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Combined Sustainable Biomass Feedstock Combustion, CO_2/EOR, and Saline Reservoir Geological Carbon Sequestration in Northern Lower Michigan, USA: Towards Negative CO_2 Emissions

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Abstract

This paper presents the results of a combined biomass combustion and geological carbon sequestration feasibility study in Northern Lower Michigan, USA related to a proposed solid fuel-fired 600 MW electric power plant, the Wolverine Clean Energy Venture (WCEV), near Rogers City, MI, USA. The biomass feedstock resource assessment, focused on low intensity, high diversity forest and agriculture in the proposed plant bioshed (<120 Km), has the potential to provide sustainable, dry biomass fuel well in excess of the maximum annual co-firing potential of 20% and offset as much as $1 Tgy^{-1}$ of the estimated annual $5.1 Tgy^{-1}$ of CO_2 emissions (using 100% western coal). CO_2/EOR potential in the Northern Niagaran Pinnacle Reef Trend is substantial. To date, seven reef reservoirs have been converted to CO_2/EOR floods and three of these fields are sufficiently mature to project recovery efficiency in excess of 40% of primary oil recovery. Using these observations and historic oil production data CO_2/EOR potential, in a region adjacent to a proposed CO_2 pipeline originating from the plant site, is estimated to be at least 7.2 Mm^3 (45 MMB) of incremental oil. Analysis of produced fluids in the same region indicates 55 Mmt of geological carbon sequestration (GCS) potential in abandoned oil and gas fields. GCS capacity is estimated at 271 Mmt in two, Paleozoic, saline reservoir targets providing a combined GCS (with abandoned oil and gas field GCS) of 326 Mmt in the pipeline study area. Estimated, combined, GCS in the proposed pipeline fairway alone is in excess of CO_2 emissions for a hypothetical 50 year design life of the WCEV project burning 100% coal of 255 Mmt. Realization of biomass co-firing potential at 20% would result in a 50MMt offset of CO_2 emissions during this 50 year period. Carbon capture and sequestration, including beneficial use in CO_2/EOR, GCS in abandoned oil and gas fields, and saline reservoir GCS Sequestration at 90% of CO_2 emissions from the proposed plant for a 50 year design life could result in the sequestration of 229.5 Mmt of CO_2. These considerations support the potential for a net negative emissions profile of -24.5 Mmt for a hypothetical 50 year design life of the proposed WCEV project.

Keywords: sustainable biomass combustion; CO_2 enhanced oil recovery, geological carbon sequestration; negitive CO_2 emissions

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1. Introduction

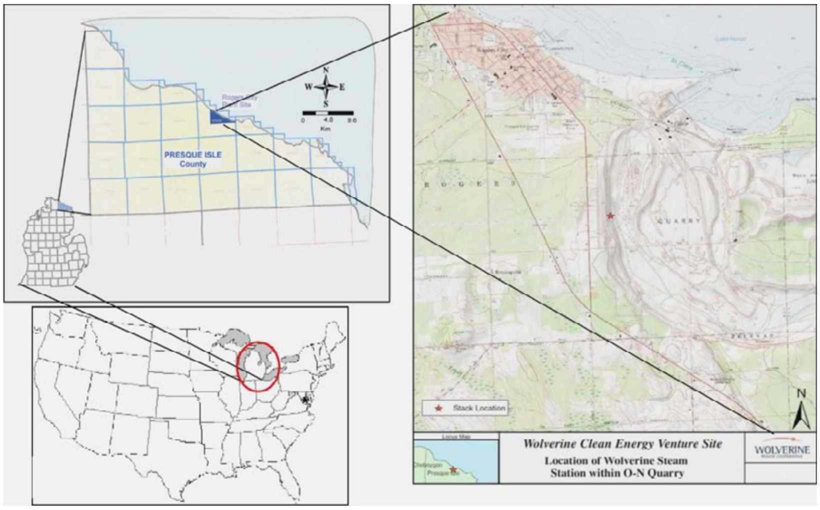

Figure 1. Location map of the WCEV project, Northern Lower Michigan, USA

Greenhouse gas (GHG) emissions mitigation at stationary sources and compliance with renewable portfolio standards (RPS) for electric power generation will be economically feasible and accomplished most cost effectively through exploitation of extant regional resources. Sixty percent of electric power generation in Michigan was coal fired in 2008. Michigan RPS of September 18, 2008, mandates that 10 % of the state's energy will come from renewable sources by 2015. Two key technologies that exploit local GHG emissions reduction-related resources are sustainable biomass combustion (BC) and carbon capture and sequestration (CCS). Available synergies, in suitable locations, for coupling BC and CCS will result in substantial emissions reductions and contribute to regional RPS. Successful deployment of such resources may also validate the potential for negative CO_2 emissions technologies in the future. Abundant forest and agriculture resources in Northern Lower Michigan suggest that displacing coal with biomass is a promising option and will contribute to RPS requirements. The Northern portion of the Michigan geological basin also possesses abundant CO_2/Enhanced Oil Recovery (EOR) and Saline Reservoir Geological Carbon Sequestration (GCS) opportunities.

This study presents the results of a combined BC and GCS potential in Northern Lower Michigan, USA. The context for the study is a proposed, solid fuel-fired 600 MW, circulating fluidized bed boiler electric generation facility (Wolverine Clean Energy Venture, WCEV) within the footprint of a large, existing limestone quarry in Rogers City, Michigan (Figure 1). As proposed, the facility will burn 2.5 terragram per year (Tgy^{-1}) of solid fuel, primarily western coal, but is capable of co-firing biomass at up to 20% of its design heat input. Assumptions regarding CO_2 emissions from 100% coal combustion are 5.1 Tgy^{-1} and emissions offsets through BC are 1 Tgy^{-1} at 20% biomass combustion.

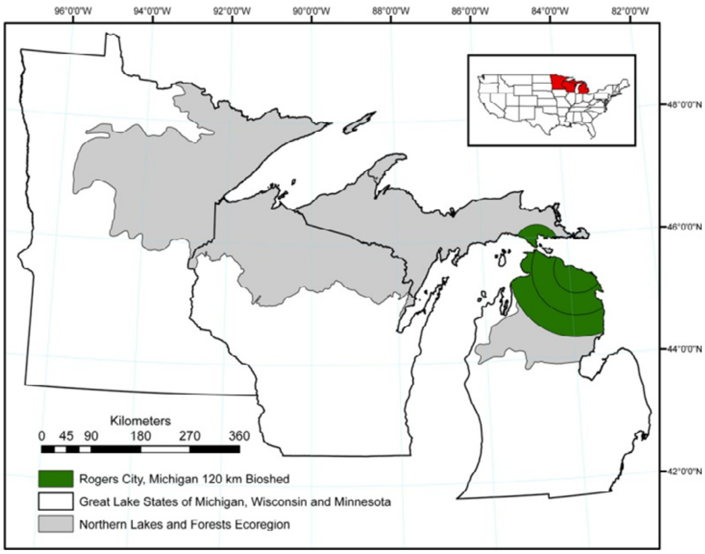

Figure 2. Northern Lakes and Forests Ecoregion and WCEV bioshed in Northern Lower Michigan; from: Froese RE, et al (2009).

2. Biomass Feedstock Opportunities

The emphasis in this biomass feedstock resource assessment is on low intensity, high diversity (LIHD) forest and agriculture in managed ecosystems comprised of polycultures of native species in the bioshed of the proposed plant. These systems maximize offset of GHG emissions through emphasis on low intensity (defined as inputs of energy and nutrients and the degree to which management alters an ecosystem from a native successional trajectory) because high intensity biomass production tends to lower benefit. The analysis indicates that GHG emissions mitigation is maximized in existing forest and idle agriculture land in the Northern Lakes and Forests Ecoregion (Figure 2) comprising extensive cover of forests, nutrient poor glacial soils, relatively low agricultural productivity, and long distances to potential urban markets (Froese RE, et al, 2009).

Analysis of cover class in the available land area of 18,619 km^2 within 120 km radial distance of the proposed site indicates predominantly rural, substantially timberland dominated by private ownership. Idle agricultural lands dominate actively cultivated crop and forage lands and in total cover more than 40,000 ha within just 40 km of the proposed facility, and nearly 300,000 ha within the entire study area (Figure 2, Table 1).

Cover class*	Distance Band (km)			Bioshed total
	0–40	40–80	80–120	
National forest	0	427	1282	1709
State forest	644	1522	2233	4399
Other public forest	11	35	46	92
Private forest	1514	3086	3641	8241
Total forest	*2168*	*5070*	*7202*	*14,441*
Crop and forage	248	412	623	1282
Herbaceous open-land	252	677	1056	1985
Upland shrub	166	319	426	910
Total agriculture	*666*	*1407*	*2105*	*4178*

Table 1.Biomass cover class and areal extent (in km2) in the WCEV bioshed; from: Froese RE, et al., (2009).

Woody energy crops (e.g., switchgrass, hybrid poplar) are the most advantageous, high intensity agricultural options. Managed forests and low intensity, high diversity (LIHD) forest or mixed perennial grassland systems also provide advantageous sources of biomass feed stocks. Native forests can also provide direct (pulp and logs more valuable as energy crop compared to conventional products) and indirect (branches, tops, rough logs, and low value species) biomass feedstock.

Biomass inventory and availability were determined for 3 concentric bands; 0-40 km, 40-80 km, and 80-120 km, comprising the project bioshed using three approaches: 1) Land-based inventories of forests themselves, from the USDA Forest Service Forest Inventory and Analysis Program (FIA), 2) USDA survey-based inventories of raw materials consumed by forest industries, compiled into a Timber Products Output database (TPO), and 3) approximate agricultural biomass feedstock productivity by scaling land inventory by expected productivity on a per hectare basis. This third method provided estimates of potential energy crop biomass production by determining available land base suitable for cultivation from Michigan Department of Natural Resources, Integrated Forest Management and Prescription (IFMAP) project data and estimated average yearly production rate for the target crop.

Results of this study of sustainable biomass fuel production indicate that land and forest resources, suitable for dedicated energy crop systems, are not a limiting factor at the rates of BC possible at the proposed plant. Potential biomass feedstock production was determined for biomass from forestry residuals in the WCEV bioshed with the potential to provide 180,000 megagrams per year (Mg y^{-1}) dry biomass. This constitutes 6% of the WCEV Project annual fuel requirements. Biomass from energy crops in the bioshed has the potential to provide 800,000 Mg y^{-1} of dry biomass, or 27% of annual fuel requirements for the project. The WCEV bioshed (<120 km) has the potential to provide sustainable, dry biomass fuel well in excess of the maximum annual design potential of 20% for the proposed plant. Presumably putting these fallow agricultural lands into dedicated energy crop production would be attractive to property owners and to local communities

3. CO_2/Enhanced Oil Recovery Potential in the Northern Niagaran Pinnacle Reef Trend, Northern Lower Michigan

Guelph Formation (Silurian-Niagaran) pinnacle reef oil fields are the most prolific petroleum reservoirs in the Michigan basin with nearly 64 million cubic meters (Mm^3; 468 million barrels, MMB) of oil and 76.5 billion cubic meters (Bm^3; 2.7 trillion cubic feet, TCF) of natural gas produced from over 1800 wells in over 800 northern Lower Michigan fields at depths of at least 800 m to 2150 m (Figure 3). The Northern Niagaran Pinnacle Reef (NNPR) trend comprises a giant hydrocarbon resource in closely-spaced but highly compartmentalized oil and gas fields (Figure 4) most at their economic limit in primary production mode. These reservoirs represent a significant opportunity for CO_2/ EOR and GCS in abandoned fields. To date, seven reef reservoirs in the trend have been converted to CO_2/EOR floods. Three of these fields are considered “mature “and CO_2/EOR production data are used to assess the recovery efficiency in reef reservoirs. Four fields are in the early stages of CO_2/EOR and

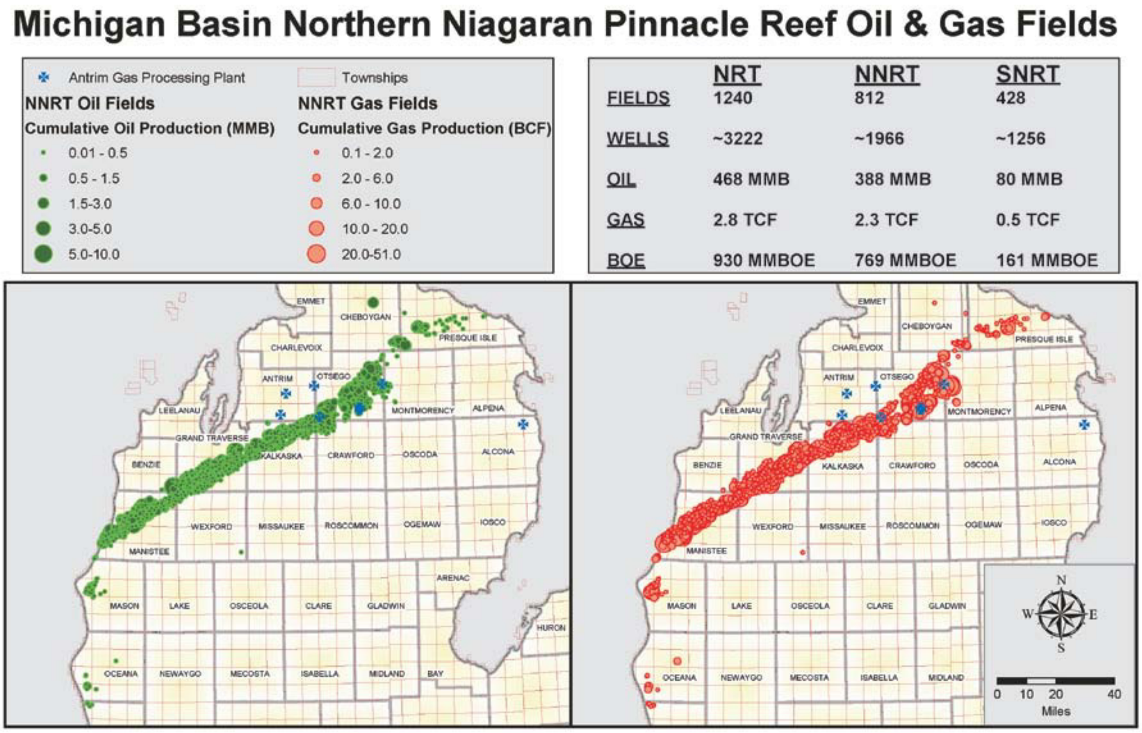

Figure 3.Michigan basin, Northern Niagaran pinnacle reef oil and gas field production.

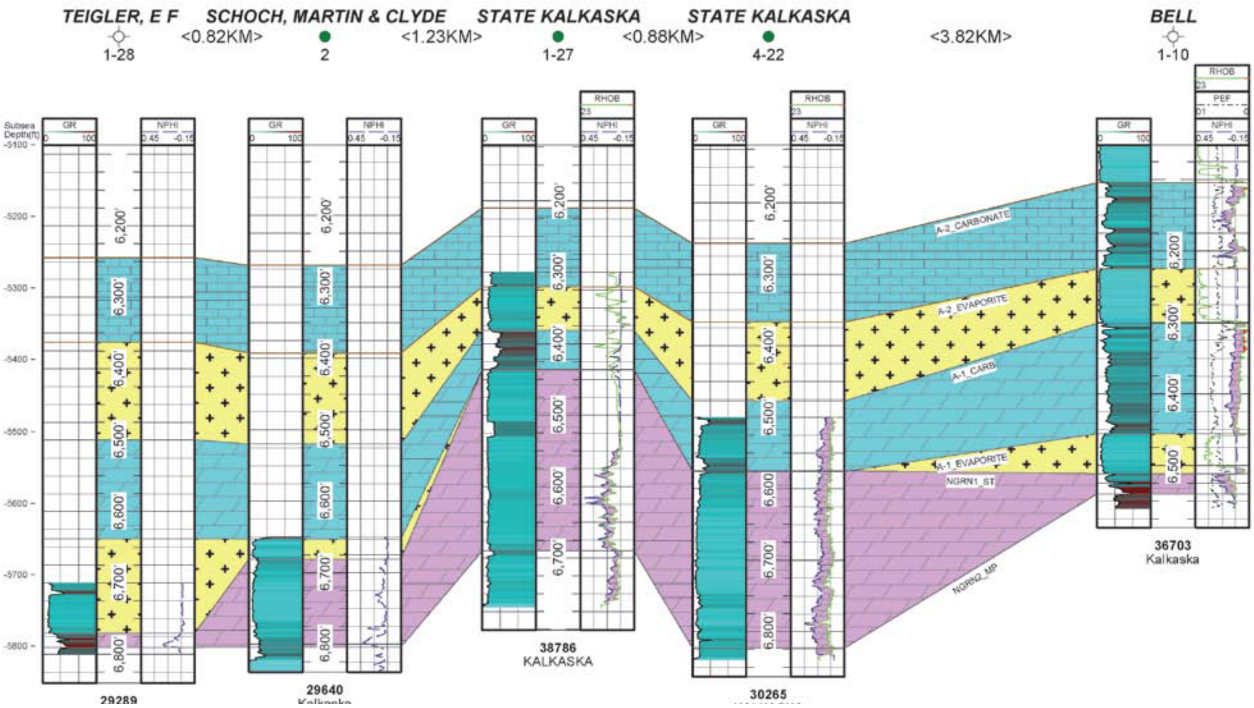

Figure 4. Structural, wire-line log cross section through the Kalkaska 21 oil field in Kalkaska CO., MI. The approximate, effective lateral extent of the oil field is less than 3 km. Primary oil production is 1.0 Mm^3 (5.3 MMB) of oil and 510 Mm^3 (18 BCF) of Natural gas

production data do not yet represent CO_2/EOR potential. The total incremental produced CO_2/EOR from all seven fields is over190, 000 m^3 (1.2 MMB) of oil using high purity CO_2, a by-product of natural gas production in the region. The average incremental oil recovery in the 3 mature fields is 34% relative to primary recovery and the highest recovery factor is over 38% in the most mature field. Recovery factors relative to primary recovery are projected to exceed > 40% even though optimal CO_2 injection volumes have not been utilized due to economic constraints of the projects.

CO_2/EOR potential for the entire NNPR trend fields in Northern Lower Michigan is substantial.

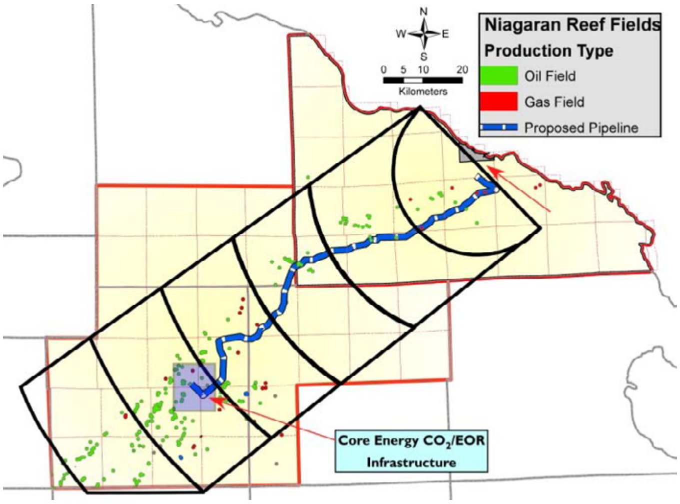

Figure 5.Proposed CO2 pipeline fairway polygonal study area and NNPR trend oil and gas fields.

Fields in excess of 79,500 m^3 (~0.5 MMB) of primary oil production may be candidates for CO_2 floods and cumulative production from these fields (205 fields in the NNPR trend) is approximately 52 Mm^3 (328 MMB) of oil. Using recovery factors of 40-60% (observed, see above; and suggested by Advanced Resources INT, 2006), potential CO_2/EOR for the entire NNPR trend is estimated at between 20.7 to 47.7 Mm^3 (~130 and 200 MMB) of oil.

Estimates of CO_2/EOR and abandoned oil and gas reservoir GCS potential were undertaken in the vicinity of the proposed WCEV. The study area was defined by a polygonal fairway approximately 96 Km (60 miles) by 31 Km (19.3 miles) encompassing a proposed CO_2 pipeline originating at the proposed plant site (Figure 5). Fields in this area with primary oil equivalent production in excess of 79,500 m^3 (~0.5 MMB) total approximately 18.4 Mm^3 (116 MMB) of cumulative oil production and 9.5 billion m^3 (336 BCF) of cumulative natural gas production. CO_2/EOR potential in the fairway is estimated at approximately 7.2 Mm^3 (45 MMB) of incremental oil.

Minimum GCS potential in abandoned oil and gas fields in the fairway study area was also considered through a produced fluids methodology. Produced fluids volumes, including oil, brine, and natural gas (at formation conditions) provides a minimum estimate of abandoned oil/gas field GCS capacity. Natural gas occurs as a discreet phase but also dissolved in oil in NNPR trend fields. A conversion factor for natural gas volume (reported at surface pressure and temperature) at reservoir conditions was calculated from the ideal gas law (for average NNPR trend depths) and determined to be 6.25×10^{-3}.These results compare closely to an analysis by Barth (2005). Using volume to mass conversion factors of 1 m^3 (6.4 barrel) = 0.7 metric ton and 1.4 m^3 (50 ft^3) = 1 metric ton of supercritical CO_2, the volume of cumulative produced oil, brine, and gas from the pipeline fairway area in reef fields is estimated to be equivalent to55 Mmt of CO_2.

Cumulative Primary Oil Production (fields >0.5 MMBO)	Cumulative Primary Gas Production (fields >0.5 MMBOE)	CO_2/EOR @40% (*60%*) of Primary Recovery	Abandoned Oil/Gas field GCS through Fluid Replacement
116 MMBO	336 BCF	~45 (*70*) MMBO	~55 MMt

Table 2. CO_2/EOR and abandoned oil and gas field GCS in the proposed Pipeline fairway study area

4. Michigan's Deep Saline Reservoir Geological Carbon Sequestration Zones

GCS potential in Michigan has been estimated at as much as 40 Tg of CO_2. The Michigan basin comprises as much as 4.9 km of Paleozoic sedimentary strata including multiple, stacked saline reservoir and regional CO_2/Enhanced Oil Recovery (EOR) targets in Devonian through Cambrian strata. Prospective saline reservoir GCS targets in Northern Lower Michigan include the Upper Silurian Bass Islands dolomite and the Ordovician St. Peter Sandstone (Figure 6a and b).

The St. Peter Sandstone is an important natural gas producer throughout the Michigan basin. Throughout Northern Lower Michigan, the St. Peter is present in the subsurface at sufficient depth to serve as a GCS injection zone and has significant storage capacity in generally high porosity/low permeability, clay-rich sandstone facies at the top of the formation. Injectivity in this unit is not well constrained but CO_2 storage capacity potential is likely to exceed 200 megagrams per hectare ($Mgha^{-1}$).The Bass Islands dolomite is a widespread, brine-filled carbonate unit and a regionally significant GCS target within the Michigan basin. The Bass Islands has an estimated geological storage capacity of nearly 1.5 Tg of CO_2, basin wide, with areas of highest storage capacity of 250 $Mgha^{-1}$ centered in Northern Lower Michigan. The Bass Islands was the injection target in a recent Regional Carbon Sequestration Partnership (RCSP) demonstration project and was shown to possess suitable injectivity for CO_2 sequestration on the order of several hundred thousand metric tons of CO_2 y^{-1} $well^{-1}$.

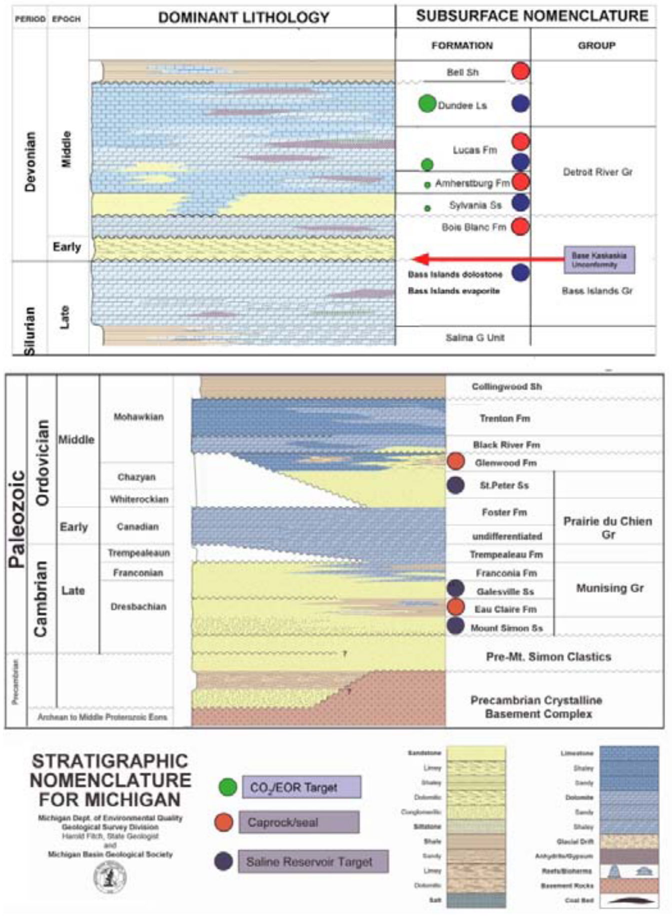

Figure 6.Stratigraphic columns from the Upper Silurian to Middle Devonian (a) and Lower Paleozoic (b) in the Michigan geological basin. GCS injection and confining zones and CO2/EOR opportunities are indicated.

Digital, wire-line log well data from the two prospective saline reservoir GCS target injection zones was quality control/validated from wells in the study area Thirty-six wells in the St. Peter Sandstone and forty-seven wells in the Bass Islands dolomite contain open-hole, porosity log (bulk density, RHOB, and neutron porosity, NPHI) data from the entire reservoir intervals in the study area. Porosity data was calibrated using an average density porosity-neutron porosity method (Asquith and Krygowski, 2004) to account for the sandstone and dolomite rock matrix of the St. Peter and Bass Islands, respectively.

Calibrated log porosity was then used to assess net effective porosity (porosity-height, PHIH) in each well on the basis of an effective porosity cutoff for each unit. PHIH is calculated using the following formula:

$$\mathbf{PHIH = \sum PHIAe * T}$$

where PHIH is net effective porosity (in m^3m^{-2}); PHIAe is decimal porosity per meter above effective porosity cutoff (10% for the St. Peter Sandstone, and 11% for the Bass Islands dolomite); and T is thickness (in meters).

Net effective porosity, PHIH, for each well was then mapped using geostatistical methods to determine the predicted spatial distribution. CO_2 density is assumed to be a minimum of 700 kg/m^2. Storage efficiency is influenced by various factors (see DOE-NETL, 2008) but a conservative estimate of 4% efficiency is used here. The calculation of storage capacity using these variables is given below:

$$\mathbf{SC = Øh * \rho CO_2 * \xi * Ag * C}$$

where SC = CO_2 storage capacity in metric tons (mt) per unit area; PHIH = net porosity; ρCO_2 = CO_2 density (a constant value of 700 kg/m3 was used for all depths); ξ = storage efficiency of 4%; Ag = grid cell area; and C = a constant for unit conversion to metric tons. The calculated total GCS capacity by polygonal ring areas and the total GCS capacity is shown in Figure 7. Total GCS capacity in the proposed pipeline fairway is 271 Mmt of CO_2.

5. Conclusions

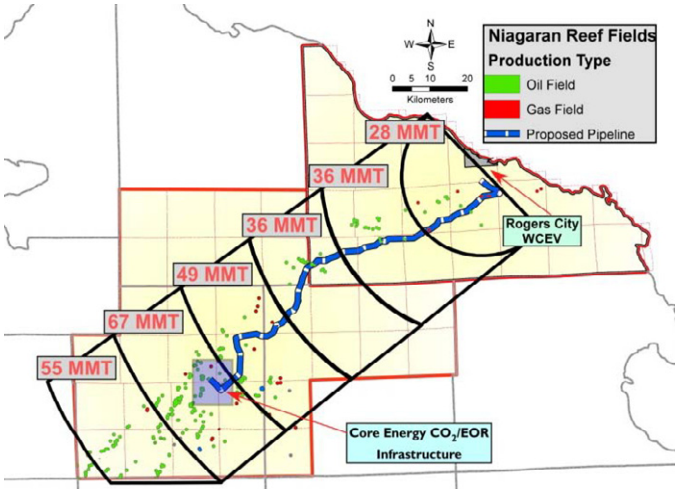

Figure 7.Proposed pipeline fairway study area showing composite GCS capacity in saline reservoirs by 16 km ring segments.

The proposed WCEV bioshed (<120 km) could provide sustainable, dry biomass fuel well in excess of the maximum annual design potential of 20% for the proposed plant. Biomass co-firing at the maximum design rate of 20% could provide a substantial contribution to renewable portfolio standard requirements in Michigan and, presumably, putting these fallow agricultural lands into dedicated energy crop production would be attractive to property owners and to local communities.

CO_2/EOR potential in NNPR trend oil fields along a proposed CO_2 pipeline fairway from the WCEV is estimated at in excess of 45 MMBO. Saline reservoir and abandoned oil field GCS potential in Northern Lower Michigan is substantial. Estimated GCS in the proposed pipeline fairway alone (~326 Mmt) is in excess of CO_2 emissions for a 50 year design life of the WCEV project burning 100% coal (255 Mmt).

The proposed WCEV project CO_2 emissions during a hypothetical design life of 50 years are estimated at 255 Mmt. The realization of biomass co-firing potential at 20% would result in 50MMt of CO_2 emissions during this 50 year period. If these biomass co-firing emissions were considered carbon neutral (although a more careful life-cycle analysis has not been undertaken) net carbon emissions during the 50 year design life of the proposed plant may be as little as 205 Mmt of CO_2.

Carbon capture and sequestration including , beneficial use in CO_2/EOR in the NNPR trend, GCS in abandoned oil and gas fields, and saline reservoir GCS Sequestration at 90% of CO_2 emissions from the proposed plant for a 50 year design life could result in the sequestration of 229.5 Mmt of CO_2. These considerations support the potential for a net negative emissions profile of up to -24.5 Mmt for a hypothetical 50 year design life of the proposed WCEV project.

6. Acknowledgments

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