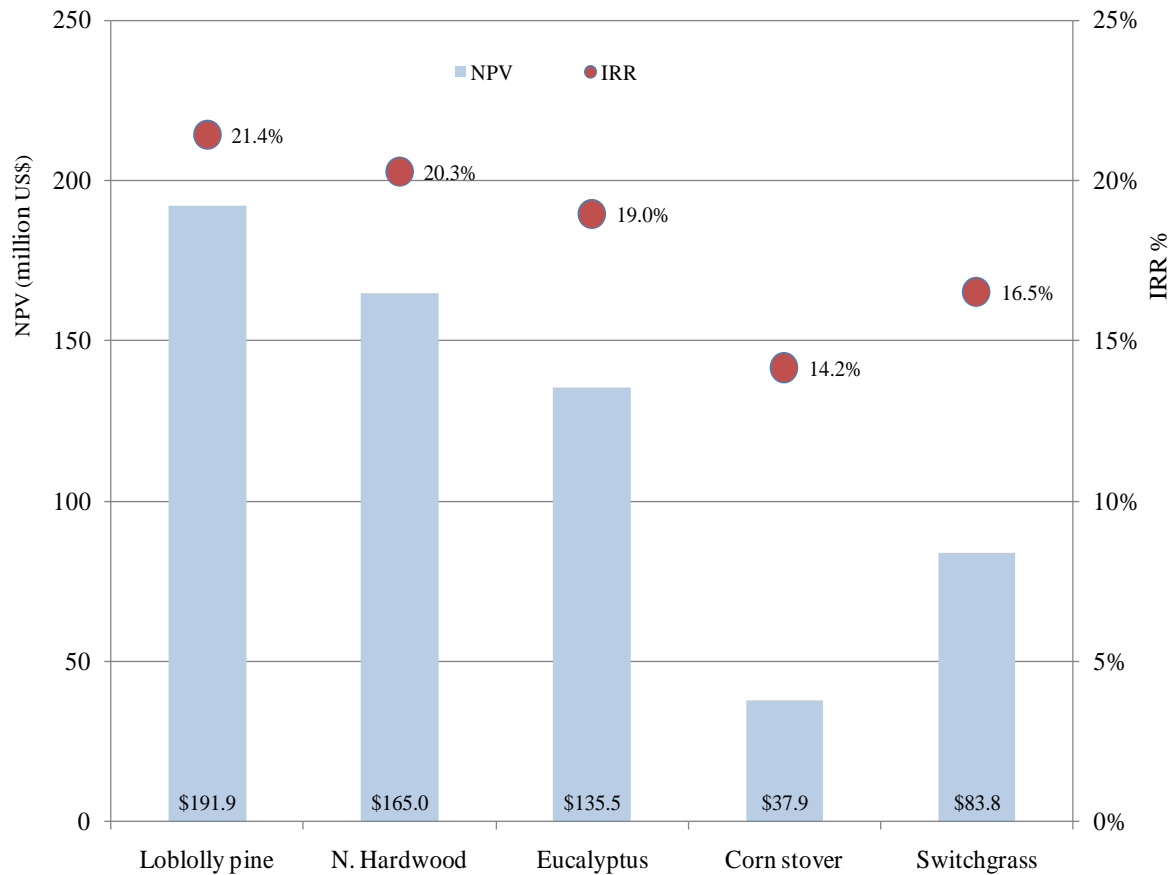


Figure 9-3 NPV and IRR for the each of the feedstock

Alcohol production for each of the biomass, IRR and payback is presented in figure 9-4. Ethanol (ethanol and propanol to ethanol equivalent) greatly varies depending on the type of biomass used, with values ranging from 169 to 183 million liters of alcohol (for corn stover and switchgrass respectively) to 186 to 204 million liters of alcohol (forest feedstock, loblolly pine and Eucalyptus respectively). Payback, number of years required to offset initial investment, is higher those biomass with lower productivity (figure 9-4) and ethanol yield (figure 9-5).

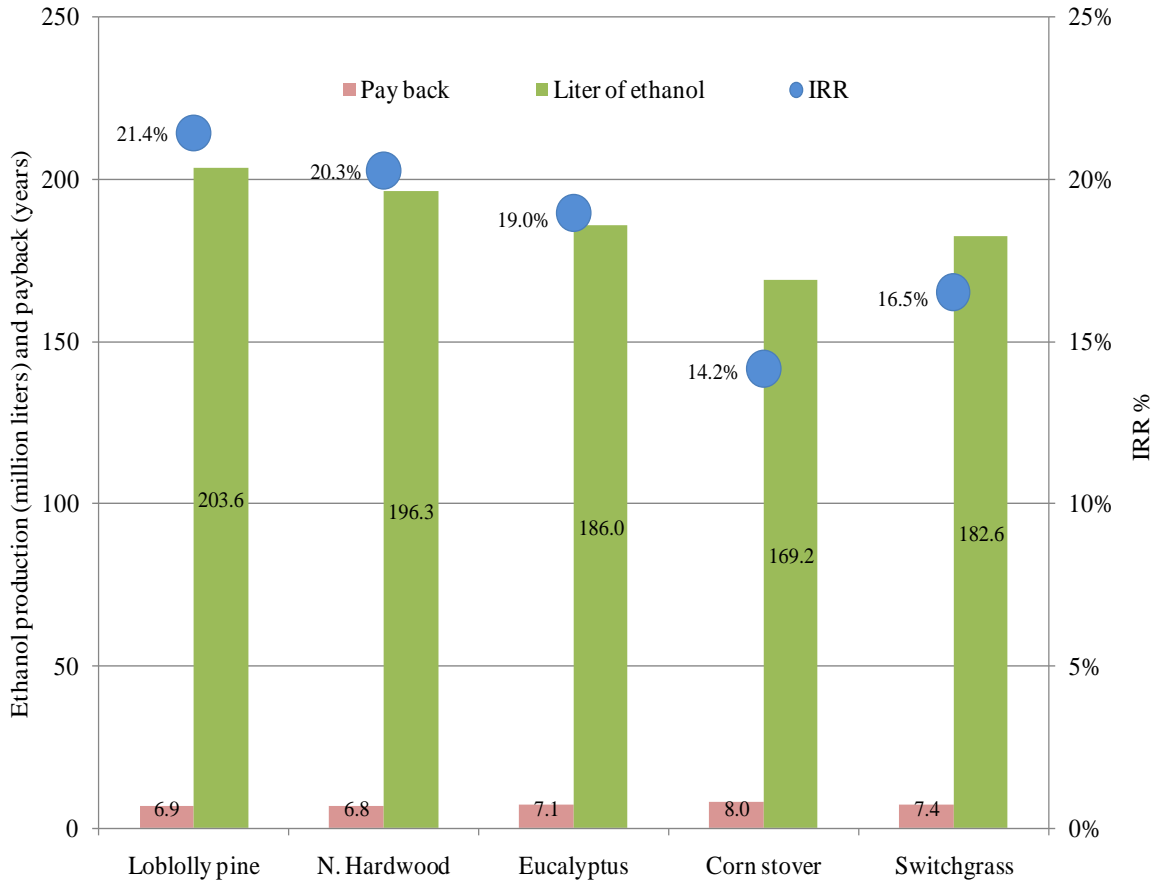


Figure 9-4 IRR, ethanol yield (liter per dry metric ton) and payback (years) for each of the biomass

9.4.3 Alcohol yield

Alcohol yield and CAPEX (US\$ CAPEX per liter of alcohol) for each of the biomass are illustrated in figure 9-5. As expected from figure 9-4 and 9-5, higher alcohol yields are found in those forest feedstock (pine, natural hardwood and Eucalyptus), with values ranging from 449 liter of alcohol per dry ton (loblolly pine) to 373 liters alcohol per dry ton (corn stover). Higher CAPEX per liter of alcohol is found in those biomass with lower yield (corn stover), with values ranging from US\$ 1.5 to US\$ 1.8 per liter of alcohol.

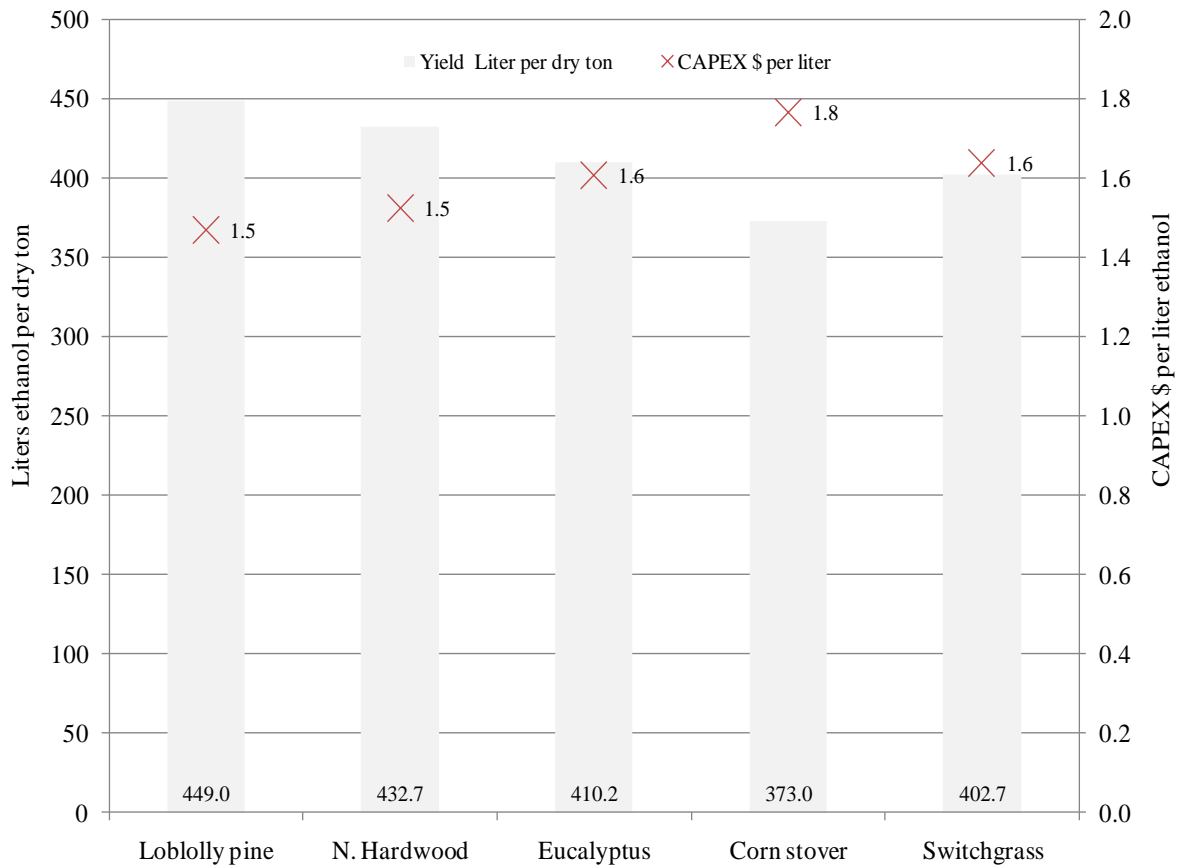


Figure 9-5 Ethanol production and CAPEX per liter of ethanol

9.4.4 Minimum ethanol selling price (MESP):

One frequent indicator used in alcohol production economic analysis is the minimum ethanol selling price (MESP), this is the price (US\$ per liter of alcohol) required to achieve a specific rate of return, in this case 12%. As expected lower MESP are found in those biomass with higher alcohol yield (loblolly pine, natural hardwood and Eucalyptus), with MESP

ranging from US\$ 0.54 to US\$ 0.59 per liter of alcohol, higher MESP is found for corn stover (US\$ 0.71 per liter of alcohol).

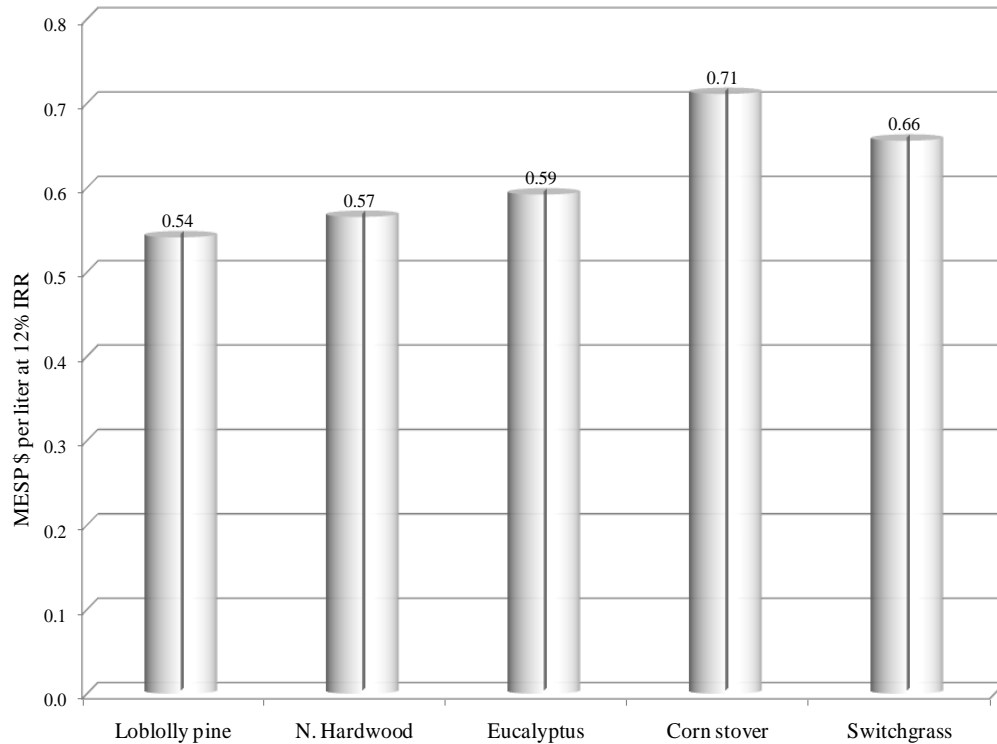


Figure 9-6 Minimum ethanol selling price back calculated to achieve 12% IRR for each of the biomass

9.4.5 Sensitivity analysis

Sensitivity analysis was carry out for loblolly pine, natural hardwood, corn stover and switch grass, to understand how sensible is each combination of biomass to process conversion with changes of +/- 25% for the following divers: alcohol price (alone, do not

include subsidy), alcohol yield (ethanol and propanol to ethanol equivalent), CAPEX and biomass cost, figure 9-7. Major sensitivity is represented by changes in alcohol yield and selling price (for all the four biomasses). CAPEX and biomass cost seems to have higher effect in corn stover and switchgrass, when compared to forest feedstock. Higher effect for all the changes in sensitivity seems to take place in switchgrass and corn stover, mainly related to their lower yield and overall profitability.

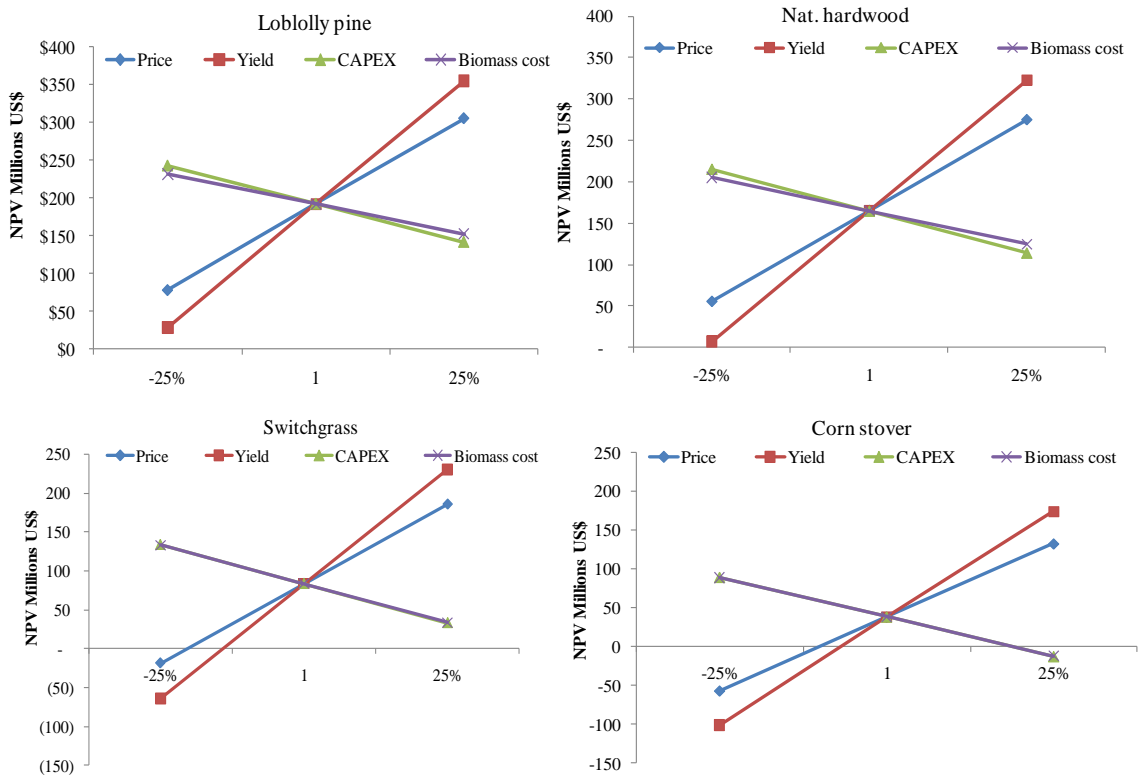


Figure 9-7 Sensitivity analysis +/- 25% in price, ethanol yield, CAPEX and biomass cost for loblolly pine, natural mixed hardwood, switchgrass and corn stover

9.4.6 Moisture content variation in raw material

In order to understand the effect of moisture content in the profitability of the process, loblolly pine at 35%, 45% and 55% moisture content were simulated in the conversion process and output data was used to understand its effects in the alcohol yield, NPV and IRR of the conversion process, biomass costs were kept as those presented in table 9-2, it is assumed that there is not premium or cost reduction for changes in moisture content. As previously explain in the method section, drying the biomass is an energy consuming process, energy that otherwise would be used to produce more alcohol. When biomass is fed at a lower moisture content (35%), NPV, IRR and alcohol yield are increased, with respect to the central assumption used in this paper of forest feedstock (45% moisture content). A reduction of 10% in moisture content in fact increase NPV by US\$ 66 million, with also a positive change in IRR by 2.8 points. Conversely, biomass with higher moisture content (55%) reduce alcohol yield and negatively affect the financial indicators of the project.

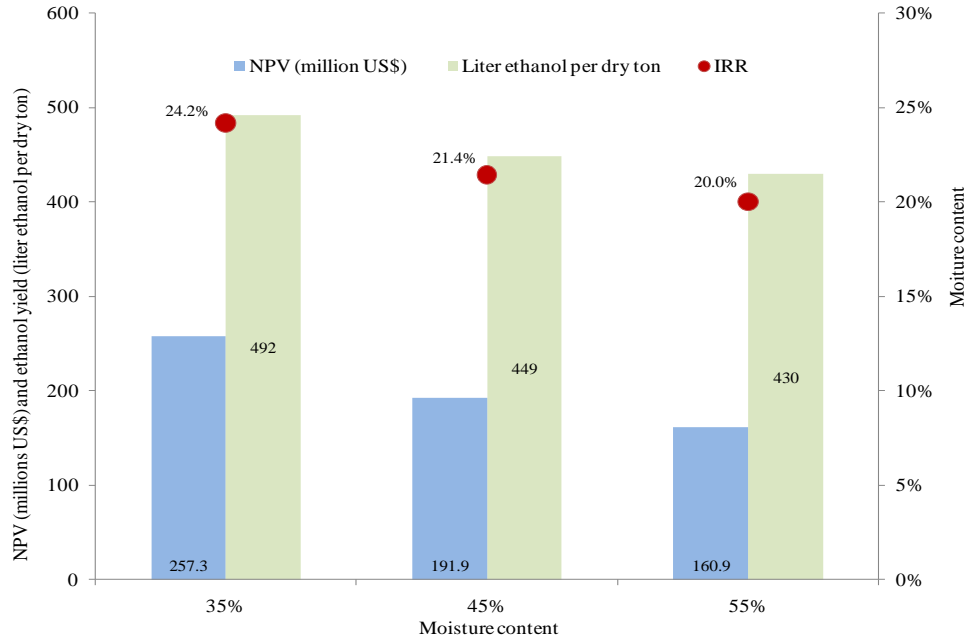


Figure 9-8 Effect of moisture content in biorefinery profitability

9.4.7 Effect of raw material on profitability, isolating raw material cost

As presented along this document, raw material has an important effect on the profitability of the biorefinery, mainly because of alcohol yield and biomass cost. In order to isolate the effect of biomass costs and better appreciate the effect of biomass composition in the economy of the biorefinery, a fixed cost of US\$ 60 per dry short ton (US\$ 66.14 per dry metric ton) was assumed for all the biomasses. Even in this scenario, the economic performance of corn stover and switchgrass is meager when compared to the scenarios where forest feedstocks are used.

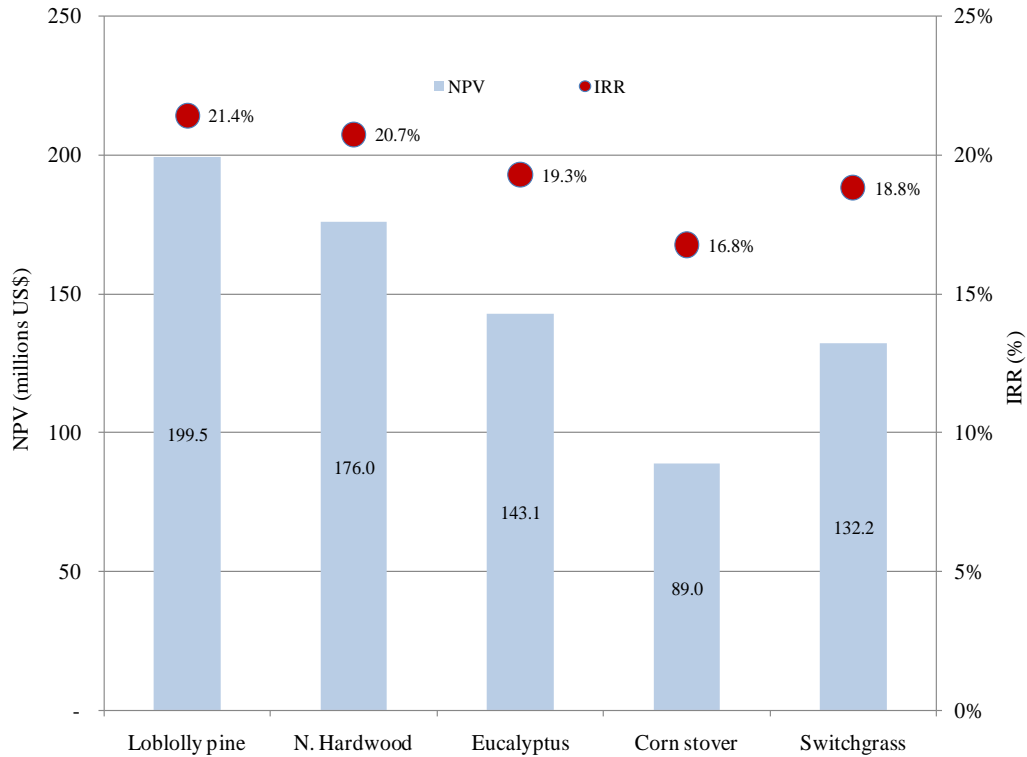


Figure 9-9 Gasification process for ethanol production

9.5 Conclusions

Despite there are not clear winner in cellulosic ethanol production between biochemical and thermochemical pathways, thermochemical conversion process has an interesting well known advantage of virtually handle different types of biomass. This grants competitive advantage to the biorefinery in term of using low cost feedstock available across the year. Forest biomass feedstock, as loblolly pine, natural hardwood and eucalyptus presenting higher % C and H% content and lower % ash content, positively impact alcohol yield in the process. In general terms, forest feedstock seems to have better financial returns

when compared to energy crops (as switchgrass) and agriculture residues (as corn stover), even when the same delivered cost was used for all the biomasses. In addition cellulosic ethanol production using switchgrass and corn stover seems to be more susceptible to changes ethanol price, alcohol yield, biomass cost and CAPEX. Major sensitivity is recorded by changes in alcohol yield and selling price (for all the four biomasses). CAPEX and biomass cost seems to have higher effect in corn stover and switchgrass, when compared to forest feedstock. Higher effect for all the changes in sensitivity seems to take place in switchgrass and corn stover, mainly explained for their lower yield and overall profitability. Moisture content in biomass is also an important player; lower moisture content in feedstock clearly benefits the financial performance of the project.

9.6 References

- Adebayo A, Wang J, Dawson-Andoh B, Mcneel J, Armstrong J (2009) Assessment of Appalachian hardwood residue properties and potentials for bioenergy utilization. *Wood and Fiber Science*, **41. 1**, 74-83.
- Aden A, Ruth M, Ibsen K *et al.* (2002) Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. NREL.
- Aspen-Tech (2004) Aspen Plus version 2004.1. *Aspen Technologies Inc.: Cambridge, MA*.
- Baker E, Keisler J (2009) Cellulosic Biofuels: Expert Views on Prospects for Advancement. 2010. <http://www.ecs.umass.edu/mie/faculty/baker/biofuelselicsuppmat.pdf>.
- Blaschek H, Boateng A (2009) Introduction to Session 4: New Biofuels and Biomass Chemicals. *Applied biochemistry and biotechnology*, **154. 1**, 1-2.
- Doe U (2010) Biomass Feedstock Composition and Property Database. 2010. http://www1.eere.energy.gov/biomass/feedstock_databases.html.
- Epa (2010) EPA Finalizes Regulation for the National Renewable Fuel Standard Program for 2010 and Beyond. 2010. <http://www.epa.gov/oms/renewablefuels/420f10007.pdf>.
- Foust T, Aden A, Dutta A, Phillips S (2009) An economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion processes. *Cellulose*, **16. 4**, 547-565.
- Goldemberg J (2007) Ethanol for a sustainable energy future. *Science*, **315. 5813**, 808.
- Gonzalez R, Saloni D, Dasmohapatra S, Cabbage F (2008) South America: industrial roundwood supply potential. *BioResources*, **3. 1**, 255-269.

- Gonzalez R, Treasure T, Phillips R, Jameel H, Saloni D, Abt R, Wright J (2010a) Converting Eucalyptus biomass into ethanol: Financial and sensitivity analysis in a co-current dilute acid process. Part II. *Biomass and Bioenergy*, **35. 2**, 767-772.
- Gonzalez R, Treasure T, Wright J, Saloni D, Phillips R, Abt R, Jameel H (2010b) Exploring the potential of Eucalyptus for energy production in the Southern United States: Financial analysis of delivered biomass. Part I. *Biomass and Bioenergy*, **35. 2**, 755-766.
- Mitchell D (2008) A note on rising food prices. The World Bank Development Prospects Group. Policy Research Working Paper 4682.
- Mosier N, Hendrickson R, Dreschel R, Dien B, Bothast R, Welch G, Ladisch M (2003) Principles and Economics of Pretreating Cellulose in Water for Ethanol Production. American Chemical Society National Meeting
- Mosier N, Wyman C, Dale B, Elander R, Lee Y, Holtzapple M, Ladisch M (2005) Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource technology*, **96. 6**, 673-686.
- Mu D, Seager T, Rao P, Zhao F (2010) Comparative Life Cycle Assessment of Lignocellulosic Ethanol Production: Biochemical Versus Thermochemical Conversion. *Environmental Management*, **46**. 565-578.
- Phillips R (2010) Capital Expenditure of Biorefineries. Personal communication
- Phillips S, Eggeman T, Jechura J, Dayton D (2007) Thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass. National Renewable Energy Laboratory. NREL/TP-510-41168. Task No. BB07.3710.
- Pirraglia A, Gonzalez R, Saloni D (2010) Techno-economical analysis of wood pellets production for US manufacturers. *BioResources*, **5. 4**, 2374-2390.

- Rfa (2010) 2010 Ethanol industry outlook. Climate of opportunity. 2010. http://www.ethanolrfa.org/page/-/objects/pdf/outlook/RFAoutlook2010_fin.pdf?nocdn=1.
- Schuetzle D, Tamblyn G, Tornatore F, Macdonald T (2007) Alcohol Fuels from Biomass: Assessment of Production Technologies. Citeseer. Report to the Western Governor's Association. 2007, TSS Consultants and the California Energy Commission.
- Tao L, Aden A (2009) The economics of current and future biofuels. *In Vitro Cellular & Developmental Biology-Plant*, **45. 3**, 199-217.
- Wu X, McLaren J, Madl R, Wang D (2010) Biofuels from Lignocellulosic Biomass. *Sustainable Biotechnology*, 19-41.
- Wyman C (2007) What is (and is not) vital to advancing cellulosic ethanol. *TRENDS in Biotechnology*, **25. 4**, 153-157.
- Wyman C (2008) Cellulosic ethanol: A unique sustainable liquid transportation fuel. Material Research Society. 33.
- Yan W, Acharjee T, Coronella C, Vásquez V (2009) Thermal pretreatment of lignocellulosic biomass. *Environmental Progress & Sustainable Energy*, **28. 3**, 435-440.