Economic analysis of CO₂-enhanced oil recovery in Ohio: Implications for carbon capture, utilization, and storage in the Appalachian Basin region

Isis Fukai*, Srikanta Mishra, & Mark A. Moody

*Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201, USA*

*Corresponding author (Fukai@battelle.org)

Office: (614) 424-5422

Fax: (614) 578-5422

Abstract

A cost-benefit analysis is presented to evaluate the economic feasibility of carbon dioxide (CO₂)-enhanced oil recovery (EOR) in Ohio. Ohio-specific data is integrated with reservoir performance and economic models to define the analysis framework. The analysis is applied to two Ohio oil fields to illustrate how the methodology can be used to constrain project economics and profitability. The regression derived from the CO₂ break-even price calculated for a range of oil prices indicates that the change in the unit value of CO₂ for EOR is approximately four times the corresponding change in the unit value of oil. A similar correlation observed in other oil fields suggests differences in reservoir properties may not significantly alter the price elasticity of CO₂ relative to the prevailing oil price. The break-even correlation presented here represents a standalone metric that can be applied for project screening purposes to determine the price conditions at which CO₂ becomes a viable purchase for EOR and a marketable asset for power plants with capture technology.

Keywords: CO₂-EOR, CO₂ utilization, geologic storage, cost-benefit analysis

Acronyms and Terminology

AFE	Authorization for Expenditure
ARI	Advanced Resources International
BLS	US Bureau of Labor Statistics
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CMU	Carnegie Mellon University
CO ₂	Carbon dioxide
CPI	Consumer Price Index
CURC	Coal Utilization Research Council
D&C	drilling and completion
DOE	Department of Energy
ECOF	East Canton Oilfield
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ft	feet
G&A	general and administrative
HCPV	hydrocarbon pore volume
IEAGHG	International Energy Agency Greenhouse Gas Programme
MCOF	Morrow Consolidated Oilfield
mD	millidarcy
NETL	National Energy Technology Laboratory
NPV	net present value
O&M	operation and maintenance
OOIP	original oil in place
RMSE	root mean square error
scf	standard cubic foot
STB	stock tank barrel
U.S.	United States
USD	U.S. dollars

1.0 Introduction and Scope

Carbon capture, utilization, and storage (CCUS) is a vital component of the strategy to achieve CO₂ emission reductions in the power generation sector (Benson and Friedmann, 2014). In the state of Ohio, the latest EPA data indicate that 129 million metric tons of CO₂ were emitted in 2013 from 229 stationary sources, with twenty-two coal-fired power plants contributing 63% of total emissions (EPA, 2014; Battelle, 2015). Coal is projected to remain an important fossil fuel for electricity generation along with natural gas for the next several decades in the United States (U.S.). As such the decreased but continued use of coal will likely be instrumental in maintaining affordable electricity prices and meeting rising energy demands (CURC-EPRI, 2015; EIA, 2015a).

Balancing potential CO₂ emission reduction requirements with the high costs of modern CCUS technology is currently a major challenge for coal-fired power plants (Hamilton et al., 2009; Zhai et al., 2015). The oil industry practice of CO₂-EOR (enhanced oil recovery) is a utilization pathway that could provide a revenue stream and market for captured CO₂ to help improve CCUS project economics (Monea, 2014; Rubin et al., 2015). The economic incentives associated with CO₂ utilization and storage via EOR may be especially important for deploying CCUS in regions where the economic welfare is strongly tied to coal and coal-fired power generation, such as the Appalachian Basin in the U.S.

Ohio ranks among the top ten states for highest coal-production, electricity generation, and CO₂ emissions in the U.S. (EIA, 2015b). The potential for utilization and storage of captured CO₂ via EOR in Ohio exists in depleted oilfields that contain as much as 80–90% of the original oil in place (OOIP) due to poor primary recovery (Sutton, 1965; Overby, 1971; Riley et al., 2002; Riley et al., 2010; ODNR, 2013; Mishra et al., 2014) which occur alongside twenty-two major CO₂-emitting coal-fired power plants located in the state (Figure 1). The objective of this study is to conduct a cost-benefit analysis to evaluate the economic feasibility of CO₂-EOR to act as a commercial driver for CCUS in the Appalachian Basin region.

The cost of CO₂ capture from power plants has been evaluated in several techno-economics studies on CCUS (e.g., David and Herzog, 2000; Rubin et al., 2007; IEAGHG, 2009; Rubin, 2012; Tola and Pettinau, 2014; Rubin et al., 2015), with reported CO₂ capture costs ranging from

\$28 to \$87 2013 U.S. dollars (USD) per tonne (t) for new coal-fueled power plants (supercritical pulverized coal and integrated gasification combined cycle) and a variety of capture systems (pre-, post-, and oxy combustion) (see Tables 2, 4-6 in Rubin et al., 2015). Fewer assessments have been conducted on the costs and economics of CO₂-EOR co-storage projects, with existing studies focused primarily on states in the southwestern U.S. such as Texas, Louisiana, and New Mexico (ARI, 2006; McCoy, 2009; McCoy and Rubin, 2009; King et al., 2010). A detailed economic analysis of CO₂ utilization and storage via EOR has not been published for Ohio.

This study integrates Ohio-specific reservoir and cost data with CO₂-EOR performance-cost models established in previous studies to evaluate the economic feasibility of CO₂-EOR in Ohio, and the resulting implications for CCUS deployment in the region. The cost-benefit analysis methodology is applied to the East Canton (ECOF) and Morrow Consolidated (MCOF) oil fields (Figure 1) for various CO₂ and oil price scenarios to illustrate how key parameters of the analysis can be used to derive high-level estimates of CO₂-EOR project economics and profit potential in Ohio. These depleted oil fields represent two of the more attractive targets for CO₂-EOR in the state (Sutton, 1965; Riley et al., 2011; Mishra et al., 2014). An important outcome of this study is the correlation established through the CO₂ break-even analysis that can be used to determine the potential market value of captured CO₂ for EOR as a function of the prevailing oil price (McCoy, 2009; McCoy and Rubin, 2009). The cost-benefit analysis presented in this study can be used to help guide decision-making processes related to CCUS policy, investments, and marketing strategies in Ohio and neighboring states in the Appalachian Basin.

The paper is organized as follows. Section 2 of this paper begins with an overview of the cost-benefit analysis methodology, followed by detailed descriptions of the reservoir performance, revenue and cost models. Application of the methodology to the ECOF and MCOF is detailed in Sections 3 and 4 respectively, including reservoir performance and economic outcomes for various oil and CO₂ price scenarios. Section 5 examines the specific price points at which captured CO₂ can be economically purchased for EOR in the two fields, with implications for CCUS commercialization in the study region. The significance and utility of the correlation established in this study for CO₂ break-even price is discussed in concluding remarks.

Figure 1. Map showing the East Canton and Morrow consolidated oilfields in Ohio along with the locations of major CO₂-emitting coal-fired power plants. Note: Other large oil fields are shown in gray.

2.0 Cost-Benefit Analysis Methodology

2.1 Analysis Framework

The framework employed in this cost-benefit analysis of CO₂-EOR co-storage in Ohio includes a reservoir performance model, a revenue model, and a cost model (Figure 2). This analysis framework builds upon previous work by Advanced Resources International (ARI) and researchers at Carnegie Mellon University (CMU) in collaboration with the U.S. Department of Energy's National Energy Technology Laboratory (U.S. DOE-NETL) (ARI, 2006; McCoy and Rubin, 2006; McCoy, 2009; McCoy and Rubin, 2009; U.S. DOE-NETL, 2011, 2014a). These previous studies are widely reviewed and accepted methods for estimating CO₂-EOR and storage costs (Jablonowski and Singh, 2010; U.S. DOE-NETL, 2014a; Wei et al., 2015). Calculation

schemes were selected from these existing studies and populated with Ohio-specific data to define the components of the reservoir performance, revenue, and cost models in this study.

Figure 2. Schematic of the cost-benefit analysis framework used in this work.

CO₂-EOR performance results from the reservoir model are integrated into separate revenue and cost models that calculate net revenue and total project costs, respectively. The resulting net cash flow is then discounted to derive the net present value (NPV) of the project. The break-even price of CO₂ is calculated to representing the maximum price a CO₂-EOR operator could pay for CO₂ without incurring loss on the project, and is calculated as a function of oil price to help determine a viable market price for captured CO₂ based on the prevailing price of oil.

Due to the uncertainty in the regulatory landscape of CCUS the cost model does not consider the value of incentives and credits that could potentially be received for CO₂ storage, which could help offset costs. CO₂ storage is treated as a byproduct of EOR operations and is not directly associated with incurrence of project costs. As such, injection wells considered in this assessment can be categorized as Class II EOR wells, rather than Class VI under the U.S. EPA Underground Injection Control program. Similarly the costs of CO₂ site monitoring, verification, and accounting are cited as being a negligible part of total CO₂-EOR project costs, with estimates reported at \$0.04-0.09 USD per tonne of CO₂ stored (Benson et al., 2004; Jablonowski and Singh, 2010), and are not included in the analysis. Studies conducted on CO₂ transport costs indicate estimates can vary greatly due to dependence on factors that are difficult to systematically correlate with costs, such as transport terrain, existing land use, and sharing of pipeline networks (e.g., McCoy and Rubin, 2009; Rubin et al., 2013; IEAGHG, 2014; U.S. DOE-NETL, 2014b; Rubin et al., 2015). The cost model employed in this study only considers transport costs associated with local CO₂-EOR site operations, and does not account for the costs associated with CO₂ capture and regional pipeline transport. The cost model assumes the CO₂ initially delivered to the site via trunkline will be of sufficient purity and pressure for miscible injection. The costs and revenue associated with recovery of natural gas and natural gas liquids were not included in the analysis.

2.2 Reservoir Performance Model

The oil recovery, and CO₂ injection, production, and recycling performance of the reservoir must be known in order to evaluate the potential of CO₂-EOR as a viable avenue (and economic incentive) for commercial-scale CCUS implementation. A simplified stream tube reservoir performance model (CO₂-PROPHET) was used to estimate incremental oil recovery from CO₂ injection for the ECOF and MCOF. CO₂-PROPHET is a predictive model for CO₂-EOR reservoir performance developed by Texaco (Dobitz and Prieditis, 1994) for the U.S. Department of Energy, and has been used as a screening tool in several techno-economic studies on CO₂-EOR (e.g., ARI, 2006; King et al., 2013; DiPietro et al., 2015). CO₂-PROPHET requires input to define the field/operational parameters, reservoir characteristics, and fluid properties for the CO₂-EOR simulation, as shown in Table 1.

Water, oil and gas are the three fluid components included in the model, with the terms “gas” and “solvent” used interchangeably with CO₂. Based on input provided by the user, the model generates streamlines to simulate fluid flow between the injection and production wells, assuming no crossflow occurs between layers of the reservoir. OOIP is user-specified or calculated volumetrically based on pattern area, net thickness, porosity, and fluid saturation inputs. Oil displacement and recovery is then calculated along streamlines, with areal sweep efficiency incorporated within the well spacing coordinates, fluid mobility ratios, and reservoir heterogeneity inputs that define the streamline boundaries. The mixing parameters defined by Todd and Longstaff (1972) are used to simulate CO₂ miscibility. The effects of gravity on fluid segregation and mixing are not considered in the model.

Table 1. Parameters and definitions of input required for CO₂-PROPHET CO₂-EOR simulation.

CO ₂ -Prophet Designation	Input Definition
<i>Field/Operational Conditions</i>	
PATTERNS	Well Pattern
NWELLS, NOINJ	No. of total wells, No. of injection wells
WELLX, WELLY, WELLQ	Well coordinates, flow rates
NTIMES	No. of injection periods
OUTTIM	Time increment for output (year)
SOLRAT	Surface injection rate of CO ₂ (MMscf*/day)
HCPVI	Incremental hydrocarbon pore volumes of CO ₂ injected
TMROVL	Fraction of injection which is water
<i>Reservoir Characteristics</i>	
AREA	Pattern area (ft ²)
TRES	Reservoir temperature (°F)
P	Initial reservoir pressure (psia)
MMP	Minimum miscibility pressure (psia)
DPCOEF	Dykstra-parsons coefficient in the producing zone
PERMAV	Average permeability in the producing zone (mD)
THICK	Net thickness of the producing zone (ft)
POROS	Porosity of the field (dec.)
SOINIT	Initial oil saturation (dec.)
SWINIT	Initial water saturation (dec.)
SGINIT	Initial gas saturation (dec.)
XKVH	Ratio of vertical to horizontal permeability
<i>Fluid Properties</i>	
VISO	Viscosity of oil, cp
VISW	Viscosity of water, cp

BO	Oil formation volume factor (rb/STB)
RS	Solution gas-oil ratio (scf/sSTB)
API	Oil gravity (°API)
SALN	Brine salinity, ppm TDS
GSG	Gas-specific gravity

*M represents one thousand

CO₂-EOR performance results were simulated for one 40-acre 5-spot well pattern at a constant CO₂ injection rate until two hydrocarbon pore volumes (HCPV) of total CO₂ injection was achieved. An injection rate of 0.5 MMscf/day is consistent with injection rates observed in present-day CO₂-EOR field operations, and was chosen for both the ECOF and MCOF to facilitate comparisons between the two fields and with other studies that employ similar injection rates (Mortis, 2006; McCoy and Rubin, 2009). In CO₂-PROPHET the simulation is conducted over a quarter of the area in a 5-spot well pattern, and the results are scaled over the entire pattern following symmetry operations associated with well coordinate information (Figure 3). Other simplifying assumptions of the simulation include delivery of supercritical CO₂ of suitable purity for injection and miscible flood conditions. The volume of CO₂ recycled and reused for injection was assumed to be equal to the volume of CO₂ produced. The difference between the volume of CO₂ injected and produced represents the volume of CO₂ permanently stored in the reservoir. The CO₂ stored via physical and/or chemical trapping in the reservoir (within and outside of the pattern simulation) becomes unavailable for subsequent injection, and is used to calculate the volume of new CO₂ required for purchase to maintain the specified injection rate. Oil recovery results were used in the revenue model to calculate net revenue for the project. Results of oil, water, and CO₂ production, along with CO₂ recycling rates were incorporated into the cost model to calculate costs of CO₂, capital, and operation and maintenance (O&M).

Figure 3. Schematic showing 40-acre 5-spot well pattern spacing and the CO₂-EOR simulation method employed by CO₂-PROPHET.

2.3 Revenue Model

The revenue model calculates net revenue from oil recovered and sold at a specified oil price, with relevant tax deductions (Table 2). Royalties comprising 15% of the gross revenue were included in the calculation, derived from the average royalty percentage employed in the ARI and CMU models. A severance tax of 2.0% was chosen as a representative value based on the current Ohio severance tax on conventional crude oil production (\$0.20/STB), and a 6.6% tax rate imposed in Michigan; the nearest state with large-scale CO₂-EOR (Michigan Department of Treasury, 2014; Weinstein et al., 2015). An Ad Valorem tax of 1.5% was derived from the average tax percentage levied on mineral properties in Ohio counties (Ohio Department of Taxation, 2014). Severance and Ad Valorem taxes were deducted from the remaining revenue after royalty taxes. The revenue model calculation scheme produces a time series of incoming net cash flows in which the resulting net revenue of the project can be evaluated incrementally during specific periods of operation, and cumulatively at the end of the project life.

Table 2. Inputs and definitions of parameters included in the revenue model.

Revenue Model	Input/Definition
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Parameter	
Oil Produced (STB)	Volume of incremental or cumulative oil produced during reservoir performance simulations
Oil Price (USD/STB)	Market price of oil
Gross Revenue (USD)	Revenue from oil recovered and sold at the specified market price; <i>oil recovered (STB) x oil price (\$/STB)</i>
Royalty (%)*	15% of gross revenue; <i>0.15 x gross revenue (\$)</i>
Severance Tax (%)*	2.0% of revenue after royalty tax; <i>0.02 x (0.15 x gross revenue \$)</i>
Ad Valorem Tax (%)*	1.5% of revenue after royalty tax; <i>0.015 x (0.15 x gross revenue \$)</i>
Net Revenue (USD)	Revenue after deduction of royalty, severance, and ad valorem taxes; <i>Gross revenue (\$) - Royalty (\$) - Severance (\$) - Ad Valorem (\$)</i>

*See Section 2.3 text for explanation

2.4 Cost Model

The cost model calculated total costs for the CO₂-EOR project, and can be broken into three main categories: well costs, CO₂ costs, and O&M costs. Well costs account for equipment, services, labor and site-related capital costs associated with well drilling and completion (D&C), new production and injection well equipment, and existing well conversion. CO₂ costs include the capital and operational costs associated with CO₂ purchase for injection, trunkline transport and on-site distribution, and CO₂ recycling. Capital costs in the cost model are accrued at of the beginning of the project. Total O&M costs account for consumables, services, and labor associated with ongoing site operation and maintenance (surface and subsurface), liquid lifting/handling, and general and administrative (G&A) expenses. A comprehensive table of definitions and list of expense items associated with each cost model parameter is provided in Appendix A (Table A-1).

Cost data were acquired for Ohio wells to derive calculation schemes for estimating well costs in the cost model (see Table 3 for details). Equations established by the previous studies described in Section 2.1 were used to calculate costs of parameters for which Ohio data was insufficient or unavailable. All cost data was adjusted to represent constant 2014 U.S. dollars (USD) using the Bureau of Labor Statistics (BLS) Consumer Price Index (CPI). It is noted that relative to the inflation-based, constant-dollar analysis employed in this paper using the BLS-CPI, other

industry-specific indices may be better suited for tracking the escalation of costs in the oil and gas sector, such as the IHS Upstream Capital Cost Index (UCCI). While the BLS-CPI-based inflation adjustment may be appropriate for a methodological study such as this one, we recommend that any field-specific, cost-benefit analysis take into account historical trends in upstream capital costs for that geographic region vis-à-vis oil price fluctuations in its cost model. Additionally, costs (capital and operational) associated with the oilfield industry can be very volatile due to many factors that are difficult to constrain, such as market and field conditions. The calculation schemes used in this study represent correlations derived from the best available data, and are inherently subject to the price volatility of the industry. The equations for each cost parameter and the associated data sources are defined in Table 3.

Well cost calculations for the ECOF and MCOF example cases considered new well drilling, completion and equipment costs for a quarter of an injection well and a quarter of a production well in the 5-spot patterns in each field. This balances the fixed capital costs of the CO₂ recycling facility to one pattern to allow for scaling of results in accordance to phased field development scenarios (see Section 2.5.1). There are no costs incurred for existing well conversions in the two examples. In practice, some existing wells would likely be converted/reworked to satisfy pattern requirements, resulting in lower total well costs relative to the higher costs associated with drilling and completing all new wells. The trunkline distance for transport of CO₂ from the regional pipeline to the EOR site was assumed to be 10 miles.

Table 3. Cost model parameters, equations, and associated references.

Cost Model Parameter	Equation*	Study Referenced
Well Costs		
Drilling & Completion (D&C)	$\$65,703e^{(0.0004 \times \text{depth ft.})}$	(1) <i>Ohio cost data (this study)</i>
Production Well Equipment (EQ _p)	$(\$10.12 \times \text{depth ft.}) + \$20,210$	(2) <i>Ohio cost data (this study)</i>
Injection Well Equipment (EQ _i)	$(\$18.33 \times \text{depth ft.}) + \$11,626$	(3) <i>ARI, 2006; DOE-NETL, 2011, 2014</i>
Well Conversion	$(0.48 \times \$D\&C) + (0.50 \times \$EQ_{p,i})$	(4) <i>McCoy, 2009; McCoy & Rubin, 2009</i>
CO₂ Costs		
CO ₂ Transport & Distribution	$\$187,985 + (\text{mi} \times \text{USD/mi})$	(5) <i>ARI, 2006; DOE-NETL, 2011, 2014</i>
CO ₂ Recycling Plant	$\$877,264 \times \text{Max.CO}_2 \text{ recycling rate MMscf/day}$	<i>ARI, 2006; DOE-NETL, 2011, 2014</i> (6)
CO ₂ Recycling O&M	$(0.01 \times \text{USD/STB oil}) \times \text{CO}_2 \text{ recycled MMscf}$	<i>ARI, 2006; DOE-NETL, 2011, 2014</i> (7)
Total O&M Costs		
Periodic O&M	$\$33,684e^{(0.0001 \times \text{depth ft.})} \times \text{no. of wells}$	(8) <i>McCoy, 2009; McCoy & Rubin, 2009</i>
Liquid Lifting Costs	$\$0.25 \times (\text{produced BBLs water} + \text{oil})$	(9) <i>ARI, 2006; DOE-NETL, 2011, 2014</i>
General & Administrative (G&A)	$0.20 \times (\$O\&M + \$\text{Liquid Lifting})$	(10) <i>ARI, 2006; DOE-NETL, 2011, 2014</i>

*Values reported in constant 2014 USD

2.4.1 Well Costs

Well costs are capital costs of well design and installation incurred during the initial stages of the EOR project. Well costs can be subdivided into new well D&C costs, production and injection well equipment costs, and well conversion costs. D&C costs are defined as the tangible and intangible costs of on-site drilling and completion phases for new production and injection wells, including leasehold, rig, cementing, casing, site reclamation and plugging costs. Production and injection well equipment costs include purchase and installation of items such as tubing, rods, storage tanks, electrical services, pumps, separators, and wellheads. Well conversion costs are defined as the tangible and intangible costs of updating or converting existing wells to establish the number of suitable injection and production wells required for the well pattern/project, such as stimulation treatment, pressure tested lines, and fabrication materials and services. A more

comprehensive list of items associated with each well cost category in the cost model is provided in Appendix A (Table A-1).

Ohio data from itemized cost reports and Authorization for Expenditures (AFEs) were supplemented by informal expert elicitation to estimate well costs in the cost model. Inputs were provided by six operators for twenty-six wells drilled and operated in Ohio between 2005 and 2015 at depths of 1,308 – 9,200 ft. Well type, configuration, depth, and associated costs for each well are included in Appendix A (Table A-2). The 2014 adjusted well cost data was plotted as a function of depth to derive Ohio-specific regressions for cost model calculations. D&C costs and associated depths reported for Ohio wells exhibit an exponential regression trend (Figure 4), represented by Equation 1 in Table 3. The higher costs of the two injection wells shown in Figure 4 represent costs of brine injection wells in Ohio, and relative to production wells, have slightly higher D&C costs associated with factors such as larger well diameters, and higher completion costs. The cost data from these two brine injection wells may therefore not be representative of CO₂-EOR injection well costs and other practitioners are strongly encouraged to use their own regional well data to develop more reliable cost regressions. The regression¹ derived from production well equipment costs plotted against depth takes on a linear form as shown in Figure 5. The cost data received for injection well equipment and well conversion was insufficient to develop robust regressions. The regression equation (3) from the ARI (2006) cost model was used to calculate injection well equipment costs (e.g., Table 3). The equation (4) developed by McCoy and Rubin (2009) was incorporated into the cost model to estimate the costs of well conversion.

¹ A root mean square error of $\pm \$16,281$ is associated with the production well equipment cost regression (Equation 2), and can be used as an error estimate in cost calculations to account for the relatively low coefficient of determination (R^2) of the regression.

Figure 4. Drilling and completion well cost regression derived from Ohio well data and used in cost model calculation scheme. Note: Depths of the producing formations from the MCOF and ECOF are also indicated by the dashed lines on the plot.

Figure 5. Production well equipment cost regression derived from Ohio well data and used in cost model calculation scheme. Depths of the producing formations from the MCOF and ECOF are also indicated by the dashed lines on the plot. A root

mean square error (RMSE) of $\pm \$16,281$ associated with the relatively low R-squared value can be used as an error estimate.

2.4.2 CO₂ Costs: Purchase, Transport, & Recycling

CO₂ costs include the fixed and variable costs associated with CO₂ purchase, transport from the regional pipeline to on-site distribution, recycling, processing, and recompression. CO₂ transport and on-site distribution costs were estimated based on a cost per distance of trunkline for transport of the CO₂ from the regional pipeline to the site, the trunkline diameter required to facilitate the maximum CO₂ injection rate, and all flow lines and manifolds required for on-site distribution of CO₂ (Table 3, Equation 5). The maximum CO₂ recycling rate derived from the CO₂-PROPHET simulation in standard cubic feet (scf; 60°F, 1 atm) per day was used to estimate the capital costs of the CO₂ recycling facility (Equation 6). CO₂ recycling including on-site separation, processing, and compression as shown in Figure 6, with ongoing O&M costs determined by the volume of CO₂ recycled (scf) per time series set at 1% of the price of oil per barrel (STB) to reflect the cost of on-site generation of the energy required for operation (Equation 7).

Figure 6. Simplified diagram showing components of CO₂ injection and recycling operations.

2.4.3 Total O&M costs

Total O&M costs for the site include periodic O&M costs, liquid lifting costs, and G&A expenses. Periodic O&M costs reflect ongoing expenses associated with operation and maintenance of the CO₂-EOR site at the required capacity over a given time period, including electricity, consumables, periodic well work over, surface and subsurface repairs (Equation 8). Periodic O&M costs are also dependent on the number and depth of wells used in the project. Liquid lifting costs are estimated as \$0.25 per volume of oil and water produced (Equation 9). G&A costs are calculated as 20% of the sum of periodic O&M and liquid lifting costs (Equation 10).

2.5 Analysis Scenarios and Evaluation Metrics

2.5.1 Price Scenarios

For the purposes of this analysis, cost model results are reported on a per pattern basis, and can be scaled in accordance with any field development schedule of interest. It should be noted that certain cost components will not scale linearly with pattern development, such as CO₂ recycling facility costs, and capital well costs. For example, in a phased development scenario, the recycling facility will be constructed for a maximum injection capacity determined by aggregation of flows from multiple patterns. If pre-existing wells are expected to be used to meet well requirements for a certain percentage of patterns, the capital costs of well conversion should be included in place of new well drilling and completion costs.

Several market scenarios were examined for the cost-benefit analysis of potential CO₂-EOR co-storage projects in the ECOF and MCOF: oil prices of \$40, \$70, and \$100 per barrel were each evaluated at CO₂ prices of \$40, \$80, and \$120/t. \$70/STB oil and \$80/t CO₂ was defined as the median price scenario, bound by the lowest (\$40/STB oil and \$120/t CO₂) and highest (\$100/STB oil and \$40/t CO₂) NPV calculated in the analysis. The CO₂ prices analyzed in this study are slightly higher (~ 40% markup) than CO₂ capture costs reported in Rubin et al., (2015) for new coal-fired power plants (\$28 – \$87/t CO₂ in 2013 USD).

The effect of discount rate on CO₂-EOR project economics was also evaluated at the median price scenario analyzed. The discount rate represents the percentage difference between the

present and future value of an expected cash flow, accounting for the time-dependent value of money and risk associated with a future investment. Discount rates of 10%, 15%, and 20% were examined for the price scenario of \$70/STB oil and \$80/t CO₂, and are within the range of discount rates used in the ARI and CMU studies. A discount rate of 15% was used for all other calculations as a representative, median discount factor. These different analysis scenarios are intended to represent relevant market conditions that may influence CO₂-EOR project economics in Ohio, based on historical and of current interest rates in the U.S. (e.g., Federal Reserve).

2.5.2 Net Present Value

The value of future cash flows accrued incrementally and cumulatively over the duration of the CO₂-EOR project is represented by the NPV. The NPV is calculated as the sum of cash inflows and outflows, discounted to account for the time value of money and the risk/uncertainty associated with future cash flows. The net revenues (incoming cash flows) from the revenue model were integrated with total costs (outgoing cash flows) calculated by the cost model to derive a time series (years) of NPV estimates. The cumulative NPV calculated at the end of the operation was then used to evaluate the profitability of the CO₂-EOR operation, such that positive values represent scenarios of profit and negative values represent financial losses incurred by investor(s) in the project.

2.5.3 CO₂ Break-Even Price

The break-even price of CO₂ is the CO₂ purchase price that results in a NPV to equal to zero, and can be interpreted as the maximum price an EOR operator could pay for CO₂ without incurring loss on the project (McCoy, 2009; McCoy and Rubin, 2009). The break-even price of CO₂ was calculated as a function of various oil prices (\$40–100/STB) to define the specific price conditions at which CO₂ becomes a viable purchase for EOR, and a marketable asset for capture facilities. The overall trend observed in the CO₂ break-even price² calculated over the range of oil prices was used to derive the unit value of CO₂ relative to oil for the oil field of interest. We note the possibility that our capital cost assumptions using an inflation-based constant dollar scenario may not fully reflect any downward adjustments in capital costs due to drop in oil prices. The net effect is that breakeven costs calculated using our model can be expected to be

² It should be noted that CO₂-EOR requires higher upfront capital and operational investments, such that the break-even price represents a different timeline compared to primary oil production.

an upper bound. However, since upstream capital cost reductions are generally muted compared to changes in oil price, the degree of conservatism reflected in our calculations should be moderate.

3.0 Application of Methodology to the ECOF

3.1 Reservoir Description

The ECOF is an oil field located in northeast Ohio that produces from the Silurian “Clinton” sandstone. Active drilling began in the 1960’s, with 96 MMSTB of oil produced to-date from the estimated 1,537 MMSTB of OOIP. Approximately 3,100 wells have been drilled in the field, following a 40 acre pattern spacing (Perry and Riley, 2011). The Clinton sandstone occurs at an average depth of 5,200 ft in the ECOF, with the productive zone comprising approximately 175,000 acres. On average, the reservoir exhibits a net thickness of 20 ft, matrix porosity of 6%, and permeability of 5.2 millidarcies (mD). Secondary and enhanced recovery in the ECOF has been limited to small-scale water flood tests. Average reservoir, field, and fluid characteristics for the Clinton sandstone are included in Table 4.

Table 4. Key reservoir performance model parameters for the ECOF

Parameter	ECOF Input	
Reservoir	Clinton sandstone	
Pattern	5 spot	
Production History	Primary	
Injection Rate	0.5 MMscf/day (26 t/day)	
HCPV CO₂	2	
Field Area	175,000 acres (708 km ²)	
Reservoir Temperature	107°F	(314.8 K)
Initial Reservoir Pressure	1,450 psia	(10 MPa)
Reservoir Depth	5,200 ft	(1,585 m)
Minimum Miscibility Pressure (MMP)	1,450 psia	(10 MPa)
Dykstra-Parsons Coefficient	0.70	
Permeability	5.2 mD	
Net Thickness	20 ft	(6 m)
Porosity	0.06	
OOIP	1,537 MMSTB	
Initial Oil Saturation	0.40	
Initial Water Saturation	0.40	
Initial Gas Saturation	0.20	
Vertical:Horizontal Permeability	0.10	

Viscosity of Oil	1.00 cp
Viscosity of Water	0.68 cp
Formation Volume Factor, B_o	1.21 rb/stb
Solution Gas:Oil Ratio, R_s	443 scf/stb
Oil API Gravity	41°

3.2 Reservoir Performance Results

CO₂-PROPHET results of oil production, water production, CO₂ production/recycling, and CO₂ injection, were simulated for one 40-acre 5-spot well pattern in the ECOF, assuming a ready supply of CO₂ available to maintain an injection rate of 0.5 MMscf/day (26 t CO₂/day).

Incremental and cumulative results of the CO₂-PROPHET simulation are shown in Figure 7 and 8, respectively for 2 HCPV of total CO₂ injection. The maximum CO₂ production/recycling rate simulated in the ECOF is 0.47 MMscf/day (25 t CO₂/day). A total of 56 thousand (M) barrels (STB) of oil production and a cumulative volume of 1,085 MMscf of CO₂ injection (57,505 t), is predicted over a pattern life of ~6 years (Table 5). Of the cumulative volume of CO₂ injected, 918 MMscf (48,654 t) was produced, and 167 MMscf (8,851 t) was purchased and permanently stored in the formation, corresponding to net and gross CO₂ utilization factors of 3 Mscf (0.16 t) and 19 Mscf CO₂ (1 t) per barrel of oil, respectively.

Figure 7. Incremental CO₂-EOR reservoir performance in the ECOF pattern shown in volumes per quarter year for 2 HCPV of total CO₂ injection and a constant injection rate.

Figure 8. Cumulative CO₂-EOR reservoir performance in the ECOF at 2 HCPV of total CO₂ injection and a constant injection rate.

Table 5. CO₂-PROPHET results of the CO₂-EOR simulation for the ECOF.

Time (years)	1	2	3	4	5	6	Cumulative
Oil Produced (MSTB)	24	10	7	6	4	4	56
H₂O Produced (MSTB)	14	4	3	2	2	2	27
CO₂ Injected (MMscf)	183	183	183	183	183	172	1085
CO₂ Produced/Recycled (MMscf)	106	153	162	166	170	162	918
CO₂ Stored (MMscf)	77	30	21	16	13	10	167

3.3 Revenue & Cost Model Results

Well costs calculated for the ECOF pattern total to \$0.31 million for a reservoir depth of 5200 ft. Costs of the CO₂ recycling facility, trunkline, and on-site distribution equipment were estimated at \$0.63 million, with total capital costs for the ECOF totaling to \$0.94 million. The capital cost estimates and associated cost model input for the ECOF pattern are shown in Table 6.

Table 6. Field and operational input for the ECOF and per pattern capital cost calculations from the cost model.

Field/Operational Parameters	Input
Field	ECOF
State	OH
Formation	Clinton
# of patterns	1
Depth (ft)	5200
Distance of trunkline (mi)	10
Cost of trunkline \$/mi	\$33,475
On-site distribution lines	\$187,985
Max. CO ₂ recycling rate (MMscf/day)	0.47
Max. CO ₂ injection rate (MMscf/day)	0.50
New injector wells	0.25
New producer wells	0.25
Total wells required	0.5
<i>Cost Model Calculations – Capital Costs in Millions of 2014 US Dollars (USD)*</i>	
New well D&C	\$ 0.26
Production Well Equipment	\$ 0.02
Injection Well Equipment	\$ 0.03
CO ₂ Recycling Plant	\$ 0.41
CO ₂ Transport & On-Site Distribution	\$ 0.22
Total Capital Costs	\$ 0.94

*Capital costs represent one 40-acre 5-spot well pattern

3.3.1 \$120/t CO₂ Scenario

The NPV accumulated at the end of the CO₂-EOR project in the ECOF was assessed for a CO₂ price scenario of \$120/t at oil prices of \$40/STB, \$70/STB, and \$100/STB and, all other parameters held constant (Figure 9). At \$120/t CO₂ and an oil price of \$40/STB, a potential CO₂-EOR project in the ECOF would not break-even; generating \$1.82 million in net revenue from the 56 MSTB of oil recovered, and \$2.60 million in total costs at the end of the ~6 year pattern life (NPV of -\$0.75 M). At an oil price of \$70/STB, the net revenue at the end of the pattern life is estimated to be \$3.18 million, with total costs of \$2.87 million. The CO₂-EOR project breaks-even during year two and begins to accrue profit totaling to a NPV of \$0.13 million. An oil price of \$100/STB results in a net revenue of \$4.54 million and total costs of \$3.14 million. The project begins to accrue profit at this price scenario during year 0.75, with an estimated NPV of \$1.02 million.

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383

384 **Figure 9. NPV curves for a CO₂-EOR operation in the ECOF at \$40, \$70, and \$100 per**
 385 **barrel of oil and a CO₂ price of \$120/t.**

386

387 3.3.2 \$80/t CO₂ Scenario

388 The cumulative NPV of a potential ECOF CO₂-EOR project was calculated for oil prices of
 389 \$40/STB, \$70/STB, and \$100/STB, a discount rate of 15%, and a CO₂ price of \$80/t (Figure 10).

390 The project does not break-even at an oil price of \$40/STB, with pattern costs of \$2.25 million
 391 resulting in a NPV of -\$0.48 million. At an oil price of \$70/STB the project is estimated to
 392 break-even shortly after one year, ending with a net revenue of \$3.18 million, total costs of \$2.52
 393 million, and a NPV of \$0.41 million (Table 7). At an oil price of \$100/STB the CO₂-EOR project
 394 breaks even after six months of operation, accruing a NPV of \$1.29 million.

Figure 10. NPV curves for a CO₂-EOR operation in the ECOF at \$40, \$70, and \$100 per barrel of oil and a CO₂ price of \$80/t.

3.3.3 \$40/t CO₂ Scenario

The resulting NPV of the CO₂-EOR operation in the ECOF pattern is shown in Figure 11 for oil prices of \$40/STB, \$70/STB, and \$100/STB and a low CO₂ price scenario of \$40/t. An oil price of \$40/STB incurs total costs of \$1.90 million, and does not break-even during the life of the project. A price scenario of \$70/STB oil results in a net revenue of \$3.18 million and total cost of \$2.17 million, breaking even during the first year to accrue a NPV of \$0.70 million. At an oil price of \$100/STB the CO₂-EOR project in the ECOF breaks-even after six months of operation, accruing a NPV of \$1.56 million.

Figure 11. NPV curves for A CO₂-EOR operation in the ECOF at \$40/STB, \$70/STB, and \$100/STB and a CO₂ price of \$40/t.

3.3.4 Median Price Scenario: \$80/t CO₂, & \$70/STB Oil

The effect of discount rate on CO₂-EOR project economics was also evaluated for the ECOF at the median price scenario analyzed. Market prices of \$80/t CO₂ and \$70/STB oil result in a net revenue of \$3.18 million and total costs of \$2.52 million. At a discount rate of 15%, this results in a NPV of \$0.41 million at the end of the 6-year operation. The NPV curves for the median price scenario at this reference discount rate and those at 10%, and 20% are shown in Figure 12. The time at which the NPV equals zero and the project breaks even increases slightly (~1.5 months) as discount rates increase from 10% to 20%.

Figure 12. Graph of the NPV curves for the median price scenario of \$80/t CO₂ and \$70/STB oil at discount rates of 10%, 15%, and 20% for the ECOF.

Table 7. Break down of ECOF EOR pattern costs for a price scenario of \$70/STB oil and \$80/t CO₂.

Cost Item	Cost (Million USD)
New well D&C	0.26
Production well equipment	0.02
Injection well equipment	0.03
Total Well Costs (\$M)	0.31
CO ₂ purchase cost	0.70
CO ₂ recycling facility	0.41
CO ₂ recycle O&M	0.64
CO ₂ trunkline & on-site distribution	0.22
Total CO₂ Costs (\$M)	1.97
Periodic O&M	0.18
Liquid lifting	0.02
G&A	0.04
Total O&M (\$M)	0.24
Total Costs (\$M)	2.52

3.3.5 CO₂ Break-Even Price vs. Oil Price

The break-even price of CO₂ is the price of CO₂ that results in a NPV equal to zero at the end of the project, all other parameters held constant. As such, A CO₂ purchase price greater than the calculated break-even price will result in a financial loss on the CO₂-EOR project, whereas a CO₂ price lower than the break-even price will result in financial gains. The break-even CO₂ price was calculated as a function of oil prices between \$20/STB and \$150/STB (Figure 13). At a discount rate of 15%, the break-even price was found to be \$10/t at an oil price of ~\$40/STB. At a higher oil price of \$100/STB, the calculated CO₂ break-even price suggests that an EOR operator would be willing to pay up to \$269/t for CO₂. The slope of the line (in USD/t/STB) shown in Figure 13 defines the relationship between oil price and economic viability of captured CO₂ for EOR in the ECOF pattern, indicating that for every \$1 dollar increase in the market price of oil per barrel, the value of one tonne of CO₂ increases by \$4.31.

Figure 13. Plot of the CO₂ break-even price calculated as a function of the price of oil for the CO₂-EOR operation modeled for the ECOF pattern.

4.0 Application of Methodology to the MCOF

4.1 Reservoir Description

The MCOF is one of the most prolific oil fields in Ohio, located in the north-central part of the state. Since discovery of the MCOF in 1959, 46 MMSTB of oil produced have been produced out of estimated 177 MMSTB of OOIP (McDowell, 2005). Production has occurred primarily from the Copper Ridge Dolomite, with approximately 1,000 wells drilled at an average depth of 3,500 ft and 10–40 acre spacing (Baranoski and McDonald, 1995; Riley et al., 2010). The productive zone occurs within erosional remnants of the Upper Copper Ridge that comprise a total of 16,000 acres in the MCOF and have an average thickness of 34 ft. The reservoir exhibits an average porosity of 7% and an average permeability of 18 mD. Secondary water flooding and air injections were attempted in the MCOF Copper Ridge Dolomite during the 1960s, but resulted in little to no success due to poor well management and pattern design (Riley et al., 2010). Reservoir, field, and fluid characteristics of the MCOF Copper Ridge Dolomite are included in Table 8.

Table 8. Key reservoir performance model parameters for the MCOF

Parameter	MCOF Input	
Reservoir	Copper Ridge Dolomite	
Pattern	5 spot	
Production History	Secondary	
Injection Rate	0.5 MMscf/day (26 t/day)	
HCPV CO ₂	2	
Field Area	16,000 acres	(64.7 km ²)
Reservoir Temperature	87°F	(303.7 K)
Initial Reservoir Pressure	1087 psia	(7.5 MPa)
Reservoir Depth	3,500 ft	(1067 m)
Minimum Miscibility Pressure (MMP)	1087 psia	(7.5 MPa)
Dykstra-Parsons Coefficient	0.70	
Permeability	18.1 mD	
Net Thickness	34 ft	(10.4 m)
Porosity	0.07	
OOIP	177 MMSTB	
Initial Oil Saturation	0.40	
Initial Water Saturation	0.40	
Initial Gas Saturation	0.20	
Vertical:Horizontal Permeability	0.30	
Viscosity of Oil	1.42 cp	
Viscosity of Water	0.81 cp	

Formation Volume Factor, B_o	1.13 rb/stb
Solution Gas:Oil Ratio, R_s	300 scf/stb
Oil API Gravity	41°

4.2 Reservoir Performance Results

At a constant injection rate of 0.5 MMscf/day (26 t CO₂/day), cumulative production of 112 MSTB oil, and injection of 2,326 MMscf of CO₂ (122,348 t) was simulated over a 13 year lifespan for the 40-acre 5-spot well pattern in the MCOF. Similar to the ECOF, the maximum CO₂ production/recycling rate in the MCOF is 0.47 MMscf/day (24 t/day). Incremental and cumulative results of the CO₂-PROPHET simulation are shown in Figure 14 and 15, respectively, for 2 HCPV of cumulative CO₂ injection. Of the cumulative volume of CO₂ injected, 1,979 MMscf (104,095 t) was produced and 347 MMscf (18,252 t) was permanently stored in the formation. This corresponds to a gross CO₂ utilization factor of 21 Mscf/STB (1.1 t/STB) and net CO₂ utilization of 3 Mscf/STB (0.16 t/STB). Table 9 lists results of the CO₂-EOR simulation for the MCOF.

Figure 14. Incremental CO₂-EOR reservoir performance in the MCOF pattern shown in volumes per quarter year at 2 HCPV of total CO₂ injection and a constant injection rate.

Figure 15. Cumulative CO₂-EOR reservoir performance in the MCOF at 2 HCPV of total CO₂ injection and a constant injection rate.

Table 9. CO₂-PROPHET results of the CO₂-EOR simulation for the MCOF

Time (years)	1	2	3	4	5	6	7	8	9	10	11	12	12.7	Cumulative
Oil Produced (MSTB)	26	21	12	9	7	7	6	6	5	4	4	4	2	112
H₂O Produced (MSTB)	19	8	5	4	3	3	2	2	2	2	2	2	1	54
CO₂ Injected (MMscf)	183	183	183	183	183	183	183	183	183	183	183	183	135	2,326
CO₂ Produced/Recycled (MMscf)	89	122	148	157	161	163	165	167	168	170	171	172	127	1,979
CO₂ Stored (MMscf)	94	61	35	26	22	20	18	16	15	13	11	10	7	347

4.3 Revenue & Cost Model Results

Well costs for the MCOF pattern were calculated at \$0.16 million for a depth of 3,500 ft. in the Copper Ridge Dolomite. Using the CO₂ injection rate of 0.5 MMscf/day, the estimated costs of the CO₂ recycling facility, trunkline, and on-site distribution equipment are \$0.63 million, the same as the ECOF. Total capital costs for the MCOF pattern equal \$0.80 million (Table 10).

Table 10. Field and operational input for the MCOF and per pattern capital cost estimates from the cost model.

Field/Operational Parameters	Input
Field	MCOF
State	OH
Formation	Copper Ridge Dolomite
# of patterns	1
Depth (ft)	3,500
Distance of trunkline (mi)	10
Cost of trunkline \$/mi	\$33,475
On-site distribution lines	\$187,985
Max. CO ₂ recycling rate (MMscf/day)	0.47
Max. CO ₂ injection rate (MMscf/day)	0.50
New injector wells	0.25
New producer wells	0.25
Total wells required	0.5
Cost Model Calculations – Capital Costs in Millions of US Dollars (USD)*	
New well D&C	\$ 0.13
Production Well Equipment	\$ 0.01
Injection Well Equipment	\$ 0.02
CO ₂ Recycling Plant	\$ 0.41
CO ₂ Transport & On-Site Distribution	\$ 0.22
Total Capital Costs (\$M)	\$ 0.80

*Capital costs reflect one 40-acre, 5-spot well pattern.

4.3.1 \$120/t CO₂ Scenario

The CO₂-EOR project modeled in the MCOF pattern for a high CO₂ price scenario of \$120/t does not break-even at oil prices of \$40/STB, with a negative NPV calculated for the entire duration of the operation (Figure 16). At \$70/STB the 112 MSTB of oil recovered from the MCOF results in a net revenue of \$6.42 million and total costs of \$4.80 million, breaking even after year one to accrue a total NPV of \$1.03 million at end of the ~13 year pattern life. An oil

price of \$100/STB the EOR project is estimated to gain \$9.17 million in revenue and incur a total cost of \$5.37 million. The project breaks even at the \$100/STB oil price scenario after 0.75 years of operation, with a NPV of \$2.49 million estimated at the end of the operation.

Figure 16. NPV curves for a CO₂-EOR operation in the MCOF at \$40, \$70, and \$100 per barrel of oil and a CO₂ price of \$120/t.

4.3.2 \$80/t CO₂ Scenario

At a CO₂ price scenario of \$80/t the EOR project in MCOF incurs \$4.06 million in total costs at a market price of \$40/STB oil, resulting in a NPV of \$24,000 after breaking-even at 4.5 years of operation (Figure 17; Table 11). An oil price of \$70/STB the project breaks-even during year one and accrues a total NPV of \$1.49 million. The EOR project breaks-even after 0.5 years of operation at a higher oil price of \$100/STB, resulting in a NPV of \$2.95 million at the end of the project.

Figure 17. NPV curves for a CO₂-EOR operation in the MCOF at \$40, \$70, and \$100 per barrel of oil and a CO₂ price of \$80/t.

4.3.3 \$40/t CO₂ Scenario

At a low CO₂ price scenario of \$40/t, the CO₂-EOR project in the MCOF is estimated to break-even before year two in all three oil price scenarios analyzed (Figure 18). A CO₂ price of \$40/t and an oil price of \$40/STB results in total costs of \$2.74 million and net revenue of \$3.67 million, breaking even at 1.75 years to accrue a total NPV of \$0.49 million. At \$70/STB oil the EOR project breaks-even at 0.75 years of operation, resulting in a NPV of \$1.95 million at the end of the recovery operation. At the high oil price scenario of \$100/STB the project breaks-even at 0.5 years and accrues a NPV of \$3.42 million.

Figure 18. NPV curves for a CO₂-EOR operation in the MCOF at \$40, \$70, and \$100 per barrel of oil and a CO₂ price of \$40/t.

4.3.4 Median Price Scenario: \$80/t CO₂ & \$70/STB Oil

Net revenue of \$6.42 million and total costs of \$4.06 million were calculated for the MCOF EOR project at market prices of \$80/t CO₂ and \$70/STB oil (Table 11). At a discount rate of 15% this results in a NPV of \$1.49 million at the end of the 13 year project. Decreasing the discount rate to 10% increases the NPV of the project to \$1.71 million. A higher discount rate of 20% results in a lower NPV of \$1.44 million. The NPV curves at different discount rates are shown in Figure 19 for the MCOF EOR project at this median price scenario.

Figure 19. Graph of the NPV curves for the median price scenario of \$80/t CO₂ and \$70/STB oil at discount rates of 10%, 15%, and 20% for the MCOF.

Table 11. Break down of MCOF EOR pattern costs for a market scenario of \$70/STB oil and \$80/t CO₂.

Cost Item	Cost (Million USD)
New well D&C	0.13
Production well equipment	0.01
Injection well equipment	0.02
Total Well Costs (\$M)	0.17
CO ₂ purchase cost	1.44
CO ₂ recycling facility	0.41
CO ₂ recycle O&M	1.39
CO ₂ trunkline & on-site distribution	0.22
Total CO₂ Costs (\$M)	3.46
Periodic O&M	0.32
Liquid lifting	0.04
G&A	0.07
Total O&M (\$M)	0.43
Total Costs (\$M)	4.06

4.3.5 CO₂ Break-Even Price vs. Oil Price

In the MCOF the calculated CO₂ break-even price is \$82/t at an oil price of \$40/STB (Figure 20), indicating that at this oil price the CO₂-EOR operation simulated in this field will accrue profit when CO₂ purchase prices are less than \$82/t. At an oil price of \$100/STB the calculated break-even price suggests an EOR operator could pay up to \$336/t CO₂ before incurring loss on the project. Similar to the break-even analysis for the ECOF, the slope of the line in Figure 20 indicates the change in the CO₂ break-even price associated with the EOR operation is 4.2 times the corresponding change in the unit value of oil.

Figure 20. Plot of the CO₂ break-even price calculated as a function of oil price for the CO₂-EOR operation modeled for the MCOF pattern.

5.0 Discussion

Reservoir performance results indicate similar average rates of oil production and CO₂ storage in the ECOF and MCOF (Table 12). Greater net thickness and porosity values of the MCOF resulted in OOIP estimates that are approximately twice that of the ECOF, with the MCOF

having a longer pattern life and higher cumulative values for the two HCPVs of total CO₂ injection simulated (see Tables 5 and 9).

Table 12. Comparison of CO₂-EOR reservoir performance results* from the ECOF and MCOF

Performance Results	ECOF		MCOF	
Pattern Life	6 years		13 years	
Oil Produced	56 MSTB		112 MSTB	
Recovery (% OOIP)	22%		21%	
H ₂ O Produced	27 MSTB		53 MSTB	
CO ₂ Injected	1,085 MMscf	(57 kt)	2,326 MMscf	(122 kt)
CO ₂ Produced/Recycled	918 MMscf	(48 kt)	1,979 MMscf	(104 kt)
CO ₂ Stored	167 MMscf	(9 kt)	347 MMscf	(18 kt)

*Cumulative results for one 40 acre 5-spot well pattern in each field kilotonne (kt)

For the price scenarios analyzed, higher accrual of costs associated with ongoing CO₂ purchase, CO₂ recycling O&M, and total O&M in the MCOF relative to the ECOF are also due to the longer pattern life in the MCOF (Table 13). Higher well costs account for 12% of total project costs in the ECOF, reflecting the greater depth of the Clinton Sandstone (5,200 ft) compared to the Copper Ridge Dolomite in the MCOF (3,500 ft). At the median price scenario of \$80/t CO₂ and \$70/STB oil, total CO₂ costs represent 78% of total project costs in the ECOF and 85% in the MCOF, while total O&M accounts for 9.5% and 10.6%, respectively. These results suggest that well depth and pattern life are important considerations for constraining total CO₂-EOR project costs on a per pattern basis in the study area, with a majority of the total cost associated with CO₂ purchase, distribution, and processing.

In both the ECOF and MCOF, the average rate of CO₂ purchase and storage simulated for one 40 acre 5-spot pattern ranges from 1.4 to 1.5 kilotonnes (kt) per year. This scales to CO₂ storage potential of ~6.6 megatonnes (Mt) per year via EOR in the 175,000 acres of the ECOF (for 6 years), and ~0.6 Mt per year in the 16,000 acres of the MCOF (for 13 years). The average annual CO₂ emission rate from one coal fired power plant in Ohio is 3–4 Mt per year. The representative CO₂ capture costs reported in Rubin et al., (2015) for post-combustion capture at a new

supercritical pulverized coal plant (bituminous coal) is ~\$47/t CO₂ in 2014 USD (\$46/t in 2013 USD; see Table 2 of referenced study). Assuming this capture cost for a similar plant in Ohio, negative or low NPVs in both the ECOF and MCOF suggest CO₂-EOR may not be economically feasible at oil prices of \$40/STB and below. The economics of CO₂-EOR are more promising in each field at oil prices of \$70/STB, though negative outcomes and low returns are still possible. High NPVs suggest that when the price of oil is \$100/STB CO₂-EOR in Ohio is economically feasible at all of the CO₂ prices analyzed.

Table 13. Break down of EOR project costs for a market scenario of \$70/STB oil and \$80/t CO₂ in the ECOF and MCOF.

Cost Item	ECOF		MCOF	
	Cost (Million USD)	% of Total Cost	Cost (Million USD)	% of Total Cost
New well D&C	0.26	10.4%	0.13	3.3%
Production well equipment	0.02	0.7%	0.01	0.3%
Injection well equipment	0.03	1.1%	0.02	0.5%
Total Well Costs (\$M)	0.31	12.2%	0.17	4.1%
CO ₂ purchase cost	0.70	27.6%	1.44	35.6%
CO ₂ recycling facility	0.41	16.4%	0.41	10.2%
CO ₂ recycle O&M	0.64	25.5%	1.39	34.1%
CO ₂ trunkline & on-site distribution	0.22	8.8%	0.22	5.4%
Total CO₂ Costs (\$M)	1.97	78.3%	3.46	85.3%
Periodic O&M	0.18	7.1%	0.32	7.8%
Liquid lifting	0.02	0.8%	0.04	1.0%
G&A	0.04	1.6%	0.07	1.8%
Total O&M (\$M)	0.24	9.5%	0.43	10.6%
Total Costs (\$M)	2.52		4.06	

The CO₂ break-even analysis can be used to quantify the potential commercial viability of captured CO₂ as a function of the prevailing oil price for the oil field of interest. In both the ECOF and MCOF high CO₂ break-even prices and NPVs suggest that at an oil price of \$100/STB, captured CO₂ could be sold for EOR at prices at least twice as high (e.g. \$120/t) as the representative capture cost of \$47/t. At a discount rate of 15% and any specific oil price, the

CO₂ break-even price calculated for the MCOF is ~\$65–70 higher than that calculated for the ECOF (Figure 21). This indicates that increased revenue associated with higher cumulative oil recovery in the MCOF enabled greater affordability for CO₂ than did the lower total project costs in the ECOF. Despite this difference, the relationship between the break-even price of CO₂ and the corresponding price of oil is similar in both fields, depicting a ~\$4 increase (or decrease) in the value of one tonne of CO₂ for every \$1 increase (or decrease) in the price of oil per barrel. These values fall within range of values (\$4 – \$6/t/STB) derived from the CO₂ break-even analysis in McCoy and Rubin (2009) for oil fields in Texas and Canada (Figure 22).

Figure 21. Comparison of the CO₂ break-even price calculated as a function of oil price for the ECOF and the MCOF. The slope is in USD/t/STB units.

Figure 22. CO₂ break-even price as a function of the oil price for the ECOF and MCOF at a discount rate of 15%, compared with previous work by McCoy and Rubin (2009) at a discount rate of 12%. *Slope (m) is in USD/t/STB units.

6.0 Concluding Remarks

This study outlines a cost-benefit analysis methodology to determine of the economic feasibility of CO₂-EOR in Ohio and assess the potential of CO₂-EOR to act as a commercial driver for CCUS in the Appalachian Basin region. Ohio-specific reservoir and cost data is integrated with reservoir performance and economic models from previous studies to establish the analysis framework. The cost-benefit analysis is applied to the ECOF and MCOF in Ohio to illustrate how the methodology can be used to derive high-level estimates of CO₂-EOR project economics and profit potential for various scenarios. Based on detailed NPV calculations, the break-even price of CO₂ is calculated as a function of various oil price scenarios to define specific price points at which captured CO₂ becomes an economically viable option for EOR.

In both the ECOF and MCOF, positive NPVs generated at CO₂ prices of \$40/t suggest that CO₂-EOR may be economically feasible in the study area when oil prices are \$70/STB or higher. At oil prices of \$100/STB captured CO₂ could be sold for EOR at prices well above the representative cost of \$47/t for post-combustion capture on a new supercritical pulverized coal-

fired plant (e.g. Rubin et al., 2015). Differences observed between the ECOF and MCOF in capital and operational costs suggest well depth and pattern life are important considerations for constraining total CO₂-EOR project costs in the study region, with a majority of the cost associated with CO₂ purchase, distribution, and processing.

At any specific oil price, the CO₂ break-even price can be calculated based on the regression equations shown in Figure 21. In the MCOF the calculated CO₂ break-even prices are ~\$65–\$70 higher than those calculated for the ECOF at a given price of oil. The overall trend of the correlation is similar in both fields, indicating the change in the unit value of CO₂ required to break-even is approximately four times the corresponding change in the unit value of oil. This is consistent with values reported for CO₂-EOR operations in other regions of North America (e.g. McCoy and Rubin, 2009), suggesting differences in reservoir properties and costing methodologies may not significantly alter the price elasticity of CO₂ relative to the prevailing price of oil.

The value of the cost-benefit analysis framework presented in this paper is that it can be readily applied with limited information for project screening purposes. The break-even correlation represents a standalone metric that can be used to (re)estimate the CO₂ break-even price during times of oil price volatility, helping to constrain the specific price conditions at which CO₂ becomes a viable purchase for EOR and a marketable asset for coal-fired power plants with capture technology. Finally, a probabilistic analysis that takes into account uncertainties in reservoir performance, cost modeling, and price scenarios would help to refine the cost-benefit analysis, and provide additional useful information to decision makers regarding the techno-economic feasibility of the project.

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Appendix A. Supporting Data

This appendix contains two tables. A-1 lists the categorization and definitions of well cost parameters included in the cost model; A-2 lists the well type, configuration, depth, and associated cost data acquired for Ohio-specific well cost calculations.

Table A-1. Categorization and definitions of well cost parameters included in the cost model.

Cost Category	Definition	Items Included
Well Costs		
Drilling & Completion	<i>Tangible and intangible costs associated with on-site drilling and completion phases for production and injection wells.</i>	site survey, leasehold and prospect costs, site preparation and reclamation, labor, supervision, surface and downhole drilling equipment, drilling cost per foot, drilling cost per hour (dayrate), logging costs, perforating, hydraulic fracturing treatment, acid jobs, chemicals, drilling and completion fluid management, completion rig, all casing, cementing, plugging
Production Well Equipment	<i>Capital costs of tangible and, to a lesser extent, intangible items associated with production well equipment and installation</i>	electric services, all surface and subsurface production well equipment costs: tubing, rods, down-hole pump, pumping unit, motor, well head, hookups, and controller, separator, storage tanks, walkways gas sales meter, flowlines, gauges and valves
Injection Well Equipment	<i>Capital costs of tangible and, to a lesser extent, intangible items associated with injection well equipment and installation</i>	electrical services, all surface and subsurface injection well equipment costs: unloading pad, storage tanks, oil separation equipment, filtering system, injection pump, injection lines, injection tubing, injection packer, buildings/shelters, well head, pressure monitoring system, flow meter/totalizer, gauges and valves
Well Conversion	<i>Tangible and intangible capital costs of updating or converting existing injection and production wells to establish the number of suitable injection and production wells required for the well</i>	labor, mechanical integrity testing, re-perforating, stimulation, acid or clean up treatment, cement bond logging, fabrication services and materials, equipment replacement costs, pressure test lines, all other surface and subsurface well equipment and rework costs: packer, tubing, well head/tubing head, fittings, regulator, monitoring equipment, gauges and valves

Cost Category	Definition	Items Included
<i>pattern/project</i>		
CO₂ Costs		
CO ₂ Transport & Distribution	<i>Fixed and variable capital costs associated with transporting the volume of CO₂ required for injection from the regional pipeline to the EOR site, as well all manifolds and flow lines required for on-site CO₂ distribution</i>	high pressure trunkline pipe material, mileage, and diameter; similar to natural gas gathering systems (variable components), manifolds, valves, flow controls, and distribution lines required for transport to and from wells and the recycling facility
CO ₂ Recycling Plant	<i>Capital costs of a recycling facility of sufficient size to facilitate CO₂ separation from produced fluids during peak production and recycling operations</i>	CO ₂ /hydrocarbon & CO ₂ /water separators, fluid distribution lines, gas stream flow lines, CO ₂ compression equipment, pumps, storage tanks (crude and water), manifolds, valves, flow controls, processing equipment
CO ₂ Recycling (O&M)	<i>Expenses related to operation of the recycling facility corresponding to the rate of production, recycling, and injection simulated for a specific time period, with the energy required for CO₂ surface management, treatment and compression generated on-site</i>	energy required for recycling facility operation over a given time period, including power for separation, processing, CO ₂ CO ₂ compression to the MMP required for injection
O&M Costs		
Periodic O&M	<i>Costs associated with operation and maintenance of a CO₂-EOR site at the required capacity over a given time period, including periodic well workover, and other</i>	periodic well workover, servicing, operating expenses for labor, personnel, electricity, consumables, surface and subsurface equipment maintenance and replacement

Cost Category	Definition	Items Included
	<i>surface and subsurface repairs/remediation</i>	
Liquid Lifting Costs	<i>Operational costs of pumping (to surface), managing, and (re)distributing liquids produced during a given time period of CO₂-EOR operation, with the required energy generated on-site</i>	energy required for lifting liquids up the wellbore and surface routing
General and Administrative (G&A)	<i>Other expenses associated with routine activities and processes required for effective operation of the overall project, but not directly related to the production of marketable goods and services</i>	staff salaries/wages, insurance, accounting, consulting, management, accounting and record keeping supplies

Table A-2. Well type, configuration, depth, and associated cost data acquired for Ohio-specific well cost calculations.

Well #	Well Type	MD Depth (ft)	Year of Cost Accrual	Adjusted Costs (2014 USD)								Total
				Leasehold & Prospect	Drilling	Completion	Plugging	D&C Total	Work-over	Production Well Equipment Costs	Injection Well Equipment Costs	
1	production	3509	2011	\$ 2,462	\$ 155,020	\$ 139,869	\$11,447	\$ 308,797	\$ -	\$ 68,347	\$ -	\$ 377,144
2	production	3467	2012	\$ -	\$ 112,467	\$ 96,750	\$ 2,439	\$ 211,655	\$ -	\$ 76,606	\$ -	\$ 288,261
3	production	4700	2014	\$ 32,500	\$ 184,687	\$ 87,974	\$11,000	\$ 316,161		\$ 85,222		\$ 401,383
4	production	4460	2013	\$ 45,730	\$ 132,435	\$ 91,848	\$11,178	\$ 281,191	\$ -	\$ 78,431	\$ -	\$ 359,621
5	-	4033						\$ -	\$ 77,649			\$ 77,649
6	production	4800	2014		\$ 333,366	\$ 133,203		\$ 466,568		\$ 113,140		\$ 579,708
7	production	3900	2015	\$ -	\$ 214,550	\$ 116,573	\$ -	\$ 331,123	\$ -	\$ 80,362	\$ -	\$ 411,485
8	production	3100	2014		\$ 102,450	\$ 50,350		\$ 152,800		\$ 45,650		\$ 198,450
9	production	2150	2014		\$ 87,963	\$ 46,550		\$ 134,513		\$ 42,625		\$ 177,138
10	production	1308	2014		\$ 84,213	\$ 103,500		\$ 187,713		\$ 34,825		\$ 222,538
11	production	4451	2012	\$ -	\$ -	\$ -	\$ -	\$ 671,804	\$ -	\$ 128,548	\$ -	\$ 800,352
12	production	5247	2010	\$ -	\$ -	\$ -	\$ -	\$ 414,736	\$ -	\$ 96,577	\$ -	\$ 511,314
13	production	4240	2013	\$ -	\$ 350,344	\$ 174,207	\$ -	\$ 524,550	\$ -	\$ 123,090	\$ -	\$ 647,641
14	production	4305	2014		\$ 356,750	\$ 171,425		\$ 528,175		\$ 124,050		\$ 652,225
15	injection	9200	2014		\$ 1,262,200	\$ 837,200		\$ 2,099,400			\$ 846,800	\$2,946,200
16	production	5100	2008	\$ -	\$ 293,564	\$ 85,288		\$ 378,853	\$ -	\$ 63,465	\$ -	\$ 442,317
17	production	6575	2010	\$ 12,747	\$ 215,319	\$ 82,457	\$ -	\$ 305,574	\$ -	\$ 45,171	\$ -	\$ 350,745
18	production	2835	2008	\$ 5,403	\$ 77,301	\$ 63,478	\$ -	\$ 146,182	\$ -	\$ 16,373	\$ -	\$ 162,555
19	injection	7305	2012	\$ -	\$ 488,784	\$ 287,861	\$ -	\$ 776,645	\$ -	\$ -	\$ 102,873	\$ 879,519
20	injection	7016	2013	\$ -	\$ 805,166	\$ 480,166	\$ -	\$1,285,331	\$ -	\$ -	\$ 432,240	\$1,717,571
21	production	5500	2011	\$ -	\$ 141,368	\$ 110,828	\$ -	\$252,196	\$ -	\$ 54,639	\$ -	\$ 306,835
22	production	6700	2011	\$ -	\$ 230,923	\$ 104,806	\$ -	\$335,728	\$ -	\$ 49,540	\$ -	\$ 385,268
23	production	3997	2012	\$ -	\$ 116,203	\$ 92,779	\$ -	\$208,982	\$ -	\$ 46,444	\$ -	\$ 255,426
24	production	4470	2012	\$ -	\$ 164,017	\$ 94,613	\$ -	\$258,630	\$ -	\$ 48,254	\$ -	\$ 306,884
25	production	6319	2012	\$ -	\$ 217,368	\$ 102,144	\$ -	\$319,512	\$ -	\$ 76,846	\$ -	\$ 396,358
26	production	4000	2015	\$ -	\$ 164,301	\$ 93,369	\$ -	\$257,670	\$ -	\$ 56,726	\$ -	\$ 314,396

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