

FUNDAMENTAL LIMITATIONS ON CO₂ CAPTURE PROCESSES

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

Client Private
September 2012



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	xix
1. INTRODUCTION	1
1.1 SCOPE AND OBJECTIVE.....	1
1.2 METHODOLOGY	3
1.3 BACKGROUND.....	6
1.3.1 Scale of CO ₂ capture from stationary point sources.....	6
1.3.1.1 Total quantity of CO ₂ emitted worldwide per annum	6
1.3.1.2 Typical annual large power plant CO ₂ emissions	7
1.3.1.3 Typical annual refinery CO ₂ emissions.....	7
1.3.1.4 Typical annual petrochemical (olefins plant) CO ₂ emissions	7
1.3.2 Methods for CO ₂ capture from stationary point sources.....	9
1.3.2.1 Post combustion	9
1.3.2.2 Pre combustion	10
1.3.2.3 Oxy Fuel combustion	10
1.3.2.4 Capturing CO ₂ byproduct streams.....	11
1.4 REPORT CONTRIBUTORS.....	14
1.5 REFERENCES	16
2. GENERAL LIMITATIONS ON CO₂ CAPTURE IN COMMERCIALY AVAILABLE PROCESSES.....	17
2.1 OVERVIEW OF A CO ₂ CAPTURE SCENARIO.....	17
2.1.1 CO ₂ capture facility feeds.....	17
2.1.1.1 Hydrocarbon gases containing CO ₂	18
2.1.1.2 Synthesis gas containing CO ₂	18
2.1.1.3 Post oxy-combustion flue gas.....	18
2.1.1.4 Post combustion flue gas	19
2.1.2 CO ₂ gathering network.....	19
2.1.3 Captured CO ₂ end-destination.....	20
2.1.4 Transportation of CO ₂	20
2.1.5 The considered CO ₂ capture scenario	21

2.2	ENERGY REQUIREMENTS FOR CO ₂ CAPTURE	21
2.2.1	Energy requirement for the CO ₂ capture process	21
2.2.1.1	Typical CO ₂ capture process energy requirements.....	22
2.3	EQUIPMENT SIZE REQUIREMENTS.....	24
2.3.1	CO ₂ absorber (contactor) diameter	25
2.4	CAPITAL AND OPERATING EXPENSES	25
2.4.1	Operating cost and resultant cost of electricity.....	26
2.4.1.1	Effective cost of electricity generated	27
2.5	COST OF SOLVENTS, ADSORBENTS AND OTHER CHEMICALS	28
2.6	SAFETY CONCERNS WITH HIGH VOLUMES OF CO ₂	29
2.7	SAFETY CONCERNS WITH SOLVENTS AND CHEMICALS USED	30
2.8	CO ₂ CAPTURE PROCESS CHARACTERISTICS AND OPERATING CONDITIONS.....	30
2.8.1	Low pressure and high temperature.....	30
2.8.2	Detrimental flue gas contaminants	31
2.8.2.1	Presence of oxygen in flue gas.....	31
2.8.2.2	Presence of SO ₂ in the flue gas	31
2.8.2.3	Presence of NO _x in the flue gas.....	32
2.8.2.4	Presence of fly ash	32
2.8.2.5	Presence of soot.....	32
2.9	CORROSION, EROSION AND SOLVENT MAKE-UP AND MAINTENANCE ISSUES.....	32
2.9.1	Corrosion and erosion.....	33
2.9.2	Solvent losses and make-up requirements.....	33
2.10	BY-PRODUCT DISPOSAL ISSUES	34
2.10.1	Amine units.....	34
2.10.2	Gasification plants	35
2.11	CO ₂ TRANSPORT OPTIONS.....	35
2.11.1	Large scale long distance transport by pipelines	36
2.11.1.1	Cost of CO ₂ pipelining.....	37
2.11.2	Transport of CO ₂ in the liquid state.....	37
2.11.2.1	A Synergistic “food-for-thought” solution	38
2.11.3	Better yet, transport CO ₂ in the solid state	39
2.12	COMPRESSION REQUIREMENTS.....	39

2.12.1	CO ₂ Compression challenges	39
2.12.2	CO ₂ Compression drivers	40
2.12.3	Integrated CO ₂ compression and pumping.....	40
2.12.4	Ramgen compression technology.....	40
2.13	DEHYDRATION REQUIREMENTS	40
2.13.1	Applicable CO ₂ dehydration technologies	41
2.13.1.1	Absorption to glycols	41
2.13.1.2	Adsorption to solid desiccants.....	42
2.14	CO ₂ CORROSION AND MATERIALS OF CONSTRUCTION	43
2.14.1	Compatible materials of construction for wet CO ₂ service.....	44
2.15	GRASSROOTS CONSTRUCTION INFRASTRUCTURE AND PLOT AREA REQUIREMENTS.....	44
2.15.1	Proximity to industrial source(s) of CO ₂ feeds	45
2.15.2	Proximity to end-destination	45
2.16	RISK ASSESSMENT AND IMPLICATIONS.....	46
2.17	MITIGATING LIMITATIONS WITH SOME FURTHER “FOOD-FOR- THOUGHT”	48
2.17.1	Concentration of CO ₂ in flue gas	48
2.17.2	Boosting pressure of flue gases.....	49
2.17.3	Associated risks.....	49
2.18	REFERENCES.....	50
3.	SPECIFIC LIMITATIONS ON CO₂ CAPTURE, BY PROCESS	53
3.1	POST COMBUSTION CO ₂ CAPTURE PROCESSES.....	53
3.1.1	Absorption processes.....	53
3.1.1.1	Chemical absorption processes	53
3.1.1.2	Physical solvent absorption processes.....	56
3.1.1.3	Inorganic chemical absorption processes	59
3.1.1.4	Chilled ammonia absorption process	62
3.1.2	Liquefaction / cryogenic processes to separate CO ₂	63
3.1.2.1	Possible scenarios and process schemes	64
3.1.2.2	Cryogenic distillation of CO ₂ from hydrocarbons	65
3.1.3	Adsorption Processes	66
3.1.3.1	Adsorbents used for gas purification and CO ₂ removal.....	66
3.1.3.2	CO ₂ capture from power plant scenarios.....	67

3.1.3.3	Methods of regeneration	69
3.1.3.4	Advanced adsorption technology	69
3.1.4	Membrane permeation processes.....	69
3.1.4.1	Membrane permeation process applied to CO ₂ capture	71
3.1.5	Emerging developments	72
3.1.5.1	CO ₂ capture from flue gas with a dry solid carbonate process.....	73
3.1.5.2	CO ₂ capture from flue gas using micro-porous metal organic framework (MOF) adsorbents.....	73
3.1.5.3	CO ₂ capture from gas fired flue gas with facilitated transport membranes.....	73
3.1.5.4	Membrane gas/liquid contactor technology for CO ₂ separation.....	74
3.1.5.5	Risk Assessments and Implications.....	74
3.2	PRE-COMBUSTION CO ₂ CAPTURE PROCESSES	75
3.2.1	Hydrogen as a fuel – properties and problems	76
3.2.1.1	Equipment design and material of construction limitations	77
3.2.1.2	Process limitations.....	78
3.2.2	Gasification to produce hydrogen.....	79
3.2.2.1	Coal.....	81
3.2.2.2	Biomass and waste.....	82
3.2.2.3	Residue	86
3.2.2.4	Process limitations of gasification vs. direct combustion.....	86
3.2.3	Steam methane reforming of natural gas and oil to produce hydrogen.....	87
3.2.3.1	Process limitations.....	89
3.2.3.2	CO ₂ recovery from syngas and reformer flue gas	90
3.3	OXY FUEL COMBUSTION	90
3.3.1	Air separation technology.....	90
3.3.2	Scale and purity of oxygen	91
3.3.3	Integration opportunities.....	99
3.3.4	Cryogenic vs. non-cryogenic air separation processes	99
3.3.5	Nitrogen byproduct.....	102
3.3.6	Safety.....	103
3.3.7	Assessment and implications.....	103
3.4	NOVEL AND EMERGING CO ₂ CAPTURE TECHNOLOGIES.....	104
3.4.1	Near term technology developments currently underway.....	104
3.4.1.1	Chemical looping combustion.....	104

3.4.1.2	Torrefaction of biomass.....	106
3.4.1.3	Biofuel fermentation.....	109
3.4.2	Potential advantages over commercially proven process.....	110
3.4.3	Speculative technology.....	111
3.4.4	Key risks and barriers to commercialization.....	112
3.4.5	Risk assessment and implications.....	113
3.5	REFERENCES.....	113
4.	INDEX.....	119

FIGURES

Figure 1.3.1	Global CO ₂ Emissions in 2010 by Fuel.....	7
Figure 1.3.2	Global CO ₂ Emissions in 2010 by Region.....	8
Figure 1.3.3	U.S. CO ₂ Sources, 2010.....	9
Figure 2.2.1.1	Typical Amine Process Flow Diagram.....	22
Figure 2.4.1	Cost of electricity for power plants with and without CO ₂ capture.....	27
Figure 2.11.1	CO ₂ Thermodynamic PH phase diagram.....	36
Figure 2.11.2	Typical cost of CO ₂ transport by pipeline.....	37
Figure 2.11.3	The Green LNG Chain with carbon return loop.....	38
Figure 2.13.1	Typical TEG Dehydration Process.....	42
Figure 2.13.2	Typical Adsorption Dehydration Process Flow Diagram.....	43
Figure 3.1.1	IFPexol Process for CO ₂ capture from HP synthesis gas.....	58
Figure 3.1.2	Basic Benfield hot potassium carbonate process flow diagram.....	61
Figure 3.1.3	Block Flow Diagram of CO ₂ Liquefaction from Oxy-Combustion Flue Gas.....	64
Figure 3.1.4	Process flow scheme for adsorption CO ₂ capture from synthesis gas.....	68
Figure 3.2.2.1	Total Stored Carbon (tonnes carbon).....	84
Figure 3.2.2.2	Carbon Recovery Times (tonnes).....	85
Figure 3.2.2.3	Key process blocks and the choices available.....	87
Figure 3.2.2.4	General scheme for syngas production for natural gas feedstocks.....	88
Figure 3.3.1.1	Approximate lowest cost oxygen supply methods – new plants.....	90
Figure 3.3.2.1	Flow Sheet for a typical cryogenic plant.....	92
Figure 3.3.2.2	Effect of various factors on Oxygen Price.....	98

Figure 3.3.4.1	VPSA Unit.....	101
Figure 3.4.4.1	Chemical Looping Process	105

TABLES

Table 2.1.1	CO ₂ Capture Facility Feeds	17
Table 2.2.1.1	Amine Process Design Guidelines.....	23
Table 2.2.1.2	Energy Demands of a 6,000 Metric ton/day CO ₂ Capture Project	24
Table 2.4.1	Capture Facility Investment Cost Breakdown for a 6,000 Metric Ton/day CO ₂	26
Table 2.4.2	CO ₂ Capture Facility Operating Costs for 1,000 Metric Ton CO ₂ Per Day ...	27
Table 2.5.1	Key Process Parameters for CO ₂ Recovery Plant.....	28
Table 2.5.2	Chemicals and Dessicants Consumption	29
Table 2.10.1	Estimated Maximum and Minimum Amine Emission from 420 MW Power Plant.....	35
Table 3.1.1	Relative Solubility of Compounds in Selexol	57
Table 3.1.2	Molecular Kinetic Diameter of Various Compounds	66
Table 3.1.3	Relevant Physical Properties of Commercial Adsorbents	67
Table 3.1.4	Relative Permeability of Various Gaseous Compounds Through a Typical Membrane.....	71
Table 3.1.5	Global Hydrogen Consumption Billion Nm ³ /year	76
Table 3.2.1	Summary of the Gasification Industry 2007.....	79
Table 3.3.2.1	Components of Dry Air	92
Table 3.3.2.2	Effect of Various Factors on the Capital for a 3,000 TPD Oxygen Plant Providing the Oxygen at 72 Bars for a High Pressure Gasifier	97