ftc&h

engineers
scientists
architects
constructors

1515 Arboretum Dr., SE
Grand Rapids, MI
49546
ph: 616.575.3824
fax: 616.575.8155
www.ftch.com

March 16, 2011
Project No. G06783B

Ms. Melissa Byrnes
Air Quality Division
Michigan Department of Environmental Quality
Constitution Hall, 3rd Floor, North
525 West Allegan Street
Lansing, MI 48933

Re: Green House Gas Best Available Control Technology (GHG BACT) Determination
Wolverine Power Supply Cooperative, Inc. (Wolverine) Air Use Permit to Install
Application No. 317-07

Dear Ms. Byrnes:

On behalf of Wolverine, Fishbeck, Thompson, Carr & Huber, Inc. (FTC&H) is submitting a GHG BACT determination for Air Use Permit to Install Application No. 317-07 for a 600 megawatt (net) steam electric power plant. Wolverine's submittal is attached.

As of the date of this submittal, Wolverine believes there is a basis for concluding that the GHG BACT determination is not legally required for its application, the application having been technically and/or administratively complete well before the proposed date of any GHG BACT requirement arising under the federal Clean Air Act or the Michigan State Implementation Plan. Accordingly, Wolverine at this time reserves its right to contend that this submittal is not necessary to address any applicable requirement relative to its pending application and that any resulting permit conditions relating to GHG emissions are not an applicable requirement.

If you have any questions or require additional information, please contact me at 517-887-4024 or jfcaudell@ftch.com.

Sincerely,

FISHBECK, THOMPSON, CARR & HUBER, INC.

John F. Caudell, P.E.

tc
Attachment
By e-mail
cc: Ms. Mary Ann Dolehanty – MDEQ
Mr. Brian L. Warner, CHMM – Wolverine
Mr. Steven C. Kohl – Warner Norcross & Judd, LLP
Mr. Michael L. Robinson – Warner Norcross & Judd, LLP
Mr. William Campbell III – AECOM
Mr. Michael Zebell, P.E. – AECOM
Mr. John Lagomarsino – Burns and Roe Enterprises, Inc.
Ms. Jacquelyn F. Linck, P.E. – FTC&H
Mr. David M. Yanochko, P.E. – FTC&H

Prepared for:
Wolverine Power Supply Cooperative, Inc.
Cadillac Michigan

Greenhouse Gas BACT Determination Supplement to Air Pollution Control Permit Application No. 317-07

Wolverine Clean Energy Venture

Rogers City, MI

AECOM Technical Services, Inc.
March 2011
Document No.: 60139072

Greenhouse Gas BACT Determination Supplement to Air Pollution Control Permit Application No. 317-07

Wolverine Clean Energy Venture

Rogers City, MI

Michael Zebell

Prepared By – Michael Zebell, P.E.

William C. Campbell III

Reviewed By – William Campbell III

AECOM Technical Services, Inc.
March 2011
Document No.: 60139072

Contents

List of Tables

List of Figures

List of Appendices

List of Abbreviations

BACT	Best Available Control Technology
$CaCO_3$	Calcium carbonate
CCS	Carbon Capture and Sequestration
CFB	Circulating Fluidized Bed
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EAB	Environmental Appeals Board
EOR	Enhanced Oil Recovery
GHG	Greenhouse gas
GWP	Global warming potential
H_2S	Hydrogen sulfide
HFC	Hydrofluorocarbon
HHV	Higher heating value
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LAER	Lowest Achievable Emission Rates
lb/MMBtu	pound per million British thermal units
LHV	Lower heating value
MCL	Michigan Compiled Law
mTPY	Metric tons per year
MW	Megawatt
MRCSP	Midwest Regional Carbon Sequestration Partnership
N_2O	Nitrous oxide
NOx	Nitrogen oxides
NSR	New Source Review
O&M	Operation and Maintenance
pet coke	petroleum coke
PFC	Perflourocarbon
PRB	Powder River Basin
PSD	Prevention of Significant Deterioration

RACT	Reasonably Available Control Technology
RBLC	RACT/BACT/LAER Clearinghouse
SF_6	Sulfur hexafluoride
SNCR	Selective Non-Catalytic Reduction
TPY	Tons per year
USDOE	U.S. Department of Energy
USEPA	U. S. Environmental Protection Agency
VOC	Volatile organic compound
WCEV	Wolverine Clean Energy Venture

1.0 Overview and Introduction

Wolverine Power Supply Cooperative, Inc. (Wolverine) is a not-for-profit generation and transmission cooperative whose business purpose in proposing this project is to develop a base load electric power generation resource in northern Lower Michigan within the region of the state served by Wolverine's member cooperatives. The project is intended to utilize locally grown and harvested renewable biomass fuel, take advantage of regional water transport resources which the Great Lakes provide, and employ locally quarried limestone in operation of the plant and air pollutant emission control equipment. The project is being developed to provide Wolverine's membership with reliable and economical long-term electrical generation capacity. Consistent with this business purpose, Wolverine proposes to construct a 2x300 MW (net) Circulating Fluidized Bed (CFB) power generation facility following four years of siting, economic and technical studies and permitting. These studies have led Wolverine to propose construction of a new state-of-the-art solid fuel-fired power generation facility to be located southeast of Rogers City, Michigan upon land acquired from and immediately adjacent to the active limestone quarry operated by Carmeuse North America with easement access to Camueuse's existing commercial harbor on Lake Huron. The proposed generating facility is referred to as the Wolverine Clean Energy Venture (WCEV) and will include two multi-fuel CFB boilers with advanced emission controls. This facility, by employing CFB technology, will have the capability to utilize a mixture of solid fuels (including biomass) and limestone over the 30 year (minimum) life of the facility. This fuel flexibility mitigates the risk, given the absence of rail to the site, that transportation disruptions for one source of fuel would force a shutdown of the facility.

A detailed air pollution control permit application (Application No. 317-07) was prepared and submitted to the Michigan Department of Environmental Quality (MDEQ) in September of 2007. Since the air permit application was submitted and a draft permit issued, the U.S. Environmental Protection Agency (USEPA) has promulgated rules that regulate carbon dioxide (CO_2) from certain stationary sources. On June 3, 2010, the USEPA issued a final rule that "tailors" the applicability provisions of the Prevention of Significant Deterioration (PSD) program under New Source Review (NSR) to regulate emissions of greenhouse gases (GHG). Under the Tailoring Rule certain proposed new major sources with a potential to emit more than 75,000 tons per year (TPY) of carbon dioxide equivalent (CO_2e) became subject to new permitting requirements beginning in 2011. CO_2e is defined as the sum of six GHG compounds and accounts for the "global warming potential" of each compound with CO_2 equal to 1. The new permitting requirements include application of the Best Available Control Technology (BACT) for controlling GHGs.

This report supplements the BACT review and determination for the proposed WCEV. The BACT review presented here follows a five step "top-down" process for GHG emissions from the proposed WCEV facility. Technologies evaluated include carbon capture and sequestration (CCS), biomass fuel augmentation, and energy efficiency opportunities in design of the plant.

1.1 Framework for BACT Analysis

The following subsections describe the process used in this BACT report. In November 2010, the USEPA issued guidance for GHG BACT reviews as part of NSR permitting (PSD and Title V Permitting Guidance for Greenhouse Gases, Prepared by the Office of Air Quality Planning and Standards USEPA, November 2010). This BACT review is consistent with USEPA GHG BACT Guidance. The methodologies employed in this review apply to the BACT determination for the main boilers at the proposed WCEV and for the ancillary fuel-burning equipment.

1.1.1 Inherent Design Considerations

In its November 2010 guidance, the USEPA affirmed that a BACT review for a project should not operate to redefine the project. "EPA has recognized that a Step 1 list of options need not necessarily include inherently lower polluting processes that would fundamentally redefine the nature of the source proposed by the permit applicant. BACT should generally not be applied to regulate the applicant's purpose or objective for the proposed facility." The November 2010 guidance continues, "The 'redefining the source' issue is ultimately a question of degree that is within the discretion of the permitting authority." Similarly, the USEPA's March 2011 "Guidance for Determining Best Available Control Technology for Reducing Carbon Dioxide Emissions from Bioenergy Production" states, "However, while Step 1 is intended to capture a broad array of potential options for pollution control, this step of the process is not without limits. EPA has recognized that a Step 1 list of options need not necessarily include inherently lower polluting processes that would fundamentally redefine the nature of the source proposed by the permit applicant. BACT should generally not be applied to regulate the applicant' s purpose or objective for the proposed facility."

The USEPA's statements in its November 2010 and March 2011 guidance must be considered in the overall legal context. In *Sierra Club v U.S. Environmental Protection Agency*, 499 F. 3d 653 (7th Cir. 2007) the federal appellate court affirmed that BACT did not extend to a redesign and rejected the contention that low-sulfur coal needed to be considered as BACT for SO_2 emissions for a facility proposed to be sited as a "mine-mouth" plant utilizing high sulfur coal. What was critical to the court was that although the plant could burn low-sulfur coal, requiring use of low-sulfur coal would mandate a reconfiguration of the proposed project as a whole and extend the BACT analysis beyond what was required by the Clean Air Act. Moreover, the court made it abundantly clear that alternative generation technologies (e.g., wind, hydro, nuclear) were clearly well beyond the scope of BACT for the project.

Given that the WCEV project has been uniquely designed (including the selected site) to satisfy a number of case-specific objectives, it is apparent that a number of technologies should readily be excluded from this BACT analysis because they would constitute a "redesign" or "reconfiguration" of the project.

- Combined Cycle Gas Turbine

  Natural gas supply adequate for significant power generation is not available within the region of the proposed site for the WCEV. Additionally, this generation technology would not derive any benefit from the inherent characteristics of the proposed site (limestone and existing harbor). Finally, the technology cannot utilize the native biomass resource as fuel.

- Pulverized Coal (sub-critical, super critical, ultra-super critical)

  This technology was initially screened and eliminated in the Technology Selection Study submitted with the initial application. The optimal configuration for a pulverized coal boiler would be 1 x 600 MW and would eliminate the beneficial operating redundancy afforded a 2x 300 MW CFB facility. Additionally, this technology would not be advantaged to the same extent as CFB technology to the proximate supply of limestone. Further this technology does not have the demonstrated ability to utilize the mixture of fuels proposed for the WCEV.

- Super Critical CFB

  While discussed in further detail in this document, this technology has not been commercially demonstrated to be capable of utilizing the mixture of fuels proposed for the project and, in particular, to operate with biomass fuels. Additionally, the only commercial deployment of this technology has not been demonstrated as capable of meeting emission levels for other pollutants that equate with the proposed BACT for the WCEV 2x300 CFB configuration.

- Integrated Coal Gasification Combined Cycle

  This technology has already been addressed in previous submissions related to this permit application and demonstrated not to constitute BACT for other pollutants. In addition, it was screened and eliminated in the Technology Selection Study and has not been demonstrated with the fuel mixture proposed for the WCEV. Finally, back-up natural gas is not available at the proposed site in the event of gasifier plant interruption.

- Biomass Gasification

This technology is restricted in feasible size to 50 MW (gross) maximum and would not meet the needs of the proposed project.

- 100% Biomass Combustion

This technology is restricted in feasible size to 50 MW (gross) maximum and would not meet the needs of the proposed project.

1.1.2 Top-Down BACT Process

BACT requirements are intended to ensure that a proposed project will incorporate control systems that reflect the latest demonstrated practical techniques for that particular facility. The BACT evaluation requires the documentation of performance levels achievable for control technology on a pollutant-by-pollutant basis. BACT is defined in the PSD Regulations (40 CFR Part 62) as:

> An emissions limitation based on the maximum degree of reduction for each air pollutant subject to regulation, taking into account energy, environmental and economic impacts, and other costs. The Regional Director will verify the BACT on a case-by-case basis, and it may include reductions achieved through the application of processes, systems, and techniques for the control of each air pollutant.

The USEPA GHG BACT Guidance document presents information on BACT applicability to new and modified sources, and outlines the five step process for determining BACT. The USEPA recommends that a "top-down" approach be taken when evaluating available air pollution control technologies. This guidance approach to the BACT process involves determining the most stringent control technique available, Lowest Achievable Emission Rate (LAER), for a similar or identical emission source. If it can be shown that the LAER is technically, environmentally or economically impractical on a case-by-case basis for the particular source, then the next most stringent level of control is determined and similarly evaluated. The process continues until a control technology and associated emission level is determined which cannot be eliminated by any technical, environmental or economic objections. The top-down BACT evaluation process is described in the USEPA draft document "New Source Review Workshop Manual." The five steps of a top-down BACT evaluation are:

1. Identify all available control options with practical potential for application to the specific emission unit for the regulated pollutant under evaluation;
2. Eliminate technically infeasible or unavailable technology options;
3. Rank remaining control technologies by control effectiveness;
4. Evaluate most effective controls and document results; if top option is not selected as BACT, evaluate next most effective control option; and
5. Select BACT, which will be the most effective practical option not rejected based on energy, environmental, and economic impacts.

The "top-down" approach is used in this analysis to evaluate available pollution controls for CO_2 emissions from the planned CFB units at the WCEV.

1.1.3 Previous BACT/LAER Determinations

USEPA's RACT/BACT/LAER Clearinghouse (RBLC) is a listing of RACT, BACT and LAER determinations by governmental agencies for many types of air emission sources. AECOM consulted this database to determine if there are any permits issued with CO_2 limits listed in the RBLC. The results of the RBLC search indicate that there are CO_2 limits set for five processes at five facilities. Information on these facilities is included in Appendix A. The basis for these CO_2 limits is erroneously listed as PSD-BACT. All of the listings in the RBLC indicate that no control was found to be cost effective, with the exception of the Red River Environmental Products facility that listed the control as *"good combustion control."* However, this conclusion does not fit with accepted knowledge that the better the combustion efficiency the more CO_2 is produced.

1.1.4 Cost Estimates

Cost estimates for emerging technology are difficult to estimate as equipment vendors are typically unwilling to disclose information on control systems during the development phase of the technology. Some costs can be obtained from the literature; however, without a history of a technology in a competitive market, there is no reliable information on the capital or operation and maintenance (O&M) cost of CO_2 control.

In addition to the cost of CO_2 capture, CCS involves geologic or terrestrial sequestration or conversion of the CO_2 for long-term storage. The costs associated with sequestration are very site-specific and can involve substantial costs for items such as pipeline construction, pumping, drilling and well construction, and monitoring. These costs are not estimated because there is too much uncertainty in the sequestration option for the site.

Finally, energy efficiency of system components is an integral part of a power generation facility design. The detailed design process is based on detailed performance specifications. The process of evaluating energy efficiency is a balance between equipment cost and load reduction. No detailed costs are presented for various system components because the plant design is not at the stage of balancing equipment costs versus load.

The cost-effectiveness of an available control technology is normally based on the annualized cost of the available control technology and its potential annual pollutant emission reduction. Cost effectiveness for a given control technology is calculated by dividing the annualized cost of the control technology by the tons of pollutant expected to be removed or reduced by the control technology each year.

2.0 Source Discussion

The following subsections describe the magnitude of CO_2 emissions from the planned WCEV CFB boilers. In addition, other GHG emissions from the proposed source are discussed and quantified. GHG emissions other than CO_2 are controlled by various air pollution control equipment or means as discussed.

2.1 Greenhouse Gases

In addition to CO_2, there are a number of other chemical compounds believed to contribute to global warming including water (H_2O), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perflourocarbons (PFCs), and sulfur hexafluoride (SF_6). The primary man-made sources of CO_2 emissions include fossil fuel combustion and industrial processes. CH_4 emissions result from activities such as landfill operation, production and distribution of natural gas and petroleum, fermentation from the digestive system of livestock and rice cultivation, as well as fossil fuel combustion. N_2O also results from fossil fuel combustion and activities such as fertilizer and nylon production. HFCs are used in refrigeration, aluminum smelting and semiconductor manufacturing. PFCs are used in aluminum production and the semiconductor industry. SF_6 is an electrical insulating gas used in sealed equipment in electrical transmissions and distribution systems. Of these compounds, all but H_2O are being regulated in the U.S. as GHGs under the Clean Air Act.

The planned combustion units at WCEV will emit CO_2, CH_4 and N_2O. Each of the GHGs has a global warming potential (GWP) that expresses its potential contribution to warming of the atmosphere relative to CO_2 with a GWP of 1. The USEPA assigns a GWP of 21 to CH_4 and 310 to N_2O. This means that in accounting for GHG emissions reported as tons of CO_2, the tons of CH_4 emitted by a source is multiplied by 21 and the tons of N_2O is multiplied by 310.

2.2 CFB Boilers

Fuel combustion in CFB boilers produces CO_2, N_2O, and CH_4. CO_2 is produced in a CFB boiler through two mechanisms. The primary mechanism of CO_2 production is through the complete combustion of fuel. The secondary mechanism is through calcination of limestone in the boiler. Calcination is the thermal decomposition of limestone to calcium oxide (lime). At approximately 1,550°F, a portion of the limestone in the CFB will be calcined following the reaction as follows:

$$CaCO_3 \rightarrow CaO + CO_2$$

The planned CFB boilers at the WCEV will have a controlled bed temperature in the range of 1,600°F and there will be some calcination of the limestone within the boiler to lime. The exact extent of the calcination reaction is not known.

Emissions of N_2O are part of the nitrogen oxides (NOx) emissions of the units and are the result of thermal and fuel NOx as described in the original permit application (Permit to Install Application for a 600 Megawatt (net) Solid Fuel Steam Electric Power Plant – Wolverine Clean Energy Venture, September 2007). The main factors affecting the emission of N_2O from fluidized bed combustion are the type of fuel, the temperature and the amount of combustion air. The N_2O emission increases when the temperature drops and the combustion air increases. In addition, the N_2O emission tends to be higher for geologically older fuels than for younger fuels (e.g., peat and wood). The emissions of N_2O were considered within the BACT review for NOx emissions in the original permit application. That review led to the determination of Selective Non-Catalytic Reduction (SNCR) as the BACT control device and 0.074 pound per million British thermal units (lb/MMBtu) as the NOx BACT limit.

CH_4 emissions were indirectly considered in the volatile organic compound (VOC) BACT review in the original permit application. CH_4 is not regulated as a criteria pollutant, so no BACT review was performed that specifically included CH_4; however, the mechanism of CH_4 formation and control is the same as that for VOC. The VOC BACT determination limits the CFB boilers to 0.0066 lb/MMBtu using good combustion control.

2.2.1 Estimate of GHG Emissions as CO_2 Equivalent

Table 1 shows an estimate of the maximum amount of GHG emissions produced by the proposed WCEV CFB units and ancillary fuel burning equipment. All of the emission factors used are from the U.S. Energy Information Administration[1] except for the emission factor for the CO_2 from limestone calcination. The limestone calcination emission factor is from the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories[2]. Use of the IPCC factor is conservative because it assumes that all of the limestone added to the CFB is calcined to lime, while in reality, only a portion of the limestone is calcined. All of the maximum consumption values are based on permit conditions with the exception of the maximum limestone make-up to the boilers, which comes from the Burns and Roe Enterprises Technology Selection Study[3]. The estimate is based on a capacity factor of 1 for the CFB units.

Greenhouse gas emissions from all of the combustion sources at the WCEV facility including the CFB boilers, auxiliary boiler, black start generator, emergency generator, and the diesel fire pump are quantified and shown in Table 1. The emissions are based on the design fuel blend. Emissions of GHGs are from combustion of the carbon in the fuel, limestone calcinations, the N_2O portion of NOx emissions, and methane from incomplete combustion. The GWP for each constituent is used to determine the CO_2 emissions in TPY for the facility and then converted to CO_2e in metric tons per year (mTPY).

---

[1] www.eia.doe.gov/oiaf/1605/coefficients.html
[2] http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html
[3] http://www.deq.state.mi.us/aps/downloads/permits/CFPP/2007/317-07/Updated_App_Appendix03.pdf

Table 1 – Greenhouse Gas Estimate

Source of CO_2	Emission Factor (1)		Maximum Consumption (4)		GWP (5)	CO_2 TPY	CO_2e mTPY
CFB Boiler							
Carbon in Fuel							
70/25/5% Pet coke/PRB/Biomass	211.1	lb/MMBtu	53,085,600	MMBtu/yr	1	5,603,716	5,083,691
Limestone Calcination	0.44	Ton/Ton (2)	267,180	TPY (3)	1	117,559	106,650
N_2O Portion of NOx	0.0033	lb/MMBtu	53,085,600	MMBtu/yr	310	27,153	24,633
Methane	0.0022	lb/MMBtu	53,085,600	MMBtu/yr	21	1,226	1,112
Total Maximum From CFB Units						5,749,655	5,216,087
Auxiliary Boiler							
Carbon in Fuel (Distillate Oil)	22.4	lb/MMBtu	289,600	MMBtu/yr	1	3,244	2,943
N_2O Portion of NOx	0.0013	lb/MMBtu	289,600	MMBtu/yr	310	58	53
Methane	0.0066	lb/MMBtu	289,600	MMBtu/yr	21	20	18
Black Start Generator							
Carbon in Fuel (Distillate Oil)	22.4	lb/MMBtu	1,960,000	MMBtu/yr	1	21,952	19,915
N_2O Portion of NOx	0.0013	lb/MMBtu	1,960,000	MMBtu/yr	310	395	358
Methane	0.0066	lb/MMBtu	1,960,000	MMBtu/yr	21	136	123
Emergency Generator							
Carbon in Fuel (Distillate Oil)	22.4	lb/MMBtu	13,965	MMBtu/yr	1	156	142
N_2O Portion of NOx	0.0013	lb/MMBtu	13,965	MMBtu/yr	310	3	3
Methane	0.0066	lb/MMBtu	13,965	MMBtu/yr	21	1	1
Diesel Fire Pump							
Carbon in Fuel (Distillate Oil)	22.4	lb/MMBtu	1,518	MMBtu/yr	1	17	15
N_2O Portion of NOx	0.0013	lb/MMBtu	1,518	MMBtu/yr	310	0.3	0.3
Methane	0.0066	lb/MMBtu	1,518	MMBtu/yr	21	0.1	0.1
Total Maximum From Facility						5,775,637	5,239,658

(1) All factors from the U.S. Energy Information Administration (www.eia.doe.gov/oiaf/1605/coefficients.html) unless otherwise noted.

(2) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Assumes that all added limestone is calcined and results in CO_2 emission.

(3) *Technology Selection Study - Exhibit 54 (pg 85), maximum of 30.5 TPH limestone make-up.*

(4) All values based on permit or design values.

(5) 40 CFR Part 98, Subpart A, Table A-1

3.0 BACT Evaluation for WCEV CFB Boilers

The following subsections present the case-by-case BACT evaluation for each of the proposed CFB boilers and the ancillary fuel-burning equipment.

3.1 CFB Boiler CO_2 Analysis

The following top-down BACT is performed in accordance with the USEPA's November 2010 GHG BACT Guidance.

Step 1 – Identify All Control Technologies

The possible control technologies identified for the CFB units at WCEV include CCS technologies, biogenic fuel augmentation, and energy efficiency. Control of N_2O and methane from the CFB boilers is not evaluated here. The N_2O emissions represent approximately 0.45% of the overall CFB CO_2e emissions. Methane represents approximately 0.02% of the overall CFB CO_2e and methane is already controlled using BACT level controls (good combustion control).

As with any exhaust gas treatment system, CO_2 capture is highly dependent on the CO_2 source. There are several CO_2 capture technologies that are oriented to the source of CO_2 and are not considered in this BACT review for a CFB boiler. These steam generating technologies involve processes that generate a more concentrated exhaust flow of CO_2. Examples of these steam generating technologies are Integrated Gasification Combined Cycle (IGCC) and Oxy-Fired Flue-Gas Recycle (or Oxy-Fired CO_2 Recycle boiler technology). IGCC was considered in the original WCEV application and rejected as not representing BACT. Oxy-fired technology involves replacement of combustion air with pure oxygen to create a more concentrated CO_2 flow in the combustion exhaust. This technology is in the early stages of development and is not considered commercially available in this review.

Step 2 – Eliminate Technically Infeasible Options

In the top down process, potentially applicable control technologies identified in Step 1 are further evaluated at Step 2 in order to eliminate any potentially applicable methods that are not technically feasible. Step 2 involves determining for each technology whether it is demonstrated, which means that it has been installed and operated successfully on a full-scale on a similar emission unit and has operated for a sufficient period of time. If an identified technology is not demonstrated, one must then assess whether the technology is both available and applicable.

Carbon Capture and Sequestration Discussion

There are two fundamental concepts in the control of CO_2 emissions from combustion sources – capture and sequestration. This process is collectively referred to as carbon capture and sequestration (CCS). CO_2 capture is the separation of CO_2 from emissions sources or the atmosphere. Sequestration is the means that are employed to keep the CO_2 out of the atmosphere on a long-term basis either through storage or conversion of the CO_2 into another form.

In CCS, CO_2 is recovered in a concentrated stream that is amenable to sequestration through storage or conversion. It is important to note that recovering CO_2 is expensive and involves capital and operation costs. The recovered CO_2 must then be transported through a pipeline to the sequestration site. The following sections present a discussion of CCS as they relate to the proposed WCEV facility. Information on the technologies under development is provided including a description of the technology, how it works, and where it is currently being developed. None of the technologies are currently considered to be demonstrated in practice and for the purpose of this review, are not considered to represent BACT for CO_2 for the WCEV.

CO_2 Capture

This report includes post-combustion CO_2 capture technologies currently under investigation that do not involve pre-combustion or the oxy-fuel approach to control – those technologies do not fit the WCEV business purpose and their application would mandate a redesign of the project. The technologies discussed include absorption processes (liquid), hybrid solution (mixed physical and chemical solvent), adsorption process (solid surface, ionic liquid), and physical separation (membrane, cryogenic separation). In addition absorption, adsorption, and physical separation, some researchers are investigating biological uptake of CO_2 in algae. These technologies are in various stages of development from the laboratory bench scale through pilot-scale demonstration. The following is a discussion of each of these emerging technologies.

CO_2 Capture Absorption Processes

Absorption processes under investigation for CO_2 capture include chemical and physical absorption. In chemical absorption, CO_2 is scrubbed from the flue gas through a chemical reaction with the scrubbing medium. In physical absorption systems there is no chemical reaction between the CO_2 and the scrubbing medium. Generally, the energy to regenerate, or desorb the CO_2 from the scrubbing medium, is greater for chemical absorption than physical absorption because the chemical reaction must be reversed in the chemical desorption regeneration process.

Chemical Absorption

Chemical absorption is characterized by the occurrence of a chemical reaction between the gas component being absorbed and a component in the liquid to form a compound. The most prevalent chemical absorbent under investigation for CO_2 removal from flue gas are amine solutions. An amine is a class of basic, nitrogen containing organic compounds derived from ammonia. Gas scrubbing systems employing amine solvents are used for a wide variety of gas or liquid hydrocarbon treating applications where hydrogen sulfide (H_2S) or CO_2 are present in a gas or in a liquid hydrocarbon feed stream. Close contact between the gas and the liquid amine solution is provided to promote the mass transfer of the target compound and the amine. Both H_2S and CO_2 have high solubility in the amine scrubbing solution. Several amine solvents are commercially used in amine scrubbing solutions including monoethanolamine (MEA), diethanolamine (DEA), triethanolamine (TEA), diisopropanolamine (DIPA), diglycolamine (DGA), methyldiethanolamine (MDEA), n-methylethanolamine (NMEA), alkanolamine and various proprietary mixtures of these amines. A simple amine scrubbing solution consists of one or more of these amine solvents diluted with water. The amine solvent concentration is typically in the range of 10-60%. The research on CO_2 capture from combustion sources has focused on the use of MEA and MDEA. Ammonia is employed as the chemical sorbent in Powerspan Corporation's ECO_2 process. Another organic-based chemical absorbent under consideration is potassium carbonate solution with a catalytic amount of piperazine; however, investigation of this material is in the early stages.

Other chemical absorbents currently under laboratory or bench-scale evaluation include a number of inorganic sorbents. A lithium-silicate based ceramic material developed by Toshiba is reported as having the ability to absorb up to 500 times its volume of CO_2. Regeneration of the material and release of the CO_2 occurs when the material is heated above 1,300 ^{o}F.

CO_2 capture using the carbination-calcination cycle with lime as the CO_2 sorbent material is also under evaluation. In this process CO_2 reacts with lime at temperatures between 1,100 and 1,500 ^{o}F to form calcium carbonate ($CaCO_3$). The $CaCO_3$ particles are then separated into a separate vessel for calcination at 1,650 ^{o}F where the CO_2 is liberated from the $CaCO_3$ and newly formed (regenerated) lime is formed for reinjection into the process. A pilot-scale reactor is currently under development. Other sorbent materials including sodium bicarbonate or sodium sesquicarbonate (trona) are being evaluated in the laboratory as suitable sorbents in the carbination-calcination cycle.

Physical Absorption

The chemical component being absorbed in physical absorption is more soluble in the liquid absorbent than other gas components in a gas mixture, but does not react chemically with the absorbent. Physical absorbents under investigation for CO_2 capture include propylene carbonate, Selexol™, Rectisol™ and Morphysorb™. Close contact between the scrubbing solvent and the gas forces the CO_2 into solution. The process is used commercially to remove CO_2 from natural gas in natural gas production. Although the energy required to regenerate physical sorbents is less than that of chemical sorbents, they are less effective than chemical sorbents at removing CO_2 from dilute gas streams.

Hybrid Absorption

Hybrid absorption involves a mixture of chemical and physical sorbents. In theory the sorbent mixture can be tailored to the specific application. The process is currently used to remove intermediate concentrations of CO_2 from natural gas in natural gas production.

CO_2 Adsorption

Laboratory evaluations of natural zeolite, manufactured zeolite molecular sieves, and activated carbon have all shown that these materials preferentially adsorb CO_2 over nitrogen, oxygen, and water vapor at elevated pressures. These materials show promise for CO_2 capture from high pressure gas streams such as those found in IGCC syngas. However, these materials have not shown high CO_2 capture potential for the dilute, lower pressure exhaust from a CFB unit. Desorption of the CO_2 is accomplished by reducing the pressure, known as a “pressure swing,” on the adsorbed CO_2, thus regenerating the adsorbent material and releasing the CO_2 for subsequent sequestration.

Physical Separation

The physical separation technologies available include membrane separation and cryogenic separation. The following is a brief discussion of each. These technologies are in the initial stages of investigation by researchers.

Membrane Separation

Polymer-based membrane separation of CO_2 is currently under investigation. Membrane separation is potentially less energy intensive than other methods because there is no chemical reaction or phase change in the process. Currently, potential membrane materials are prone to chemical and thermal degradation.

Cryogenic Separation

In cryogenic separation of CO_2, the gas is cooled and compressed to condense CO_2. This process is only effective on dry gas streams with very high CO_2 concentrations and is not applicable to the dilute gas streams from a CFB boiler.

Biological Uptake

There is ongoing research into algae strains that can uptake CO_2 from a concentrated stream and produce bio-fuel. The mechanism for CO_2 uptake is photosynthesis. This research is in the beginning stage and there are no commercial products available at this time for treating CO_2 from CFB exhaust.

CO_2 Sequestration Discussion

To achieve the objective of reducing the CO_2 in the atmosphere, CO_2 must be kept from the atmosphere once it is captured. This process is referred to as carbon sequestration. Carbon sequestration is the long-term isolation of CO_2 from the atmosphere through physical, chemical, biological or engineered processes. In theory, carbon sequestration can be achieved through storage in geologic formations or terrestrial ecosystems or conversion into commercial products. The following is a brief description of carbon sequestration and conversion.

Geologic Sequestration

Geologic sequestration refers to the injection and storage of captured CO_2 in a location where it will not readily escape into the atmosphere, such as within deep underground rock formations (typically 1 kilometer below ground surface) at pressures and temperatures where CO_2 is in the supercritical phase. In general, CO_2 storage is successful in porous, high permeability rock formations that are overlain by a continuous layer of low-permeability rock or other physical barrier, such as areas of trapped methane or saline water, where CO_2 may remain immobilized beneath the ground surface for extended periods of time.

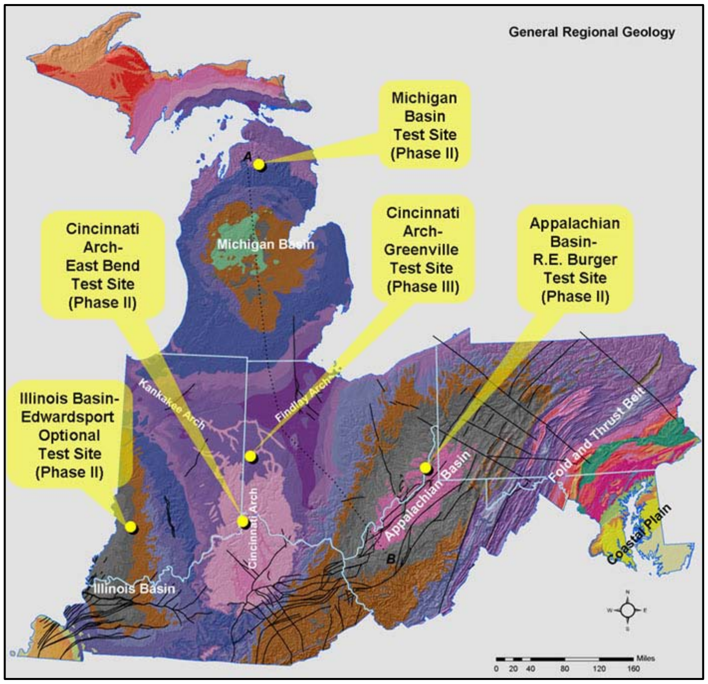
To achieve substantial reductions in atmospheric CO_2, geological storage must be utilized at a large scale. Saline sedimentary basins located beneath land or beneath the sea on the continental shelf are thought to represent one of the most ideal locations for the storage of CO_2, due to the potential storage capacity and broad distribution of these formations. Other geologic formations deemed suitable for geologic sequestration include coal beds that are too thin or deep to be cost effectively mined and depleted oil and gas reservoirs, where in addition to CO_2 storage, economic gains may also be achieved (most notably through the use of Enhanced Oil Recovery [EOR] to obtain residual oil in mature oil fields).

In the case of saline formations and depleted oil and gas reservoirs, the storage mechanisms involved include the immobilization of CO_2 by capillary forces; the dissolving of CO_2 in pore fluids; or precipitation of CO_2 as new carbonate minerals. In coal beds, CO_2 may be physically adsorbed onto the coal surface and displace other gases. An understanding of storage mechanisms at a local scale within these types of geologic formations is critical to determining the ultimate CO_2 storage capacity and feasibility of geologic sequestration in a particular area. Other factors to consider when determining the feasibility (both economically and physically) of geologic sequestration is the cost of transportation of captured CO_2 from the source to the ultimate geologic sequestration site; and the amount of measurement, monitoring (baseline, operational, etc.) and verification of CO_2 distribution required following injection into the subsurface to ensure the risk of leakage of CO_2 is minimized or eliminated. Additionally, feasibility is impacted by a number of legal issues not clearly addressed through statute or regulation. In Michigan, no developed law exists addressing the character of property rights which must be acquired and maintained for geologic sequestration or the liabilities and financial assurance that may be attached to such projects.

Michigan

Several “test sites” for the geologic sequestration of CO_2 are located in the vicinity of northern lower Michigan, most notably within saline formations associated with the Mount Simon, Sylvania and Saint Peter sandstones, which are thought to have a suitable geology for CO_2 storage. Studies are currently ongoing by the Midwest Regional Carbon Sequestration Partnership (MRCSP) to determine the suitability and feasibility of these formations for geologic sequestration. In early 2007, approximately 10,000 tons of CO_2 were injected into the subsurface near Gaylord, Michigan, and the site is currently in the CO_2 monitoring stage. Results from the test as of late 2008 indicated that geologic sequestration and monitoring techniques utilized at the site are reasonably effective and within the parameters of the initial models. While the amount of CO_2 injected at this test site was small, it is expected that the observations and results from this test may be utilized to assist in identifying other specific areas suitable of geologic sequestration.

Figure 1 - Midwest Regional Carbon Sequestration Partnership Test Sites



Source: MRCSP, 2008 (http://216.109.210.162/GeologicDemonstrations.aspx)

Terrestrial Sequestration

Terrestrial sequestration takes advantage of the concept that plants absorb CO_2 from the air during photosynthesis and ultimately metabolize and store carbon as tissue or transfer it to the soil. Terrestrial sequestration involves changing the management of forests, rangelands, agricultural lands and wetlands to either remove more CO_2 from the atmosphere or reduce CO_2 emissions from these ecosystems. This can be accomplished by the alteration of land management practices to decrease the decomposition of organic matter (which releases CO_2), to reduce accumulations of “fire fuels” (e.g., excessive brush), and to sustainably increase the rate of plant photosynthesis per acre. These practices can be enhanced by promoting land uses that tend to remove CO_2 from the atmosphere, such as green spaces and parks, and discouraging land uses that tend to increase CO_2 emissions, such as suburban development.

Terrestrial sequestration is generally simpler and less expensive than industrial CO_2 capture and geologic storage, but it has a lower ultimate storage capacity and requires that any changes to land use management be maintained for long periods of time to prevent inadvertent CO_2 releases (e.g., forest fires).

Summary of Existing Power Generation CO_2 Capture Projects

The following is a summary of the operating CO_2 capture projects on U.S. power generation facilities. It is important to note that none of the facilities treats the full exhaust flow. In addition, a number of the facilities has commercial markets for the captured CO_2; however, that CO_2 is not sequestered or converted, it is used in the food processing industry and presumably makes its way into the atmosphere.

> **AES Shady Point Power Plant, Oklahoma** – The Shady Point Power Plant is a 320 MW combined heat and power plant consists of two 160 MW, coal-fired CFB units. The facility supplies steam to the adjacent CO_2 production unit where a slipstream of the CFB flue gas is scrubbed using MEA solvent to produce 200 tons of CO_2 per day. The extracted CO_2 is used for food processing and related processes

AES Warrior Run Power Plant, Maryland – This facility is a 180 MW combined heat and power plant with a coal-fired CFB unit. The facility supplies steam to the adjacent CO_2 production unit where a slipstream of the CFB flue gas is scrubbed using MEA solvent to produce 150 tons of CO_2 per day. The extracted CO_2 is used for food processing and related processes.

Bellingham Cogeneration Facility, Massachusetts – The Bellingham plant consists of a 320 MW gas-fired combined cycle unit. The facility runs under base load conditions and provides steam to an adjacent Carbon Dioxide Recovery Plant. An MEA scrubber system is used to scrub the CO_2 from a 15% slipstream of the flue gas to produce 320-350 tons per day of high-grade carbon dioxide for sale to two major distributors. Capture costs are estimated to be approximately $100/ton. The end use of the CO_2 is in the food processing industry.

Pleasant Prairie Power Plant (P4), Wisconsin – This pilot project used chilled ammonia to capture CO_2 from a slipstream of the P4 facility. P4 is a 1,210-megawatt pulverized coal-fired generating station owned by We Energies. The pilot project began operation in March 2008 and concluded in 2009. The system achieved 90% CO_2 capture from the slipstream.

IMC Global Inc. Soda Ash plant, California – The IMC Chemicals Facility in Trona, California captures CO_2 using MEA solvent from the exhaust gas from the onsite combined heat and power generation. Captured CO_2 is used in carbonation of brine for the commercial production of sodium carbonate.

AES Mountaineer, West Virginia – This demonstration project uses the chilled ammonia process for post-combustion CO_2 capture of a slipstream of the exhaust. The process uses ammonium carbonate to absorb CO_2. The resulting ammonium bicarbonate is converted back to ammonium carbonate in a regenerator and is reused to repeat the process. The captured CO_2 is compressed into a liquid-like state and is injected into rock layers approximately 1.5 miles beneath the surface.

First Energy Burger Power Plant, Shadyside, Ohio – The ECO_2 pilot unit began operation on a slipstream from a 50-MW pulverized coal-fired unit at First Energy's Burger Power Plant in early 2008. The plan is to provide the captured CO_2 for sequestration on-site in an 8,000-foot test well. FirstEnergy is collaborating with the Midwest Regional Carbon Sequestration Partnership on the sequestration test project. The Burger pilot program could be the first such program to demonstrate both CO_2 capture and sequestration at a conventional coal-fired power plant.

All of these facilities use chemical absorption using either MEA or ammonia as the solvent. Published cost data for installation and operation of an MEA capture system are in the range of 140 – 460 $/kW (Göttlicher, G. The Energetics of Carbon Dioxide Capture in Power Plants, February 2004). The cost of CO_2 liquefaction, transportation, and sequestration are added on top of that. In addition, installation of a carbon capture system would reduce the net generating capacity of a plant by 29 – 35% depending on the technology.

CCS technologies are in the very early stage of development; consequently, very little information exists for these technologies. In 2010 Wolverine applied for CCS demonstration funds for the WCEV in response to the U.S. Department of Energy (USDOE) Solicitation DE-FOA-0000015 Section III D, "Large Scale Industrial CCS Projects from Industrial Sources" Technology Area 1. The demonstration project was to remove 1,000 metric tons per day of CO_2 from the WCEV. The design of the CCS demonstration system included Hitachi Power Systems America's CO_2 capture system and advanced amine technology to be provided by a Dow Chemical Company unit. The captured CO_2 was proposed to be compressed and transported for EOR and deep saline sequestration purposes. The projected capital costs for the demonstration project were estimated for purposes of responding to the USDOE solicitation and are included in the following step-by-step, top-down BACT review.

The current state-of-the-art of CCS is described in Section 3 of this report. The point of development of the capture technologies identified varies from conceptual through operation on a slipstream. The sequestration methods described in Section 3 are limited to geological and terrestrial sequestration. Conversion of captured CO_2 is mentioned, however, the effectiveness of conversion as a sequestration method is debatable and limited to specific opportunities. Wolverine applied for demonstration project funding from the USDOE to construct a CCS system at the WCEV. Burns and Roe Enterprises, Inc. conducted an engineering study to determine the appropriate CCS system for inclusion in the demonstration project for WCEV. Amine absorption was proposed under the USDOE grant with desorption/recovery, and EOR sequestration. The system was designed to remove 1,000 metric TPD CO_2, roughly 7% of the CO_2 emissions from the CFB units at WCEV.

A technology is considered available if it can be obtained by the permit applicant through vendors with commercial terms of sale. An available technology is applicable if it can reasonably be installed and operated on the source type under consideration. Conceptual, pilot-scale, or developing technologies are not considered available under BACT. Control technologies that require government subsidies, such as projects funded under the U.S. Department of Energy Clean Coal Program, are not considered available control technologies. Based on these criteria, all of the technologies identified in this Section 3 can be eliminated from further consideration; however, the CCS system proposed under the USDOE demonstration funding for WCEV is carried forward in this evaluation for informational purposes.

Biomass Fuel Augmentation

On February 3, 2011, the USEPA announced by July 2011 it plans to complete a rulemaking that will defer permitting requirements for CO_2 emissions from biomass-fired and other biogenic sources for three years. On March 14, 2011, the USEPA published a proposed rulemaking and its BACT guidance for bioenergy production. The USEPA's actions reflect a policy judgment that biomass combustion may be recognized as resulting in relatively low net or neutral production of CO_2e compared with fossil fuel combustion because the CO_2 generated during combustion of wood equals the CO_2 consumed during the lifecycle of the tree. The USEPA's March BACT guidance also states, "Renewable fuels policies, which in some cases provide incentives for the substitution of renewable fuels for fossil fuels, have not traditionally been part of the BACT energy impacts analysis. However, consideration of renewable energy policies could become part of the BACT analysis, especially if state policies mandate the replacement of fossil fuel with biogenic fuel."

This discussion of biomass fuel for the WCEV is to present specific information for the WCEV project.

Michigan, through legislation, has already made the policy judgment that biomass from sustainably managed resources is "renewable." Consistent with Michigan law and USEPA guidance, this BACT review considers the cellulosic biomass used as a co-firing fuel for the WCEV to be carbon neutral. A basis for this determination is found in the Life Cycle Assessment section (Section 3) of the attached (Appendix B) study conducted by Michigan Technological University (Biomass Co-firing for the Wolverine Clean Energy Venture, January 2008) and is further supported by the Michigan Renewable Portfolio Standard. Wolverine will utilize cellulosic biomass in accordance with the biomass condition in the draft MDEQ air quality permit (Draft Permit to Install No. 317-07). To ensure that all biomass utilized by the WCEV is procured from sustainable forest resources, Wolverine will procure cellulosic biomass from only the feedstock sources included in the State of Michigan's Renewable Portfolio Standard for biomass, including forest residue, short rotation woody crops and wood derived from sustainably managed forests as defined by MCL 18.1261c

Section 460.1003(f) of the Michigan Clean, Renewable, and Efficient Energy Act 295 of 2008 (Act 295) establishes the renewable portfolio standard for electric providers, including Wolverine's member cooperatives, as follows:

- Achieve a retail supply portfolio that includes at least ten percent renewable energy by 2015.
- Starting in 2012, electric providers must demonstrate compliance with renewable energy requirements through the purchase and/or production of Renewable Energy Credits (RECs).

Act 295 also provides that electricity generated from combustion of biomass fuel is renewable energy and provides a definition of biomass fuel for Michigan. In Act 295 biomass "means any organic matter that is not derived from fossil fuels, that can be converted to usable fuel for the production of energy, and that replenishes over a human, not a geological, time frame." The definition lists a number of specific biomass fuels including all of those identified in the Draft WCEV permit (Material Limit SC II.3.) as follows:

> Biomass is defined as non-chemically treated wood and wood residue, bark, or any derivative fuel or residue thereof, in any form, including but not limited to sawdust, sander dust, wood chips, scraps, slabs, millings, shavings, processed pellets made from wood or other forest residues, switchgrass, and other similar fuels.

The sustainability provisions included in MCL 18.1261c provides the following definition:

> . . ."sustainably managed forests or procurement systems" are those certified by an independent third party under one or more of the following certification programs:
>
> (a) The sustainable forestry initiative/American forest and paper association;
>
> (b) The American tree farm systems/American forest foundation;
>
> (c) The Canadian standards associations sustainable forest management system standards;
>
> (d) The forest stewardship council;
>
> (e) The Pan-European forest certification;
>
> (f) The Finnish forest certification system;
>
> (g) The United Kingdom woodlands assurance scheme;
>
> (h) International standards organization (ISO) standard 14001.

The implementation of a sustainability standard for the use of biomass by the WCEV is the key to documenting the carbon neutrality of the cellulosic biomass utilized by the WCEV. While the science of carbon mitigation and biomass is relatively young, several studies have documented the ability to increase forest carbon stocks while sustainably utilizing forest growth for bionenergy fuel production[4]. Other forest management practices such as "forest preservation" can mitigate carbon emissions. However, the IPCC has concluded that the practice of sustainable forest management is the most effective forest land management carbon mitigation strategy. "[I]n the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fiber or **energy from the forest**, will generate the largest sustainable mitigation benefit."[5]

WCEV Investigations into Co-Firing Biomass

Wolverine has investigated the feasibility of co-firing biomass at the proposed WCEV CFB boilers. As established in the permit record, CFB boilers are well suited to firing a variety of solid fuels. There are a number of limiting factors for co-firing biomass at the WCEV including a sustainable supply of woody biomass, material handling equipment, and the impact on plant efficiency (heat rate). The following is a discussion of these limiting factors on the WCEV project.

Generally, the optimal size of a stand-alone, 100% biomass-fired electric generating unit is 50 MW (gross), and the radius of fuel source is between 50 and 75 miles. Wolverine commissioned a study conducted by Michigan Technological University (Biomass Co-firing for the Wolverine Clean Energy Venture, January 2008). The study investigated the availability of forest residuals within a 75 mile radius of the proposed plant. The

---

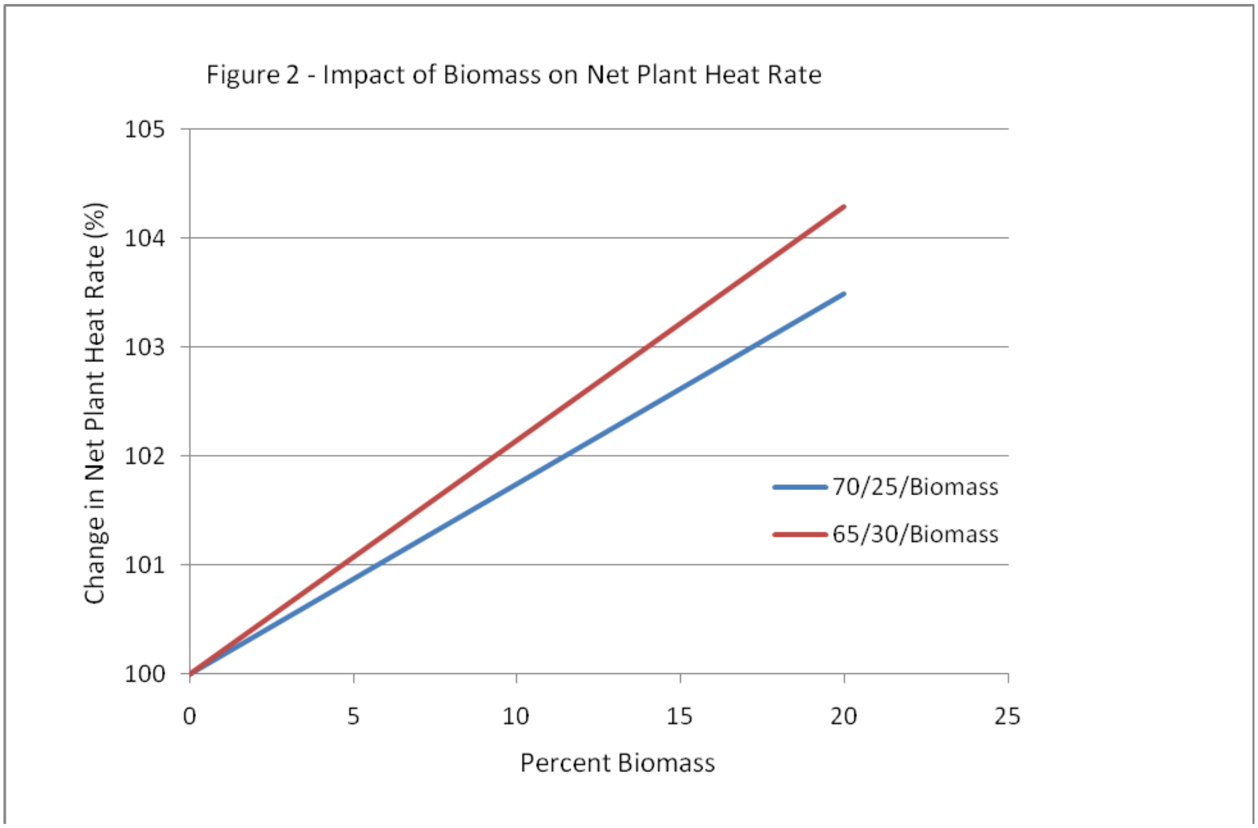
[4] Eriksson, H., Hall, J., and Helynen, S., 2002, Rationale for Forest Energy Productions. In Richardson, J., Bjorheden, R., Hakkila, P., Lowe, A., Smith, C (Eds.) *Bioenergy from Sustainable Forestry: Guiding Principles and Practice,* Kluwer Academic Publishers, Dordreht, Netherlands, pp-1-17.

[5] IPCC Fourth Assessment Report, working Group III, Chapter 9, Executive Summary.

study concluded that the forest resource within the study area, under appropriate management, could sustainably generate over 890,000 greens tons of woody biomass annually including approximately 286,000 green TPY of forest residuals.

The material handling system design of WCEV facility can handle a limited amount of biomass before additional separate material handling must be designed and installed. Biomass fuel handling and preparation systems have different requirements than coal and petroleum coke (pet coke) handling. A separate system for receiving and handling biomass fuel is required. The biomass subsystems include all equipment associated with the receipt of biomass, fuel storage, material sizing, and conveyance of biomass to the inlet of metered feeding bins. This equipment includes truck scales, conveyors, stacking equipment, reclaiming systems and metering bins. This equipment would result in an added cost to the project and was not included in the design when the air pollution control permit application was submitted in September 2007. In addition, a separate biomass material handling system would result in a separate particulate emission source at the planned facility.

Finally, the heat rate of the planned CFB units would be significantly degraded by the addition of more than 5% of the heat input. The heat rate degradation is due to the moisture in the biomass. The moisture in the biomass must be driven off in the combustion process, making combustion heat transfer less efficient. Figure 2 shows the increase in heat rate when combusting the design fuel with biomass. The fuel mix represented is 70% pet coke, 25% PRB coal, and 5% biomass.



Co-firing biomass in partial substitution for fossil fuels is a viable means of reducing fossil fuel derived CO_2 emissions from the planned WCEV facility and the technology is carried forward in this review for further evaluation.

Energy Efficiency

The November 2010 USEPA guidance for GHG BACT reviews as part of NSR permitting (PSD and Title V Permitting Guidance for Greenhouse Gases, Prepared by the Office of Air Quality Planning and Standards USEPA, November 2010) states that in step 1 of the BACT process the following may be considered:

- Add-on Controls,
- Inherently Lower-Emitting Processes/Practices/Designs, and
- Combinations of Inherently Lower Emitting Processes/Practices/Designs and Add-on Controls.

Add-on controls for GHG control have been addressed in Section 3 of this BACT review. Inherently lower-emitting processes, practices, and designs for a CFB are related to the efficiency of the CFB design and operation. There are a number of different ways to describe and assess the efficiency of a thermal power generating facility. There exist published performance test procedures such as those from the American Society of Mechanical Engineers (ASME) that can be used to define the efficiency of a thermal power generating facility; however, these tests are not rigorously applied as a standard and claims to unit efficiency are consequently not directly comparable from unit to unit. The efficiency of a thermal power generating plant is a relative term that is used to compare unit performance in general. Some of the common terms used to describe thermal power generating efficiency include heat rate, Carnot efficiency, rational efficiency, effective electrical efficiency, and energy utilization factor. Heat rate is the most common measure of efficiency in the electric power industry and is expressed in terms of British Thermal Units per kilowatt hour (Btu/kWh) of electrical output. As the heat rate reduces, the plant efficiency increases.

The heat rate of a unit can be expressed on either a gross or net basis. The net heat rate accounts for the energy consumed to operate the plant, also known as the parasitic load. Parasitic loads are created by integral parts of the electrical generating unit including parts such as the fans, air pollution control, cooling cycle (heat rejection), fuel handling and processing equipment. In addition to parasitic load, thermal losses in the process contribute to the efficiency of converting fuel into electrical energy. The following is a discussion of the energy efficiency considerations at the planned WCEV facility.

Circulating Fluidized Bed Technology

In 2009 construction of the first supercritical CFB boiler was completed in Lagisza, Poland (Lagisza Power Plant) at a reported cost of $279,000,000 (boiler island only). The CFB unit at the Lagisza Power Plant is 460 MW (gross). The unit has undergone initial start-up; however, there is limited information on the results of performance testing. In theory, the steam turbine efficiency increases by up to 3 % when operated by supercritical steam as opposed to conventional, subcritical steam. The calculated LHV net plant efficiency for Lagisza is reported as 43.3% and net power output is 439 MW.

The Lagisza unit emission limits are 0.14 lb/MMBtu SO_2, 0.14 lb/MMBtu NOx, and 0.02 lb/MMBtu filterable particulate matter. There is no add-on control for SO_2 or NOx for the Lagisza unit. The SO_2 emissions are controlled by limestone feed to the CFB and NOx is controlled through the inherent low combustion temperature of CFB boilers. Neither of these control methods would be accepted as meeting BACT in the U.S.. It is likely that a polishing scrubber for SO_2 control and selective non-catalytic reduction would be required in the U.S. – both of these air pollution control technologies add a parasitic load to the unit and thus degrade the overall plant efficiency.

The design gross plant heat rate (HHV) for Lagisza is 7,850 Btu/kWh (gross) due in large part to the flue gas heat recovery system. Such a heat recovery system would not be available in the US because the system precludes the use of a polishing scrubber and SNCR. No U.S. CFB unit would be able to meet BACT for SO_2 without a polishing scrubber or BACT for NOx without an SNCR system. The Lagisza SO_2 and NOx limits would far exceed any BACT limits. In addition, the Lagisza unit has a once-through cooling system. No U.S. CFB unit would be able to be permitted with once-through cooling. If designed without the flue gas heat recovery system, with SO_2 and NOx control and with cooling towers the Lagisza gross heat rate would be approximately 8,270 Btu/kWh (gross), comparable to the design value of the WCEV units at 8,262 Btu/kWh (gross; calculated as 90% of design net heat rate of 9,180 Btu/kWh).

Finally, the Lagisza CFB boiler is operating on European bituminous coals. The WCEV needs to be able to burn a variety of eastern and western U.S. coals as well as pet coke and biomass. If the WCEV pursued the supercritical design, it would be the first to be designed to accommodate such a wide range of coals and biomass and Wolverine is not able to take that business risk. Given that the Lagisza unit is the first of its kind, supercritical CFB technology is still considered a developing technology and is viewed as not consistent with the business purposes of the WCEV facility.

Parasitic Load

Table 2 shows an approximation of the parasitic load contribution from various components of the planned WCEV CFB units. Each of these contributes to a degradation of the overall plant electrical generation efficiency. The system components included in the design are there to meet plant operation requirements and various environmental requirements like air pollution control and plant cooling water. For example, the combination of cooling water pumping and cooling tower operation account for a 4.2% parasitic load. Although cooling water is readily available for the WCEV (Lake Huron), environmental considerations and regulatory uncertainty have lead the design of the WCEV away from once-through cooling. For plants that have once-through cooling systems, the parasitic load due to plant cooling is reduced to an impact of greater than 2% but less than 4.2%, because the load impact of increased pumping in once-through cooling is offset by the elimination of cooling tower operation.

Table 2 - Approximate Parasitic Loads at WCEV

System Component	Approximate Load Impact on Gross Capacity	Nature of Impact on Gross Capacity and Heat Rate
Air Pollution Control	3.00%	Due to air pollution control including the polishing scrubber, SNCR, and fabric filter.
Cooling Water	2.00%	Impact related to condenser losses.
Cooling Tower	2.40%	Operation of "closed cycle" cooling as opposed to once-through cooling.
Major Fans	2.50%	Forced draft, primary air, and induced draft fan operation.
Other	0.10%	Includes material handling, air heater operation, instrument air, and plant thermal and electrical demands.
Total	10%	Approximate

In the design and specification of large-scale power plants best engineering practice dictates that the design firm specifies cost effective, efficient electrical and thermal components that contribute to the plant heat rate. The end purpose of the plant is to produce economical electrical power for the grid and not for the purpose of running the plant. To this end, there are a number of design specifications that directly address minimizing the plant heat rate including the following:

- Specify variable speed motors for all motors over a size threshold,
- Minimize the pressure drop across the air pollution control devices,
- Maximize the thermal performance of heat transfer components both for insulation and heat exchange, and
- Follow the manufacturer's O&M guidelines for energy consuming plant components.

Incorporating energy efficiency into the design of the WCEV facility is carried forward in this BACT analysis for further evaluation.

Step 3 – Rank Remaining Control Technologies

The CCS system proposed under the USDOE demonstration funding for WCEV, biomass fuel augmentation, and energy efficiency are the control technologies carried forward. The technology with the most potential for control of CO_2 emissions is CCS followed by biomass fuel augmentation and then energy efficiency.

Step 4 – Evaluate and Document Most Effective Controls

The following is an evaluation of CCS, biomass fuel augmentation, and energy efficiency for the WCEV project. The evaluation is presented in order of effectiveness with CCS presented first followed by biomass fuel augmentation, then energy efficiency.

CCS

Table 3 shows the CCS system costs proposed under the USDOE demonstration funding for the WCEV. The capital costs, fixed O&M costs, and the variable O&M costs are taken directly from the USDOE demonstration project report (Wolverine Carbon Capture and Storage Project Phase 1 Draft Topical Report, USDOE Cooperative Agreement #DE-FE0002477, March 29, 2010). The capital costs are annualized over 20 years at 7% interest. The resultant cost effectiveness of the CCS technology is $126 per ton of CO_2e removed.

Table 3 – Carbon Capture and Sequestration Costs for WCEV

Years	20
Interest Rate	7
Capital Recovery Factor	0.094
Capital Costs	$ 210,060,000
Fixed O&M (years 2 - 20)	$ 8,223,000
Variable O&M	$ 9,663,000
Annual Capital Cost	$19,828,178
Annualized Cost	$37,714,178
CO_2 Removed (metric TPY CO_2e)	300,000
Cost Effectiveness ($/ton)	126

Determining an appropriate threshold cost for CO_2e is a challenge. For comparison purposes, one could calculate the threshold value of cost effectiveness for CO_2e based on the relative cost effectiveness of control of a criteria pollutant at some threshold value per ton of pollutant removed and the major source threshold of 100 TPY. This approach is supported by the USEPA's own rulemaking under the "Tailoring Rule." Through rulemaking, the USEPA has "tailored" greenhouse gases such that 100,000 tons of CO_2e is equal to100 tons of a criteria pollutant for the purpose of PSD applicability. So, by USEPA's own rulemaking construct, if a criteria pollutant has a cost effectiveness threshold in the range of $8,000 per ton, then the CO_2e cost effectiveness should be 0.001 times as much, or $8/ton controlled. Based on this criterion, the CCS demonstration system for the WCEV is found to be infeasible based on cost.

Biomass Fuel Augmentation

Wolverine has determined that the current design of the facility as proposed can combust up to 5% of the heat input as biomass without redefining the project by forcing substantive changes to the auxiliary equipment. Based on an average biomass heat content of 4,670 Btu/lb at 45% moisture, a maximum heat input to the boilers of 6,060 MMBtu/hr and a capacity factor of 0.90, the annual usage of biomass at WCEV is 255,000 TPY (green). This usage rate is consistent with the biomass resource documented in the Michigan Technological University study as available proximate to the proposed facility. This will result in a reduction of over 257,000 mTPY (284,000 TPY) of CO_2e emissions from fossil fuels.

Energy Efficiency

Wolverine's business purposes include to design, construct and operate a reliable, economical and energy efficient plant and will instruct the design engineers to optimize the energy efficiency through the design specification for the plant. This will include specification of cost effective variable speed motors for all system components with a motor over 100 horsepower, balancing the pressure drop across air pollution control system components with system performance, consideration of plant thermal component efficiency, and following the manufacturer's guidelines on O&M of plant components.

Step 5 – Select BACT CFB Boilers

BACT is determined to be the following:

- Combustion of at least 5% biomass on a heat input basis on a 12-month rolling average,
- Specification of cost effective variable speed motors for all system components with a motor over 100 horsepower, and
- Following the manufacturer's guidelines on O&M of plant components

These steps will result in a reduction of 4.7% of CO_2e emissions attributable to fossil fuel combustion. The total CO_2e emission from the CFB units will be capped at 5,722,000 short tons of carbon dioxide per 12-month rolling average. The 5,722,000 short tons will be directly measured with continuous emission monitors at the CFB stack and represents the CO_2 emissions from the carbon in the fuel and limestone calcinations in the CFB bed.

3.2 Ancillary Fuel-burning Equipment

The following subsections present information on control of GHG emissions from the ancillary fuel-burning equipment at the planned WCEV facility. This equipment includes the auxiliary boiler, black start generator, emergency generator, and diesel-fired fire pump. All of the ancillary fuel-burning equipment fire distillate fuel oil. There is no natural gas available at the site, so fuel oil is the only feasible fuel option.

Step 1 – Identify All Control Technologies

The control technologies available for control of GHG emissions from oil-fired equipment include CCS and energy efficient design. Control of N_2O and methane from the CFB boilers is not evaluated here. The N_2O emissions represent approximately 0.45% of the overall CFB CO_2e emissions. Methane represents approximately 0.02% of the overall CFB CO_2e and methane is already controlled using BACT level controls (good combustion control).

Step 2 – Eliminate Technically Infeasible Options

In the top down process, potentially applicable control technologies identified in Step 1 are further evaluated at Step 2 in order to eliminate any potentially applicable methods that are not technically feasible. Step 2 involves determining for each technology whether it is demonstrated, which means that it has been installed and operated successfully on a full-scale on a similar emission unit and has operated for a sufficient period of time. If an identified technology is not demonstrated, one must then assess whether the technology is both available and applicable.

A technology is considered available if it can be obtained by the permit applicant through vendors with commercial terms of sale. An available technology is applicable if it can reasonably be installed and operated on the source type under consideration. Conceptual, pilot-scale, or developing technologies are not considered available under BACT. There are no CCS options available for the ancillary fuel-burning equipment at the WCEV; therefore, CCS is eliminated from further consideration.

The specification and operation of the ancillary fuel-burning equipment is the only opportunity to reduce the GHG emissions from these sources. The auxiliary boiler, black start generator, emergency generator, and diesel-fired fire pump each have inherrent energy efficiency features that can be included in a performance specification. In addition, following the equipment manufacturer's recommendation on proper O&M will ensure that the design efficiency is maintained as fully as possible over the course of the life of the equipment.

Step 3 – Rank Remaining Control Technologies

Energy efficiency through the performance specification and proper O&M practices are the only remaining GHG control techniques for the ancillary fuel-burning equipment.

Step 4 – Evaluate and Document Most Effective Controls

Energy efficiency through the performance specification and proper O&M practices are the only remaining GHG control techniques remaining for the ancillary fuel-burning equipment.

Step 5 – Select BACT

BACT for CO_2 emissions from the ancillary fuel-burning equipment at the proposed WCEV CFB units is as follows:

- Specify energy efficient and cost effective equipment, and
- Follow the manufacturer's recommended O&M practices.

4.0 Conclusion

Through this BACT review it is determined that GHG control represents for the proposed WCEV CFB units is as follows:

- Combustion of at least 5% biomass on a heat input basis,
- Specification of cost effective variable speed motors for all system components with a motor over 100 horsepower, and
- Following the manufacturer's guidelines on O&M of plant components.

The total CO_2e emission from the CFB units will be capped at 5,722,000 short tons of carbon dioxide per 12-month rolling average. The 5,722,000 short tons will be directly measured with continuous emission monitors at the CFB stack and represents the CO_2 emissions from the carbon in the fuel and limestone calcinations in the CFB bed

BACT for the ancillary fuel-burning equipment at the facility is proposed as follows:

- Specify energy efficient and cost effective equipment, and
- Follow the manufacturer's recommended O&M practices

Appendix A

RBLC Entries

Carbon Dioxide Limits Listed in the RACT/BACT/LAER Clearinghouse Database

RBLC ID: TX-0361 (Permit issued 10/08/98)
Corporate/Company: EQUISTAR CHEMICALS, LP
Facility Name: EQUISTAR CHEMICALS, LP
Process: (2) USC FURNACES M - N
Pollutant: Carbon Dioxide
Controls No Feasible Controls
Emission Limit 1: 14.1000 LB/H EACH
Emission Limit 2: 61.8000 T/YR EACH
Standardized: 0.0500 LB/MMBTU EACH, CALCULATED

RBLC ID: TX-0347 (Permit issued 10/16/01)
Corporate/Company: BP AMOCO CHEMICAL COMPANY
Facility Name: CHOCOLATE BAYOU PLANT
Process: DECOKE STACK, DDF-101
Pollutant: Carbon Dioxide
Controls No Feasible Controls
Emission Limits:
Emission Limit 1: 36.5000 LB/H
Emission Limit 2: 7.2000 T/YR

RBLC ID: TX-0481 (Permit issued 11/02/04)
Corporate/Company: AIR PRODUCTS LP
Facility Name: AIR PRODUCTS BAYTOWN I I
Process: EMERGENCY GENERATOR
Pollutant: Carbon Dioxide
Controls No Feasible Controls
EMISSION LIMITS: Unknown
Emission Limit 1: 2.2400 LB/H
Emission Limit 2: 0.9900 T/YR

RBLC ID: AL-0231 (Permit issued 06/12/07)
Corporate/Company: NUCOR CORPORATION
Facility Name: NUCOR DECATUR LLC
Process: VACUUM DEGASSER BOILER
Pollutant: Carbon Dioxide
Controls No Feasible Controls
EMISSION LIMITS:
Emission Limit 1: 0.0610 LB/MMBTU
Emission Limit 2: 5.8000 LB/H

RBLC ID: LA-0148 (Permit issued 05/28/08)
Corporate/Company: RED RIVER ENVIRONMENTAL PRODUCTS LLC
Facility Name: ACTIVATED CARBON FACILITY
Process: MULTIPLE HEARTH FURNACES / AFTERBURNERS
Pollutant: Carbon Dioxide
Controls: Add-on Control Equipment
Add-on Description: AFTERBURNER AND GOOD COMBUSTION PRACTICES
EMISSION LIMITS:
Emission Limit 1: 37.6000 LB/H 3-HOUR

Appendix B

Michigan Technological University Study

Biomass Co-Firing for the Wolverine Clean Energy Venture

An Environmental Sustainability and Life Cycle Analysis of Biomass for Bioenergy

Robert E. Froese and Chris A. Miller
School of Forest Resources and Environmental Science

David R. Shonnard and Ken Koers
Department of Chemical Engineering

Dana M. Johnson, Madeleine Norman and Cassie Miller
School of Business and Economics

FINAL REPORT

January 30, 2008

Michigan Technological University
1400 Townsend Drive
Houghton, Michigan 49931 USA

Tel: 1-800-WOODS-MI
Email: froese@mtu.edu
Web: www.mtu.edu

Executive Summary

The purpose of this study is to examine the feasibility and sustainability of biomass co-firing as part of the proposed Wolverine Power Cooperative Clean Energy Venture (WCEV) near Rogers City, Michigan. The study focuses on a typical "bioshed", extending 75 miles from Rogers City, and includes areas in the Northern Lower and Eastern Upper Peninsulas of Michigan.

Biomass Resource Assessment

Our analysis shows that unused logging residues and other removals from timberland within 75 miles of Rogers City total about 220,000 dry t·yr^{-1}, sufficient alone to meet the estimated requirements to initiate co-firing at more than 6.5%. However, average harvest levels in the Northern Lower Peninsula are only about 1/3 of current growth, suggesting that much higher harvest levels are sustainable given sufficient demand for the resource. If the totality of this biomass were utilized, co-firing at more than 20% would be feasible using existing forest biomass alone and a supply radius of substantially less than 50 miles. Much of this biomass is likely put to better use as a raw material for high-value forest products, such as sawlogs, veneer or poles. If the full potential of Michigan forests were to be utilized for conventional forest products, and only residues were available for co-firing, within 100 miles residues alone would still be sufficient for co-firing at more than 20%. Clearly, substantially more biomass is available than is necessary for the Wolverine Clean Energy Venture to initiate co-firing, within a 75-mile transportation distance.

Over the longer term, land resources for the development of dedicated energy crop systems are not a limiting factor in the given study area. Within 75 miles of Rogers City more than 490,000 acres of "herbaceous open land", likely abandoned agricultural lands, are present and likely suitable for energy crop production. Which energy crop is best for those lands would depend on such issues as the relative cost for establishment and harvest, site quality and operability, and how the feedstock quality fits with the bioenergy production system considered. At a conservative production rate of even 2 dry t·ac^{-1}·yr^{-1}, these lands would yield more than 980,000 dry t·yr^{-1}, realized without replacement of current commodities grown on cropland. This obviates any concerns about competition with other agricultural commodities. Price remains an important consideration, but our results suggest biological potential and land availability is far from limiting the potential for co-firing at the WCEV for the long term.

Some evidence suggests that the substantial untapped potential for biomass production in the Northern Lower Peninsula is at least partly explained by low market prices that are insufficient to stimulate utilization. Yet, pressure is rapidly mounting for increased production of renewable energy and offsetting of anthropogeneous carbon emissions. Developing biomass for bioenergy in Michigan would be facilitated by regionalizing national-scale information on cost, productivity and sustainability. The highest-priority research needs are in agricultural and open-land conversion and restoration, feedstock productivity, and carbon storage and cycling in biomass production systems. Increased, localized understanding of the costs, outputs and environmental profiles has the potential to reduce the threshold both of the risk premium required for private investment and the level of subsidy required to stimulate bioenergy production.

Neither inherent productivity nor environmental sustainability is holding back biomass production. Clearly, Michigan and Wolverine have the potential to be national leaders in renewable bioenergy production.

Life Cycle Assessment

Life cycle assessment is a methodology to evaluate environmental impacts, energy consumption, resource depletion, and other impact categories for an entire product system. The goal of this LCA is to compare the environmental effects of standard technology for generating power from coal to several scenarios intended to reduce the carbon dioxide emissions, while comparing the total amount of **fossil energy** used to do so as well as **greenhouse gases emitted**. Biomass co-firing ranging from 1 – 20% displacement of coal was simulated, and different sources of biomass were included: logging residues, a woody crop (a managed aspen stand), and switchgrass. Geologic sequestration of CO_2 as well as use of forest sequestration was also included as scenarios.

These LCA results indicate that co-firing with logging residue is the optimal approach to maximize both fossil energy and greenhouse gas savings. Compared to the coal-fired base case, 20% co-firing with logging residues reduced fossil energy consumption per kWh of electricity generated by (12.2-9.03)/12.2 (100) = 26.0% and decreases CO_2 (eqv.) emissions by 19.8%. Geologic sequestration shows promise, but would require higher sequestration rates than 20% to show improvement in GHG savings over the 20% co-firing scenarios. However, to capture 20% of the CO_2 in managed stand growth would require close to 85,000 hectares.

A Note on Units and Standards

A surprising lack of disclosure is given in works reporting potentials for biomass productivity and inventory in the United States. While most units follow usual conventions, little clarity or consistency exists for conversion of woody biomass from conventional forestry measures (e.g., “cords”) to standardized mass (e.g., dry tons).

Unless otherwise noted, we adopt the following Units and Standards for woody biomass:

- For wood, in general 1 ft^3 of solid wood = 30 lb. dry mass (Perlack et al. 2005)
- The Higher Heating Value (HHV) for wood, bone dry, is 7,500 Btu per lb
- “Dry” means “field dry” or approximately 15% moisture
- 1 t = 1 ton = 2000 lb.
- 1 cord = 85 ft^3 of solid wood, including bark

Table of Contents

List of Tables

List of Figures

1 Introduction

Co-firing of biomass as part of the Wolverine Clean Energy Venture, near Rogers City, MI, provides an opportunity to mitigate the environmental impacts of base-load generation using locally produced, sustainable energy resources. When wood is co-fired with coal or petroleum coke, the substitution involves replacing a fossil carbon source with a climate neutral carbon source. The greater the substitution, the greater the benefit (Figure 1). Co-firing may also generate co-benefits; where lands are converted to biomass feedstock production the cropping system may increase sequestration of carbon in soils and the litter layer, offsetting some of the fossil carbon release. In Michigan, forests provide a readily available source of biomass, either in the form of residues from forest harvesting, sawmilling or from intermediate treatments like thinning and tending of existing stands. These may be augmented with biomass from dedicated plantings, using native species mixtures or crops such as willow, poplar or switchgrass. Alternative benefits may be obtained through co-location that utilizes waste heat and CO_2 sequestration projects that operate in parallel with electric generation.

The purpose of this study was to examine technical and economic issues, feasibility and sustainability of biomass co-firing as part of the proposed Wolverine Power Cooperative Clean Energy Venture near Rogers City, Michigan. Specifically, through this project, we addressed the following questions:

1. What is the nature of the biomass feedstock resource within the feasible supply “bioshed” near the proposed facility?
2. Is a sufficient and affordable biomass supply available to initiate co-firing?
3. Over the longer term, what are the impacts of biomass production on biomass price and supply and the environmental and ecological sustainability of forest resources?
4. What potential exists for utilization of alternative feedstocks, such as switchgrass or willow cultivated as dedicated energy crops?
5. How does biomass co-firing compare to conventional fueled generation in a Life Cycle Assessment, considering fossil energy, total energy, byproducts and waste generation?
6. What near term opportunities exist for CO_2 sequestration through forest management activities?

Figure 1. Illustration of substitution of climate-neutral biomass fuels are co-fired with fossil fuel.

1.1 Biomass Feedstock Requirements

The amount of biomass required for co-firing at different percentages may be calculated knowing the overall plant capacity, heat content of the biomass feedstock, and the planned operating schedule. We calculated requirements assuming a total plant heat rate of 6,060 MMbtu/hr, a capacity factor of 95% and a heat content of 7,500 Btu/lb for dry biomass. Results are shown in Table 1, for a variety of levels of co-firing. Depending on the type of biomass selected, the feasibility of burning a certain percentage of biomass may change. Readily available, unutilized sources of biomass may create an opportunity to co-fire a higher percentage while high-demand biomass may only offer lower co-firing potential.

1.2 Relationship to Other Reports

In recent years, a number of high-profile studies have been published that address the potential for a bioenergy industry and describe a vision for technology and industry development. The seminal report addressing the potential for a sustainable biomass feedstock supply is the "Billion Ton Vision", jointly published by the US Department of Agriculture and the Department of Energy (Perlack 2005). Complementing these reports have been a number of state-level analyses of sustainable feedstock supply. For example, comprehensive assessments were completed for Wisconsin in 2006 (Willyard and Tikalsky 2006) and Vermont in 2007. In Michigan, Simpkins (2006) appraised the potential for bioenergy from wood residues, and Launder (2002) examined the potential for dedicated energy crops in the State. Notably, these studies all draw from national-scale studies when they assess supply and price.

In this study, all project activities were framed in the context of the proposed Wolverine Clean Energy Venture (WCEV), near Rogers City, MI. Though many of our analyses drew from prior national-scale studies and national databases, regionalizing this information was our primary concern. We discovered that, in many cases, sufficient information simply is not available to draw strong conclusions, and this has guided our recommendations for future research, study and analysis. Like related national and regional reports, however, we concluded that the potential for bioenergy in general, and co-firing using biomass at the WCEV is tremendous.

Table 1. Biomass requirements for a variety of hypothetical co-firing rates at the WCEV.

Co-Firing Rate	Generation (MW)	Feedstock (dry t·yr^{-1})
20%	120	672,418
15%	90	448,279
10%	60	336,209
5%	30	168,105
1%	6	33,621

1.3 Study Area

The study bioshed for this report extends approximately 75 miles from Rogers City, and includes areas in the Northern Lower and Eastern Upper Peninsulas of Michigan (Figure 2). In studies of biomass for bioenergy, the feedstock supply areas, or "biosheds", usually extend no more than 75 miles from the proposed facility, because of diminishing returns due to high transportation costs for feedstocks beyond this range.

Land cover in the region is predominately forest, and has high outdoor recreational and aesthetic values, surrounded by the Great Lakes of Michigan, Huron, and Superior. Intermixed with the forest are areas of agriculture production abandoned from past activity and currently viable. The Northern Lower Peninsula is home to three State Forests, the Au Sable in the eastern portion, the Pere Marquette to the west, and the Mackinac in the northern tip. The Lake Superior State Forest dominates the portion of the Upper Peninsula included in the study area. Also found in this region are three National Forests: the Huron and Manistee in the Lower Peninsula and the Hiawatha in the Upper Peninsula.

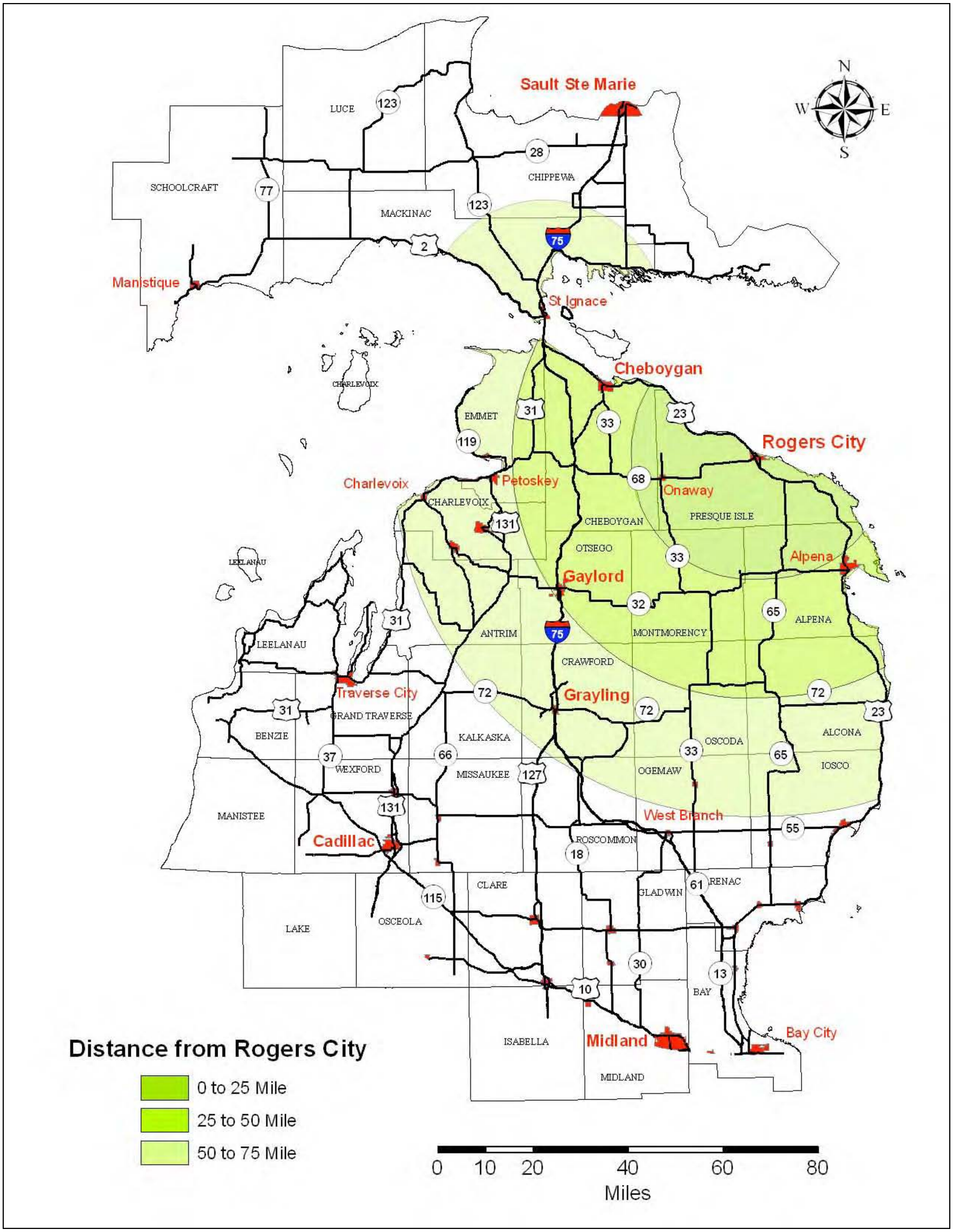


Figure 2. Geographic context for the WCEV with distance bands. The typical 75-mile bioshed is indicated in green.

2 Biomass Resource Assessment

2.1 Introduction

If co-firing with biomass, the WCEV will utilize relatively low-impact, clean fuels available in bulk from stable sources. Thus, we did not consider municipal waste, construction and demolition waste, and other materials such as tires and railroad ties. We distinguished production systems in terms of intensity. Dedicated energy crops were grouped together, though they include both woody species and grasses. Low intensity crops included managed forests that utilize native species and low intensity forage crops.

2.1.1 Dedicated Energy Crops

Dedicated energy crops are fast-growing plants cultivated in an agricultural setting usually as monocultures and managed to maximize biomass production. The most promising energy crop systems include the perennial grasses switchgrass (*Panicum virgatum* L.) and *Miscanthus* (*Miscanthus* spp.), and woody species of willow (*Salix* spp.) and poplar (*Populus* spp) (Figure 3). All but *Miscanthus* are native species in the United States, and have been established operationally or in test plots to examine their potential. Woody species have an advantage over grasses in some applications because they may be harvested year-round while grasses are harvested only in fall or early winter.

For all dedicated energy crops careful control and optimization of the production system using monocultures of fast-growing species is used to ensure the highest possible biomass production. Breeding and biotechnology programs are being promoted as ways to increase yield further in the future (US DOE 2006). Establishment nearly always involves aggressive tillage, multiple herbicide applications and several applications of fertilizer or irrigation.

The *Miscanthus* species used in biomass production is a naturally occurring sterile hybrid (*Miscanths* x *giganteus*) from Asia. European experience suggests yields in the range of 4-11 dry $t \cdot ac^{-1} \cdot yr^{-1}$ (Lewandowski et al. 2000). Because *Miscanthus* is sensitive to cold soils, suitability as an energy crop in Michigan seems questionable. In contrast, switchgrass is a native, fertile, open-pollinated grass and substantial experience has been gained with switchgrass production in the United States (Parrish and Fike 2005). Both grasses are efficient at translocating nutrients to roots in the fall. Therefore, harvests conducted after senescence minimize the need for post-establishment fertilization. Switchgrass

[a] (Image courtesy of Christopher Webster) [b] (Image courtesy of Robert Froese) [c] (Image courtesy of Robert Froese)

Figure 3. Energy crop examples: [a] switchgrass in Northern Wisconsin; [b] hybrid willow near Escanaba, MI; [c] hybrid poplar near Escanaba, MI.

[a] (Image courtesy of Christopher Webster) [b] (Image courtesy of Larry Leefers) [c] (Image courtesy of Christopher Webster)

Figure 4. LIHD feedstocks: [a] CRP grasslands in Wisconsin; [b] red pine thinning in Michigan; [c] natural aspen forest in northern Wisconsin.

productivity is also high, with yields at 4-10 dry t·ac^{-1}·yr^{-1}.

Poplars and willows are woody species that include a number of natives, European species, and natural and artificial hybrids. Poplar has a long history of development as a biomass crop and reported yields of 4-10 dry t·ac^{-1}·yr^{-1} over a 6-10 year rotation are typical (Tuskan 2000). At a trial near Escanaba, 6-year poplar yields ranged from 1.5-3.6 dry t·ac^{-1}·yr^{-1}, depending on variety (Miller 2004). While poplars are re-established after harvest from cuttings, willows re-sprout vigorously and are usually harvested up to seven times on 3-year rotations before “stools”, or root stock, are re-established. Reported willow yields approach 14 t·ac^{-1}·yr^{-1} in test plots, but operational trials in New York and Michigan suggest typical yields should be closer to 3-4 t·ac^{-1}·yr^{-1} (Miller 2007, personal communication; Keoleian and Volk 2005). Like poplars, variability among clones is substantial and matching clone to site is critical for high yields.

2.1.2 Low-Intensity, High-Diversity Sources

Managed ecosystems comprised of polycultures of native species provide low-intensity, high-diversity (LIHD) sources of biomass feedstocks. Examples include native and naturalized cool-season grasslands, residues from forestry operations, or whole-tree utilization from woodlands and forests not reserved from management (Figure 4). Key advantages of these systems are low-inputs, which reduce cost of establishment and production and mitigate many environmental impacts, including carbon emitted in management. In parallel, high-diversity systems tend to support high-diversity wildlife and plant assemblages that conserve native biodiversity (Flaspohler et al. 2007).

Perennial grasslands can be competitive with dedicated energy crops in some instances. Florine et al (2006) found late June yields from simple pasturelands in southern Iowa averaging nearly 2.0 dry t·ac^{-1}, with few inputs. In Michigan, 5-year average county-level hay production data (USDA NASS 2006) suggest an average yield of approximately 2.7 dry t·ac^{-1} in the 33 counties nearest to Rogers City. If these had been fall harvests, yields would likely have been higher. When planted on degraded agriculture lands in Minnesota, Tilman et al. (2006) found yields of about 2.0 dry t·ac^{-1}·yr^{-1} from LIHD perennials, which were similar to Conservation Reserve Program (CRP) plantings.

Forestry residues, such as branches, tops, rough logs and low-value species not utilized in conventional forestry operations are an indirect source of biomass feedstock. These sources are indirect because they are residual to a primarily activity; i.e., harvesting of conventional forestry products. Also because they are indirect estimating productivity of residues is difficult. National-scale studies (e.g., Perlack et al 2005; Walsh 2006), often cited in regional reviews (e.g., Sherman 2007; Simpkins 2006; Willyard and Tikalsky 2006), rely on survey-based estimates compiled by the USDA Forest Service (e.g., Smith et al. 2004). Flaspohler et al. (2007) derive an estimate of productivity by dividing national estimates of residues by timberland area, yielding a rate of about 0.1 dry $t{\cdot}ac^{-1}{\cdot}yr^{-1}$. This small number is misleading; it is a reflection of the very low rates of harvest on US timberlands, not low rates of productivity.

Unutilized inventory could be a direct source of biomass. Across all of Michigan's 18.7 million acres of timberland available for management (e.g., outside of parks and preserved areas) forests are accumulating on average 923 million $ft^3{\cdot}yr^{-1}$ beyond that harvested or lost to mortality (Hansen and Brand 2006). This amount is equivalent to about 0.74 dry $t{\cdot}ac^{-1}{\cdot}yr^{-1}$. In essence, productivity is accumulating as unutilized inventory. Observed productivity likely underestimates the potential of MI forests because unmanaged, mature and degraded stands are included that could be managed to their full potential. For example, in the Lake States reported aspen yields can approach 4.5 dry $t{\cdot}ac^{-1}{\cdot}yr^{-1}$ (Crow 1987; USDA FS 1977). Because aspen re-sprouts vigorously from suckers, such yields are conceivably sustainable on relatively short rotations (< 30 years) with effectively no planting or tending costs, and no fertilizer inputs.

2.2 Biomass Production Systems

The hypothetical WCEV bioshed includes all or a portion of 33 counties, four in the Upper Peninsula. We characterized the forested land base using data from the USDA Forest Service, Forest Inventory and Analysis Program (FIA) (Miles 2007) and the agriculture and open-land base using data from the State of Michigan's IFMAP (Integrated Forest Monitoring, Assessment and Prescription) program (MI DNR 2006). We used the FIA definition of "timberland" to define the forest land base. Such lands are producing or capability of producing in excess of 20 cubic feet per acre per year of industrial wood and are not specifically withdrawn from production by statute (USDA FIA-TPO 2006).

The land base within the hypothetical bioshed is dominated by forests, but has a substantial agricultural component (Table 2). Most forested lands are in private ownership, but the State is also a major owner in the region. Comparatively less land is in agricultural or open-land condition, though of these lands only about 31% are actively managed. From personal communication with county extension and USDA personnel (Bartlett 2007 and Smeltzer 2007), the lands characterized as herbaceous open-land are often found to be abandoned farm land and represent a high potential for dedicated energy crop production.

Table 2. Land area (acres) by cover class in the bioshed proximal to Rogers City, MI.

Cover Class	Distance Band (mi)			Bioshed Total
	0 - 25	25 - 50	50 - 75	
National Forest	0	105,491	316,837	422,328
State Forest	159,038	376,081	551,782	1,086,901
Other Public Forest	2,658	8,721	11,328	22,707
Private Forest	374,017	762,571	899,811	2,036,399
Total Forest	535,713	1,252,864	1,779,758	3,568,335
Crop and Forage	61,213	101,684	153,982	316,879
Herbaceous Open-Land	62,358	167,192	260,885	490,435
Upland Shrub	40,917	78,713	105,350	224,980
Total Agriculture	164,488	347,589	520,217	1,032,294

Source: Miles (2007) and MI-DNR (2006)

2.2.1 Indirect Sources

Estimates of timber harvests by product classes (e.g., veneer logs, sawlogs, pulpwood), are available from the USDA Timber Products Output (TPO) database (USDA FIA-TPO 2006). As potential bioenergy feedstocks, we focus on the “unused” portion of annual removals, comprised of logging residues that are normally left on site and “other” removals, such as road and right-of-way clearing and thinning treatments. These materials are often burned on-site or land filled. Typically, gross residue estimates are reduced by a factor that accounts for equipment, site and sustainability requirements. We report amounts that are 65% of the gross estimate. Based on these data, unused biomass as residues produced from annual cultural or product removals within the bioshed totals nearly 220,000 dry t·yr^{-1}. Notably, this value depends on harvest rates; if the full potential of Michigan forests for conventional forest products was utilized, residue production would increase accordingly.

Table 3. Unused portion of annual removals (dry t·yr^{-1}).

Product	Distance Band (mi)			Bioshed Total
	0 - 25	25 - 50	50 - 75	
Logging Residue	20,859	62,492	94,240	177,591
Other removals	2,539	7,103	31,868	41,510
Total	23,398	69,595	126,109	219,102

Source: USDA TPO

2.2.2 Direct Forestry Sources

An estimate of the total potential of all forestry sources was obtained from FIA inventory data (Miles 2007). These data show that, from the nearly 3.6 million acres of timberland shown in Table 2, the standing volume of growing stock (trees larger than 5 in. in diameter) within the bioshed is nearly 4,800 million ft^3. Each year Michigan forests are growing more wood than is removed from timber harvesting or natural mortality. Annual growth in the bioshed is about 103 million ft^3, over and above mortality and annual harvest of 42 million ft^3. Another way of considering these data is illustrated in Figure 5; on average, only 1/3 of the potential of forest growth is actually utilized. Notably, when broken down by owner class, National Forests are the least utilized with harvests at only 8% of growth. Using a conversion factor of 30 lb·ft^{-3} (Perlack et al. 2005) and short tons (2000 lbs.) unutilized forest potential amounts to about 1,500,000 dry t·yr^{-1}.

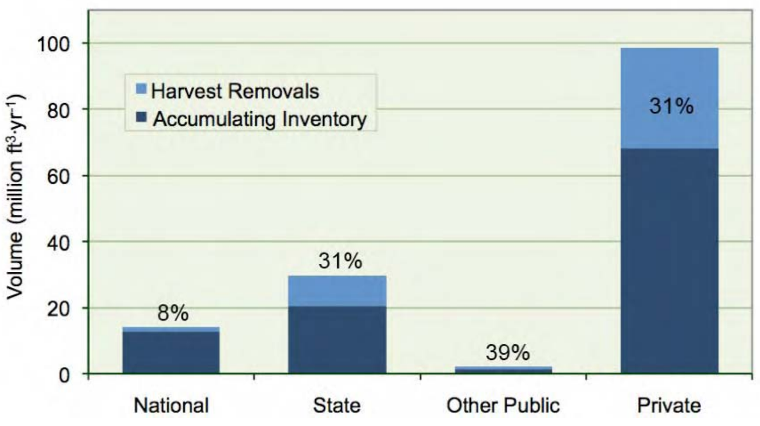


Figure 5. Net annual growth and harvest removals from timberlands in the hypothetical WCEV bioshed.

2.2.3 Dedicated Energy Crops

For agricultural lands, we approximate agricultural feedstock productivity by scaling land inventory by expected productivity on a per acre basis. Production of dedicated energy crops has been limited to small test plots in our study region, and localized yield data is sorely needed. Switchgrass plots that have been, or are in early establishment show promise (Bonnet 2007). Plantings thus far have been limited to relatively small (10 – 30 acres) for wildlife cover or cattle forage and one-acre test plots. Assuming a conservative estimate of 2 dry $t \cdot ac^{-1} \cdot yr^{-1}$, across the 490,345 ac of abandoned agricultural land a potential of about 980,000 dry $t \cdot yr^{-1}$ is theoretically possible. Higher production may be possible and an expanded assessment including test plots and a method to scale these to the landscape would greatly reduce uncertainty about the true potential.

2.3 Cost

The usual approach to cost estimation is an engineering approach, using time and cost to algebraically model per acre costs for various phases of a given activity. Unfortunately, models for forestry sources are outdated (Walsh 2007, personal communication) and Walsh (2006) recommends development of a new residue model. Peterson (2005) provides some summaries of estimated costs for forest residues from operations in the Lake States, but these are not documented in enough detail to estimate their reliability. We conducted unstructured phone interviews in October 2007, calling logging and hauling firms located in the northern Lower Peninsula. From these calls three trends emerged: (1) the market price for delivered chips was less than $20 per ton; (2) operators were leaving the industry due to low prices; and, (3) transportation costs are approaching $0.10 per ton per mile.

Information is available for cost components and establishment and conversion costs for energy crops in greater detail than that for forestry sources. This is likely because these crops follow well-understood agricultural models. Launder (2002) reports establishment costs for switchgrass, poplar and willow at about $100, $200-250 and $650-890 per acre, respectively. De La Torre Ugarte et al. (2003) report comparable numbers, at $117, $220 and $818 (in 1999 dollars) for the same three feedstocks in the Lake States. However, key studies do not provide single production "costs" for energy crops. The authors recognize that cost is a function of the level of inputs and the price of competing uses for land. Crop substitution takes place when new markets develop for existing resources. Hence, supply curves are created that indicate relative supply as market price changes.

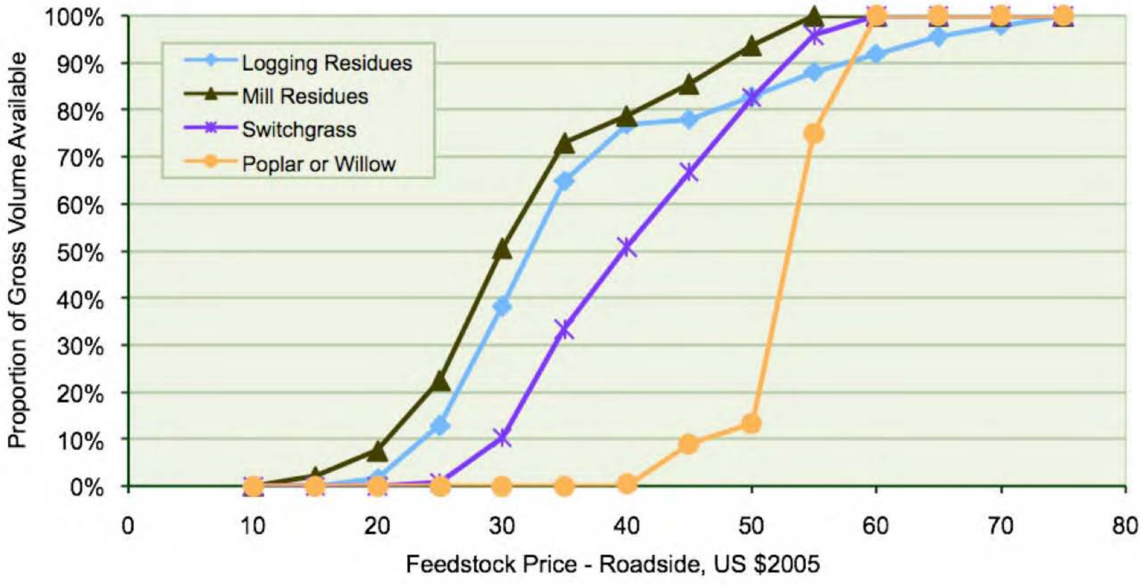


Figure 6. Biomass feedstock supply curves (relative) for the United States. Prices are in dollars per dry ton, farmgate or roadside.

We modified national supply curves developed by Walsh (2006) using updated national forestry data and expressed these curves on a relative basis (Figure 6). Stated prices are farmgate or roadside cost, and exclude transportation or storage cost components. These are national curves and are at best only generally indicative of the relative cost of different feedstocks within the conterminous U.S. Nevertheless, a clear order is revealed, with some mill and forest residues available at $20-30 per dry ton, and little to no willow or poplar production possible at prices less than $50 per dry ton. We question whether substitution would actually take place for saw or pulp mill residues when the new market is co-firing in a power plant. Essentially, these residues are already used in energy generation at processing facilities offsetting power purchased from the market.

2.4 Sustainability and Environmental Impact

In a large part, interest in biomass and bioenergy has been driven by concerns about the environmental impact of current energy sources and fossil carbon emissions. Yet, development of new biomass production systems and increasing utilization of biomass from traditional forest operations may have impacts of their own. Biomass production, from limited recovery of logging residues through intensive energy crop production, will have impacts on the relevant ecosystems. These impacts are not always negative, however. For example, the CRP program has provided straightforward evidence of restoration of bird and fish populations since the program began (Herkert et al. 1993). The kinds of land management prescribed under CRP, such as the establishment of low-intensity, high diversity perennials, could be a model for bioenergy production systems.

Environmental issues such as soil and water conservation, biodiversity, and wildlife habitat, while general in nature, have site-specific considerations. Removal of logging residues may impact soil and water quality through increased erosion (Lal 2006) and leaching due to exposure of the forest floor. Nutrient losses, in particular of calcium, may affect site productivity if material is removed in excess (McLaughlin and Wimmer 1999). These residues often form the basis for wildlife habitats and thus biodiversity and must be taken into account before prescribed removals. The amount of residue that may be safely removed from a given site to not compromise these issues must become part of the harvest prescription.

Dedicated energy crop production, through its monoculture nature, may have adverse impacts on biodiversity (Roth 1976; Siemann 1998). Planting and harvesting schedules should be such that these plantings occur across the landscape mosaic and provide multiple growth structure for wildlife habitat and biodiversity. Furthermore, in order for any benefit to be derived from the use of biomass feedstocks for energy production, inputs to these systems must remain low. The use of herbicides and pesticides, fertilizers and other soil amendments, cultivation and harvesting practices, and transport of material are critical in selection of the proper feedstock for a given site. When selecting a feedstock for a given facility or location tradeoffs will be necessary among sustainability attributes (Table 4).

Sustainability is an important topic, and many concerns are site and species-specific. Focused attention to sustainability in greater depth than presented here will be an essential part of any operational biomass for bioenergy production system. For more detail, please see reviews by Richardson et al. (2002), Flaspohler et al. (2007) and Janowiak (2008) as starting points for further information. Some guidance is already available through existing programs. In Michigan, “Best Management Practice” (BMP) guides for protection of water resources and guidelines for “Generally Accepted Forest Management Practices” (GAFMP) are already in place. At present, the Michigan DNR is in the process of developing BMPs for biomass production from forests (LaCourt 2007).

Table 4. A comparative summary of sustainability attributes for key biomass feedstocks.

The Ideal Biomass Crop?	Forest Residues	LIHD Perennials	Short-rotation Woody Crops	Monoculture Grasses	Cereal Grain or Stover
Highly productive	no	yes	yes	yes	very
Widely available	yes and unutilized	somewhat	near none	near none	limited
Site impact	low	low	moderate	moderate	very high
Biodiversity impact	neutral to restorative	neutral to restorative	high	high	high
Energy inputs	very low	low	moderate	moderate	very high
Noninvasive	yes	yes	genetically-modified	usually	yes
Few pests or disease	usually	yes	sometimes	usually	no
Uses existing technology	yes	yes	sometimes inefficiently	yes	yes
Need storage facilities	harvest year-round	yes	harvest year-round	yes	yes

2.5 Biomass Production for Carbon Sequestration

Biomass combustion mitigates some of the environmental impact of electricity generation by displacing fossil fuels that would have otherwise been combusted, and thusly reducing the net emission of fossil carbon to the atmosphere. A different, and often complementary, approach to mitigation is to undertake activities that sequester atmospheric carbon in new biomass. These activities must be additional; i.e., sequestration must occur because new activities increase background sequestration rates. We consider two options: restoration of degraded or abandoned lands and altered management of production systems.

All ecosystems contain some carbon, either in live vegetation, plant parts in various states of decay or highly decomposed organic carbon often bound to soil particles. This biomass contains important nutrients (e.g., nitrogen) that are released as plant matter decomposes, and also acts as an amendment, improving the water and nutrient holding capacity of soils. In degraded ecosystems, management has depleted these carbon stores, usually by reducing biomass inputs or increasing the rate at which existing carbon decays. Restoration involves putting carbon back, perhaps through afforestation or planting of prairie grasses (Table 5).

Note that the estimates in Table 5 are for about the first 10 years of growth after conversion. Above and below-ground carbon storage may eventually reach a plateau, or perhaps decline, depending on the ecosystem (Birdsey et al. 2006). Lewandrowski et al. (2004) note that, in soils, the plateau level is likely many times greater than current levels, and is not likely limiting in the near term. Tilman et al. (2006) suggest that sequestration rates in degraded soils restored to mixed grasses could be sustained for 100 years. Thus, many of the reported rates could be sustained much longer than 15 years.

Sequestration may also be enhanced by altering stored carbon trend in managed ecosystems. One way to do this is to slow harvest rates; Smith (2007) quantified 6-year projected sequestration for a managed Northeastern US hardwood forest at about 0.46 $t \cdot ac^{-1} \cdot yr^{-1}$, which included some harvest but at a rate less than total growth. The purpose of the calculation was to determine the credit that might be obtained selling the sequestration as an offset on the Chicago Climate Exchange. Notably, Michigan has participated in the exchange through a pilot program to sell forest carbon offsets (Delta Institute 2007). Webster and Giardina (2004) examined high and low-intensity harvest regimes in Michigan northern hardwood forests. The low intensity regime favors production of logs that end up as high-value, long lived products like fine furniture. The effect was small through the change in stand management, effectively sequestering only 0.1 $t{\cdot}ac^{-1}{\cdot}yr^{-1}$. This conclusion was sensitive to assumptions, and should be investigated further.

Table 5. Some potential carbon sequestration rates for restoration practices on cultivated lands.

Land-Use Change	Location	Sequestration ($t{\cdot}ac^{-1}{\cdot}yr^{-1}$)	Source
Afforestation in general	U.S. average	0.72 – 1.56	Birdsey (1996)[1]
Red pine afforestation	Michigan	1.1 – 2.0[2]	Anderson (1998)
Hybrid poplar plantation	Michigan	up to 3.8[3]	Miller (2004)
Mixed perennial grasses	U.S. average	0.23 – 0.46	Eve et al. (2000)[1]
Mixed perennial grasses	Minnesota	> 1.6	Tilman et al. (2006)

[1] Cited in Lewandrowski et al. (2004)

[2] Roots, bole and branches only; excludes soil and forest floor carbon. Thus, realized sequestration is probably higher.

[3] Estimated by adding 0.25 $t{\cdot}ac^{-1}{\cdot}yr^{-1}$ in soil and root sequestration estimated by Adler et al. (2007) in Pennsylvania to Miller's (2004) estimate of above-ground productivity in Michigan.

2.6 Conclusions

2.6.1 Biological Potential

The most readily available source of biomass is in the form of forest residues. Our analysis shows that unused logging residues and other removals from timberland, within 75 miles of Rogers City, total about 220,000 dry $t{\cdot}yr^{-1}$ (Table 3). This amount represents 65% recovery, with the remainder serving environmental sustainability objectives. This source, alone, is sufficient to meet the estimated requirements for co-firing at more than 6.5%. However, average harvest levels in the Northern Lower Peninsula are only about 1/3 of current growth, suggesting that much higher harvest levels are sustainable given sufficient demand for the resource. The untapped forest resource within less than 50 miles is sufficient to meet the feedstock requirements for co-firing at 20%, sustainably and with very low input requirements. Much of this biomass is likely put to better use as a raw material for high-value forest products, but residues from these harvests could still be available. Even in this case, if the full potential of Michigan forests were to be utilized for conventional forest products, within 75 miles the associated ***residues*** alone would still be sufficient for co-firing at more than 20%.

As biomass and bioenergy industries develop, demand for feedstock will increase, and the long-term potential for biomass production in the vicinity of Rogers City will require use of abandoned agricultural or open lands. Within 50 miles, nearly 230,000 acres of these lands are available. Which energy crop is best for those lands would depend on such issues as the relative cost for establishment and harvest, site quality and operability, and how the feedstock quality fits with the bioenergy production system considered. Low-intensity, High-Diversity perennial grasses, at a conservative production rate of even 2 dry $t{\cdot}ac^{-1}{\cdot}yr^{-1}$, would yield more than 460,000 dry $t{\cdot}yr^{-1}$. Aspen, grown on land with a site index of 80 for thirty years, potentially yields over 4.0 dry $t{\cdot}ac^{-1}{\cdot}yr^{-1}$ (USDA FS 1977), or more than 920,000 dry $t{\cdot}yr^{-1}$ on the same lands within 50 miles of Rogers City. These amounts are realized without replacement of current commodities grown on cropland, obviating any concerns about competition with other uses. Again, price remains an important consideration, but our results suggest biological potential is far from limiting the opportunity for co-firing at the WCEV.

2.6.2 Information and research needs

Some evidence suggests that the substantial untapped potential for biomass production in the Northern Lower Peninsula is at least partly explained by low market prices that are insufficient to stimulate utilization. Low pulpwood prices seem related to pulp and paper mill closures and our regional contacts suggest logging and trucking operators are leaving the industry because low demand has lead to low chip prices. Yet, pressure is rapidly mounting for increased production of renewable energy and offsetting of anthropogeneous carbon emissions. In a world with renewable energy portfolio standards and fossil CO_2 emission caps, as well as bioenergy production and carbon sequestration credits, bioenergy may not just become competitive with fossil fuels, but necessary by mandate.

National and international-scale studies have demonstrated the biological potential and economic feasibility of biomass production, from forests and from low and high-intensity agricultural production systems. Developing biomass for bioenergy in Michigan requires regionalizing this information. In the area of feedstock production, we believe the highest-priority research needs are in agricultural and open-land conversion and restoration, feedstock selection and cultivation, and carbon storage and cycling in biomass production systems.

Increased, localized understanding of the costs, outputs and environmental profiles of biomass production systems has the potential to reduce the threshold both of the risk premium required for private investment and the level of subsidy required to stimulate bioenergy production. Clearly, Michigan and WCEV have the potential to be national leaders in biomass, and bioenergy, production.

3 Life Cycle Assessment (LCA)

3.1 Basic Concepts of Life Cycle Assessment (LCA)

Life cycle assessment is a methodology to evaluate environmental impacts, energy consumption, resource depletion, and other impact categories for an entire product system. The purpose of LCA is to inform decision makers in industry and government on the best product or technology alternative to satisfy a particular customer or societal need in an environmentally sound manner. Uses of LCA might include decisions on investments, communication with stakeholders, guiding research and development, product marketing, and establishing government or corporate policies (Allen and Shonnard, 2002). Standards to guide the conduct of LCA have been developed and published by the International Organization for Standardization (ISO 14040-14049).

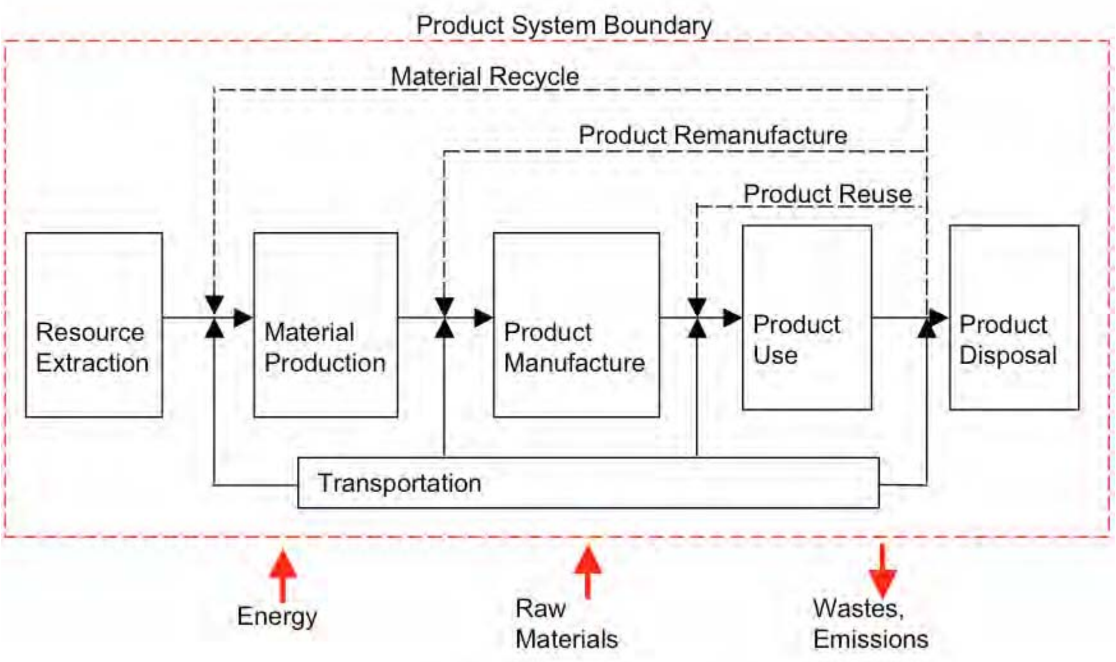


Figure 7. Product life cycle: linked stages with transportation, recycle, remanufacture, and reuse.

The scope of LCA is comprehensive and includes all stages in a product's life cycle, as shown in Figure 7. At the beginning of the life cycle, raw materials are extracted from the environment, intermediate materials are produced, end products are manufactured, the product is used in society, and ultimately disposed of back to the environment. Recycle, remanufacture, and reuse are possible fates of the product prior to disposal. Transportation in various forms (road, rail, ship, etc.) is also included. At each stage in the life cycle energy is consumed, raw materials or other products are also input, and waste/emissions are the system outputs. Because the purpose of most life cycle assessments is to compare alternative products, all of the alternative product systems must be defined.

3.2 Methods

3.2.1 Process Comparisons:

The base case for this study is the generation of electricity using conventional coal-fired power plant technology. This includes the extraction of the coal from the mine, transportation to the facility, conversion of the energy in coal to electricity at the power plant, and the manufacture and construction of all associated process equipment (shown in Figure 8 (black)). For the cases of co-firing with biomass, several biomass source scenarios were included: logging residues, short rotation woody crops, and switchgrass. For these cases, the environmental impacts of the establishment, cultivation, harvesting and transportation of the biomass were added to the base case scenario (green) in proportion to the co-firing percentage. The cradle-to-grave impacts for the coal displaced by the biomass were then subtracted from the system, including combustion emissions at the power generation facility (shown in Figure 8 in teal). Finally, there are two carbon sequestration cases considered. Geological sequestration involves capturing CO_2 from the plant exhaust gases, compressing them, and injecting them into an underground geological formation. The impacts of the CO_2 capture, pipeline transport, and sequestration were added to the base case scenario, while the CO_2 emissions that were sequestered are subtracted. The other form of sequestration takes place as a credit given for forest biomass growth on depleted land due to improved growth management practices. The impacts of stand establishment and management are added.

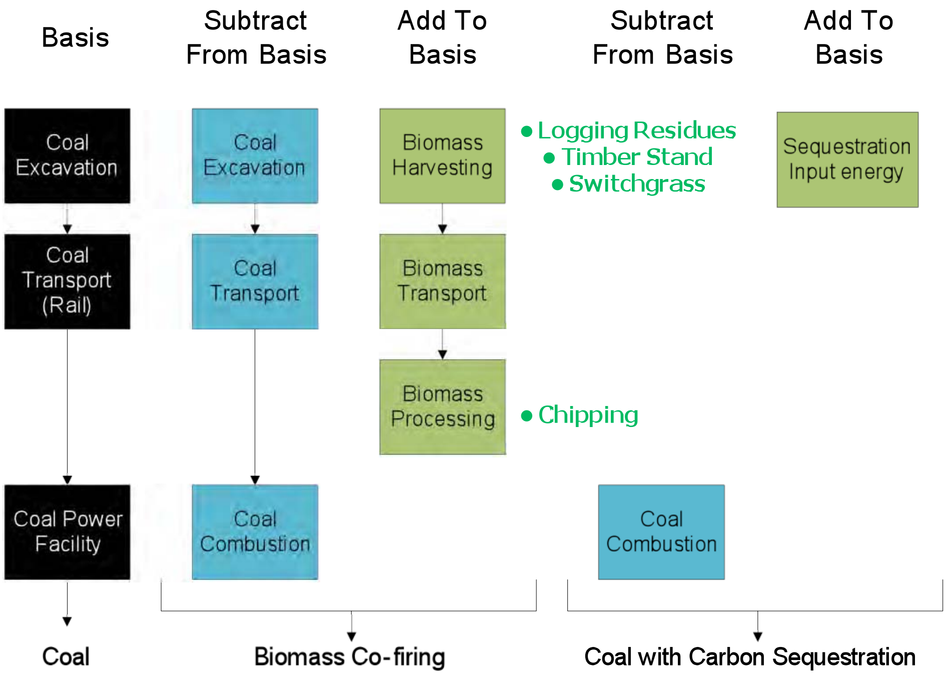


Figure 8. Life cycle diagrams for the base case coal power (black). For the biomass co-firing, the portion of coal avoided is subtracts (teal), and the biomass process is added (green). Similarly for sequestration cases, the combustion emissions (teal) are subtracted from the base case, and the energy used for sequestration (green) is added.

3.3 LCA Study Assumptions and Inputs

3.3.1 Goal and Scope Definition:

The goal of this LCA is to compare the environmental effects of standard technology for generating power from coal to several scenarios intended to reduce the carbon dioxide emissions, while comparing the total amount of **fossil energy** used to do so as well as **greenhouse gases emitted**. The scope of the study is from fuel extraction (biomass or coal), including transportation steps, through the process for generation of electricity. To add robustness to the study, several different biomass feed stocks will be assessed, as well as two scenarios for CO_2 sequestration.

3.3.2 Study Inputs:

The software used for this LCA was SimaPro 7.0. It has a large database of LCA inputs for materials and electricity generation. For the purposes of this report, the impact assessment methods used in SimaPro 7.0 were Cumulative Energy Demand and greenhouse gas emissions obtained from the Eco-indicator 95™ method. The Cumulative Energy Demand is intended to show all of the fossil energy that is consumed in a process to produce the product of interest from “cradle to gate”, and the primary forms of that energy. Eco-indicator 95™ is an important impact methodology because it gives the amount of greenhouse gases given off throughout the life of the process. The output is in CO_2 equivalents for all of the emissions, for example N_2O has the GHG potential of 296 compared to CO_2 (IPCC, 2001).

Co-firing of Powder River coal with logging residues, with stand growth timber, and switchgrass were simulated over a range of displacement percentages; 1%, 5%, 10%, 15% and 20% based on electricity generated. Inventory data for the baseline coal fired electricity came from Simapro 7.0, the LCA software used in this study, representing current European average technology. Data for electricity generation efficiency, coal heating value, and coal transportation distances was provided by Wolverine Power Cooperative, whereas other data for biomass heating values as well as other inputs were obtained from various sources; Mann & Spath (2001), Amos (2001), SimaPro 7.0). The geological sequestration scenario assumed that 20% of the CO_2 emissions from the base case coal scenario were captured and sequestered using monoethylamine (MEA) as the separating agent, followed by compression of the captured gas, transport in a pipeline to the point of injection, and then re-compression/injection. Inventory data for the geological sequestration scenario were obtained from the study by Spath & Mann (2004). For the scenario with sequestration by managed timber growth, data were obtained from Anderson (1998) and SimaPro 7.0 ecoprofile values. Transport distance for biomass in co-firing scenarios was set conservatively at 125 miles, to account for the difference between straight-line distance in a typical bioshed (e.g., 75 miles) and actual road distances.

3.3.3 Definition of Functional Unit:

The functional unit for this LCA is **1 kilowatt-hour** of electricity produced. Inventories of inputs of materials and energy over the life cycle for each fuel product were accumulated based on this functional unit.

3.4 Results

3.4.1 Cumulative Fossil Energy Demand

Figure 1 displays the cumulative fossil energy demand for each electricity generation scenario, where all co-firing is at 20% and sequestration scenarios are also at 20% . For more detailed results over a range of percentages of co-firing for cumulative energy demand, please see Appendix C of the main report. The units on these graphs are megajoules (MJ) of primary fossil energy per functional unit (1 kWh electricity generated).

The base case of 100% coal generation yields in 12.2 MJ of fossil energy consumed through the life cycle. All three biomass co-firing cases are nearly identical, with logging residue and the short rotation woody crops both requiring 9.03 and 9.04 MJ of fossil energy, respectively. The decrease in fossil energy demand comes from the mining and long-range transportation of coal that has been avoided by co-firing, which has been replaced by harvesting and short-range transportation of biomass. Switchgrass is slightly higher, using 9.13 MJ, due to more intensive cultivation required compared to the other biomass options.

Geological sequestration has an increase in fossil energy, with 13 MJ of input energy, due to the increased fossil requirements of capturing and pressurizing the CO_2 from the flue gases. Sequestration using improved land management and growth shows no change in fossil energy demand from the base case. This is not unexpected, since the only change is a small impact from planting and tending a site. Overall, the biomass co-firing has the lowest fossil energy demand over the life cycle of all the scenarios, with geological sequestration actually increasing the amount of fossil energy consumed for each kWh generated for the customer.

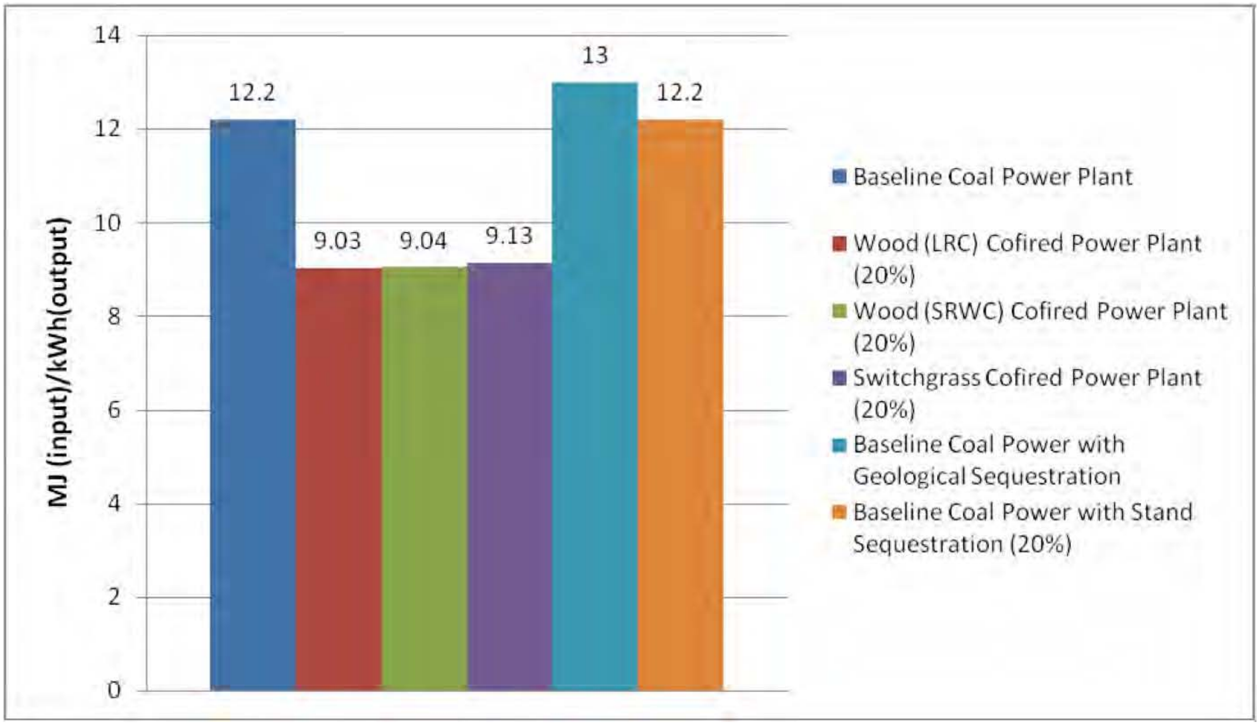


Figure 1. Cumulative energy demand (CED), in fossil energy, for each scenario, at 20% CO_2 emissions reduction: Lumber residue, chipped (LRC), Short-rotation woody crop (SRWC).

3.4.2 Greenhouse Gas Emissions

Greenhouse gas emissions were also analyzed for reach electricity generation scenario, with 1%, 5%, 10%, 15%, and 20% co-firing scenarios. For comparative analysis, Figure 2 includes data for 20% only. Further results with varying co-firing percentages are included in Appendix C of the main report. The impact category unit here is kilograms (kg) of CO_2 equivalence per kWh electricity generated. The base case has an impact of 1.03 kg CO_2 eq. per kWh electricity. Both wood co-firing cases are again identical, at 0.826 kg CO_2 eq. per kWh. There appears to be little difference in GHG emissions for the life cycle processes and activities for either logging residues or short rotation woody crops (short rotation woody crop, such as willow or poplar). Switchgrass shows a small increase over wood in GHG emissions, at 0.844 kg CO_2 eq. Sequestration by geological storage has a higher GHG emission than co-firing at 0.899 kg CO_2 eq. per kWh. This is due to the energy demands of capturing and pressurizing the CO_2. Managed stand growth sequestration shows very little change over co-firing, at 0.84 kg CO_2 eq., because the site tending is the only greenhouse gas output, which is very similar to the impacts of managing and harvesting a forest for lumber.

Operating at 600 MW output continuously throughout the year, 5.09 million metric tons of CO_2 are generated. To sequester 20% of this is equal to 1.02 million tons of CO_2 each year. For geological sequestration, this would require a large underground reservoir to encase this, which is locally available within 150 miles, based on discussions with Wolverine Power. For biomass sequestration, and based on our assumption data for carbon uptake rates for afforestation of degraded land, 4,150 kilograms of CO_2 can be sequestered per year per hectare, for at least 60 years, sustainably. Requirements of at least 245,000 hectares are needed for this 20% rate.

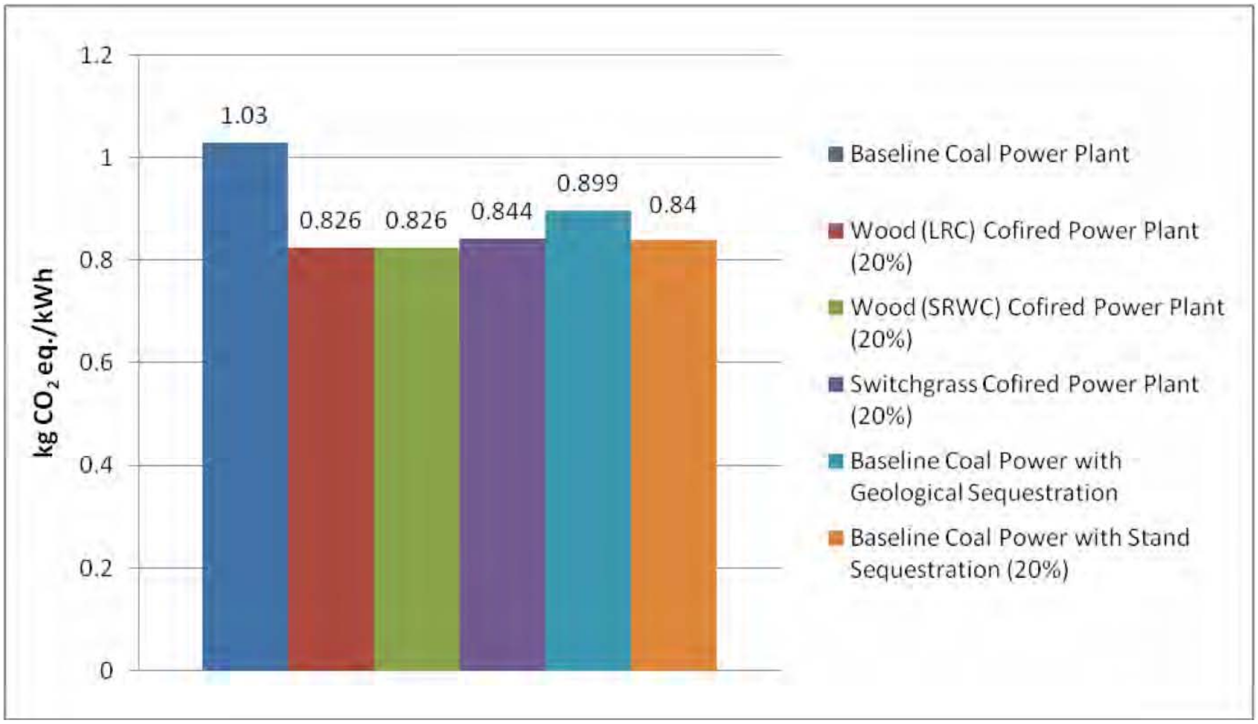


Figure 2. Greenhouse gas emissions, in CO_2 equivalence, for each scenario at 20% CO_2 emissions reduction.

3.5 Conclusions

These LCA results indicate that co-firing with logging residue is the best approach to maximize both fossil energy and greenhouse gas savings. Compared to the coal-fired base case, 20% co-firing with logging residues reduced fossil energy consumption per kWh of electricity generated by (12.2-9.03)/12.2 (100) = 26.0% and decreases CO_2 (eqv.) emissions by 19.8%. In particular, biomass as wood shows a slight improvement over switchgrass. Geologic sequestration shows promise, but would require higher sequestration rates than 20% to show improvement in GHG savings over the 20% co-firing scenarios. To capture 20% of the CO_2 in managed stand growth would require an estimated 245,000 hectares of land. Therefore, the most viable short-term solution is to co-fire wood biomass, since it has both the greatest benefits and the least impacts of all of the scenarios. Co-firing with biomass at lower percentages is also a viable option, but we estimate that the benefits derived from co-firing are proportional to the rate of co-firing.

4 References

Adler, P.R., S. J. Del Grosso and W.J. Parton. 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications, 17(3): 675-691.

Allen, D.T., Shonnard, D.R. et al. 2002. Green Engineering: Environmentally Conscious Design of Chemical Processes. Upper Saddle River, NJ: Prentice-Hall.

Amos, W. A. 2001. Results from the Chariton Valley Biomass Project: Switchgrass Co-fire Testing. Golden, CO: National Renewable Energy Laboratory.

Anderson, B. 1998. Using afforestation to mitigate anthropogenic carbon dioxide: a case study and theoretical analysis. M.Sc. project report, Michigan Technological University, Houghton, MI. 59 pp.

Bartlett, B. 2007. Ben Bartlett, Cheboygan, Emmet, Otsego, and Presque Isle County's MSU Extension Agent. Personal communication, November, 2007.

Birdsey, R. 1996. Regional estimates of timber volume and forest carbon for fully stocked timberland, average management after cropland or pasture reversion to forest. Appendix 3 *in*: Forests and Global Change, Vol. 2. Forest Management Opportunities for Mitigating Carbon Emissions. American Forests, Washington, D.C. Cited in: Lewandrowski et al. (2004).

Birdsey, R., K. Pregitzer and A. Lucier. 2006. Forest carbon management in the United States: 1600-2100. Journal of Environmental Quality, 35: 1461-1469.

Bonnet, M. 2007. Matt Bonnet, Cheboygan County Farmer. Personal communication, November, 2007.

Crow, T.R. 1987. Biomass and production in three contiguous forests in northern Wisconsin. Ecology, 59: 265-273.

De La Torre Ugarte, D.G., H. Shapouri, M.E. Walsh, S.P. Slinsky. 2003. The Economic Impacts of Bioenergy Crop Production on U.S. Agriculture. U.S. Department of Agriculture, Office of Chief Economist, Office of Energy Policy and New Uses. Agriculture Economic Report No. 816.

Delta Institute, The. 2007. Michigan Forest Carbon Offset Trading Program: Enrollment Instructions. Chicago, IL. Available from www.p2e2center.org/documents/WorkingForestsEnrollmentPackage.pdf; accessed December 19, 2007.

Eve, M.D., K. Paustian, R. Follet and E.T. Elliott. 2000. United States submission on land-use, land-use change, and forestry, August 1. US Department of State, US submission to the United Nations Framework Convention on Climate Change. Cited in: Lewandrowski et al. (2004).

Flaspohler, D.J, C.R. Webster and R.E. Froese. 2008; in press. Biomass, Bioenergy and Biodiversity: A review of key issues for terrestrial and aquatic ecosystems. in: B.D. Solomon and V.A. Luzadis (eds.), Renewable Energy from Forest Resources in the United States. Taylor & Francis, NY.

Florine, S.E., Moore, K.J., Fales, S.L., White T.A., and Burras, C.L. 2006. Yield and composition of herbaceous biomass harvested from naturalized grassland in southern Iowa. Biomass and Bioenergy, 30: 522-528.

Hanson, M.H. and G.J. Brand. 2006. Michigan's forest resources in 2004. USDA Forest Service, North Central Research Station, Resource Bulletin NC-255. 41 pp.

Herkert, J.R., Szafoni, R.E., Kleen, V.M., and Schwegman, J.E. 1993. Habitat establishment, enhancement and management for forest and grassland birds in Illinois. Division of Natural Heritage, Illinois Department of Conservation, Natural Heritage Technical Publication #1, Springfield, Illinois. 20 pp.

IPCC. 2001. IPCC Climate Change 2001: The Scientific basis. In Houghton JT (ed), Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press.

Janowiak, M.K. 2008; in review. Ensuring ecological sustainability in woody biomass harvesting. USDA Forest Service, Northern Institute of Applied Carbon Science. Available from the author; janowiak@mtu.edu.

Keoleian, G.A. and Volk, T.A. 2005. Renewable energy from willow biomass crops: life cycle energy, environmental and economic performance. Critical Reviews in Plant Sciences, 24: 385-406.

LaCourt, D. 2007. Donna LaCourt, Michigan State Forester. Personal communication, November 4, 2007.

Lal, R. 2006. Soil and environmental implications of using crop residues as biofuel feedstock. International Sugar Journal, 108: 161-167.

Launder, K. 2002. Energy Crops and Their Potential Development in Michigan. Michigan Biomass Energy Program, Michigan Department of Consumer and Industry Services. Lansing, MI.

Lewandowski, I., Clifton-Brown, J.C., Scurlock, J.M.O., and Huisman, W. 2000. *Miscanthus*: European Experience with a novel energy crop. Biomass and Bioenergy, 19: 209-227.

Lewandrowski, J., M. Sperow, M. Peters, M. Eve, C. Jones, K. Paustian and R. House. 2004. Economics of sequestering carbon in the U.S. Agricultural sector. USDA Economic Research Service, Tech. Bull. No. 1909.61 pp.

McLaughlin, S.B., and Wimmer, R. 1999. Calcium physiology and terrestrial ecosystem processes. New Phytologist, 142: 373-417.

Mann, M.S. 2001. A Life Cycle Assessment of Biomass Cofiring in a Coal-Fired Power Plant. Clean Prod. Processes, 81-91.

MI DNR. 2006. Michigan Integrated Forest Inventory and Analysis Prescription. Available from www.michigan.gov/dnr .

Miles, P. 2007. Forest inventory mapmaker web application 3.0. USDA Forest Service, St. Paul, MN. Available from http://ncrs2.fs.fed.us/4801/fiadb/; accessed October, 2007.

Miller, R.O. 2004. Fiber farming using *Populus* hybrids, aspen and European larch in Michigan’s Upper Peninsula. Michigan State University, Upper Peninsula Tree Improvement Center.

Miller, R.O. 2007. Ray Miller, Michigan State University, Upper Peninsula Tree Improvement Center. Personal communication, November 2007.

Parrish, D.J. and Fike, J.H. 2005. The biology and agronomy of switchgrass for biofuels. Critical Reviews in Plant Science, 24: 423-459.

Perlack, R.D., L.L. Wright, A.F. Turholow, R.L. Graham, B.J. Stokes and D.C. Erbach. 2005. Biomass as a feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. DOE/GO-102005-2135. Oak Ridge National Laboratory, Oak Ridge, TN.

Peterson, D.R. 2005. The real cost of extracting logging residue study. Lumberjack Resource Conservation and Development Council, Inc. 17 pp.

Richardson, J., P. Bjorheden, P. Hakkila, A.T. Lowe and C.T. Smith (editors). 2002. Bioenergy from sustainable forestry: guiding principles and practice. Klewer, New York.

Roth, R.R. 1976. Spatial heterogeneity and bird species diversity. Ecology, 57: 773-782.

Sherman, A.R. 2007. The Vermont wood fuel supply study: an examination of the availability and reliability of wood fuel for biomass energy in Vermont. Biomass Energy Resource Center, Montpelier, VT. 69 pp.

Siemann, E. 1998. Experimental tests of effects of plant productivity and diversity on grassland arthropod diversity. Ecology 79: 2057-2070.

Simpkins, D. 2006. Clean energy from wood residues in Michigan. Michigan Biomass Energy Program, MI Dept. Labor & Econ. Growth. 58 pp.

Smeltzer, P. 2007. Perry Smeltzer, Soil Conservation Officer, USDA Service Center, Onaway, MI. Personal communication, November, 2007.

Smith, M., 2007. Carbon market may offer opportunities for forest landowners. The Forestry Source. Available from www.mfpp.org/Data/carbonmarket.forestry_source_2007.pdf; accessed 13 August 2007.

Smith, W.B., Miles, P.D., Vissage, J.S., and Pugh, S.A. 2004. Forest resources of the United States, 2002. USDA For. Serv., St. Paul, MN.

Spath, P.L. 2004. Biomass Power and Conventional Fossil Systems with and without CO_2 Sequestration - Comparing the Energy Balance, Greenhouse Gas Emissions and Economics. Golden, CO: National Renewable Energy Laboratory.

Tilman, D., Hill, J., Lehman, C. 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science, 314: 1598-1600.

Tuskan, G. 2000 Popular poplars: trees for many purposes. Oak Ridge National Laboratory, Oak Ridge, TN. Available from bioenergy.ornl.gov/misc/poplars.html; accessed 8 November 2007.

US DOE. 2006. Breaking the biological barriers to cellulosic ethanol: a joint research agenda. U.S. Department of Energy Office of Science and Office of Energy Efficiency and Renewable Energy, DOE/SC-0095. Available from http://genomicsgtl.energy.gov/biofuels/b2bworkshop.shtml; accessed June 2006.

USDA FIA-TPO. 2006. Forest Inventory and Analysis – Timber Product Output Databases. Available from www.fia.fs.fed.us.

USDA FS. 1977. Managers Handbook for Aspen In The North Central States. General Technical Report NC-36. North Central Forest Experimental Station, Forest Service – USDA, St. Paul, MN.

USDA NASS. 2006. US and All States Data. National Agriculture Statistics Service, US Department of Agriculture, Washington, D.C. Available from www.nass.usda.gov.

Walsh, M.E. 2007. Marie Walsh, University of Tennessee. Personal communication, November 2007.

Walsh, M.E. 2006. Marie Walsh, University of Tennessee. Personal communication, September, 2006.

Walsh, M.E. 2006. US cellulosic biomass feedstock supplies and distribution. Unpublished manuscript, available from author (m.e.biomass@comcast.net).

Webster, C.R. and C.P. Giardina. 2004. Northern hardwood improvement project. Michigan Technological University and USDA Forest Service, North Central Experiment Station. Unpublished manuscript; available from cwebster@mtu.edu.

Willyard, C.J. and S.M. Tikalsky. 2006. Bioenergy in Wisconsin: the potential supply of forest biomass and its relationship to biodiversity. State of Wisconsin, Department of Administration. 48 pp.