

CO₂ UTILIZATION: BEYOND EOR

A techno-economic investigation
commissioned by the members of the
Carbon Dioxide Capture & Conversion (CO₂CC) Program

Client Private
September 2018



The Carbon Dioxide Capture & Conversion (CO₂CC) Program

The **CO₂CC Program** is a membership-directed consortium whose members are involved in the development, monitoring and utilization of the “state-of-the-art” in technological progress and commercial implementation of carbon dioxide capture/clean-up and conversion. By the direction of the member companies (through balloting and other interactive means), the program delivers a range of timely and insightful information and analyses which are accessible exclusively to members and protected by confidentiality agreements. The objective is to document technically and commercially viable options for CO₂ capture/clean-up as well as its conversion into useful products which meaningfully address the challenges posed by CO₂ life-cycle and overall sustainability issues.

Members receive three in-depth **CO₂CC Techno-economic Reports** which are written by leading scientists and experienced industry professionals in areas selected by the membership (via ballot); weekly *CO₂CC Communiqués* (delivered via e-mail) which provide the latest updates on technical breakthroughs, commercial events and exclusive development opportunities; and attendance at the CO₂CC Program **Annual Meeting**.

The **Carbon Dioxide Capture & Conversion (CO₂CC) Program** is available on a membership basis from The Catalyst Group Resources (TCGR). For further details, please contact John J. Murphy at John.J.Murphy@catalystgrp.com or +1.215.628.4447 (x1121).



P.O. Box 680
Spring House, PA 19477 U.S.A
ph: +1.215.628.4447

CONTENTS

EXECUTIVE SUMMARY	xxvii
1. INTRODUCTION	1
1.1 ENHANCED OIL RECOVERY.....	1
1.2 ENHANCED GAS RECOVERY	2
1.3 ENHANCED COALBED METHANE RECOVERY.....	3
1.4 AUTHORS AND CONTRIBUTORS	3
1.5 REFERENCES.....	5
2. CO₂ ENHANCED OIL RECOVERY	7
2.1 INTRODUCTION	7
2.2 IMPROVED OIL RECOVERY.....	9
2.2.1 Waterflooding	9
2.2.2 History and Overview of Waterflooding.....	9
2.2.3 Evaluation of Waterflooding Performance	10
2.2.4 Economic Analysis of Waterflooding.....	11
2.3 ENHANCED OIL RECOVERY (EOR).....	11
2.3.1 Introduction to EOR.....	12
2.3.2 Overview of EOR Processes	12
2.4 CO ₂ -EOR	17
2.4.1 Technical Aspects of CO ₂ -EOR.....	19
2.4.2 Reservoir Characterization.....	22
2.4.3 Operational Aspects of CO ₂ -EOR.....	24
2.5 ECONOMIC ANALYSIS OF CO ₂ -EOR PROCESSES	26
2.5.1 Original Oil in Place in the World	27
2.5.2 Original Oil in Place in the U.S.	27
2.5.3 Operational Costs of Oil Reservoirs	28
2.5.4 Operational Costs of CO ₂ -EOR	28
2.5.5 Future Outlook of CO ₂ -EOR.....	29
2.6 CASE STUDY: CARBON DIOXIDE ENHANCED OIL RECOVERY AND THE PETRA NOVA POWER PLANT	30
2.6.1 Economics of EOR.....	30
2.6.2 CO ₂ for EOR from Power Plants: The case of Petra Nova	31

2.7	INDUSTRY PERSPECTIVE ON CARBON DIOXIDE ENHANCED OIL RECOVERY	32
2.7.1	Dr. Richard Esposito, Program Manager of Geosciences, Carbon Capture and Utilization, Southern Company	32
2.7.2	Michael E. Moore, Managing Partner, EWSA (East-West Strategic Advisors)..	34
2.7.3	George Koperna, Vice President, Advanced Resources International.....	35
2.8	REFERENCES.....	37
3.	CO₂ ENHANCED GAS RECOVERY	41
3.1	INTRODUCTION	41
3.2	INTRODUCTION TO RESERVOIR ENGINEERING.....	41
3.2.1	Hydrocarbon Reserves and Resources	41
3.2.2	Reservoir Rock Properties.....	42
3.3	DIFFERENT TYPES OF RESERVOIR FLUIDS.....	43
3.3.1	Black Oil	44
3.3.2	Volatile Oil.....	45
3.3.3	Retrograde Gas.....	45
3.3.4	Wet Gas.....	46
3.3.5	Dry Gas	46
3.4	PROPERTIES OF DRY GAS.....	46
3.5	PROPERTIES OF WET GAS	48
3.6	PROPERTIES OF GAS CONDENSATES	48
3.7	GAS RESERVOIR ENGINEERING	49
3.7.1	Properties of Natural Gas	49
3.7.2	Properties of CO ₂	51
3.7.3	General Material Balance Equation for Gas Reservoir.....	55
3.7.4	Methods for Calculation of Reserve-In-Place.....	56
3.7.5	Prediction of the Performance of Gas Reservoirs	58
3.8	IMPROVED GAS RECOVERY	58
3.8.1	Primary Recovery from Gas Reservoirs	58
3.8.2	Waterflooding for Gas Reservoirs	59
3.8.3	CO ₂ -Flood for Enhanced Gas Recovery	59
3.9	ECONOMIC ANALYSIS OF CO ₂ ENHANCED GAS RECOVERY	60
3.9.1	Evaluation of the Natural Gas Reserves	60

3.9.2	Recoverable Volume of Natural Gas	62
3.9.3	Operational Costs of Gas Reservoir Development	64
3.10	CASE STUDY: ENHANCED GAS RECOVERY AND EXAMPLES.....	65
3.10.1	Case Studies	65
3.10.2	Future Developments	66
3.11	INDUSTRY PERSPECTIVE ON ENHANCED GAS RECOVERY	67
3.11.1	Dr. John Mansoori, Senior Reservoir Engineering Advisor, Encana.	67
3.11.2	Michael E. Moore, Managing Partner, EWSA (East-West Strategic Advisors).....	67
3.11.3	George Koperna, Vice President, Advanced Resources International.....	68
3.12	REFERENCES.....	68
4.	CO₂ FOR ENHANCED COALBED METHANE RECOVERY	71
4.1	INTRODUCTION	71
4.2	CURRENT AND FUTURE MARKET OF NATURAL GAS.....	71
4.3	CLEAN ENERGY STATUS AND TRENDS.....	73
4.4	CONVENTIONAL NATURAL GAS RESOURCES	74
4.5	UNCONVENTIONAL NATURAL GAS RESOURCES	75
4.5.1	Coalbed Methane (CBM) Resources	79
4.6	MAJOR CBM PLAYS IN THE U.S.....	84
4.7	SORPTION OF CO ₂ AND METHANE FOR ENHANCED CBM RECOVERY AND CO ₂ SEQUESTRATION	85
4.7.1	Principles of Adsorption	85
4.7.2	Methane Retention by Coal Seams	87
4.7.3	Evaluation of Methane Content in the Coal Seams	88
4.7.4	CO ₂ Retention by Coal Seams	88
4.8	CBM RESERVOIR ANALYSIS AND MANAGEMENT	89
4.9	ENVIRONMENTAL CHALLENGES OF CO ₂ -CBM RECOVERY	94
4.9.1	Water Production and Disposal in CBMs	94
4.9.2	Chemicals Associated with CBM Water.....	94
4.10	ECONOMIC EVALUATION OF CO ₂ -CBM RECOVERY.....	96
4.10.1	Resource Evaluation.....	96
4.10.2	Capital and Operating Costs	96
4.10.3	Tax Credits.....	97

4.10.4	Limits of Profitability.....	97
4.10.5	Future Outlook of CO ₂ CBM Recovery.....	97
4.11	CASE STUDY: ENHANCED COAL BED METHANE RECOVERY AND THE ALBERTA PILOT PROJECT.....	98
4.11.1	Alberta Pilot Project.....	98
4.11.2	Economics.....	99
4.11.3	Site Requirements.....	99
4.11.4	Future Developments.....	100
4.12	INDUSTRY PERSPECTIVE ON ENHANCED CBM RECOVERY.....	100
4.12.1	Dr. John Mansoori, Senior Reservoir Engineering Advisor, Encana.....	100
4.12.2	Michael E. Moore, Managing Partner, EWSA (East-West Strategic Advisors).....	101
4.12.3	George Koperna, Vice President, Advanced Resources International.....	102
4.13	REFERENCES.....	103
5.	INDEX.....	111

FIGURES

Figure 3.1	Phase diagram of CO ₂	52
Figure 3.2	Density of CO ₂ as a function of pressure and temperature.....	53
Figure 3.3	Compressibility factor of CO ₂ as a function of pressure and temperature.....	53
Figure 3.4	Viscosity of CO ₂ as a function of pressure and temperature.....	54
Figure 3.5	Solubility of CO ₂ in water as a function of pressure, temperature, and water salinity.....	54
Figure 3.6	Global proven natural gas reserves (British Petroleum, 2017).....	61
Figure 4.1	History of development of dual sources in the U.S. (Energy Information Administration, 2013).....	72
Figure 4.2	One Projection for U.S. natural gas production (Energy Information Administration, 2018).....	73
Figure 4.3	Alternative Projection for U.S. natural gas consumption (Energy Information Administration, 2018).....	74
Figure 4.4	Resource triangle (Holditch, 2013).....	75
Figure 4.5	Global distribution of the unconventional resources (Radialdrilling).....	76

Figure 4.6 Historical annual production rate of natural gas in the U.S. (Energy Information Administration, 2018)..... 77

Figure 4.7 Effect of coal rank on storage capacity (Ahmed & Meehan, 2012)..... 83

Figure 4.8 Five categories of adsorption isotherms as defined by Brunauer (Brunauer et al., 1938)..... 86

Figure 4.9 Langmuir isotherms for CH₄, CO₂, and N₂ (Sinayuc et al., 2011). 89

TABLES

Table 2.1 Typical primary recovery factor from oil reservoirs based on the recovery drive mechanism (AAPG, 2016; Satter et al., 2008)..... 8

Table 2.2 Ultimate recovery factor from oil reservoirs after each phase of production (Bui, 2010)..... 12

Table 2.3 CO₂ volumes injected for EOR projects in the U.S. (adapted from Kuuskraa et al., 2011)..... 18

Table 2.4 Screening criteria for various EOR methods [adapted from (J. J. Taber, F. Martin, & R. Seright, 1997)] 23

Table 2.5 Average cost for producing one barrel of oil 29

Table 2.6 Cost comparison for EOR in three different reservoirs (Advanced Resources International, 2011) 32

Table 4.1 Properties of the main shale gas plays in the U.S. (Islam, 2015)..... 78

Table 4.2 Coal rank by ASTM (Rogers et al., 2007; Standard, 2012)..... 83

Table 4.3 Global CBM resource distribution adapted from (Godec et al., 2014)..... 84

Table 4.4 Properties of the main CBM plays in the United States (Rogers et al., 2007)..... 85

Table 4.5 Comparison between conventional and CBM reservoirs (Rogers et al., 2007).... 90

Table 4.6 Average chemical content of the coalbed waters in the United States, mg/L (OJEIFO et al.)..... 95