ECONOMIC ANALYSIS OF WOODY BIOMASS SUPPLY CHAIN LOGISTICS FOR BIOFUEL PRODUCTION IN MICHIGAN

Final Report

FOREST BIOMASS STATE-WIDE CENTER OF ENERGY EXCELLENCE

Sub-task B.2 - Analyze the Economic and Logistics Performances of Woody Biomass Harvesting, Forwarding, and Processing Systems from Natural Forest Stands and Energy Plantations in Michigan

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EXECUTIVE SUMMARY

This report pertains to Sub-task B.2, "Analyze the Economic and Logistics Performances of Woody Biomass Harvesting, Forwarding, and Processing Systems from Natural Forest Stands and Energy Plantations in Michigan," and is a section of the overall project entitled "Forestry Biofuels Statewide Collaboration Center."

The goal of the sub-task was to address the question: How can we efficiently harvest, move and produce biofuel in Michigan? To attempt to answer this question, two more questions needed to be addressed:

- Is there enough workforce and equipment capacity in Michigan to supply biomass from natural forestlands and plantations?
- What is the optimal biofuel potential from different biomass supply systems including natural forests and plantations?

This sub-task examines the harvesting, forwarding, and processing (HFP) systems in Michigan. The first step was to complete an inventory of HFP equipment and methods used statewide in Michigan. This required contacting logging companies, extension educators, and equipment manufacturers. Data collected includes equipment capital cost, operating cost, field capacity and efficiency. Second, an assessment of these HFP systems commonly used in Michigan was made. Systems most commonly used in Michigan are whole tree harvesting followed by skidding to landing site and cut to length followed by forwarding. Several models to compute system cost were considered that would be suitable for Michigan conditions. Some available models required knowing all machine and stand data needed to calculate cost such as machine prices, fuel consumption, productivity and forest stand data. FRCS model, developed for western United States had some desirable features such as it had built in regression equations to compute the necessary attributes needed to calculate production cost for a HFP system. However, these regression models did not adequately represent Michigan conditions. Thus the model was adapted to Michigan conditions using results of the logger's survey for comparison. A sensitivity analysis was conducted to determine the impact of the various management parameters on production cost.

This study analyzed the supply chain and logistics linked to harvesting natural forestlands and plantations in Michigan and their optimal conversion potentials for different bioenergy scenarios. To understand the extent of the operating capacity and the state of the technology of harvesting operations, it was necessary to assess existing logging capacity to harvest and supply biomass from natural forests and plantations-based woody biomass. Subtask B.2 was divided into three sections that are reported herein: 1) a comprehensive survey of the logging community within Michigan; 2) modeling of supply chain scenarios for the supply of wood from natural stands using different harvesting operations in Michigan; 3) analyzing the conversion of natural stand or plantation material to woodchips, wood pellets and torrefied wood pellets at Regional Biomass Processing Depots (RBPDs) in Michigan. The bioenergy systems examined in Subtask B.2 were compared to develop recommendations for future analyses.

Surveying Michigan loggers resulted in a snapshot of the harvesting, forwarding and processing equipment available in 2009 and 2010. Several observations can be made after reflecting upon the survey results. First, as most harvesting operations were from partial cut treatments, it would not be prudent to assume that an entire area would be clear cut to supply biomass to new facility. Second, most products were extracted from lands defined as "private non-industrial" and then delivered to pulp and paper industries. Third, saw logs and pulpwood were the most common types of product removed from the forest while woodchips were the least. Fourth, a variety of logging equipment was used; including mechanical whole tree harvesting, cut-to-length harvesting and manual whole tree harvesting. Fifth, skidding distance was reported and show the significance of biomass skidding costs. A sixth observation is that most biomass procurement operations do not involve equipment for residue removal or chipping. These observations and others were borne of the loggers' survey and are discussed more thoroughly in

Section I of this report. Overall, the survey was successful in receiving responses from over 200 logging firms statewide.

Modeling of biomass supply from natural stands provided estimates of biomass costs for the various supply chains relevant in Michigan as determined by the survey. Table B2.1 contains the cost of producing wood chips from natural stands under different treatment scenarios for a variety of stand conditions. Values in this table range from $13.28 to $23.14. Increasing the amount of removal significantly reduces these costs. Overall, harvesting costs are highly variable and dependent upon the type of equipment, level of harvesting (clear-cut vs. selective cut), type of forest, and the tree stand density. Generally, the FRCS predicted costs were higher than those provided by the loggers' survey, which suggests increased productivity by Michigan loggers. Pulpwood harvesting costs ranged from as low as $8.91/GT for clear-cutting natural hardwoods by WT system to as high as $27.11/GT for 30% natural hardwoods by CTL system.

Table B2.1 *Production cost ($/ton) for biomass products using a WT harvesting system (whole-tree chipping)*

	Forest type	Felling	Skidding	Chipping	Total
30% Cut	Natural Hardwoods	8.72	8.27	4.37	21.36
	Mixed Hardwood / Softwood	8.86	8.41	4.37	21.65
	Natural Softwoods	9.63	9.14	4.37	23.14
	Softwood Plantations	8.09	7.68	4.37	20.15
70% Cut	Natural Hardwoods	6.85	6.50	4.37	17.71
	Mixed Hardwood / Softwood	7.01	6.65	4.37	18.03
	Natural Softwoods	6.46	6.13	4.37	16.96
	Softwood Plantations	6.02	5.71	4.37	16.10
Clear cut	Natural Hardwoods	4.76	4.51	4.37	13.64
	Mixed Hardwood / Softwood	4.92	4.67	4.37	13.96
	Natural Softwoods	5.05	4.80	4.37	14.22
	Softwood Plantations	4.57	4.34	4.37	13.28

In addition to comparing harvesting and handling systems for delivering woody biomass, alternative preprocessing technologies were compared to identify potential bioenergy supply chains for electrical power generation. Comparisons were made by determining the cost of electricity generation at a 100 MWe power plant in which wood chips, wood pellets, or torrefied wood pellets were co-fired with coal. In accordance with Michigan Public Act 295, ten percent of the electrical power produced in our model scenarios was assumed to be provided by renewable energy. The specific preprocessing technologies considered for bioenergy production included chipping, pelletization and torrefaction with pelletization. Chipping and pelletization create a material that is more easily transportable than forest slash and small diameter plantation trees, while torrefaction produces a mildly carbonized wood product with several desirable characteristics. In the systems analyzed, preprocessing was assumed to occur at either the roadside or in Regional Biomass Preprocessing Depots (RBPDs) that are located near to harvest regions because densification is central to reducing transportation cost. Finally, these technologies were compared to determine the bioenergy systems that are most appropriate for the range of site conditions within the State of Michigan.

Torrefaction is a preprocessing technology that upgrades woody biomass to a form with desirable physical and chemical properties. In torrefaction, heat is added in the absence of oxygen to perform a mild pyrolysis of the structural components of biomass. Torrefaction has been previously investigated by the Energy Center for the Netherlands (Bergman, P.C.A. 2005a) and Agri-Tech Producers LLC (2011) for the purpose of determining technical and economic feasibility. The advantages of torrefied wood pellets versus wood chips include: 1) reduced transportation costs due to densification, 2) improved storage stability due to increased hydrophobicity, and 3) reduced grinding costs due to increased friability. Scenarios that involve long distance transportation are especially benefitted by torrefaction and pelletization. Overland truck transport costs reflect this conclusion for the three products investigated by our analysis as shown in Table B2.2. We conclude that for bioenergy systems that involve long transportation distances, torrefaction and pelletization are justified. It is important to note, the cost contribution to electrical power generation portrayed in the figure and tables of this report does not include the cost of coal. As only 10% of the total electricity is produced by these bioenergy systems, the actual cost contribution to power generation is one tenth of that reported when coal is assumed to produce the remaining 90%.

Table B2.2. Costs of wood chips, wood pellets and torrefied wood pellets using poplar (grown in a six year rotation) as feedstock when delivered to the power plant assuming a 300 mile transport distance. Costs are portrayed as $ per ton (as received); $ per GJ (as received; lower heating value); and cents per kWh of electricity produced (cost contribution of feedstock to the cost of electrical power; not including coal).

	Wood chips	Wood Pellets	Torrefied Wood Pellets
Moisture wt. %	20%	8%	3%
$/t	71.01	97.71	117.59
$/GJ	5.917	5.851	5.600
$/Kwh	0.059	0.059	0.056

Figure B2.1. Cost contribution to electrical power generation from wood chips, wood pellets and torrefied wood pellets when a distance of 300 miles from the RBPD to the power plant is applied. Poplar was used as the feedstock at a biomass cost of $41.33/dt.

As seen in Figure B2.1, the cost of poplar wood chips is the largest contributor to overall cost for each of the three scenarios. Torrefaction costs are also a large cost component when torrefied wood pellets are produced, but the equipment costs required at the power plant to store, handle and grind wood chips and wood pellets are not included in this study. As such, we recommend that further analysis be performed to examine the costs of generating wood chips, wood pellets and torrefied wood pellets. Though energy plantations of this sort currently do not exist, the Billion-ton StudyUpdate (Perlack, R.D. and Stokes, B.J. 2011) clearly states the importance of such energy crops. For long distance transportation (250 miles by truck in this study), the costs of torrefied wood pellets are lower than those for wood pellets and wood chips. Shorter transportation distances may also be justifiable when the additional processing costs at power plants are included for wood chips and when accurate torrefaction investment costs are made available. Multiple modes of transportation (truck/rail/ship) offer reduced cost for some scenarios and could be considered in further studies. Optimization of torrefaction will provide a clear opportunity for further reducing the costs of this bioenergy scenario, and new torrefaction technologies should be considered to improve the outlook for this alternative energy technology.

A SNAPSHOT OF THE EXISTING LOGGING INDUSTRY IN MICHIGAN

Introduction

The availability of a steady source of woody biomass at a cost effective price is critical to developing a biofuels industry. This depends upon the logging capacity as determined by the number and type of logging equipment available for harvesting woody biomass. In order to determine the current logging capacity and related operational characteristics in the State of Michigan, a comprehensive survey was completed in 2011. The survey was conducted over two stages that started in 2009-2010 that covered the Upper and Northern Lower Peninsula of Michigan and another in 2010-2011 with similar questions that covered the remaining parts of the state. Results were collected, aggregated and analyzed to provide an overall statewide snapshot of the state of the logging industry. Results of both surveys are presented here to summarize the status of the logging industry in Michigan.

ID CODE #_______

Logging Equipment and Transportation Survey

The purpose of this study is to identify the logging capacity in the State of Michigan. This survey serves as a key component of the larger research project that Michigan State University and Michigan Technological University are carrying out to assess existing logging capacity to identify optimum harvesting, forwarding and processing equipment and systems for timber and biomass harvested from natural forest stands as well as plantations. Your responses to the survey questions will help describe the current state of the harvesting and transportation equipment, the current production, the potential production and what is needed to reach this potential production for the start-up of potential new facilities. Your participation in this survey is voluntary and the information provided is confidential and will be used only for study purposes.

You can complete an online version of the questionnaire instead at: http://www.loggingMI.ippsr.msu.edu/

You indicate your voluntary consent to participate in the study by completing and returning the questionnaire by mail or fax to:

Office for Survey Research - IPPSR
321 Berkey Hall
Michigan State University
East Lansing, MI 48821-1111 Fax (517) 432-1544

If you have questions or comments about the research, please contact:

Dr. Dalia Abbas, Department of Biosystems and Agricultural Engineering
Michigan State University
Tel. (517) 355-7493 Fax (517) 432-2892
Email: abbasd@msu.edu

Please return your completed questionnaire in the envelope provided. Thank you very much for your help and for taking the time to complete this survey.

Questionnaire designed by the Office for Survey Research

Figure B2.2. Survey introductory page

Methodology

In 2009 at the onset of the project, the project team contacted local experts and reviewed the literature about existing information. No comprehensive study of the existing harvesting and transportation technology in the state existed. As a result it very difficult to undertake a study that explains harvesting and supply logistics technology for the entire state of Michigan without knowing the information presented in this section of the report. As a result, a comprehensive analysis of needed questions was developed to explain the business sectors, equipment use and productivity, and operational capacities. The survey development process took around 6 months of consultations and edits. When a draft was prepared it was piloted with local logging firms. The result was a 14-page survey that was mailed out to an entire group of logging firms from an existing MSU-database. Full survey and notices using the Dillman method were sent out to logging firms, but there were several incorrect mailing addresses and firms that were no longer in business. Finally, the survey was successful in receiving responses from over 200 logging firms statewide. The data collected offers a unique opportunity to understand the state of the harvesting technology in the State of Michigan. Based on survey response a large database was developed that spanned over 500 records of responses.

<u>Developing Survey Instrument</u>

Survey instrument development involved identifying, developing and piloting questions based on project objectives outlined in the proposal. Request for information and survey criteria were developed with relevance to the program objectives for a snapshot of existing harvesting technology in Michigan. A larger survey was first developed to accommodate every thought possible in the process. The survey was approved by MSU Institutional Review Board to comply with human subjects' protection. The steps in developing the survey involved consultation with loggers regularly both in the State of Michigan and out of state. Several survey drafts were developed and passed on to expert loggers and forest engineering experts nationwide for their critique.

Survey Method and Stages

The survey was based on Dillman's (2000) mail and internet survey tailored design methods and approach to mail in surveys. Each respondent had a unique web and survey ID that was entered when respondents chose the online option using the website http://www.loggingMI.ippsr.msu.edu/. Below are the stages of the survey method, in consultation with Prof. Hembroff in the Office of Survey Research of Michigan State University:

- Mailing #1: Pre-notice by mail to notify about the survey.
- Mailing #2: Mail contains the survey, a cover letter, and a business postage-paid return envelope
- Mailing #3: Postcard reminder/thank you, containing the URL to the survey site; sent to everyone about two weeks after mailing #1
- Mailing #4: Mail sent to non-respondents only about two weeks after the postcard mailing; contains a replacement questionnaire, with cover letter that includes the URL to the survey site, and a postage-paid return envelope

Results

Geospatial Distribution of Logging Firms

Out of the total 83 counties surveyed, responses were received from 44 counties (three of which are Wisconsin counties). A larger number of logging firms were located in the Upper Peninsula of Michigan. This is not surprising since this is the location of the highest concentration of timber resources in the state. Furthermore, four counties out of Wisconsin bordering Michigan responded to the survey. Those were the counties of Marinette, Florence, Villas and Wexford. Figure B2.3 shows responses from the various counties in Michigan.

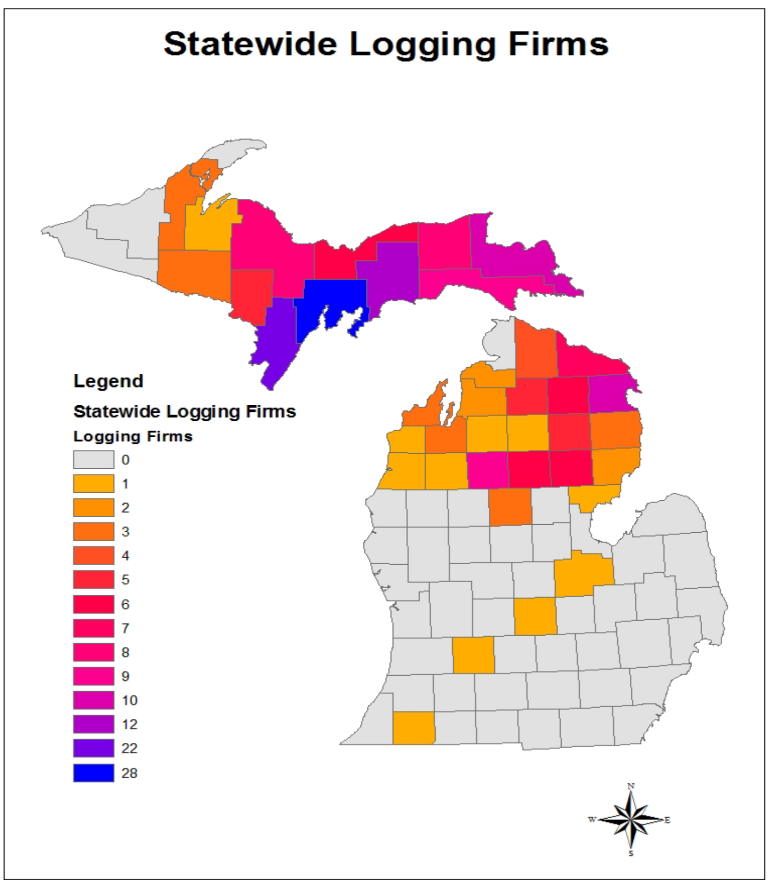

Figure B2.3. Map of Logging Firms in Michigan based on Survey Reponses <u>*Employment Analysis*</u>

The state of employment in the logging industry nationwide has been impacted by several sectors of economy. A few of these sectors are the housing, and pulp and paper industries that have witnessed a decline. In an attempt to capture the data without bias to a particular year, the survey inquired about the number of employees per firm in the particular year of the survey as well as under normal conditions. Based on survey results, on an average firms employed 6.5 employees per year.

***Table B2.3**. Number of Employees in MI Logging Firms under Normal Conditions*

Mean	6.46
Number of respondents	195

Logging Firms Ownership Trends

As a part of the survey questions, we sought to better understand the age of the logging industry Michigan. On an average firms have been in business for 28 years. The question was not targeted to the individual respondent, rather, the logging firm's age.

***Table B2.4**. Years Firms in Business in MI*

	Years Firms in Business
Mean	28
Number of respondents	216

Trends in logging firm ownership indicate that most equipment operators own their equipment. This is followed by an 8% of operators who do not own equipment and 5% of owners who do not operate the equipment they own. This is also shown in Figure B2.4.

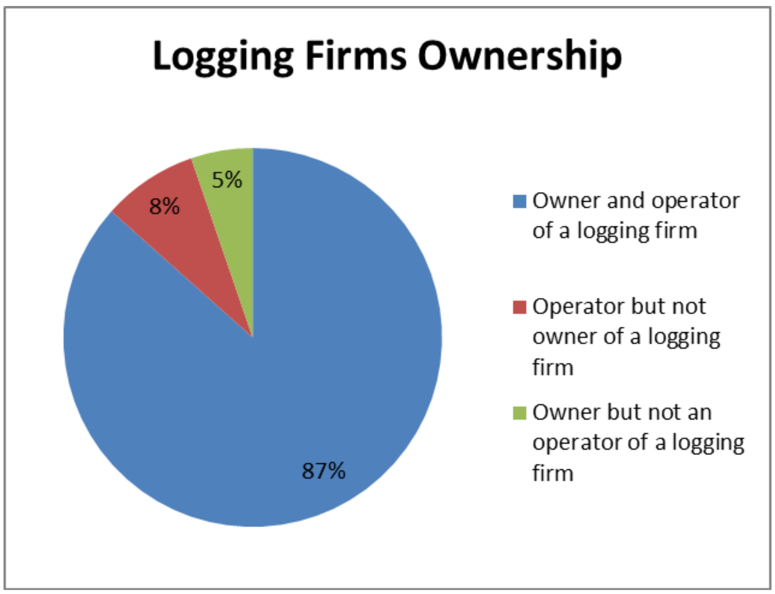

Figure B2.4. Logging Firms Ownership

Operational Capacity

Below in Table B2.5 is a summary of harvesting equipment owned by survey respondents. Respondents were asked about the number of equipment type they owned, along with basic descriptive information on the equipment. Cut-to-length processors were the predominant type of harvesting equipment seen throughout the state, and forwarders were the most common type of skidding equipment. As might be expected, there was a large variety in machine usage and fuel use among the different respondents, but the averages between surveys that were collected over 2009 and 2010 were very similar.

***Table B2.5**. Combined state of MI logging equipment summary*

Equipment type	Model year (responses)	Total machine hours (responses)	Fuel use gallons/hr (responses)
Cut-to-length processor	2003 ± 4.1[a] (132)	9,286 ± 6,543 (151)	4.9 ± 2.3 (142)
Feller-buncher	1996 ± 8.3 (35)	9,384 ± 6,696 (38)	6.3 ± 2.6 (37)
Feller-delimber	1988 (1)	12,467 ± 6,788 (3)	2.7 ± 0.6 (3)
Forwarder	1997 ± 9.5 (153)	10,666 ± 6,138 (165)	3.2 ± 1.9 (159)
Harwarder	2001 ± 5 (5)	9,053 ± 7,586 (6)	2.2 ± 0.5 (5)
Chainsaws	2006 ± 4.9 (113)	668 ± 990 (36)	1.1 ± 0.6 (35)
Grapple skidder	1995 ± 8.1 (47)	11,583 ± 6,116 (31)	5.1 ± 2.3 (33)
Cable skidder	1976 ± 8.8 (17)	8,889 ± 3,772 (9)	2.4 ± 1.0 (11)
Loaders	1996 ± 6.7 (30)	7,525 ± 7,429 (24)	3.8 ± 1.9 (26)
Grinders	2003 ± 1.0 (5)	2,459 ± 772 (6)	8.0 ± 0.9 (4)
Slashers	1995 ± 7.6 (14)	9,607 ± 7,140 (15)	3.9 ± 1.8 (18)
Delimber	1996 ± 8 (3)	6,220 ± 3,561 (5)	3.0 ± 0 (3)
Debarker	1997 ± 2 (2)	7,333 ± 1,155 (3)	13.3 ± 2.9 (3)
Chippers	1997 ± 9.1 (18)	8,798 ± 8,584 (17)	14.5 ± 8.9 (18)
Bulldozers	1992 ± 14.0 (72)	4,866 ± 3,226 (87)	3.8 ± 2.1 (79)

[a]- Numbers following ± represent standard deviations, based on number of responses in parentheses.
Below in Tables B2.6 is the reported roundwood harvesting productivity of different machine configurations, in cords of green timber per hour. Respondents were asked which harvesting equipment configuration they utilized for different harvesting scenarios, and in different forest types. Equipment configurations were grouped into three main categories to simplify the analysis, based on the type of equipment that would be cutting down the trees.

A – full processor/forwarder
B – feller buncher/skidder/slasher
C – chainsaws/skidder

Respondents also indicated their reported productivity in cords or tons of wood per hour. To simplify the analysis and reduce error from including respondents that own many pieces of equipment but do not use them equally or at all times, we focused on respondents which owned only 1 or two pieces of cutting equipment (full processors, feller-bunchers), but any respondents that indicated chainsaw use were included. Productivity was normalized to a single cutting equipment unit (i.e., productivity for 2-unit respondents was divided by 2), and the number of cutting equipment units included in the analysis is listed as N in the table. This procedure was not followed for chainsaw-based harvesting, as it is commonly assumed that multiple chainsaws are used by logging crews relying on this equipment configuration. This procedure is explained in greater detail in the COEE Q5 report. For full processors and forwarders the average reported productivity increased as the harvesting scenario increased in intensity from 30% selective cut up to clear-cutting, as would be expected. In almost every case, productivity in each harvesting scenario was highest in softwood plantations, which are typically on even terrain and stocked with optimal timber for harvesting. Tables B2.6 and B2.7 explain productivity estimates for different logging equipment configurations.

Table B2.6. *Full Processor / Forwarder*

		Productivity per harvester (cords/hr-machine)		
Treatment	Forest Type	N	Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	54	3.34	1.38
	Mixed Hardwood / Softwood	48	3.83	1.48
	Natural Softwoods	47	3.95	2.16
	Softwood Plantations	37	4.57	2.11
70% Cut (Selective)	Natural Hardwoods	43	4.09	1.80
	Mixed Hardwood / Softwood	41	4.51	1.81
	Natural Softwoods	38	4.66	2.15
	Softwood Plantations	29	4.97	2.13
Clear-cutting	Natural Hardwoods	43	5.51	2.74
	Mixed Hardwood / Softwood	47	5.67	2.50
	Natural Softwoods	40	6.07	2.79
	Softwood Plantations	35	6.97	4.02

Table B2.7. *Feller-buncher / Grapple Skidder/ Slasher*

		1 Harvester - Productivity (cords/hr)		
Treatment	Forest Type	N	Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	15	3.72	1.52
	Mixed Hardwood / Softwood	15	3.66	1.31
	Natural Softwoods	13	3.37	1.32
	Softwood Plantations	8	4.01	0.93
70% Cut (Selective)	Natural Hardwoods	14	4.74	1.43
	Mixed Hardwood / Softwood	15	4.63	1.42
	Natural Softwoods	16	5.02	1.60
	Softwood Plantations	9	5.39	1.73
Clear-cutting	Natural Hardwoods	13	6.82	2.68
	Mixed Hardwood / Softwood	13	6.59	2.98
	Natural Softwoods	11	6.42	2.83
	Softwood Plantations	9	7.10	4.19

Average production per cut types

Most operators cut 30% treatments [45%] followed by 70% removals [29%] followed by clear-cuts [26%]. This means that the supply of biomass from clear-cuts would not be expected to exceed 25% of the supplied feedstock. This is particularly important when accounting for the location of a facility or its radius of feedstock supply.

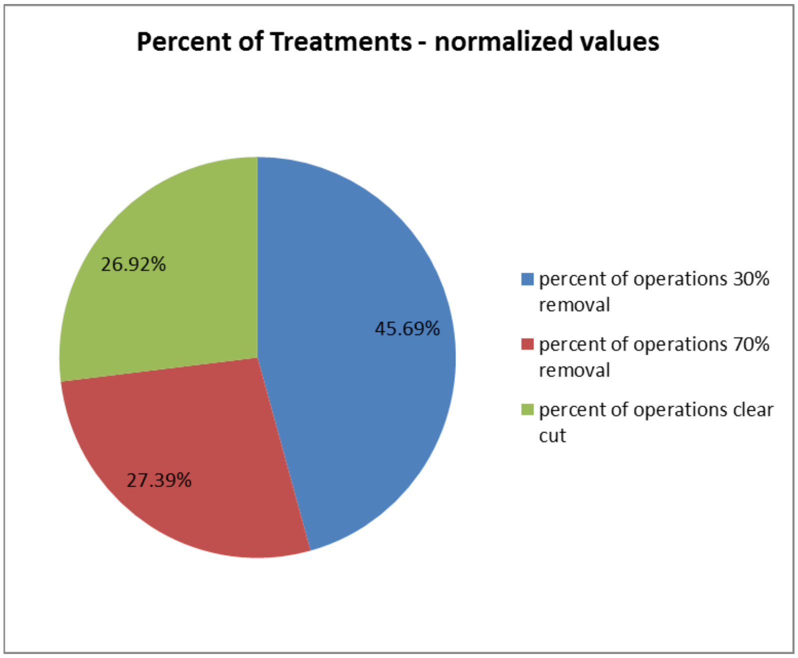

Figure B2.5. Percentage of Cut Type of Treatments in Harvesting

Table B2.8. *Normalized Values of different Percentages of Removal Operations from Forest Stands*

	Percent of operations 30% removal	***Percent of operations 70% removal***	***Percent of operations clear cut***
Mean	45.69	27.39	26.92
Number of respondents	194	194	194

Skidding and forwarding distances

Skidding material on site is a significant cost of harvesting operations. The study attempted to inquire about average and maximum skidding and forwarding of material distances. Responses were in line with data collected both years form the northern and southern regions, for verification. The skidding and forwarding distances calculated were a key factor to assess the harvesting economics using the FRCS model and employing data collected from the study.

***Table B2.9**. Average and Maximum Skidding Distances*

	Number of respondents	***Average (miles)***
Average Distance	172	0.26
Maximum Distance	165	0.78

Average Shift Hours during Summer and Winter Months

Average shift hours were collected to explain the expected number of hours operators work in summer and winter conditions. Results were overall not significantly different; however, winter hours were slightly lower. This finding is expected since winter days are shorter. The data, however, has shown that respondents were not double shifting. On average, summer weekly shift hours were 37.6 hr/week, and winter hours were 37.4 hr/week. The survey attempted to capture the number of hours spent to repair and maintain equipment. The average reported repairs hours per day were 1.3 hours, with the equipment requiring the most repairs was the cut-to-length processor. The time spent repairing and maintaining equipment results in time taken out of production thereby increasing the cost.

Equipment Ownership

Configurations with Cut-to-Length operations were almost 3 times those of feller-bunchers. On the other hand, chainsaws were the largest in number of equipment used. However, chainsaws are also used to remove vegetation and unneeded brush obstructing heavy machinery. There are twice as many forwarders as there are skidders which is a good reflection of the higher number full processor-forwarder configuration used by the logging industry. Forwarders in number are followed by skidders that yard material for both the feller-buncher and the chainsaw equipment. However, a few chainsaw operators reported yarding material using a skidder. The table below is a representation of the type of equipment used in Michigan to enter a stand and harvest sawlogs, pulpwood and chip material.

***Table B2.10**. Equipment Ownership*

Equipment type	**No. of reported equipment**
Whole Tree Buncher	57
Whole Tree Feller Delimber	4
Whole Cut Processor	191
Chainsaws	569
Harwarder	18
Forwarder	247
Grapple Skidder	86
Cable Skidder	26
Loader	54
Slasher	24
Delimber	8
Debarker	4
Grinder	9
Chipper	31
Bulldozer	132
Other equipment	40

Type of Products Removed from Harvest Operations

Survey results attempted to collect information about the type of products loggers were involved with. Results were structured into the percentage of their operations that involved sawlogs, pulpwood and woodchips products. Summary of results is presented below.

***Table B2.11**. Type of Products Removed from Harvest Operations*

	Response Rate	Total number of respondents
Sawlogs	97%	206
Pulpwood	95%	206
Woodchips	15%	132

Production Capacity

Individual responses included MBF (thousand board feet), cords and tons values. The general rules of 2.3 tons/cord and 2 cords/MBF were used. Analysis for this section involved converting all MBF values to international ¼ log rules. All Scribner log rule values were multiplied by a factor of 0.83 and all Doyle log rule values were multiplied by a factor of 0.62. Final statistical analysis was developed on converted values as shown below:

***Table B2.12**. Production Capacity*

Mean	3,438	4,328	3,228	15,668	13,889
Number of respondents	112	142	132	23	18

Harvested Stands Size Data

Survey results collected data to identify the maximum, minimum and average size of harvested stands as well as the volume of products removed. Stand size is important to help explain the cost of overall harvesting operations, since the trucking of equipment to site is a significant cost factor. When the area harvested or the volume removed is small, the entire cost of the harvest operations increase.

***Table B2.13**. Harvested Stands Size (acres)*

Statistical Analysis	*maximum stand size harvested*	*minimum stand size harvested*	*average stand size harvested*
Mean	159.97	17.12	47.54
Number of respondents	174	177	184

***Table B2.14**. Volume of Smallest Operation (cords)*

	Volume of Smallest Operation (cords)
Mean	665.64
Number of respondents	173

Percentage of Operating Capacities among Survey Participants

The forest-based industries were heavily impacted by the decline of several industries such as the housing and pulp and paper industries. To that end the emergence of biofuels industries would help ameliorate the decline. As a result, the survey aimed to capture potential decline in operating capacity.

Operations per Terrain Types

Operating on different terrain types has a significant cost increase in overall harvesting operations. As a result it was critical to understand the percentage of operations on different terrain types. Based on survey results most operations fall within the flat grounds, followed by rolling grounds, then low grounds followed by steep hills. The question required an overall 100% sum of responses to those percentages of operations per terrain types. However, this was not always the case when responses were summed up. To present valuable responses, data below shows all forms of responses. The first set describes the actual responses. The second set removed all responses that did not add up to 100% and a 0 value was inserted in empty cell responses, from those responses that added up to 100%. Trends between both normalized and real data were similar.

Table B2.15. *Actual Representation of Terrain Type Data without Normalization*

	low ground operations	*flat operations*	*rolling operations*	*steep hilly operations*
Mean	28.71	37.57	35.64	16.22
Number of Respondents	164	173	172	125

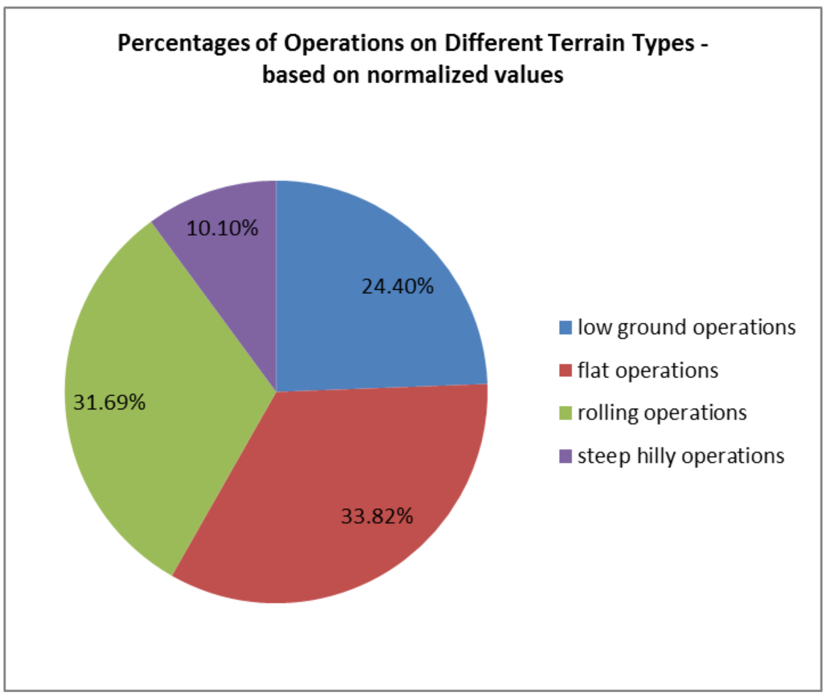

Figure B2.6. Percent of Operations on different Terrain Types

Percentages of operations that involve residue removals

To better understand the extent to which operations involved residue removal, survey questions inquired about percentages of clear-cut and partial removal operations that involved dealing with residue. Most operations do not involve residue removal. Percentage of residue removal is highest in partial cut harvesting.

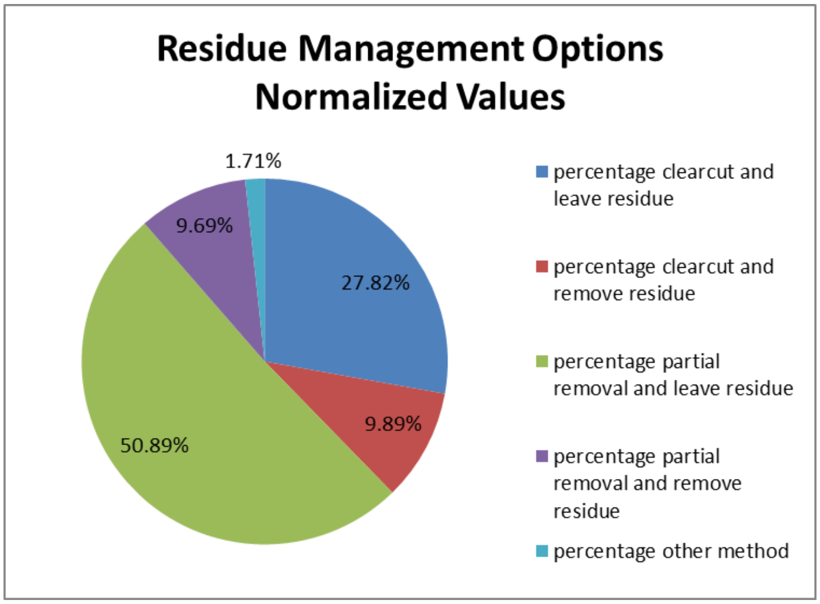

Figure B2.7. Residue Management Options

Percentages of Operations from different property types

Since land ownership to a large degree determines the amount of available resources to removal, the survey inquired about the landownership that operators worked with. Almost 60% of landownership came from private non-industrial lands.

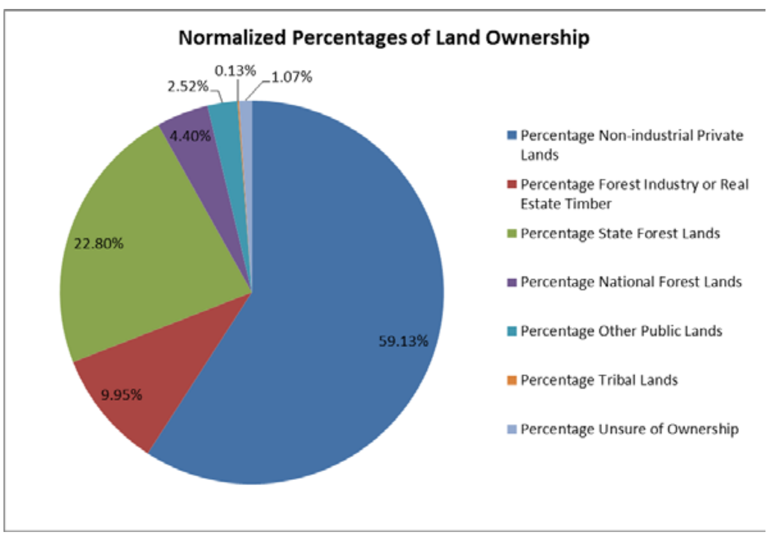

Figure B2.8. Percent of Land Ownership

Percentage of Operations with Purchased Stumpage

After a few face-to-face interviews with Michigan based logging firms, the issue of stumpage purchase was listed as a reason that stumpage purchase ought to be further considered when compensating loggers. Stumpage purchase is a very significant part of the total harvesting and supply cost incurred. As indicated by survey results the average percentage of operations that involve stumpage purchase are 70%. Whereas most of the respondents reported that in 100% of their operations they would purchase stumpage.

Percentage Delivery of Products to End Users

In order to understand the market requirements per different products removed during harvesting operations, the survey inquired about the end users that receive those products. The question required an overall 100% response to those percentages of delivery to end users. However, this was not always the case when the responses were summed up. To present valuable responses, data below shows all forms of responses. The first set describes the actual responses. And the second set removed all responses that did not add up to 100% and a 0 value was inserted in empty cell responses, from those responses that added up to 100%. Data trends between both normalized and real data were similar.

Table B2.16. *Actual Representation of Values of Percent Deliveries of Products to End Users*

Percentage of wood products supplied to	Mean	Number of respondents
Hardwood sawmill	26.76	173
Softwood sawmill	19.09	128
Veneer mill	8.91	111
Pulp mill	47.58	146
Other panel mill	13.59	54
Oriented strand board mill	23.11	66
Wood pellet fuel mill	5.51	35
Wood power generator	7.97	38
Truck/rail landing	15	50
Other location	33.78	40

The graph below presents percentages of products that were delivered to different facilities. Pulpwood and hardwood sawmills received the largest percentage of products totaling both almost 59% of the products generated from logging firms.

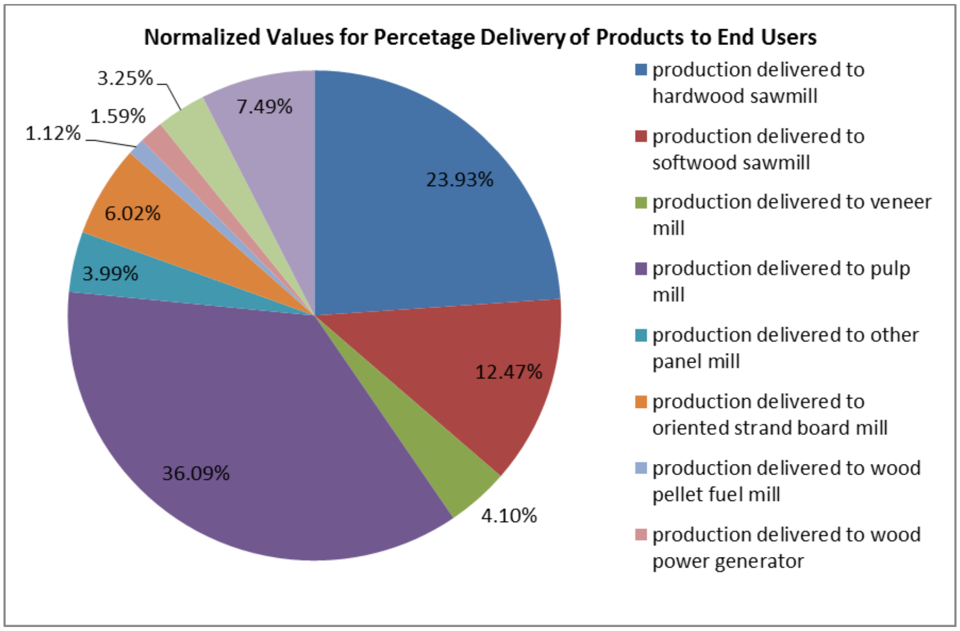

Figure B2.9. Percent of Deliveries to End Users

Truck Transportation Distances of Main Forest Products

Similar to the summary of harvesting equipment, the logging survey also asked for information about trucks used by respondents to transport biomass. Below in Table B2.17 and B2.18 we summarize some of the main characteristics of trucks owned by survey respondents. Truck data were analyzed with all reporting units. A separate analysis was conducted for the larger 10-11 axle log trucks and chip vans. Large log trucks had lower average fuel economy and larger annual usage than other trucks in the survey, but the distribution of annual mileage data for trucks varied considerably. Based on a question in the survey asking how much of the roundwood produced by each respondent was hauled by self-loading trucks (Table B2.18), we can infer that most log trucks in the state of MI are equipped with self-loaders. Over 70% of respondents (128 / 180) indicated that 100% of their roundwood production was transported with self-loading trucks.

Table B2.17. *State of MI Trucking Equipment Summary*

Year	Fuel Use (gallons/hour)	Miles/year
All trucks reported in FBSCC logger survey		
2000 ± 7	4.47 ± 1.79	54,940 ± 59,868
(156)	(148)	(150)
Large Log trucks (10-11 axles)		
2003 ± 6	3.66 ± 0.87	65,326 ± 39,276
(76)	(71)	(66)
Chip Vans		
1998 ± 7	4.19 ± 0.99	42,800 ± 28,357
(15)	(21)	(20)

Table B2.18*. Percentage of Roundwood Transported by Self-loading Trucks*

Responses	180
Average %	**86.0**
Standard deviation (%)	30.5
Responses that indicated 100%	128
Responses that indicated 0%	18

Forest products are delivered to a variety of end-users and intermediate supply chain points. Survey respondents were asked what percentage of their annual production was delivered to the different destinations listed in Table B2.19. Because not everyone responded to each destination, the average percentages in Table B2.19 do not sum to 100%, and represent the average percentage of those respondents who indicated that they delivered to the destination in question (respondents to each destination are indicated in the table as well). Pulp mills were the most popular destination for forest products in the state of Michigan. Hardwood sawmills were the most common destination, but only 27.7% of production volume went to these facilities.

Table B2.19*. Deliveries summary table*

Different destination	Responses	Percentage of production
Hardwood sawmill	148	27.7 ± 25.5
Softwood sawmill	110	19.8 ± 20.0
Veneer mill	88	8.1 ± 9.4
Pulp mill	124	49.6 ± 26.5
Particle board, med. density fiberboard	40	16.7 ± 17.9
Oriented strand board mill	44	25.8 ± 23.5
Wood pellet fuel mill	16	11.6 ± 22.2
Direct-fired wood power generator	22	12.4 ± 13.2
Truck or rail landing	36	16.9 ± 20.7
Other – mostly firewood	28	45.9 ± 40.6

[a] Numbers following ± represent standard deviations based on indicated number of responses

Transport distances for each of the three main forest products (sawlogs, pulpwood, chips) followed a similar pattern (Table B2.19, Figure B2.10). Respondents were asked to list what percentage of their annual production of sawlogs, pulpwood, and chips was transported by truck fir several mileage categories. Sawlogs were the product transported the smallest distance, as the average amount of sawlogs transported under 60 miles was over 55% as opposed to ~ 45% for the other two forest products. Wood chips were the product transported the longest distance, with over 27% of production traveling more than 90 miles by truck.

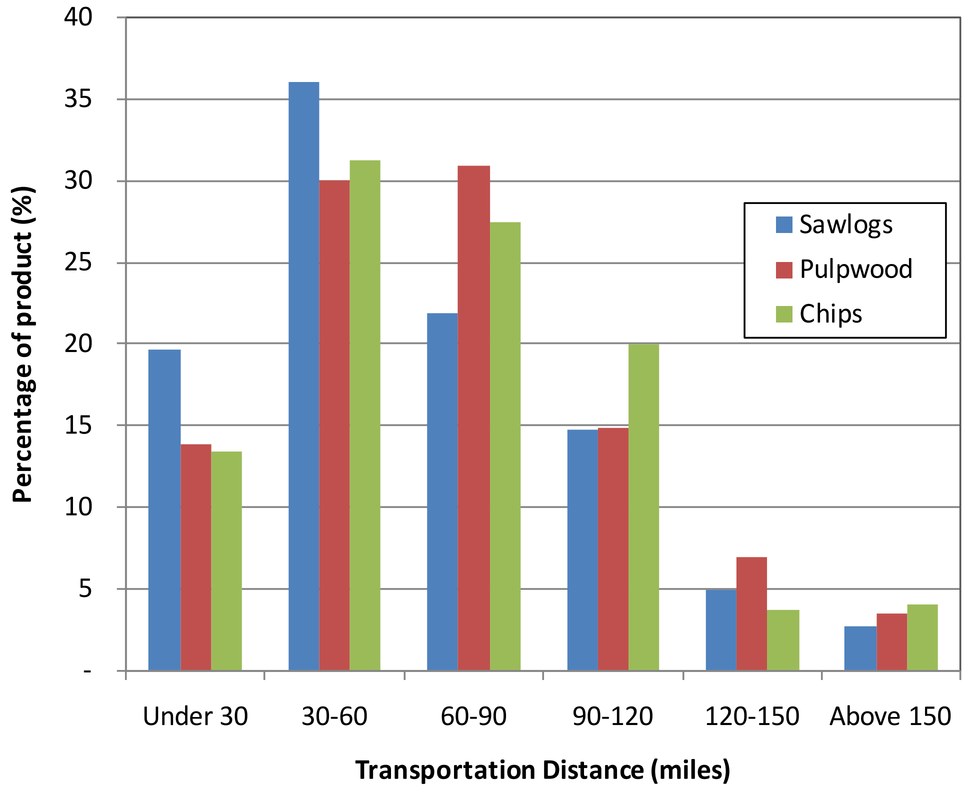

Figure B2.10. Reported Truck Transport Distances for Main Forest Products

Rail transportation

Rail transport is utilized unevenly throughout the state of MI for the transportation of forest products. In the 2010 survey respondents were asked about their most recent use of rail transportation, and over 60% of the respondents that answered the question indicated that they had never used rail transport (Table B2.20). We can also reasonably assume that a majority of the respondents who did not answer the question also did not regularly utilize rail transport. In a different survey question, respondents were asked what percentage of their annual production was moved using rail transport. The 28 respondents that indicated some portion of their production had been moved by rail (roughly 12.7% of responses) moved roughly 22.1% ± 19.2% of their annual production by rail, a significant amount. It should be noted that all of the respondents indicating a use of rail transport were based in the Upper Peninsula.

***Table B2.20**. Most recent use of Rail Transportation*

Time Frame	Responses	% of respondents
(1) In past 6 months	9	14.1
(2) In past year	2	3.1
(3) In past 3 years	3	4.7
(4) In past 5 years	4	6.3
(5) In past 10 years	5	7.8
(6) In past 15 years	2	3.1
(7) Not at all	39	60.9
( ) No response	46	--

a – data originated from 2010 respondents to FBSCC survey

When asked about the factors that limited their use of rail transport for moving forest products, survey respondents indicated that reliability of service and limited access in main work areas were the primary reasons that rail transport was not used more extensively (Table B2.21). Existing transport contracts and lack of knowledge about rail were the factors that limited use of rail transport the least among survey respondents.

***Table B2.21**. Reasons that rail use for forest products is limited in state of MI*
1= not limiting, 5 = extremely limiting

Lack of Knowledge Rail Contractual Arrangements	2.48
Reliability of Service	3.53
Speed of Delivery	3.39
Limited Rail Access in Main Work Areas	3.49
Prices Not Competitive With Other Modes	3.03
Minimum Shipment Too Large	2.49
Existing Contract with Other Provider	2.12

Significant Observations

Key observations from the study included

- Most logging firms in the state fall within the northern Upper Peninsula of Michigan and most firms are run by owner and operators of logging firms.
- Production capacities collected in this survey offered a unique level of analysis that would help make estimates of the productivity of harvesting operations.
- It was determined from the survey results that most operations were from partial cut treatments, especially within 30% selected cut types. This would need to be factored in decisions made to start industries based upon existing geographical locations within the state. In other words, it would not be prudent to assume that an entire area would be clear cut for the supply of an existing or new facility.
- Skidding distances reported have shown to what extent skidding is a significant cost factor in the delivery of biomass. Survey generated results helped in reaching calculations for harvesting supply logistics cost assessment in the next section.
- At the start of the project there was an overall understanding that industries were not working at full capacity. It turned out that a large number of respondents were operating at 100% capacity, but on average logging firms reported working over 70% of their operational capacity.

- The survey inquired about the terrain types. Most operations are within flat and rolling grounds, which is an important factor when determining where to deploy operations when identifying a location for a forest products facility.
- A significant finding in the study was that most operations do not involve residue removal or chipping of material.
- Another significant finding was that most products were extracted from other public lands whereas most products were delivered to pulp and paper industries. The age of harvesting and transportation equipment has helped describe the state of the harvesting technology in Michigan.
- Michigan loggers use a variety of logging equipment. Most commonly used systems were mechanical whole tree harvesting, cut-to-length harvesting, manual whole tree harvesting. Among the equipment owned, cut-to-length processors were the newest (average model year = 2003) with feller bunches being the oldest.
- Saw logs and pulpwood were the most common types of product removed from the forest while woodchips were the least. Consequently, pulp mills were the most common destination followed by hardwood sawmills, OSB mills, and softwood saw mills. Only a small number of loggers reported supplying woody material to pellet mills and wood power generators.
- Equipment data such as age, productivity, and fuel use were useful in completing the life cycle assessment for the forest biomass supply chain in Michigan.

ECONOMIC ANALYSIS OF HARVESTING LOGISTICS

Introduction

The primary goal of the project was to calculate cost of harvesting, extracting, and processing woody biomass for both natural forest and plantations using different harvesting systems that were commonly used in Michigan under conditions most prevalent within the State. To provide a frame of reference we assumed that the biomass would be used as feedstock to generate electrical power. It was also the objective of the study to evaluate which form of biomass upgrading would be most cost effective as biofuel feedstock. For example, round wood, woodchips, wood pellets, torrefied wood chips, or torrefied wood pellets from both natural forests as well energy plantations. This section covers the cost analysis of harvesting woody biomass from natural forests.

Methodology

There are two elements to calculating logging cost: 1) hourly operating cost of logging equipment; and 2) harvesting system cost.

<u>Hourly rate of logging equipment</u>: Machine hourly rate is expressed in \$/SMH, whereas SMH = scheduled machine hours. Machine hourly rate in \$/SMH can be converted to \$/PMH (PMH = productive machine hours) by multiplying machine utilization rate (PMH/SMH). Once cost in \$/PMH is determined, cost in \$/GT (GT=green ton) is determined by dividing this number by machine productivity (GT/hour). Machine productivity can either be determined by conducting time-and-motion studies or estimated using published data. Machine productivity is highly dependent of stock and stand tables for a given tract or plot and the type of harvesting operation i.e. partial cutting or clear cutting. In this report we used the available Forest Inventory Data (FIA) to estimate stock and stand data.

Machine hourly cost has three primary components:

1. Fixed (Owning) cost. This is the cost of owning the machine and includes depreciation, interest on investment and cost of taxes, insurance and housing of the machine. These costs are calculated as follows:
    a. $D = (P-S)/(N \cdot SMH)$, where
       D is Depreciation in \$/SMH
       P is Purchase price in \$
       S is Salvage value in \$
       N is Machine economic life in years
    b. $AAI = (P - S) \cdot (N + 1)/(2 N) + S$, where
       AAI is Average Annual Investment in \$
    c. $(Int + Ins + T) = \%\ rate \cdot AAI / SMH$, where
       Int + Ins + T is the total cost for interest, insurance, and tax in \$/SMH
2. Variable (Operating) cost. This cost is incurred when machine is operated and includes fuel and lube, tires and tracks, and repairs and maintenance. Fuel and lube cost depends on the rated fuel consumption of the machine and fuel and lube costs. Repair and maintenance cost can be estimated based on records if available or obtained from literature.
    a. Repairs and Maintenance (\$/PMH) = Depreciation x Repair and maintenance factor (%/Depreciation)
3. Labor. This cost includes hourly labor rate and labor fringe benefits (%) expressed in terms of \$/SMH.

<u>Harvesting system cost</u>: Once costs of each machine used in logging operation is determined in terms of \$/SMH it is possible to compute harvesting system cost expressed in terms of \$/GT. Harvesting system

cost depends upon the logging system used such as cut to length (CTL) or whole tree (WT) harvesting. The following are harvesting system cost components:

1. Felling. Cost of felling depends, in addition to the type of machine used to perform felling operation, upon the type of harvesting operation such as partial cutting (thinning) or clear cutting. It also depends on the type of forest i.e. hardwood, softwood or mixed and on tree size and stand density.
2. Skidding. This operation is necessary to bring cut trees to the landing site for loading onto trucks for hauling or for further processing such as chipping. The cost of skidding depends upon primarily skidding distance, terrain conditions, skid trail layout, and average turn volume.
3. Loading. This operation represents loading logs onto truck for hauling to their final destination. Please note that in this portion of the study hauling cost is computed elsewhere in the report under a separate section.
4. Move-in costs. This cost represents deployment of harvesting, forwarding, and processing equipment to the tract and depends upon tract size, moving time, and distance from home. It also depends on site preparation including roads to be built and to establish entrances. In this study we did not include any site preparation cost and assumed that all tracts were already prepared.
5. Support cost. This cost includes pickups, chain saws, foreman, and overhead. This cost is generally expressed as $/cord and then converted to $/GT.

Therefore, total harvesting cost is computed by adding all above costs in terms of $/GT.

To compute harvesting system costs we were interested in identifying a model that could be adapted to Michigan conditions and would allow cost calculations for the various equipment systems commonly used by Michigan loggers. A literature review was carried out to identify the best available model that would determine the cost of harvesting biomass from natural forests and plantations. The review was structured into two phases; the first offered a literature summary of abstracts that was organized into three categories: Modeling Fuel Reduction/Forest Harvesting, Timber Harvest Outputs/Supply Chain, and Economics/Market Impacts. The second phase was based on extensive discussions with national forest harvesting experts. The models that were of particular interest to the project were those that required customized inputs based on Michigan particular conditions. Three models were found. These are a Virginia Tech model (http://cnre.vt.edu/harvestingsystems/logcost9.html), a Auburn Harvesting Analyzer developed at Auburn University and modified by R. Visser (http://cnre.vt.edu/harvestingsystems/costing.htm#auburnharvester) and a Fuel Reduction Cost Simulator (FRCS) model developed by Bruce Hartsough and Dennis Dykstra. The VT and Auburn models require user to input all values whereas the FRCS model has many built-in default features. To use this model successfully it is critical that built-in features as well as input data flexibility allowed be clearly understood and input parameters for Michigan conditions be clearly determined. The logger's survey played an important role in our developing an understanding of the Michigan logging industry and in determining input parameters for cost calculations.

Based on the Logger's survey the most common systems used in Michigan are:

1. Whole tree system (WT) - Felling and skidding with and without chipping at landing
2. Cut to length (CTL) system - harvesting and forwarding with and without chipping at landing

The following tables list the assumptions made to compute machine costs (Table B2.22), machine hourly rate calculation intermediates (Table B2.23), and machine hourly rate calculation results (Table B2.24).

__Table B2.22:__ Machine cost assumptions and survey-based variables

	Small F-Buncher	Small Harvester	Small Skidder	Small Forwarder	Small Slasher
Purchase price as of Dec 02, P ($)	150,000	350,000	140,000	240,000	350,000
Machine power rating (hp)	150	120	120	110	120
Machine life (n, years)	5	5	5	5	5
Salvage value, S (% of P)	20	20	20	25	25
Utilization rate (%)	75 [a]	75 [a]	75 [a]	75 [a]	75 [a]
Repair and maintenance (% Depr)	100	100	100	100	100
Interest rate (%)	8	8	8	8	8
Insurance and taxes (%)	7	7	7	7	7
Fuel consumption rate (gal/hp-h)	0.026	0.029	0.028	0.025	0.022
Fuel cost per gallon ($/gal)	3.228	3.228	3.228	3.228	3.228
Lube and oil (% of fuel cost)	37%	37%	37%	37%	37%
Crew size (persons)	1	1	1	1	1
Crew wage ($/SMH)	19.43	19.43	19.43	19.43	19.43
Crew fringe rate (%)	40%	40%	40%	40%	40%
Scheduled machine hours (SMH/year)	1800 [a]	1800 [a]	1800 [a]	1800 [a]	1800 [a]

[a]: Survey-based variables.

__Table B2.23__: Machine hourly rate intermediate calculations

	Small F.-Buncher	Small Harvester	Small Skidder	Small Fowarder	Small Slasher
Salvage value (S, $)	30,000	70,000	28,000	60,000	70,000
Annual depreciation ($)	0 [a]	0 [a]	0 [a]	0 [a]	0 [a]
Average yearly investment	30,000	70,000	28,000	60,000	70,000
PMH	1350 [b]	1350 [b]	1350 [b]	1350 [b]	1350 [b]

[a]:When a piece of equipment is completely depreciated, the annual depreciation is 0.
[b]:Survey-based productive machine hours.

__Table B2.24__: Machine hourly rate calculation results

	Small F.-Buncher	Small Harvester	Small Skidder	Small Fowarder	Small Slasher
Owning costs:					
Interest cost ($/year)	2,400	5,600	2,240	3,840	5,600
Insurance and taxes($/year)	2,100	4,900	1,960	3,360	4,900
Yearly owning cost ($/year)	4,500	10,500	4,200	7,200	10,500
Owning cost per SMH ($/SMH)	2.50	5.83	2.33	4.00	5.83
Owning cost per PMH ($/PMH)	3.33	7.78	3.11	5.33	7.78
Operating costs:					
Fuel cost ($/PMH)	12.59	11.23	10.85	8.88	8.52
Lube cost ($/PMH)	4.66	4.16	4.01	3.28	3.15
Repair & maintenance cost ($/PMH)	17.78	41.48	16.59	28.44	41.48
Operating cost per PMH ($/PMH)	35.03	56.87	31.45	40.61	53.16
Labor costs:					

Labor ($/SMH)	19.43	19.43	19.43	19.43	19.43
Benefits ($/SMH)	7.77	7.77	7.77	7.77	7.77
Labor cost per SMH ($/SMH)	27.2	27.2	27.2	27.2	27.2
Machine hourly rate:					
Machine hourly rate in SMH ($/SMH)	55.97	75.69	53.12	61.66	72.90
Machine hourly rate in PMH ($/PMH)	74.63	100.92	70.83	82.21	97.20

Description of Michigan-based Plots used in the Analysis

FIA data were analyzed to establish plot conditions. Real Forest Inventory Analysis (FIA) database were integrated into regional forest plot values by Dr. Mike Vasievich to compute plot input data.

Total stands analyzed exceeded 10,000 plots from natural stands with soft and hardwood species. After removing data errors or plot data that could not be used due to missing information such as the size of trees, for example, about 2000 were over- and fully- stocked FIA plots. Aspen feedstock was differentiated from other species since it was assumed that aspen forest types would undergo clearcut treatments and all other forest types would undergo partial cut treatments. Tables below show plot data for non-Aspen data for clear cut harvesting treatment and for Aspen clear-cut treatment.

Table B2.25: *Non Aspen Stand Characteristics Using Partial Cut Treatments*

	Slope	Treatment area (ac)	Trees/ ac	ST residue fraction	ft^3/ tree	lb/ft^3	ST hardwood fraction
Mean	4.54	2002	238	0.20	9.74	58	0.56
Minimum	0.00	28.19	6.02	0.13	1.22	41.29	0.00
Maximum	40.00	6437	1062	0.35	77	84.37	1.82
No. of plots analyzed	1600	1600	1600	1600	1600	1600	1600

Table B2.26*. Aspen Stand Characteristics Using Clear Cut Treatments*

	Slope	Treatment area (ac)	Trees/ ac	ST residue fraction	ft^3/tree	lb/ft^3	Hardwood fraction
Mean	4.66	1910.12	158.8	0.25	6.39	57.9	0.89
Minimum	0.00	17.21	6.02	0.14	1.32	41.2	0.00
Maximum	37.00	4057.25	691.7	0.35	33.08	84.3	1.75
No. of plots analyzed	359	359	359	359	359	359	359

Average Statistical Analysis between stands to determine how stand characteristics inputs result in different harvesting costs between non-aspen and aspen plots. Non-aspen plots had larger trees on average. Aspen stands had lower number of trees per acre. The hardwood fraction contributes to a larger harvesting cost, and aspen stands have a higher portion of hardwoods.

Table B2.27*. Comparison between Non Aspen and Aspen Stand Characteristics*

	Trees/ac	Residue Fraction	ft3/Tree	lb/ft3	Hardwood Fraction	Slope
Non Aspen	238.67	0.20	9.74	57.63	0.56	4.54
Aspen	158.87	0.25	6.39	57.97	0.89	4.66

Harvesting System Productivity based on Logger's Survey. The following table includes harvesting system productivity data as determined from logger's survey.

Table B2.28*. Survey-based equipment configuration productivity (tons/hr. – based on the conversion of 1 cord/hr = 2.3tons/hr.)*

Treatment	Forest Type	Feller-Buncher – Skidder-Slasher	Harvester - Forwarder
30% Cut (Selective)	Natural Hardwoods	8.56	7.68
	Mixed Hardwood / Softwood	8.42	8.81
	Natural Softwoods	7.75	9.09
	Softwood Plantations	9.22	10.51
70% Cut (Selective)	Natural Hardwoods	10.90	9.41
	Mixed Hardwood / Softwood	10.65	10.37
	Natural Softwoods	11.55	10.72
	Softwood Plantations	12.40	11.43
Clear-cut	Natural Hardwoods	15.69	12.67
	Mixed Hardwood / Softwood	15.16	13.04
	Natural Softwoods	14.77	13.96
	Softwood Plantations	16.33	16.03

Results and Discussion

Survey-based production cost ($/ton)

Production cost for log products

Table B2.29 shows the production cost of log products in terms of $/ton as they are delivered to the landing in a WT harvesting system. Whole trees can be processed into log products with limbs and tops as by-products. Usually, limbs and tops will be either piled and burned or further ground or chipped up by a grinder or a chipper for biomass energy purpose.

Table B2.29*: Production cost ($/ton) for whole trees delivered at the landing using a WT harvesting system*

	Forest type	Felling	Skidding	Slashing	WT total
30% Cut	Natural Hardwoods	8.72	8.27	11.36	28.35

	Mixed Hardwood / Softwood	8.86	8.41	11.54	28.32
	Natural Softwoods	9.63	9.14	12.54	31.31
	Softwood Plantations	8.09	7.68	10.54	26.32
70% Cut	Natural Hardwoods	6.85	6.50	8.92	22.26
	Mixed Hardwood / Softwood	7.01	6.65	9.13	22.78
	Natural Softwoods	6.46	6.13	8.42	21.01
	Softwood Plantations	6.02	5.71	7.84	19.57
Clear-cut	Natural Hardwoods	4.76	4.51	6.20	15.47
	Mixed Hardwood / Softwood	4.92	4.67	6.41	16.01
	Natural Softwoods	5.05	4.80	6.58	16.43
	Softwood Plantations	4.57	4.34	5.95	14.86

In a CTL harvesting system, materials shuttled to the landing will be in the form of log length. When biomass is recovered in a CTL system, a separated forwarder trip would be required to transport limbs and tops from stump area to the landing. Table B2.30 shows the production cost of log products in $/ton as they are delivered to the landing in a CTL harvesting system.

Table B2.30: *Production cost ($/ton) for log products using a CTL harvesting system*

	Forest type	Harvesting	Forwarding	CTL total
30% Cut	Natural Hardwoods	13.14	9.60	22.74
	Mixed Hardwood / Softwood	11.46	9.76	21.22
	Natural Softwoods	11.10	10.61	21.71
	Softwood Plantations	9.60	8.92	18.52
70% Cut	Natural Hardwoods	10.72	7.54	18.27
	Mixed Hardwood / Softwood	9.73	7.72	17.45
	Natural Softwoods	9.41	7.12	16.53
	Softwood Plantations	8.83	6.63	15.46
Clear cut	Natural Hardwoods	7.97	5.24	13.20
	Mixed Hardwood / Softwood	7.74	5.42	13.16
	Natural Softwoods	7.23	5.57	12.80
	Softwood Plantations	6.30	5.03	11.33

Production cost for biomass products

In a whole tree harvesting system, if only limbs and tops of harvested trees are chipped or ground up to biomass product, limbs and tops are the by-products of felling and skidding for merchantable part (log products), the only cost that should be assigned to biomass products is the chipping or grinding cost.

The FRCS model uses 1600 SMH/year for a small chipper, we will adjust that to 1800 SMH / year to match the SMH for other machines. Therefore, the machine hourly rate was adjusted to 104.24 $/PMH. With this adjustment, the FRCS model predicted chipping cost is 4.37 $/ GT**.**

As a variety of a whole tree harvesting system, if a fraction of harvested whole trees (e.g. typically small-diameter trees) goes to a chipper or a grinder directly, or all harvested trees are chipped or ground up to biomass products, felling and skidding cost should be assigned to biomass products. At this time, felling and skidding costs of log products (if any) are equal to the felling and skidding cost of biomass products. Table B2.31 shows the production cost for biomass products in this harvesting system variety based on the existing felling, skidding and chipping calculations:

Table B2.31: *Production cost ($/ton) for biomass products using a WT harvesting system (whole-tree chipping)*

	Forest type	Felling	Skidding	Chipping	Total
30% Cut	Natural Hardwoods	8.72	8.27	4.37	21.36
	Mixed Hardwood / Softwood	8.86	8.41	4.37	21.65
	Natural Softwoods	9.63	9.14	4.37	23.14
	Softwood Plantations	8.09	7.68	4.37	20.15
70% Cut	Natural Hardwoods	6.85	6.50	4.37	17.71
	Mixed Hardwood / Softwood	7.01	6.65	4.37	18.03
	Natural Softwoods	6.46	6.13	4.37	16.96
	Softwood Plantations	6.02	5.71	4.37	16.10
Clear cut	Natural Hardwoods	4.76	4.51	4.37	13.64
	Mixed Hardwood / Softwood	4.92	4.67	4.37	13.96
	Natural Softwoods	5.05	4.80	4.37	14.22
	Softwood Plantations	4.57	4.34	4.37	13.28

In a CTL harvesting system, trees will be cut and processed in the stump area. In the circumstance when biomass is recovered, only forwarding cost and grinding/chipping cost should be assigned to the biomass products.

Our survey-based results included productivity for forwarding log products. This productivity cannot be used to estimate the cost of forwarding biomass products. A Michigan-based field study, conducted by Dr. Fei Pan in 2011, of forwarding biomass indicated that when using a medium-sized (14-ton loading capacity) forwarder to shuttle stump area biomassto landing with an average forwarding distance of 225 feet, the production rate was 34.56 GT/PMH. With a machine hourly rate of 82.21 $/PMH for forwarder (Table B2.24), the Michigan-based biomass forwarding cost will be 2.38$/GT. This is a low forwarding cost due to the fact that the machine has been completely depreciated, which results in a low machine hourly rate. In addition, the forwarding distance in this Michigan-based case is short compared with our survey-based average forwarding distance. This significantly shorten the operation cycle time and increase the productivity. With a FRCS model project chipping cost of 4.37 $/GT, the total cost for biomass products in a CTL harvesting will be 6.75$/GT.

FRCS Model simulation

Four scenarios were simulated in the FRCS model for harvesting cost projection. These scenarios include using a WT harvesting system and a CTL harvesting system to harvest non-Aspen and Aspen trees, respectively. Simulation results are summarized in Table B2.32. A comparison between survey-based production cost and FRCS model projected production cost (Table B2.33) showed that the FRCS model predicted values were significantly higher than survey-based results.

Table B2.32**:** FRCS model predicted production cost ($/ton) for various scenarios

	Non-Aspen trees, partial cut ($/GT)	**Aspen trees, clear cut ($/GT)**
Whole-tree harvesting system	29	32
Cut-to-length harvesting system	26	33

Table B2.33*: Production cost ($/GT) comparison between survey-based results and FRCS model predicted results.*

	Non – Aspen trees, partial cut		**Aspen trees, clear cut**	
	Survey-based cost ($/GT)	**FRCS predicted cost ($/GT)**	**Survey-based cost ($/GT)**	**FRCS predicted cost ($/GT)**
Whole-tree harvesting system	19.57 – 31.31	29	15.47	32
Cut-to-length harvesting system	15.46 - 22.74	26	13.20	33

Sensitivity analysis

Sensitivity analysis was performed to determine the effects of different variables on the production cost, while keeping all the other variables constant. Results comparisons and scatter plots showed how the production cost changed with the corresponding value changes in the tested variables, which included buying new machines, machine economic life, and diesel price.

<u>Effect of purchasing new equipment on production cost</u>

Table B2.34: Machine hourly rate calculations when purchasing **new** equipment (Assumptions in Table B2.22 applied)

	Small F.-Buncher	**Small Harvester**	**Small Skidder**	**Small Forwarder**	**Small Slasher**
Salvage value (S, $)	30,000	70,000	28,000	60,000	70,000
Annual depreciation ($)	24,000	56,000	22,400	38,400	56,000
Average yearly investment	102,000	238,000	95,200	163,200	238,000
PMH	1350	1350	1350	1350	1350
Owning costs:					
Interest cost ($/year)	8,160	19,040	7,616	13,056	19,040
Insurance and taxes($/year)	7,140	16,660	6,664	11,424	16,660
Yearly owning cost ($/year)	39,300	91,700	36,680	62,880	91,700
Owning cost per SMH ($/SMH)	21.83	50.94	20.38	34.93	50.94
Owning cost per PMH ($/PMH)	29.11	67.93	27.17	46.58	67.93
Operating costs:					
Fuel cost ($/PMH)	12.59	11.23	10.85	8.88	8.52
Lube cost ($/PMH)	4.66	4.16	4.01	3.28	3.15
Repair & maintenance cost ($/PMH)	17.78	41.48	16.59	28.44	41.48
Operating cost per PMH ($/PMH)	35.03	56.87	31.45	40.61	53.16
Labor costs:					
Labor ($/SMH)	19.43	19.43	19.43	19.43	19.43
Benefit ($/SMH)	7.77	7.77	7.77	7.77	7.77
Labor cost per SMH ($/SMH)	27.2	27.2	27.2	27.2	27.2
Machine hourly rate:					
Machine hourly rate in SMH ($/SMH)	75.30	120.80	71.17	92.59	118.01
Machine hourly rate in PMH ($/PMH)	100.41	161.07	94.89	123.45	157.35

Using the existing survey-based equipment productivity, the harvesting production costs were summarized in the following Tables B2.35 and B2.36 for WT and CTL systems, respectively. Production cost comparison in Table B2.37 shows that with the use of completely depreciated equipment the production cost can be reduced significantly. Results in Table B2.37 also indicated that when performing a 30% partial cut, the use of depreciated machine has the strongest effect on production cost reduction, because the production rate in the prescription of 30% partial cut is the lowest, which amplify the effect of using depreciated machine on production cost.

Table B2.35*: Production cost ($/GT) of a WT system when purchasing* ***new*** *equipment*

	Forest type	**Felling**	**Skidding**	**Slashing**	**WT total**
30% Cut	Natural Hardwoods	11.73	11.09	18.38	41.20
	Mixed Hardwood / Softwood	11.93	11.27	18.69	41.88
	Natural Softwoods	12.96	12.24	20.30	45.50

	Softwood Plantations	10.89	10.29	17.07	38.25
70% Cut	Natural Hardwoods	9.21	8.71	14.44	32.35
	Mixed Hardwood / Softwood	9.43	8.91	14.77	33.11
	Natural Softwoods	8.69	8.22	13.62	30.53
	Softwood Plantations	8.10	7.65	12.69	28.44
Clear-cut	Natural Hardwoods	6.40	6.05	10.03	22.48
	Mixed Hardwood / Softwood	6.62	6.26	10.38	23.26
	Natural Softwoods	6.80	6.42	10.65	23.88
	Softwood Plantations	6.15	5.80	9.64	21.60

***Table B2.36**: Production cost ($/GT) of a CTL system when purchasing **new** equipment*

	Forest type	Harvesting	Forwarding	CTL total
30% Cut	Natural Hardwoods	20.97	14.42	35.39
	Mixed Hardwood / Softwood	18.28	14.66	32.94
	Natural Softwoods	17.72	15.93	33.65
	Softwood Plantations	15.33	13.39	28.71
70% Cut	Natural Hardwoods	17.12	11.33	28.44
	Mixed Hardwood / Softwood	15.53	11.59	27.12
	Natural Softwoods	15.03	10.69	25.71
	Softwood Plantations	14.09	9.96	24.05
Clear cut	Natural Hardwoods	12.71	7.87	20.58
	Mixed Hardwood / Softwood	12.35	8.14	20.50
	Natural Softwoods	11.54	8.36	19.90
	Softwood Plantations	10.05	7.56	17.61

***Table B2.37:** Production cost ($/GT) comparison between using new and depreciated equipment*

	Forest type	WT total		CTL total	
		New machine	Depreciated machine	New machine	Depreciated machine
30% Cut	Natural Hardwoods	41.20	28.35	35.39	22.74
	Mixed Hardwood / Softwood	41.88	28.32	32.94	21.22
	Natural Softwoods	45.50	31.31	33.65	21.71
	Softwood Plantations	38.25	26.32	28.71	18.52
70% Cut	Natural Hardwoods	32.35	22.26	28.44	18.27
	Mixed Hardwood / Softwood	33.11	22.78	27.12	17.45
	Natural Softwoods	30.53	21.01	25.71	16.53
	Softwood Plantations	28.44	19.57	24.05	15.46
Clear	Natural Hardwoods	22.48	15.47	20.58	13.20

cut				
Mixed Hardwood / Softwood	23.26	16.01	20.50	13.16
Natural Softwoods	23.88	16.43	19.90	12.80
Softwood Plantations	21.60	14.86	17.61	11.33

Effect of machine economic life on production cost

To test the effect of machine economic life on production cost, the scenario of 70% partial cut of mixed hardwood/softwood using a CTL harvesting system was used, as this is determined to be the most representative forest type and harvesting system used currently in the State of Michigan. The production cost change by adjusting machine economic life in the other scenarios has been tested to follow the similar pattern shown in Table B2.38.

Sensitivity analysis showed that with an increase of machine economic life, machine hourly rate will decrease, resulting in a final production cost reduction. Results in Figure B2.11 also shows that the change of production cost has an exponential trend, indicating that with the increase of machine economic life, the production cost will be less sensitive to the machine economic life. This strengthens the importance of machine maintenance work at the beginning stage of its life when machine life has a stronger effect on production cost.

Table B2.38*: Production cost ($/GT) and machine hourly rate ($/PMH) change of a CTL harvesting system when applying different machine economic life (Years)*

Machine economic life (Years)	Harvester hourly rate ($/PMH)	Forwarder hourly rate ($/PMH)	Total production cost ($/GT)
4	111.29	89.32	19.12
5	100.92	82.21	17.45
6	94.00	77.47	16.34
7	89.07	74.08	15.55
8	85.36	71.54	14.95

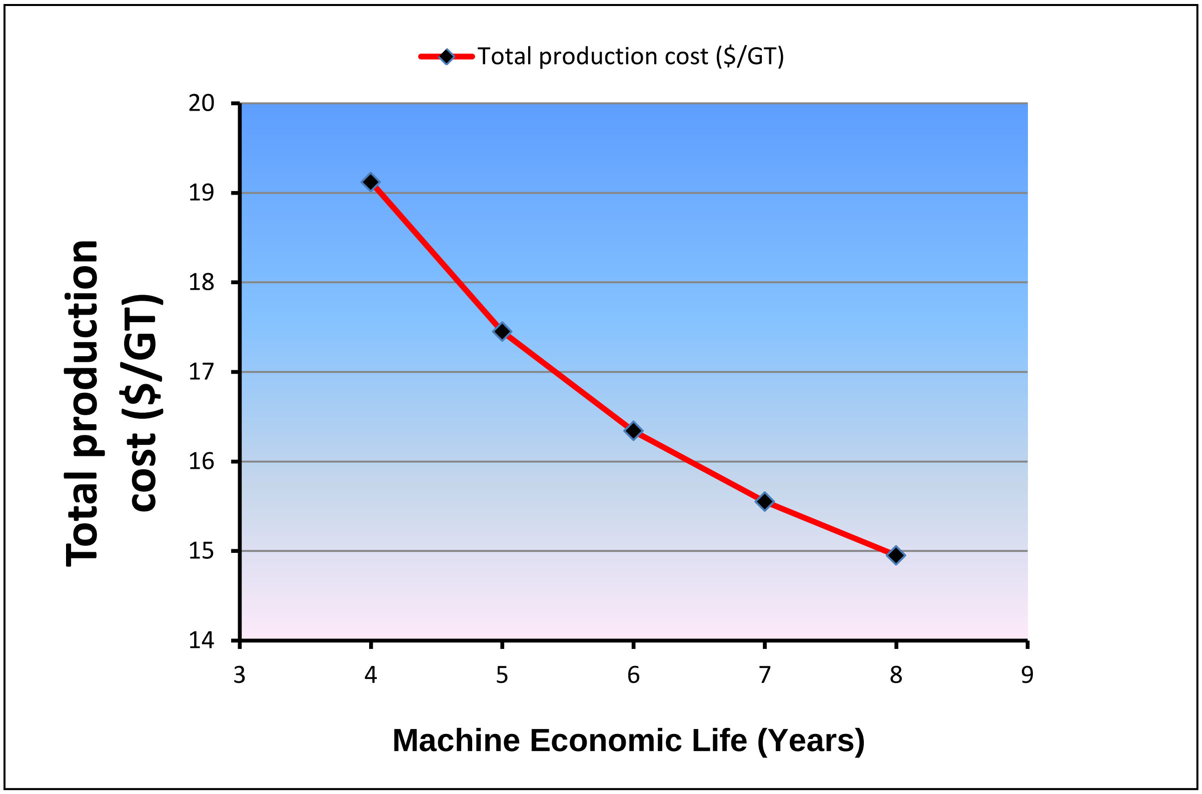

Figure B2.11: Effect of machine economic life (years) on total production cost ($/GT)

Effect of diesel price on production cost

Diesel price is the most concerned factor during harvesting operations, as once the harvesting equipment is purchased and harvesting site is laid out, the daily fluctuated diesel price becomes the most variable part for the harvesting cost control. Diesel price will affect machine operating cost, which will be reflected in the production cost. To test the effect of diesel price on production cost, the scenario of 70% partial cut of mixed hardwood/softwood using a CTL harvesting system was used again. Results in Table B2.39 shows that with an 1$/gal diesel price increase, the production cost will increase by 0.81 $/GT. Figure B2.12 shows a straight line in production cost change, indicating the effect of diesel price on production cost is constant, at some point when diesel price is high enough, the total production cost will be inflated to a level that would make the entire operation cost prohibitive.

Table B2.39*: Production cost ($/GT) and machine hourly rate ($/PMH) change of a CTL harvesting system when applying different diesel price ($/Gal)*

Diesel price ($/Gal)	Harvester hourly rate ($/PMH)	Forwarder hourly rate ($/PMH)	Total production cost ($/GT)
2.00	95.06	77.58	16.45
3.00	99.83	81.35	17.27
4.00	104.60	85.12	18.08
5.00	109.37	88.89	18.89

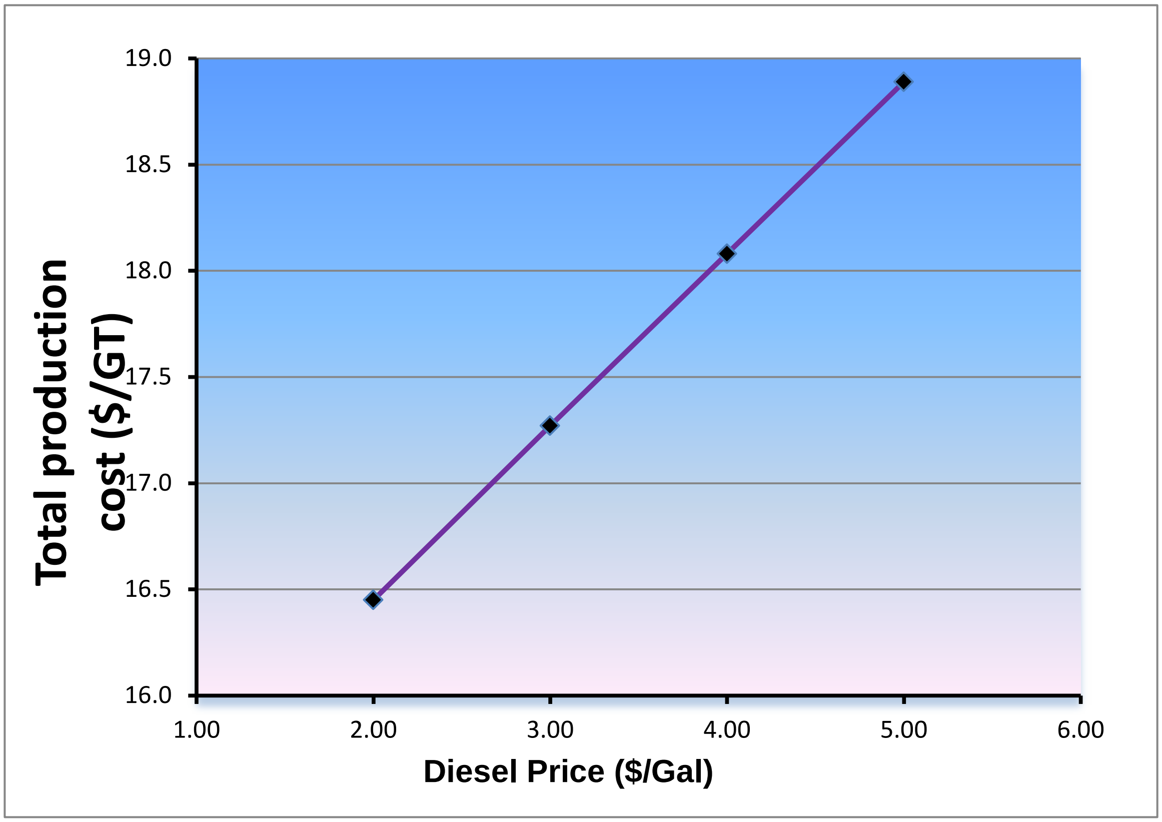

Figure B2.12: Effect of diesel price ($/Gal) on total production cost ($/GT)

Assumptions used in cost calculation

Most machine hourly cost calculation assumptions used in this report are obtained from literature (Miyata, 1980) and has been used in the FRCS model as defaults. In realistic production cost calculation, however, all the assumptions need to be verified to be reasonable. For example, the repair and maintenance cost used in the machine hourly cost calculation was assumed at 100% of yearly depreciation. When a piece of equipment is completely depreciated, it is heavily biased by the assumption that the yearly repair and maintenance cost is still 100% of yearly depreciation when this particular machine was new. Personal contact with logging contractors indicate that even when machines are completely depreciated, the repair and maintenance costs are far less than 100% of yearly depreciation. For example, the yearly repair and maintenance cost for a completely depreciated, 6 year old forwarder is around 7,000 $/year, which is less than 20% of its yearly depreciation. The decrease in repair and maintenance cost will finally lead to a reduction in production cost. Since our survey did not request this information from loggers, we kept the repair and maintenance cost at the standard level.

FRCS model predictions

Harvesting production cost comparison between our survey-based results and FRCS model predicted values showed that FRCS model always has a higher production cost. FRCS model is a forest harvesting and processing cost projection model originally developed in western United States. It has been recently updated by adding location variants to make it work for the northern states, including Michigan. However, FRCS model still has limitations For example, when simulating a WT harvesting system in Michigan, the FRCS model relevance weights information indicated that the model used nine past studies in California hardwood plantations and southern pine plantations for production cost prediction, partially because harvesting production cost information was not well documented for Michigan although the state has a long history of logging activities. The significant difference in site and terrain conditions between Michigan and other regions suggests high risks in such model predictions, especially when western mountainous areas are usually associated with higher harvesting costs.

The task of analyzing the cost of large-scale forest harvesting operations is not straightforward and is not quite involved. The nature of forest stands in terms of stand conditions and different operating technologies and logistics results in a diverse set of cost values when compared to harvesting plantation. To attempt to address this issue, the project utilized the existing Fuel Reduction Cost Simulator (FRCS) model developed by the USDA Forest Service. Model-run results employed overstocked and fully stocked stands that were harvested using partial cut for all non-aspen stands, and clearcut for all aspen stands. The results understandably were spread out. The survey results were used in an attempt to make comparisons with the FRCS results. Productivity per configuration reported in the survey was converted to units of tons per hour. Using the costing method of the FRCS model for whole tree harvesting, cut to length harvesting and manual harvesting, 43 unique values for the cost of a harvested green ton of biomass were calculated. This is an indication of the non-fixed nature of harvesting under natural stand conditions—no one size fits all. This issue was less of a concern with harvesting plantations. Plantations offer a fixed yield/year/acre that is calculated to reach harvesting cost. Variables in models are less complicated than natural stands variables. Plantation-based models use fixed input values of the number of trees per acre, spacing between stems, rotation age and production per year. Under site-specific conditions in plantations and natural forest stands there is no cheaper or more expensive option, however, plantations do offer a more steady cost analysis option. Natural stands need to be analyzed on a site-specific basis to compare with a plantation productivity cost assessment.

BIOMASS PROCESSING TECHNOLOGIES FOR BIOFUELS/BIOENERGY PRODUCTION

Introduction

In addition to comparing harvesting and handling systems for delivering woody biomass, alternative preprocessing technologies were compared to identify potential bioenergy supply chains for electrical power generation. Comparisons were made by determining the cost of electricity generation at a 100 MWe power plant in which wood chips, wood pellets, or torrefied wood pellets were co-fired with coal. In accordance with Michigan Public Act 295, ten percent of the electrical power produced in our model scenarios was assumed to be provided by renewable energy. The specific preprocessing technologies considered for bioenergy production included chipping, pelletization and torrefaction with pelletization. Chipping and pelletization create a material that is more easily transportable than forest slash and small diameter plantation trees, while torrefaction produces a mildly carbonized wood product with several desirable characteristics. In the systems analyzed, preprocessing was assumed to occur at either the roadside or in Regional Biomass Preprocessing Depots (RBPDs) that are located near to harvest regions because densification is central to reducing transportation costs. Finally, combinations of these technologies were compared to determine the bioenergy systems that are most appropriate for the range of site conditions within the State of Michigan.

Torrefaction is a preprocessing technology that upgrades woody biomass to a form with desirable physical and chemical properties. In torrefaction, heat is added in the absence of oxygen to perform a mild pyrolysis of the structural components of biomass. Operating conditions include temperatures ranging from 200°C to 400°C and residence times from 5 to 60 minutes, depending upon feedstock quality and the product mix required. Typical values for many applications are expected to be 250-280C for 8-10 minutes. Generally, 70% of the starting mass is retained in the torrefied wood and this product contains 90% of the energy because a large amount of oxygen is liberated as water and carbon oxides in the product gas.[4] Heat required by the torrefaction reactor can be supplied by combusting this gas in air with the addition of small amounts of natural gas, though autothermal operation can be achieved if sufficient gas is produced during torrefaction. Torrefaction has been investigated by the Energy Center for the Netherlands (Bergman 2005a) and Agri-tech Producers, LLC (2011) for the purpose of determining technical and economic feasibility. The analysis contained herein serves to provide guidance for the deployment of the selected technologies under Michigan-specific site conditions.

Three bioenergy systems are compared in this analysis. Different preprocessing technologies are used by each system to upgrade woody biomass; the scenarios include: 1) “Wood Chips” for direct co-firing at the power plant, 2) “Wood Pellets” with pelletization at RBPDs, and 3) “Torrefied Wood Pellets” with torrefaction and pelletization occurring at RBPDs. The bioenergy systems for creating electricity from each scenario are depicted in Table B2.41.

The bulk properties of wood chips, torrefied wood chips, wood pellets, and torrefied pellets are included in Table B2.40. The heating value per weight of torrefied materials is greater than wood chips because of the carbonization that has occurred during torrefaction. Wood pellets have a larger lower heating value (LHV) because much of the water has been removed by drying before pelletization. Moisture contents are lower for torrefied and pelletized products as is expected for these processes due to conventional drying operations and heat addition during torrefaction. Finally, the density of the pelletized materials, torrefied and otherwise, was provided by information available in the literature (Bergman 2005b; Suurs, R. 2002; Wu, M.R. et al. 2011; Prins, M.J. et al. 2006).

Table B2.40. Properties of "wood chips," "torrefied wood chips," "wood pellets" and "torrefied pellets". Torrefied wood chips have low bulk density and are not analyzed as a separate scenario.

		Chips (dried on-site)	**Torrefied Chips**	**Pellets**	**Torrefied Pellets**
LHV (as received)	GJ/t	12	21	16.7	21
Moisture	%	20%	3%	8%	3%
Density	tonne/m^3	0.2-0.5	0.23	0.60	0.80

The aim of this analysis is to identify the optimum system for electricity production from woody biomass grown in Michigan. Several densification systems are compared using feedstocks from poplar plantations, willow plantations, and natural stands. Chipping is an existing technology and its deployment is well understood. Though wood chips can be co-fired with coal, the costs of transporting wood chips, additional grinding, and costs associated with storage instability pose barriers to coal displacement. To reduce the cost of delivering biomass, densification by pelletization is deployed at RBPDs situated near to biomass harvesting areas. Increasing the bulk density of the feedstock reduces the number of trucks needed for hauling biomass to the power plant, and hence the total transportation cost. Though the bulk and energy density are increased by pelletization, the reduced transportation cost must offset the cost of capital to justify this approach. Furthermore, pelletization neither addresses the storage instability due to on-site wood decomposition nor the friability standards desired at co-fired power plants. These limitations can be overcome by RBPDs that include torrefaction followed by pelletization. Torrefaction creates a friable, hydrophobic solid with a larger heating value than wood chips or wood pellets. As such, torrefied wood pellets are considered drop-in fuels because they have physical and chemical properties that are similar to coal. Specifically, we aim to determine the circumstances that justify the expenditure of capital to purchase equipment for torrefying and pelletizing woody biomass as well as establish the parameters that encompass optimal deployment of capital equipment at RBPDs compared with investment at power plants.

RBPD Process Description

Drying

Fresh wood chips can have a moisture content exceeding 50% by weight. In order to reduce the costs of transportation and drying, harvested trees were dried on-site before chipping. It was assumed in this analysis that on-site drying for a period of eight months lowered the moisture content of biomass from 50% to 20%. As 20% moisture is still too wet for the RBPD to convert the wood chips to solid fuel, the wood chips were dried using a tube bundle dryer. For the torrefied wood pellets, the drying cost can be reduced due to the replacement of natural gas using torrefaction gases. These off-gases from biomass during torrefaction consist of a wide variety of combustible organic components[1] which can provide the heat needed for drying. As a result of drying, the cost of subsequent transportation is reduced as undesired moisture is no longer carried to the power plant.

Pelletization

Biomass pelletization is a process for reducing the bulk volume of the material by mechanical means to produce cylindrical pellets of compressed biomass. Due to smaller volume and higher volumetric energy density, wood pellets are easier to handle, transport and store compared to wood chips. The production of pellets requires small feedstock particles with a maximum characteristic length of 3–20mm and a moisture content below 10%-15% (Repellin, V. et al., 2010). A ring die pelletizer is used in this analysis as discussed by Thek et al. (2004). For this type of pelletizer, die replacement is a significant cost because of abrasion of metal surfaces.

Grinding

Hammer mills were selected to grind biomass prior to pelletization. Because torrefaction increases the friability of woody biomass, the scenario 3 (torrefied wood pellets) grinding cost was reduced greatly. Increased friability as a result of torrefaction has been documented to save up to 90% of the energy used for grinding (Repellin, V. et al., 2010).

Torrefaction

Torrefaction is a pretreatment technology that involves heating biomass to temperatures between 200°C and 400°C in the absence of oxygen to improve its heating value and storage stability. Transportation costs are reduced for torrefied wood pellets as the heating values approaches 21 MJ/kg which is greater than wood chips or wood pellets. Torrefaction and pelletization are typically performed in sequence to produce a densified, torrefied product (Bergman, 2005a) that can be transported large distances by rail, ship or truck. Storage losses are also minimized by torrefaction as torrefied wood resists the microbial decomposition that effects wood chips and wood pellets. The application of torrefaction at power plants to improve friability prior to size reduction was not considered by this analysis, but may also merit examination in future assessments.

Storage

In order to maintain continuous operation at RBPDs, the on-site storage capacity was assumed to be 8% of the annual production rate (Thek et al., 2004). As wood chips are more susceptible to microbial degradation during open storage, enclosed storage units are required. Silos are the most widely used storage units for the wood chips, and investment costs typically range from $500,000 to $900,000. According to Surrs et al., 2002, the storage cost of silos is equal to $13.5/m^3$.

Storage units are also needed at the power plant and will differ according to the various products. While wood chips and wood pellets require an enclosed system, torrefied wood pellets can be stored outdoors. Furthermore, because of the low energy density of wood chips, more wood chips have to be stored at the power plant in order to provide enough feedstock to continuously operate the boiler.

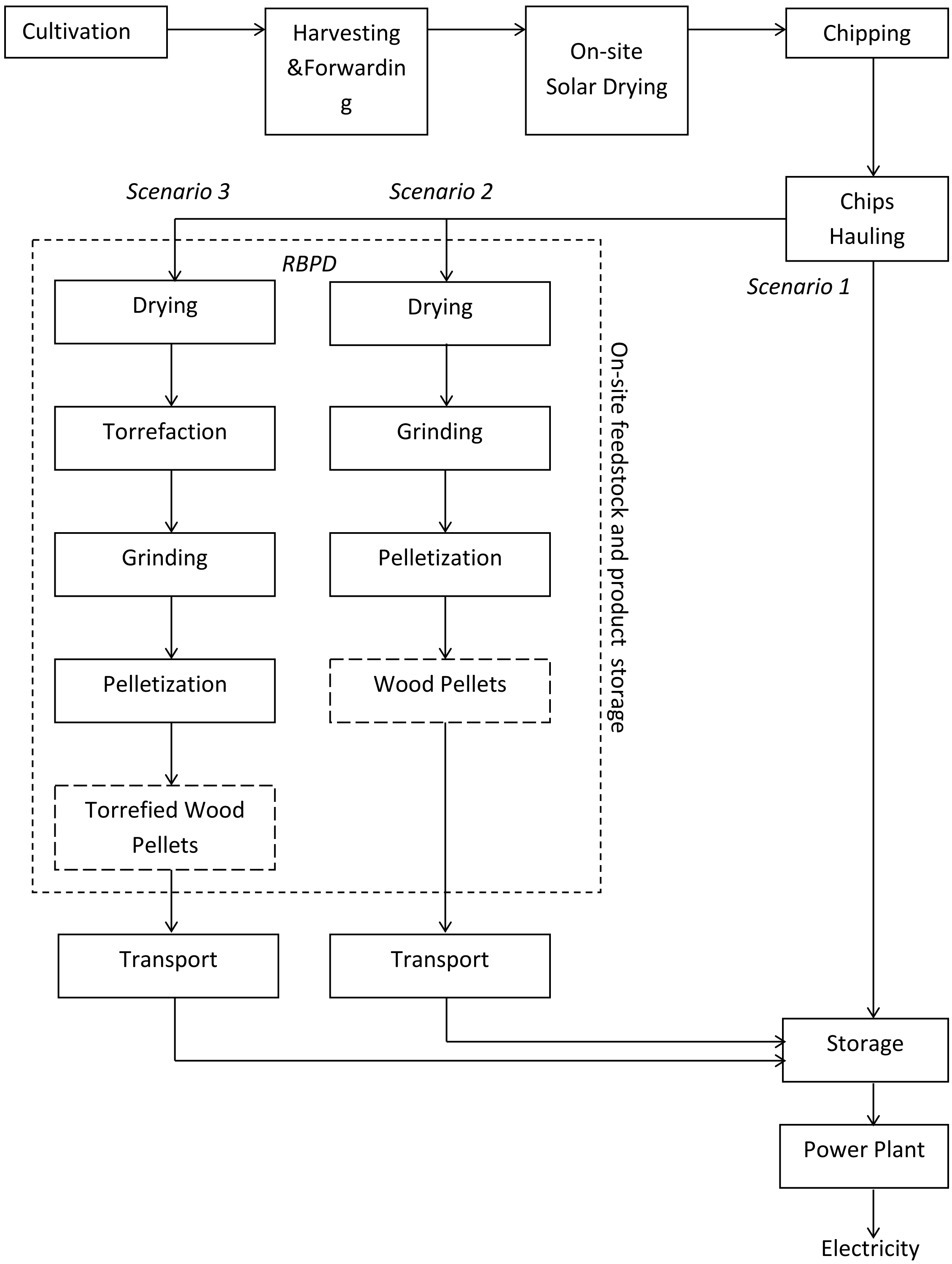

Figure B2.13. A depiction of the three systems being compared. 1) "Wood Chips" for direct co-firing at the power plant, 2) "Wood Pellets" with pelletization at RBPDs, and 3) "Torrefied Wood Pellets" with torrefaction and pelletization occurring at RBPDs.

Methodology

Select most Appropriate HFP Models for Michigan

Michigan provides suitable growing conditions for cultivating poplar and willow in energy plantations. After surveying the existing plantation models for estimating the "farm-gate" costs of harvested biomass, the EcoWillow model (v. 1.0) developed at the State University of New York (SUNY) (Tharakan, P.J. et al., 2005) and a model for poplar plantations developed at Oak Ridge National Laboratory (ORNL) were adopted and adapted for our analyses.

The SUNY model was first released in April 2008 for describing willow plantations. It is based on over 20 years of research on shrub willow as a dedicated energy crop in upstate New York. This model was used to estimate the costs of site preparation, cultivation, harvesting, and chipping. Though capable of estimating transportation, this component of the SUNY model was removed so that the costs of willow can be directly compared to the costs of biomass predicted by the ORNL and FRCS models, which do not include transportation. The model inputs to the SUNY model reflect those that can be expected of Michigan site conditions. Examples of model inputs are shown in Table B2.41. These inputs are subjected to either three or four year rotations (an option of the SUNY model) to estimate the farm-gate costs for a specified investment time frame

Table B2.41. SUNY model inputs for cultivating shrub willow under Michigan-specific site conditions.

Model Inputs	Units	Value
Project life	yrs	22
Land costs (tax, lease and insurance)	$/acre/yr	32
Headlands	% of acreage	8%
Annual harvest yield	dry ton/acre/yr	5
Planting density	cuttings/acre	5,800
Planting stock	$/cutting	0.12
Harvester speed	mi/hr	4

The ORNL model estimates the cost of harvesting poplar grown in plantations. Rotation timeframes of six and twelve years can be temporally modeled and tree spacing of 6 ft x 6 ft and 10 ft x 10 ft can be spatially modeled. The model was modified to reflect Michigan site conditions which dictate an 8 ft x 8 ft spacing (681 trees per acre) and a six year rotation (MSU Extension, 2011). Examples of model inputs are shown in Table B2.42.

Table B2.42. ORNL model inputs for growing poplar under Michigan-specific site conditions.

Model Inputs	Units	Value
Land costs (tax, lease and insurance)	$/acre/yr	32
Annual harvest yield	dry ton/ac/yr	6
Price/cutting	$/tree	0.10
Planting price/cutting	$/tree	0.05
Spacing (6 yrs rotation)	ft^2	64
Planting density (6 yrs rotation)	trees/acre	681
Spacing (12 yrs rotation)	ft^2	100
Planting density (12 yrs rotation)	trees/acre	436

Specific manufacturers of harvesting equipment were not specified in the SUNY model. Harvesting parameters that served as SUNY model inputs are displayed in Table B2.43. Conventional harvesting systems are employed by the ORNL model and the input parameters are included in Table B2.44. After drying, chipping was performed on-site prior to hauling 20 miles to the RBPD or in the case of wood chips, 20 miles plus the specified transportation distance to the power station. The cost of chipping for all scenarios is included in Table B2.44. Again, all inputs are based on Michigan site conditions.

Table B2.43. Harvesting inputs for the SUNY model.

Parameters	Units	Value
Number of harvesters		1
Transport harvester	$/mile	11
Distance	mile	50
Harvester rental	$/hr/unit	180
Harvester fuel consumption	gal/hr	16
Trailer-tractor rental	$/hr/unit	60
Trailer-tractor fuel consumption	gal/hr	2.6
Blower-tractor unit rental	$/hr/unit	50
Blower-tractor fuel consumption	l/hr	5
Maintenance	$/acre	5

Table B2.44. Harvesting inputs for the ORNL model including chipping parameters.

Equipment	Purchase Price ($)	Salvage Value ($)	Service Life (yr)	Annual Use (hrs)	Fuel use (gal/hr)
Feller-buncher head	35,000	4,353	4	1,000	0.00
100 HP tractor	40,100	6,262	12	833	4.94
Skidder-120 HP	130,000	26,713	5	2,000	3.50
Chipper-400 HP	175,000	20,437	5	2,000	9.17
Pickup truck	18,400	3,312	10	2,000	2.25

Select Feasible Processing Technologies

Biomass processing includes such unit operations as size reduction by chipping or grinding, densification by pelletization or briquetting, and feedstock upgrading by torrefaction. Alone or in combination, these processing steps are used to produce a feedstock for blending with coal at power plants. Three scenarios were considered in this study: 1) chipping in the field and direct transport to the power plant (denoted as the "wood chips" scenario), 2) chipping in the field followed by pelletization at a RBPD and transport to a power plant ("wood pellets"), and 3) chipping in the field, followed by torrefaction, milling, and pelletization at a RBPD and then transport to a power plant ("torrefied wood pellets"). As each power plant feedstock has a different heating value (as received) when combusted, comparisons are made by computing the cost contribution of each scenario to the electrical power cost, expressed in units of dollars per kilowatt-hour ($/kWh). All three scenarios are scaled to provide sufficient raw material to provide 10% renewable electricity at a 100 MWe power plant. Therefore, each scenario was solved in reverse, starting with the amount of electrical power produced in one year, followed by determining the required mass flow rate of power plant feedstock, the mass flow rate to the RBPD, and finally the amount of biomass harvested. Once the amount of harvested biomass was determined, the area of harvest was calculated assuming that only 20% of the surrounding area was available for harvest.

The costs for each scenario were determined by constructing cost models using standard engineering practice. Costs of capital and operation for each unit operation were included in the model. Feedstock costs, the largest single cost at the RBPDs, were estimated using the FRCS model for natural stands, the SUNY model for willow plantations, and the ORNL model for poplar plantations. Chipping cost information was provided by Surrs, R. (2002) while the cost of pelletization was determined by Thek et al. (2004). Torrefaction costs were estimated using the reports provided on-line by Agri-tech Producers, LLC. Models were constructed in Microsoft Excel such that key process parameters, feedstock properties and product properties can be varied to examine the sensitivity of cost to varying inputs.

Analyze Economies of Scale for Regional Processing Technologies

The effect of processing capacity on the scale of capital investment was included in this analysis using the sixth tenths rule. The sixth-tenths rule is widely accepted as appropriate for scaling capital investment and involves the use of a power law model to relate the ratio of capital investment costs (large divided by small) to the ratio of processing capacities (large divided by small) to the six-tenths power. Capital equipment costs obtained from academic literature, on-line sources, reference libraries, and vendors were scaled in this fashion to accurately compute the capital investment at the scale needed to deliver sufficient power plant feedstock to produce 10 MWe (10% of 100 MWe).

Conduct Sensitivity Analyses for HFP Systems under Consideration

A sensitivity analysis of willow plantations was performed using the SUNY model. A base case scenario using a four year rotation cycle was selected because of favorable cost. This base case scenario was simulated for a plantation area of 20 acres, a biomass yield equal to 5 dt/acre/yr, and a land cost of $32/acre. As land costs range from $14/acre to $50/acre in Michigan according to Dr. Ray Miller (2011) (Director of the Forest Biomass Innovation Center), land cost in the SUNY model was varied within this range to predict costs. Yield was also selected due to its anticipated effect on biomass cost. Willow yields in Michigan's Upper Peninsula range from 3 dt/acre/yr to 5 dt/acre/yr, while yields in the Lower Peninsula can approach 7 dt/acre/yr. Harvest yields were varied within the range of 3 to 7 dt/acre/yr to determine the impact on cost. In addition to varying land cost, diesel price and harvest yield, the cost of labor was varied. The costs of four laborers and one foreman were projected to determine total costs of willow at the farm gate.

A similar sensitivity analysis was performed on poplar plantations using the ORNL model. A six year rotation cycle was selected because of favorable economics versus twelve year rotations. The base case scenario included a tree spacing of 8 ft × 8 ft, a biomass yield 6 dt/acre/yr, and the land cost of $32/ acre. Land cost, harvest yield, diesel price and labor rate were varied in the same manner as for willow to reflect the variability to be expected in Michigan.

A sensitivity analysis was also performed for the third bioenergy scenario involving torrefaction and pelletization at RBPDs. A plot of torrefied pellet cost per gigajoule ($/GJ) versus the change in each selected variable in an amount relative to the base case (in %) was constructed to identify the variables most affecting the cost of power plant feedstock. Biomass price at the gate of the RBPD was included because of its anticipated impact on torrefied pellet cost. Electricity usage at the RBPD is a major cost when grinding and pelletization equipment are included at the RBPDs, so electricity consumption is varied accordingly. Service life was examined because the torrefaction reactor, grinding mills, and pelletizers involve moving metal parts that are subject to abrasion and corrosion. Transport distance to the power plant is included as a variable as transportation by truck impacts biomass cost. Finally, the cost of labor was varied to determine whether a refinement of the labor analysis is justified to improve the model's accuracy. The results of the sensitivity analysis for the RBPD producing torrefied pellets are applicable to the wood chips and wood pellets scenarios as these scenarios comprise a subset of the torrefied pellet scenario.

Compare Alternative Scenarios

Power generation from wood chips, wood pellets and torrefied wood pellets were compared to determine the best application of each technology sequence in the State of Michigan. The aim of this comparison is to determine the conditions for which each scenario is favored. This comparison anticipates that long-distance trucking will favor scenarios two and three which involve pelletization and the magnitude of this distance is to be determined through analysis. The cost of each scenario is computed per kWh of electricity produced from biomass alone, not including the costs inside the power plant. The cost contribution towards electrical power was then compared amongst the bioenergy systems.

Results and Discussion

Three different bioenergy scenarios were selected for producing a feedstock for electrical power generation; these scenarios are depicted in Figure B2.11 and include: 1) chipping in the field and direct transport to the power plant (denoted as the "wood chips" scenario), 2) chipping in the field followed by pelletization at a RBPD and transport to a power plant ("wood pellets"), and 3) chipping in the field, followed by torrefaction, milling, and pelletization at a RBPD and then transport to a power plant ("torrefied wood pellets"). The cost contribution to electric power was determined by estimating the costs of each component and unit operation in the system. Poplar and willow costs were estimated from previously developed plantation models by ORNL and SUNY, respectively. Capital investment was estimated using equipment costs provided in the literature and scaling with capacity using the six-tenths rule. Comparisons amongst the bioenergy scenarios are made upon determining the cost per kWh of electricity produced.

Plantation models

The SUNY model (EcoWillow v.1.0 beta) was used to estimate the costs of site preparation, cultivation, harvesting, and chipping. As mentioned in the methodology, the transportation component of this model was removed to compare the cost of biomass with the ORNL and FRCS model outcomes. The results of the SUNY model are displayed in Table B2.48 for rotation cycles of three and four years, which is an option provided by the SUNY model. As portrayed in Table B2.45, willow chips can be produced at a farm-gate cost of $55.92 per dry ton when using a four year rotation cycle under Michigan site conditions. Biomass at this cost should be available for bioenergy production as per the Billion-ton Study Update (Perlack, R.D. and Stokes, B.J. 2011).

Table B2.45. Results computed for willow by the SUNY model for three and four year rotation cycles.

SUNY Results for Willow	Rotation Cycle	
	3 years	**4 years**
Cultivation ($/dt)	36.20	35.50
Harvesting ($/dt)	21.30	16.00
Chipping ($/dt)	4.42	4.42
Total (farm gate chips $/dt)	61.92	55.92

The ORNL model was used to calculate the cost of wood chips from poplar plantations on six and twelve year rotations using a plant spacing of 6 ft x 6 ft and 10 ft x 10 ft. Michigan site conditions better support an 8 ft x 8 ft spacing for a six year rotation cycle as indicated by MSU Extension in Escanaba, Michigan (2011). Table B2.46 contains the results computed by the ORNL model for poplar plantations using six and twelve year rotation cycles. Under the six year rotation cycle, poplar chips can be made available at $41.30 per dry ton under Michigan site conditions. The cost of poplar is less than willow because fewer cuttings per acre are required due to a relatively long rotation cycle, i.e. six or twelve years vs. three or four years for willow. The cutting cost for poplar is $68/acre, which compares favorably to willow which can be as high as $580/acre. In addition, poplar has a higher annual yield at 6 dt/acre-yr compared with willow at 5 dt/acre-yr. A larger biomass stock when harvesting poplar, due to a higher yield and a longer rotation cycle, results in more efficient harvesting. Biomass at this cost should be available for bioenergy production as per the Billion-ton Study Update (Perlack, R.D. and Stokes, B.J. 2011).

Table B2.46. Results computed by the ORNL model for 6 and 12 year rotation cycles.

ORNL Results for Poplar	**Rotation Cycle**	
	6 years	**12 years**
Cultivation ($/dt)	20.65	25.81
Harvesting ($/dt)	16.23	10.39
Chipping ($/dt)	4.42	4.42
Total (farm gate chips $/dt)	41.30	41.23

Both plantation models were subjected to a sensitivity analysis to show the effects of variable inputs, parameters or properties on the output cost. Each variable was changed independently of the other variables, therefore while variation in output cost was assessed for one variable, the others were held constant. By plotting the output cost versus the percent change for each variable examined, the variable with the largest effect on output cost can be clearly identified. Figure B2.14 is a sensitivity plot of harvest yield, land cost, labor rate, and diesel fuel price versus the output cost of willow chips for a four year rotation and a 13 year investment timeframe. The base case cost of $55.92 per dry ton is presented in Table B2.46 at a change rate (abscissa) of 0%. Clearly, the harvest yield has the greatest effect on output cost, as only a slight increase in yield of 10% will decrease the output cost to approximately $50 per dry ton. Land cost, labor rate, and diesel fuel price have a lesser effect on the cost of willow chips. Figure B2.15 shows a similar analysis for poplar chips using the ORNL model for the six year rotation cycle. Again, a 10% increase in yield reduces the cost of poplar chips from $41.30 to approximately $39 per dry ton. Also consistent with willow chips, the cost of poplar chips is less sensitive to fluctuations in land cost, labor rate and the price of diesel fuel.

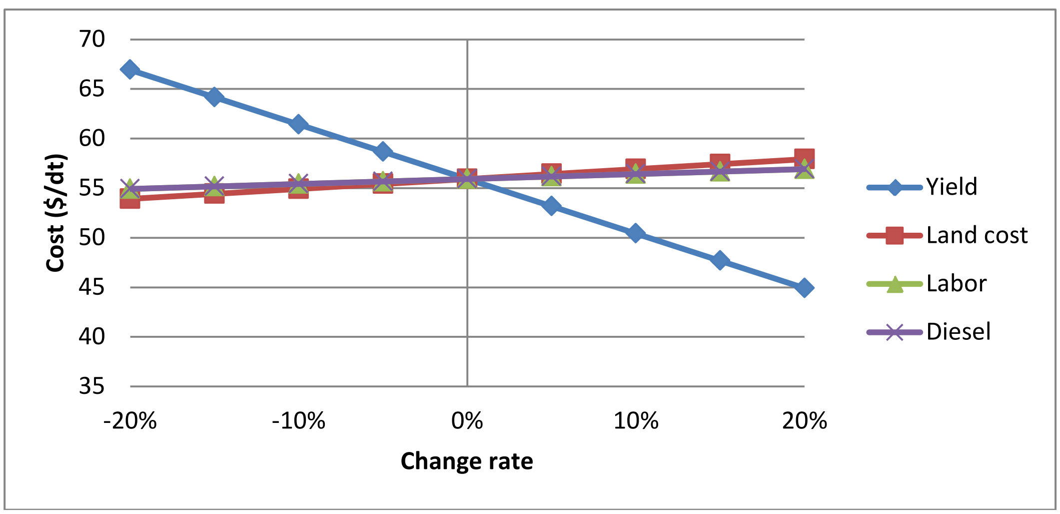

Figure B2.14. Sensitivity analysis for willow chips using a four year rotation and a 13 year investment period. A change rate of 0% corresponds to the base case specified in Table B2.45.

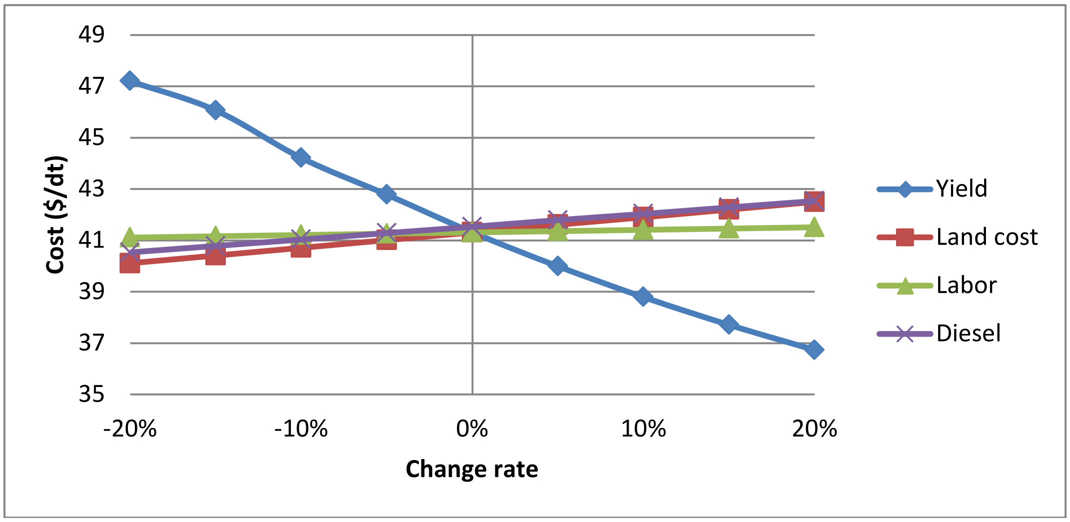

Figure B2.15. Sensitivity analysis for poplar chips using a six year rotation. A change rate of 0% corresponds to the base case specified in Table B2.49.

Preprocessing model scenarios

Three models were constructed to determine the costs and to identify the barriers to implementation associated with each scenario. All three scenarios were scaled to provide sufficient feedstock to displace 10% of the fossil energy required to operate a 100 MWe power plant for a time period of one year. The input cost to each preprocessing model was computed using the appropriate feedstock model, i.e. the SUNY model for willow plantations, the ORNL model for poplar plantations, or the FRCS model for natural stands. Scenario 1, which consists of cultivation, harvesting, on-site drying, chipping, transportation, on-site storage, and conversion to electrical power was developed by formulating mass and energy balances for each component in the system. The amount of energy required for chipping, and hence the cost, was computed by ORNL model. Transportation costs were determined upon estimation of distance-fixed and distance variables costs, $3.72 per ton and $0.074 per ton-mile respectively. Scenarios 2 and 3 also include cultivation, harvesting, on-site drying, chipping, transportation and storage costs (though storage losses at the power plant by scenario 3 are negligible). Transportation costs decrease when hauling densified material because of increased load size per truck. Scenario 2 includes the electrical costs associated with operating a pelletizer as reported by Thek et al. (2004). Scenario 3 includes pelletization costs similarly, though pelletization occurs after torrefaction and grinding. Torrefaction costs, both capital and operating, were modeled in accordance with the different reactors developed by Agri-tech Producers, LLC, and the Energy Center of the Netherlands (ECN). Grinding costs after torrefaction were modeled to reflect the increased friability observed by Repellin, V., et al. (2010). Capital and operating costs estimates are to be regarded as preliminary in nature, and may be portrayed as accurate to within plus and minus 50%. Further analytical, laboratory and pilot-scale efforts are needed to narrow the expected estimation error and further de-risk these bioenergy production systems.

Capital costs

Equipment costs were determined using previously reported costs by the academic literature and institutional reports as well as company information from brochures, websites and personal communications. All equipment costs were determined in the year 2004 or later, and these costs were not adjusted for inflation. Table B2.47 contains costs for the major equipment items in the three scenarios for the production capacities that are specified. The equipment costs displayed in Table 8 were calculated using the base equipment cost and capacity provided by the referenced source to the desired capacity using the six-tenths power-law model for scaling capital investment. Installed costs for equipment were determined using a Lang factor of 3.1, which is consistent with mature industries. A capacity of 10 MWe, which is capable of displacing 10% of the fossil electrical power produced at a 100 MWe power plant, was selected as the output for each scenario.

Operating costs

Preliminary operating costs were determined for the three scenarios. Feedstock costs were determined by the ORNL model for poplar plantations, by the SUNY model for willow plantations, and by the FRCS for natural stands. Table B2.48 contains the cost of torrefied wood pellets from each feedstock source. Natural stand feedstocks were found to be the most costly when either the FRCS was applied or when using the results of our logger survey. Poplar was found to be the least costly, because of the significantly lower cultivation and harvesting costs, therefore poplar is chosen as the feedstock for assessing the three bioenergy scenarios under consideration. Natural gas and electricity are the two primary utilities used by the three scenarios. Electricity was assumed to be available at 7.2 cents/kWh, which is in accordance with the industrial retail price in Michigan in 2010 (U.S. EIA). Natural gas was assumed to be $9.3 per standard thousand cubic feet, a value based on the average industrial retail price in 2010 in Michigan (U.S. EIA). Costs of the three products, i.e. “wood chips,” “wood pellets,” and “torrefied wood pellets,” were determined using poplar in six year plantations and are shown in Table B2.49. Wood pellets and torrefied wood pellets have higher operating costs than wood chips because of greater capital investment and higher maintenance costs. However, wood chips require further processing at the power station because of high moisture content and reduced friability when compared with coal. Therefore, when the cost of drying, constructing storage facilities, and additional grinding equipment are included in the analysis at the power facility, the cost of wood chips will increase.

Table B2.47. Capital costs and important operating information for the major equipment items considered in the three scenarios. Base equipment costs were obtained from the references provided. The equipment costs portrayed were computed by scaling the base equipment cost with capacity using the six-tenths power law model. Equipment capacity is sufficient to displace 10% of the fossil energy required to operate a 100 MWe power plant.

Parameter	Units	Value
Drying (Surrs, 2002; Thek et al., 2004)		
Unit type		Tube bundle dryer
Investment	$	983,890
Water evaporation rate	t/hr	6.7
Utilization period	yr	15
Required electrical power	kW	77.5
Torrefaction (Bergman, 2005a,c; Agri-tech, 2011)		
Unit type		Torre-tech 5.0
Investment	$	6,436,000
Capacity	t/hr	5.4
Utilization period	yr	15
Required electrical power	kW	225
required heat energy	Btu/hr	200,000
Grinding (Suurs, 2002; Repellin, 2010; Thek et al. 2004)		
Unit type		Hammer mill
Investment	$	193,622
Capacity	t/hr	5.4
Utilization period	yr	10
Required electrical power	kW	110
Pelletization (Suurs, 2002; Thek et al. , 2004)		
Unit type		Ring die
Investment	$	438,000
Capacity	t/hr	3
Utilization period	yr	10
Required electrical power	kW	233
Cooling (Thek et al. , 2004)		
Unit type		Counter flow
Investment	$	29,970
Capacity	t/hr	5
Utilization period	yr	10
Required electrical power	kW	12
Peripheral Equipment (Thek et al. , 2004)		
Unit type		
Investment	$	1,152,000
Utilization period	yr	10
Required electrical power	kW	90

Table B2.48. Comparison of torrefied wood costs using feedstock from poplar plantations, willow plantations, or natural stands. A stumpage cost of $12/green ton has been included in the cost of natural stands. Green wood was assumed to contain 50% moisture by mass.

Natural stands		**Biomass Cost $/dry ton**	**Torrefied Wood Pellet Cost ($/GJ)**
Partial Cut	Survey based results	89.48	8.18
	FRCS based results	95.38	8.52
Clear cut	Survey based results	71.66	7.15
	FRCS based results	111.02	9.43
Plantations		**$/ dry ton**	**$/GJ**
Willow	3 yrs rotation	61.92	6.59
	4 yrs rotation	55.92	6.25
Poplar	6 years rotation	41.33	5.40
	12 years rotation	41.23	5.40

Table B2.49. Costs of wood chips, pellets and torrefied pellets using poplar (grown in a six year rotation) as feedstock when delivered to the power plant assuming a 100 mile transport distance. Costs are portrayed as $ per ton (as received); $ per GJ (as received; LHV); and cents per kWh of electricity produced (cost contribution of feedstock to the cost of electrical power).

	Wood Chips	Wood Pellets	Torrefied Wood Pellets
$/t	54.80	90.67	111.39
$/GJ	4.567	5.429	5.304
Cents/kWh	4.75	5.58	5.46

Costs for the three scenarios are also compared in Figure B2.14, which displays the relative costs of each component when feedstock is transported 100 miles. The costs are determined on a kWh of electricity basis so that the three scenarios can be equivalently compared. From Figure B2.14, the cost of wood chips is greatest for the "wood chips" scenario because the higher moisture content of wood chips causes lower thermal efficiency. Storage costs are the greatest for the "wood chips" scenario as wood chips are subject to microbial degradation. Further, because the energy density of wood chips is the lowest, the largest land area is needed for on-site storage. Transportation costs for "wood chips" are also greater than for "wood pellets" or "torrefied wood pellets," a result of the increased energy density of biomass that has been pelletized. It is important to note that the lower overall costs of the "wood chip" scenario do not reflect additional equipment at the power plant that may be needed for further grinding or moisture removal. Upon including these additional equipment items, the difference between scenario costs is expected to narrow significantly when feedstock is transported 100 miles to the a centralized power plant.
Comparisons of scenarios two and three reveal several differences even though the overall cost contributions to electrical power generation are approximately the same. Wood chip cost is greater for torrefaction because of the mass loss that accompanies mild heat treatment. The cost of peripheral equipment and labor is lower for torrefaction because a higher energy value per products ton leads to more efficient operation of equipment and increased worker efficiency. Drying costs are significantly lower for torrefaction, as the co-product gas provides the needed heat, while for pelletization the purchase of natural gas is required. Though the expense of torrefaction is significant, as seen in Figure B2.16, the subsequent costs of grinding and pelletization (after torrefaction) are reduced because of increased

friability and the increased specific energy of torrefied wood. Storage costs are lower for torrefied wood as unlike wood pellets, torrefied wood is not subject to microbial degradation. Decreased transportation costs are a result of the increased energy density of the torrefied wood pellets versus wood pellets. If the costs associated with biomass torrefaction can be reduced, the torrefaction scenario will offer significant advantages versus the combustion of wood chips and wood pellets even when the transportation distance is only 100 miles.

Figure B2.16. Cost contribution to electrical power generation from wood chips, wood pellets and torrefied wood pellets when a distance of 100 miles from the RBPD to the power plant is applied. Poplar was used as the feedstock at a biomass cost of $41.33/dt.

The choice of scenario clearly changes upon increasing the transportation distance from 100 miles to 300 miles as shown in Figure B2.17. Even when the purchase of grinding and drying equipment at the power plant is not considered, the cost of wood chips exceeds the cost of wood pellets and torrefied wood chips, as a result of low energy density. Torrefied wood pellet costs are lower than wood pellet costs at this transport distance, as the increased energy density of torrefaction becomes more significant. Figure B2.18 contains a plot of transport distance versus the cost contribution to electrical power generation for the three scenarios under consideration. At distances that exceed 250 miles, the cost of torrefaction is lower than the cost of chipping and direct co-firing. Also from Figure B2.18, torrefaction is always less costly than pelletization alone, due to the increased energy density and improved properties of the torrefied wood pellets. As torrefaction appears to offer considerable benefits, further analysis is needed to verify the findings of this study. As can be clearly concluded from Figures B2.16 and B2.17, technologies that reduce the associated torrefaction cost should be actively researched and pursued to lower this component of the overall cost.

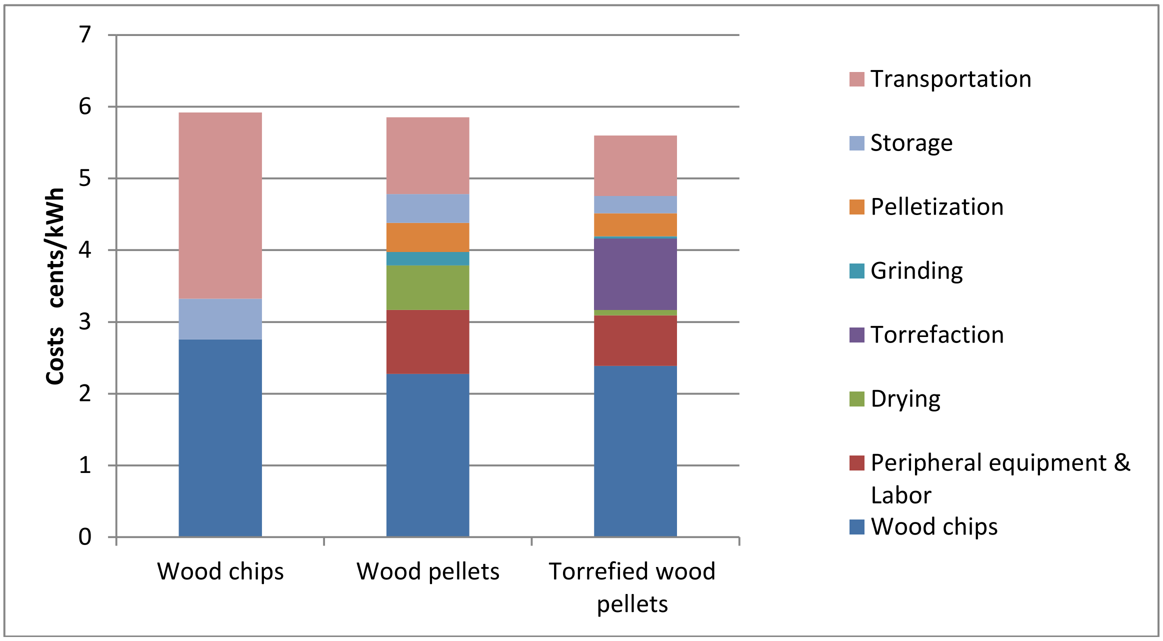

Figure B2.17. Cost contribution to electrical power generation from wood chips, wood pellets and torrefied wood pellets when a distance of 300 miles from the RBPD to the power plant is applied. Poplar was used as the feedstock at a biomass cost of $41.33/dt.

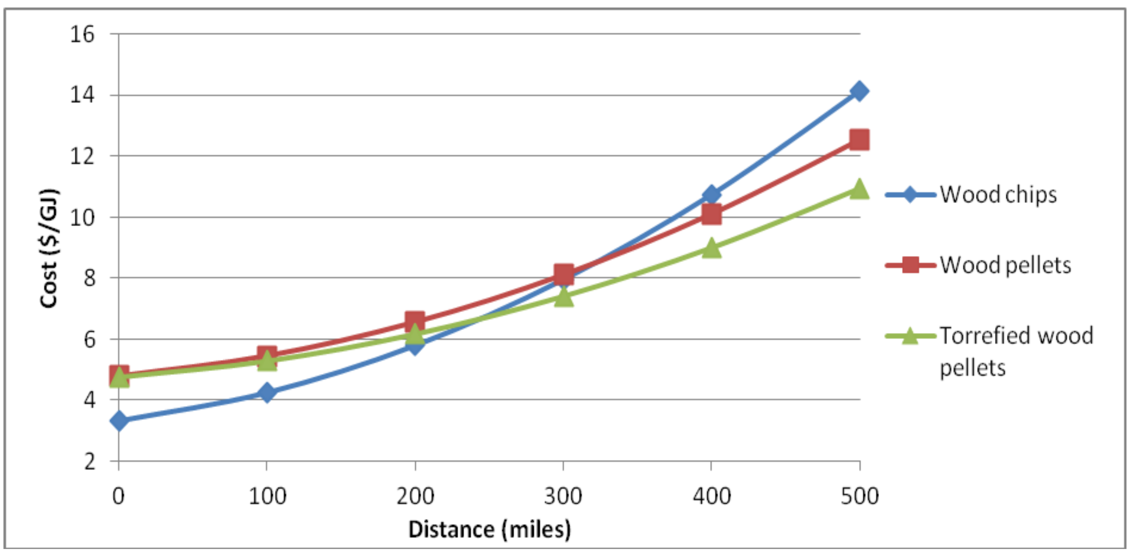

Figure B2.18. Cost comparison of the three scenarios at the power plant gate at varying transportation distance. Transport cost was calculated using a fixed cost of $3.72/ton and a variable cost of $0.074/ton-mile. An individual truck capacity of 40 tons was used for this analysis.

Figure B2.19 presents the costs of power plant feedstock for each scenario on a dry ton basis. Comparisons between the scenarios should not be made from this figure, as the energy content of each feedstock is significantly different. The relative costs of each supply chain component can be compared within each scenario using this diagram. For wood chips, cultivation, harvesting and chipping are the dominant costs, though storage and transportation are also significant. Peripheral equipment and labor, drying and transportation are also important costs for the wood pellet scenario. The cost of torrefaction contributes significant cost to the overall cost of torrefied wood pellets, and again, the design of low cost torrefaction technologies should be pursued. Overall, the cost of wood chips at least comprises the plurality of cost for all components considered.

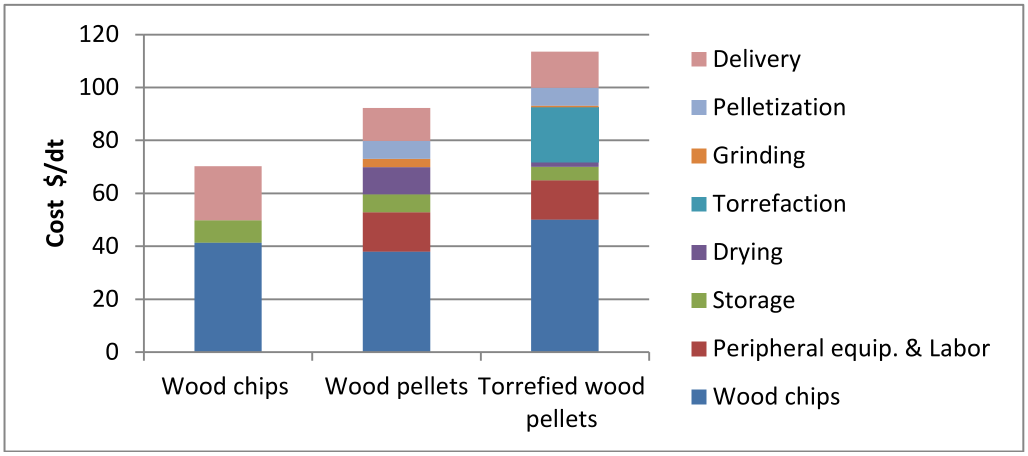

Figure B2.19. Costs of power plant feedstock of each scenario on a dry basis. Transportation cost is included as a distance of 100 miles is assumed. Poplar at a cost of $41.33/dt was used as feedstock.

Sensitivity Analysis of Scenario 3 (Torrefied wood pellets)
A sensitivity analysis of scenario 3 was performed to determine the input variables that most affect the output cost. From this analysis, graphically portrayed in Figure B2.20, the most significant variable is the biomass cost at the farm gate. Increasing biomass cost from $27/dry ton to $62/ dry ton increases the torrefied wood pellets cost from $4/GJ to $7/GJ. Service life of the equipment is the second most sensitive input, as the longer period for capital depreciation lowers the overall cost. As was previously concluded, the capital investment of the torrefaction reactor is especially important when devising a plan to reduce the costs for this scenario.

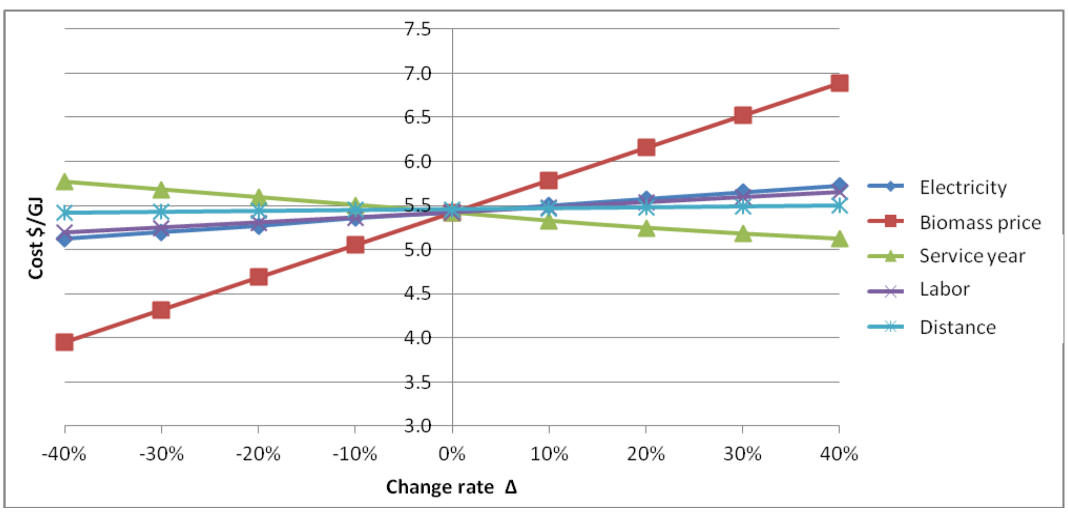

Figure B2.20. Sensitivity analysis for scenario 3: "Torrefied wood pellets." Costs are in U.S. dollars per GJ of torrefied wood pellets.

Summary

Torrefied wood pellets are hydrophobic and friable and are not likely to require significant modifications in the storage, handling and size reduction areas of the power plant. Conversely, wood chips contain significant water and will either require drying or will result in reduced combustion energy in the power plant's furnace. Furthermore, outdoor storage subjects both wood chips and wood pellets to infiltration by rainwater which will further reduce the energy quality during combustion. Wood chips and pellets will begin to decompose at moisture contents above 20% as microbial contamination converts biomass into gaseous products. Covered storage options can be explored, but will require further investment. Additionally, the cost of size reduction is greater for wood chips and pellets versus torrefied pellets because of the fibrous nature of woody biomass. Upon pulverization, particles of woody biomass tend to remain interconnected, which reduces the efficiency of combustion in the power plant's furnace. Torrefaction increases the friability of woody biomass which reduces the pulverization costs in conventional ball mills. Because of improved storage stability and increased friability, torrefied wood pellets can potentially serve as "drop-in" fuels for renewable electric power production.

Torrefied wood pellets offer significant advantages versus traditional wood pellets and wood chips. However, the cost contribution of torrefied wood pellets to electrical power generation remains greater than coal. For scenarios 2 and 3, the biomass cost contribution to electrical power generation at the entry gate of the RBPD exceeds $0.02 per kWh. Processing costs within the RBPD and subsequent transportation of 300 miles adds another $0.03 per kWh, for a total power plant feedstock cost of around $0.056 per kWh. Torrefied wood pellets and wood pellets offer another approach to meeting the 10% renewable electricity mandate set forth in MI Public Act 295 for the year 2015.

The advantages of torrefied wood pellets versus wood chips include: 1) reduced transportation costs due to densification, 2) improved storage stability due to increased hydrophobicity, and 3) reduced grinding costs due to increased friability. Scenarios that involve long distance transportation are especially benefited by torrefaction and pelletization. Preliminary analysis suggests that significant cost savings can be found when employing transoceanic transport of torrefied wood pellets versus non-densified biomass. Overland truck transport costs reflect this conclusion for the three products investigated by our analysis. We conclude that for bioenergy systems that involve long transportation distances, torrefaction and pelletization are justified.

We recommend that further consideration and analysis be given investigating the torrefaction of both poplar and willow plantation materials. Though energy plantations of this sort currently do not exist, the Billion-ton Study Update (Perlack, R.D. and Stokes, B.J. 2011) clearly states the importance of such energy crops. For long distance transportation, the costs of torrefied wood pellets are lower than those for wood pellets and wood chips. Shorter transportation distances may also be justifiable when the additional processing costs at power plants are included for wood chips and when accurate torrefaction investment costs are made available. Optimization of torrefaction will provide a clear opportunity for further reducing the costs of this bioenergy scenario, and new torrefaction technologies should be considered to improve the outlook for this alternative energy technology.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Surveying Michigan loggers resulted in a snapshot of the harvesting, extracting and processing equipment available in 2009 and 2010. Based on the observations made after reflecting upon the survey results, several conclusions and recommendations can be made for future work. First, as most harvesting operations were from partial cut treatments, it would not be prudent to assume that an entire area would be clear cut to supply biomass to a new facility. Second, from the survey, most products were extracted from lands defined as "other public lands" and then delivered to pulp and paper industries. It is recommended that the amount and types of material on "other public lands" be accurately assessed. Third, saw logs and pulpwood were the most common types of product removed from the forest while woodchips were the least. The cost of chippers and the breadth of experience that loggers have using chippers will require further assessment. Fourth, a variety of logging equipment was used; including mechanical whole tree harvesting, cut-to-length harvesting and manual whole tree harvesting. Both mechanical whole tree and cut-to-length systems were capable of delivering biomass at lower costs than the manual systems, as such loggers should consider mechanical harvesting at the large volumes required by bioenergy systems to displace fossil energy sources.

The costs of chipped wood ranged from $13.28 to $27.11 per green ton as calculated based on survey based data for a clear cut in softwood plantations and for 30% cut in natural hardwoods, respectively, and by adding $4.37 for chipping cost.. Increasing the amount of removal significantly reduces cost, which are further reduced when clear cutting. Overall, harvesting costs are highly variable and dependent upon the type of equipment, level of harvesting (clear-cut vs. selective cut), type of forest, and the tree stand density. Generally, the FRCS model predicted costs were higher than those provided by the loggers' survey. Management factors affecting cost were found to be machine economic life and price of diesel fuel.

Torrefied wood pellets are hydrophobic and friable and are not likely to require significant modifications in the storage, handling and size reduction areas of the power plant. Conversely, wood chips contain significant water and will either require drying or will result in reduced combustion energy in the power plant's furnace. Furthermore, outdoor storage subjects both wood chips and wood pellets to infiltration by rainwater which will further reduce the energy quality during combustion. Wood chips and pellets will begin to decompose at moisture contents above 20% as microbial contamination converts biomass into gaseous products. Covered storage options can be explored, but will require further investment. Additionally, the cost of size reduction is greater for wood chips and pellets versus torrefied pellets because of the fibrous nature of woody biomass. Upon pulverization, particles of woody biomass tend to remain interconnected, which reduces the efficiency of combustion in the power plant's furnace. Torrefaction increases the friability of woody biomass which reduces the pulverization costs in conventional ball mills. Because of improved storage stability and increased friability, torrefied wood pellets can potentially serve as "drop-in" fuels for renewable electric power production.

Torrefied wood pellets offer significant advantages versus traditional wood pellets and wood chips. However, the cost contribution of torrefied wood pellets to electrical power generation remains greater than coal. For scenarios 2 and 3, the biomass cost contribution to electrical power generation at the entry gate of the RBPD exceeds $0.02 per kWh. Processing costs within the RBPD and subsequent transportation of 300 miles adds another $0.03 per kWh, for a total power plant feedstock cost of around $0.056 per kWh. Torrefied wood pellets and wood pellets offer another approach to meeting the 10% renewable electricity mandate set forth in MI Public Act 295 for the year 2015.

The advantages of torrefied wood pellets versus wood chips include: 1) reduced transportation costs due to densification, 2) improved storage stability due to increased hydrophobicity, and 3) reduced grinding costs due to increased friability. Scenarios that involve long distance transportation are especially benefited by torrefaction and pelletization. Bergman et al [1] determined that significant cost savings can be found when employing transoceanic transport of torrefied wood pellets versus non-densified biomass. Overland truck transport costs reflect this conclusion for the three products investigated by our analysis. We conclude that for bioenergy systems that involve long transportation distances, torrefaction and pelletization are justified.

We recommend that further consideration and analysis be given investigating the torrefaction of both poplar and willow plantation materials. Though energy plantations of this sort currently do not exist, the Billion-ton Study Update (Perlack, R.D. and Stokes, B.J. 2011) clearly states the importance of such energy crops. For long distance transportation, the costs of torrefied wood pellets are lower than those for wood pellets and wood chips. Shorter transportation distances may also be justifiable when the additional processing costs at power plants are included for wood chips and when accurate torrefaction investment costs are made available. Optimization of torrefaction will provide a clear opportunity for further reducing the costs of this bioenergy scenario, and new torrefaction technologies should be considered to improve the outlook for this alternative energy technology.

REFERENCES

1. Abbas D; Current, D; Ryans, M; Taff, S; Hoganson, H; and Brooks, K. 2011. Harvesting forest biomass for energy: An alternative to conventional fuel treatments: Trials in the Superior National Forest, USA, *Biomass and Bioenergy*
2. Agri-Tech Producers, L., *Company brochure, written and verbal information* 2011.
3. Bergman, P.C.A., *Combined torrefaction and pelletisation.* The TOP process, 2005a.
4. Bergman, P.C.A., et al., *Torrefaction for biomass co-firing in existing coal-fired power stations.* Energy Research Centre of the Netherlands, ECN-C-05-013, 2005b.
5. Bergman, P.C.A. and J.H.A. Kiel. *Torrefaction for biomass upgrading*. 2005c.
6. BLS 2011. Bureau of Land Statistics. Operational Data Annual Statistics Database. http://www.bls.gov/oes/current/oes_mi.htm#45-0000
7. Dillman, Don 2000. Mail and Internet surveys: The tailored design method. Second Edition. Wiley. USA.
8. Dykstra, Dennis; Hartsough, Bruce; Stokes, Bryce. 2009. Updating FRCS, the Fuel Reduction Cost Simulator, for national biomass assessments. In: Hartsough, Bruce; Stokes, Bryce, compilers. 2009. Proceedings, Environmentally Sound Forest Operations. 32nd Annual Meeting of the Council on Forest Engineering, held June 15-18, 2009 at Kings Beach, California. Proceedings published on CD-ROM by the University of California, Davis, California.
9. Fight, Roger D.; Hartsough, Bruce R.; Noordijk, Peter. 2006. Users Guide for FRCS: Fuel Reduction Cost Simulator Software. Gen. Tech. Rep. PNW-GTR-668. Portland, OR: Pacific Northwest Research Station, Forest Service, US Department of Agriculture. 23 p.
10. FRCS. 2005-2010. Fuel Reduction Cost Simulator. Pacific Northwest Research Station, USDA Forest Service, Portland, Oregon. Last updated March 26, 2010. Available as a download from http://www.fs.fed.us/pnw/data/frcs/frcs.shtml.
11. *MSU Extension, Escanaba, MI.* 2011.
12. Miller, R., *Personal communication* MSU, 2011.
13. Miyata, Edwin S. 1980. Determining fixed and operating costs of logging equipment. Gen. Tech. Rep. NC-55. St. Paul, MN: North Central Forest Experiment Station, Forest Service, US Dept. of Agriculture. 16 p.
14. Perlack, R.D. and B.J. Stokes, *U.S. Billion-ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. 2011, The U.S. Department of Energy: Oak Ridge, TN. p. 227.
15. Prins, M.J., K.J. Ptasinski, and F.J.J.G. Janssen, *Torrefaction of wood: Part 2. Analysis of products.* Journal of analytical and applied pyrolysis, 2006. **77**(1): p. 35-40.
16. Repellin, V., et al., *Energy requirement for fine grinding of torrefied wood.* Biomass and Bioenergy. **34**(7): p. 923-930.
17. Suurs, R., *Long distance bioenergy logistics.* University of Utrecht, Copernicus Institute, Department of Science Technology and Society, 2002.
18. Tessa Systems, LLC 2009. Timber Supply Outlook for Kinross, Michigan. Final Report. Prepared for Frontier Renewable Resources, LLC. Marquette, MI 49855
19. Tharakan, P.J., et al., *Evaluating the impact of three incentive programs on the economics of cofiring willow biomass with coal in New York State.* Energy Policy, 2005. **33**: p. 337-347.
20. Thek, G. and I. Obernberger, *Wood pellet production costs under Austrian and in comparison to Swedish framework conditions.* Biomass and Bioenergy, 2004. **27**(6): p. 671-693.
21. *U.S. Energy Information Administration* 2010.
22. van der Stelt, M.J.C., et al., *Biomass upgrading by torrefaction for the production of biofuels: A review.* Biomass and Bioenergy, 2011. **35**(9): p. 3748-3762.
23. Wu, M.R., D.L. Schott, and G. Lodewijks, *Physical properties of solid biomass.* Biomass and Bioenergy, 2011. **35**(5): p. 2093-2105.