

TECHNOLOGY & COSTS**Technoeconomics - Energy & Chemicals (TECH)****TECH 2023S8 Direct Air Capture Technologies**

Table of Contents

A Report by **NexantECA, the Energy and Chemical Advisory company**

Published Date: October 2023

www.nexanteca.com/subscriptions-and-reports**Contents**

1	Executive Summary	1
1.1	Introduction.....	1
1.1.1	Background	1
1.1.2	Key Drivers of DAC	2
1.2	Objectives.....	4
1.3	DAC Technology and Processes	4
1.3.1	Technology Challenges.....	4
1.3.2	DAC Players and Licensors	5
1.4	Process Economics.....	8
2	Introduction.....	10
2.1	Carbon Dioxide.....	10
2.1.1	Introduction and Properties	10
2.1.2	Greenhouse Gas Impact	11
2.1.3	CO ₂ Emissions/Production Sources.....	12
2.2	Carbon Dioxide Removal Techniques.....	13
2.2.1	Point Source Carbon Capture and Storage (CCS)	13
2.2.2	Biomass Carbon Removal and Storage (BiCRS)	14
2.2.3	Bioenergy with Carbon Capture and Storage (BECCS)	15
2.2.4	Enhanced Mineralization	16
2.2.5	Direct Ocean Capture.....	16
2.2.6	Summary of CDR Methods	17
2.3	Key Drivers of DAC	17
2.3.1	Net Zero Targets	17
2.3.2	Regulatory Environment.....	18
2.3.3	Carbon Market.....	22
2.4	DAC Technology Overview	22
2.4.1	Technology Challenges.....	23
2.4.2	Inherent High Cost of DAC.....	25
3	Solid Sorbent DAC	27
3.1	Technology Description.....	27
3.1.1	DAC Sorbents	29

3.1.2	Sorbent DAC Air Contactor	30
3.1.3	Sorbent Regeneration: TSA and TVSA.....	30
3.1.4	Advantages and Disadvantages of Sorbent DAC	32
3.1.5	Areas for Innovation	34
3.2	Sorbent DAC Technology Licensors	35
3.2.1	Climeworks.....	35
3.2.2	Global Thermostat.....	38
3.2.3	Precommercial Developments	39
4	Liquid Solvent DAC	46
4.1	Technology Description.....	46
4.1.1	DAC Solvents	48
4.1.2	Solvent DAC Air Contactor	49
4.1.3	Solvent Regeneration.....	50
4.1.4	Advantages and Disadvantages of Solvent DAC.....	51
4.1.5	Areas for Innovation	52
4.2	Solvent DAC Technology Licensors.....	52
4.2.1	Carbon Engineering	52
4.2.2	Precommercial Developments	59
5	Other Developmental DAC Approaches	61
5.1	Moisture/Humidity Swing Adsorption	61
5.1.1	Technology Description.....	61
5.1.2	Energy Requirements.....	62
5.1.3	Technology Challenges.....	62
5.1.4	Precommercial Developments	63
5.2	Cryogenic DAC.....	63
5.2.1	Technology Description.....	63
5.2.2	Energy Requirements.....	64
5.2.3	Technology Challenges.....	65
5.2.4	Precommercial Developments	65
5.3	Electrochemical/Electro-Swing Adsorption DAC.....	66
5.3.1	Technology Description.....	67
5.3.2	Energy Requirements.....	67
5.3.3	Technology Challenges.....	67
5.3.4	Precommercial Developments	67
5.4	Membrane DAC.....	72
5.4.1	Technology Description.....	72
5.4.2	Energy Requirements.....	74
5.4.3	Technology Challenges.....	74
5.4.4	Precommercial Developments	75
6	Siting Considerations	77
6.1	DAC Plant Energy Source	78
6.1.1	Thermal Energy Source	78
6.1.2	Electrical Energy Source	78
6.2	DAC Plant CO ₂ End Use	79
6.3	Ambient Air Conditions	79

6.3.1	Sorbent DAC Ambient Air Considerations	79
6.3.2	Solvent DAC Ambient Air Considerations	80
6.3.3	Status of DAC Operation in Varying Ambient Air Conditions.....	80
6.4	DAC Water Usage.....	81
6.5	DAC Land Use	81
7	Captured CO ₂	83
7.1	CO ₂ Transport	83
7.2	CO ₂ Storage	84
7.2.1	Other Sequestration Options.....	84
7.2.2	CO ₂ Sequestration Safety and Risks	84
7.3	CO ₂ Utilization	84
8	Modularity and Scalability of DAC	86
8.1	Advantages and Disadvantages of Modular Systems	86
8.1.1	Advantages	86
8.1.2	Disadvantages.....	86
8.2	Optimal Degree of Modularity	87
9	Current/Planned Projects	88
10	Process Economics	89
10.1	Overview and Methodology.....	89
10.1.1	Costing Basis	89
10.1.2	Investment Basis	91
10.1.3	Pricing Basis.....	92
10.2	Key Assumptions.....	94
10.2.1	Generic Sorbent DAC Process	94
10.2.2	KOH Solvent DAC Process	97
10.3	Cost of CO ₂ Capture Estimates.....	99
10.3.1	Summary	99
10.3.2	Generic Sorbent DAC.....	103
10.3.3	KOH Solvent DAC	109
10.3.4	Process Comparison	115
10.3.5	Regional Comparison.....	117
10.3.6	Sensitivities	119

Appendices

A	Acronyms and Abbreviations.....	96
B	Definitions of Capital Cost Terms Used in Process Economics.....	125
C	Definitions of Operating Cost Terms Used in Process Economics	130
D	TECH Program Title Index (2013-2023)	133
E	References	136

Figures

Figure 1	DAC Cost of Capture Summary (USGC, WE, SEA, ME)	9
Figure 2	Global GHG Emissions by Gas Type	11
Figure 3	Global CO ₂ Emissions by Sector	12
Figure 4	Global Annual CO ₂ Emissions from Energy Combustion and Industrial Processes	12
Figure 5	CCS Value Chain	14
Figure 6	Generic DAC Process	23
Figure 7	Simplified Diagram of Solid Sorbent Adsorption	27
Figure 8	Generic Sorbent DAC	28
Figure 9	Climeworks' DAC Development Timeline	36
Figure 10	Climeworks' Direct Air Capture Process	37
Figure 11	Generic Solvent DAC	47
Figure 12	Air Contactor Packing Depth and Total DAC Costs	50
Figure 13	CE DAC Process Chemistry and Thermodynamics	53
Figure 14	CE 1 Mt-CO ₂ /year Baseline DAC Plant	54
Figure 15	Moisture Swing Adsorption Process	62
Figure 16	Cryo-DAC Process Diagram	66
Figure 17	MZT DAC Process	69
Figure 18	Generic Membrane DAC	73
Figure 19	Simplified SMART-DAC Process	76
Figure 20	Regional Suitability for DAC in the United States	78
Figure 21	Generic Sorbent DAC Process	96
Figure 22	Cost of Capture Comparison for Sorbent and Solvent DAC (USGC, Q1 2023)	116
Figure 23	Sorbent DAC Cost of Capture Regional Comparison (Q1 2023)	118
Figure 24	KOH Solvent DAC Cost of Capture Regional Comparison (Q1 2023)	118
Figure 25	Utility Sensitivity	119
Figure 26	Cost of Capture Sensitivity to IRA \$/ton CO ₂ Amount	120

Tables

Table 1	Government Support for DAC	3
Table 2	Major DAC Technology Licensors	5
Table 3	Precommercial DAC Technology Holders/Lic平sors	6
Table 4	DAC Cost of Capture Summary	9
Table 5	Properties of Carbon Dioxide	10
Table 6	BECCS Conversion Pathways	15
Table 7	Summary of CDR Technologies	17
Table 8	DAC Policy/Government Support Overview	19
Table 9	Sorbent Adsorption Characteristics Reported in Literature	29
Table 10	Sorbent Desorption Characteristics Reported in Literature	30
Table 11	Air Contactor System Type and Pressure Drop	30
Table 12	Advantages and Disadvantages of Sorbent DAC	32
Table 13	Climeworks DAC Performance Summary	38
Table 14	Developing Sorbent DAC Companies	39
Table 15	DAC Solvent Characteristics Reported in Literature	49
Table 16	Advantages and Disadvantages of Solvent DAC	51
Table 17	Process Parameters for Major Unit Operations	56
Table 18	Process Parameters for Minor Unit Operations	57
Table 19	CE Baseline Plant Performance Results	58
Table 20	Developing Solvent DAC Companies	59
Table 21	Developmental DAC Approaches	61
Table 22	MZT Pilot Plant Design Summary	70
Table 23	MZT Base Load Energy Requirements	70
Table 24	MZT Pilot Cost Summary	71
Table 25	Amine-Functionalized Sorbent DAC Performance in Different Ambient Conditions	80
Table 26	Liquid Solvent DAC Performance in Different Ambient Conditions	81
Table 27	DAC Land Area Requirements for 1 Million Ton CO ₂ per Year Plant	82
Table 28	Current/Planned DAC Projects and Demonstrations	88
Table 29	Prices Used	93
Table 30	Generic Sorbent DAC Key Process Assumptions and Performance	95
Table 31	KOH Solvent DAC Key Process Assumptions and Performance	98
Table 32	Cost of Capture Summary for Generic Sorbent and KOH Solvent DAC (USGC, Q1 2023)	100
Table 33	Cost of Capture Summary for Sorbent DAC	101
Table 34	Cost of Capture Summary for Solvent DAC	102
Table 35	Cost of Capture Estimate for Sorbent-Based Direct Air Capture of Carbon Dioxide (USGC, Q1 2023)	104
Table 36	Cost of Capture Estimate for Sorbent-Based Direct Air Capture of Carbon Dioxide (USGC, including IRA credits, Q1 2023)	105
Table 37	Cost of Capture Estimate for Sorbent-Based Direct Air Capture of Carbon Dioxide (Western Europe, Q1 2023)	106

Table 38	Cost of Capture Estimate for Sorbent-Based Direct Air Capture of Carbon Dioxide (Southeast Asia, Q1 2023)	107
Table 39	Cost of Capture Estimate for Sorbent-Based Direct Air Capture of Carbon Dioxide (Middle East, Q1 2023).....	108
Table 40	Cost of Capture Estimate for Solvent-Based Direct Air Capture of Carbon Dioxide (USGC, Q1 2023)	110
Table 41	Cost of Capture Estimate for Solvent-Based Direct Air Capture of Carbon Dioxide (USGC, including IRA credits, Q1 2023)	111
Table 42	Cost of Capture Estimate for Solvent-Based Direct Air Capture of Carbon Dioxide (Western Europe, Q1 2023)	112
Table 43	Cost of Capture Estimate for Solvent-Based Direct Air Capture of Carbon Dioxide (Southeast Asia, Q1 2023)	113
Table 44	Cost of Capture Estimate for Solvent-Based Direct Air Capture of Carbon Dioxide (Middle East, Q1 2023).....	114
Table 45	Cost of Capture Comparison for Sorbent and Solvent DAC (USGC, Q1 2023)	115
Table 46	Percent Contributions to Cost of CO ₂ Capture.....	117
Table 47	Regional Natural Gas Prices and CO ₂ Sequestration Costs.....	117



TECHNOLOGY & COSTS

Technoeconomics - Energy & Chemicals (TECH)

The NexantECA Subscriptions' Technoeconomics - Energy & Chemicals (TECH) program is recognized globally as the industry standard source for information relevant to the chemical process and refining industries. Technoeconomics - Energy & Chemicals (TECH) reports are available as a subscription program or on a single report basis.

Contact Details:

Americas:

Adam Chan, Managing Consultant
Phone: + 1-914-609-0326, e-mail: achan@NexantECA.com

Erica Hill, Client Services Coordinator, Subscriptions and Reports
Phone: + 1-914-609-0386, e-mail: ehill@NexantECA.com

EMEA:

Anna Ibbotson, Vice President, Sales and Marketing
Phone: +44-207-950-1528, aibbotson@NexantECA.com

Asia:

Chommanad Thammanayakatip, Managing Consultant
Phone: +66-2793-4606, email: chommanadt@NexantECA.com

NexantECA Subscriptions and Reports provide clients with comprehensive analytics, forecasts and insights for the chemicals, polymers, energy and cleantech industries. Using a combination of business and technical expertise, with deep and broad understanding of markets, technologies and economics, NexantECA provides solutions that our clients have relied upon for over 50 years.

Copyright © 2000-2023. NexantECA (BVI) Limited. All rights reserved