

TECHNOLOGY & COSTS**Biorenewable Insights****Carbon Dioxide to Chemicals and Fuels**

Table of Contents

A Report by **NexantECA, Inc.**

Published Date: September 2020

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

| | | |
|--------|---|----|
| 1 | Executive Summary | 1 |
| 1.1 | Overview..... | 1 |
| 1.2 | Technologies | 2 |
| 1.3 | Economics | 2 |
| 2 | Introduction..... | 3 |
| 2.1 | Properties of Carbon Dioxide | 5 |
| 2.2 | Segmentation of Sources | 6 |
| 2.3 | Capture and Sequestration of Carbon Dioxide | 7 |
| 2.4 | Non Transformative Uses of Carbon Dioxide..... | 7 |
| 2.5 | Products from Carbon Dioxide | 8 |
| 2.5.1 | Food Industry | 9 |
| 2.5.2 | Pharmaceutical Industry..... | 9 |
| 2.5.3 | Enhanced Oil Recovery (EOR) and Other Oil and Gas Production..... | 9 |
| 2.5.4 | Fertilizer Industry: Urea | 9 |
| 2.5.5 | Horticulture | 9 |
| 2.5.6 | Carbon Dioxide Reforming | 10 |
| 2.5.7 | Methanol..... | 10 |
| 2.5.8 | Drop-In Chemicals..... | 10 |
| 2.5.9 | Industrial Biotechnology Feedstock | 10 |
| 2.5.10 | Other Potential Routes for Carbon Dioxide Utilization | 10 |
| 3 | Technologies | 11 |
| 3.1 | Dry Reforming and Syngas | 11 |
| 3.1.1 | Carbon Dioxide Reforming..... | 12 |
| 3.1.2 | Syngas from Carbon Dioxide by “Solar Furnace” | 14 |
| 3.1.3 | Enzymatic Reduction of Carbon Dioxide to Syngas | 15 |
| 3.1.4 | Key Players | 16 |
| 3.2 | Electrochemical Conversion of CO ₂ | 16 |
| 3.2.1 | Methanol..... | 16 |
| 3.2.2 | Methane | 21 |

| | | |
|-------|--|----|
| 3.3 | Biotechnology Routes | 21 |
| 3.3.1 | Ethanol | 22 |
| 3.3.2 | Algae Technology..... | 32 |
| 3.3.3 | Protein | 33 |
| 3.4 | Urea..... | 33 |
| 3.4.1 | Chemistry | 33 |
| 3.4.2 | Key Players | 34 |
| 3.5 | Polycarbonates..... | 35 |
| 3.5.1 | Via Carbon Dioxide and Ethylene Oxide (Commercial Process) | 35 |
| 3.5.2 | Dialkyl Carbonate via Carbon Dioxide and Alcohol (Developing Process), Asahi Kasei | 45 |
| 3.5.3 | Diphenyl Carbonate, Shell | 48 |
| 3.5.4 | Polycarbonate polyols for Polyurethanes, Covestro | 52 |
| 3.5.5 | Other Key Players | 53 |
| 3.6 | Cement and Concrete | 53 |
| 3.6.1 | Key Players | 54 |
| 3.7 | Soda Ash..... | 55 |
| 3.8 | Other Uses | 56 |
| 4 | Economics | 57 |
| 4.1 | Prices..... | 58 |
| 4.2 | CAPEX Comparisons | 58 |
| 4.2.1 | Western Europe in 2020 | 59 |
| 4.2.2 | Asia in 2025..... | 60 |
| 4.2.3 | Comparative Analysis by Process..... | 61 |
| 5 | CO ₂ Utilization | 63 |
| 5.1 | Overview..... | 63 |
| 5.2 | Western Europe | 63 |
| 5.3 | Asia..... | 64 |
| 5.4 | North America | 64 |
| 6 | Conclusions | 65 |
| 6.1 | CO ₂ to Fuels | 65 |
| 6.2 | CO ₂ to Chemicals | 65 |
| 6.3 | Building Materials from CO ₂ | 65 |
| 6.4 | CO ₂ Use Complements Storage | 65 |

Appendices

| | | |
|---|---|----|
| A | Definitions of Operating Cost Terms Used in Process Economics | 66 |
| B | References | 68 |

Figures

| | | |
|-----------|--|----|
| Figure 1 | Carbon Stabilization Wedges | 3 |
| Figure 2 | Classification of Pathways for CO ₂ Use | 5 |
| Figure 3 | World CO ₂ Emissions by Fuel Type, 2018 | 6 |
| Figure 4 | Block Flow Diagram for Combined CO ₂ and Steam Methane Reforming..... | 13 |
| Figure 5 | Sandia's CR5..... | 15 |
| Figure 6 | Bench Scale 50 kg per day Methanol Synthesis Plant..... | 20 |
| Figure 7 | Cell Metabolic Carbon Balance | 22 |
| Figure 8 | Reductive Acetyl-CoA Pathway..... | 24 |
| Figure 9 | 300-Ton Plant at Baosteel Mill near Shanghai | 25 |
| Figure 10 | LanzaTech Block Flow Diagram..... | 27 |
| Figure 11 | LanzaTech Reactor System | 29 |
| Figure 12 | Asahi Kasei Non-Phosgene Polycarbonate Commercial Process | 36 |
| Figure 13 | Asahi Kasei Dimethyl Carbonate Process..... | 39 |
| Figure 14 | Asahi Kasei Diphenyl Carbonate Process..... | 42 |
| Figure 15 | Asahi Kasei Polycarbonate Melt Process, Polymerization Section..... | 44 |
| Figure 16 | Asahi Kasei Non-Phosgene Melt Processes, Commercial and Demonstration | 46 |
| Figure 17 | Asahi Kasei Demonstration Non-Phosgene Melt Process, DRC Production | 47 |
| Figure 18 | Shell DPC Process, Propylene Carbonate Production..... | 49 |
| Figure 19 | Shell DPC Process, DMC Production..... | 51 |
| Figure 20 | Reaction Scheme from Propylene Oxide and Carbon Dioxide to Cardyon to Polyurethanes..... | 52 |
| Figure 21 | CarbonCure Technology Process Flow Diagram | 54 |
| Figure 22 | CO ₂ to Chemicals and Fuels - WE Economic Competitiveness..... | 59 |
| Figure 23 | CO ₂ to Chemicals and Fuels - China Economic Competitiveness | 60 |
| Figure 24 | Ethanol (Syngas Fermentation) Comparative Economics by Region | 61 |
| Figure 25 | Ethylene Carbonate Comparative Economics by Region | 61 |
| Figure 26 | Cement Comparative Economics by Region..... | 62 |
| Figure 27 | Methane Comparative Economics by Region | 62 |
| Figure 28 | Renewable Methanol Comparative Economics by Region | 62 |
| Figure 29 | Western Europe CO ₂ Utilization Potential | 63 |
| Figure 30 | Asian CO ₂ Utilization Potential | 64 |
| Figure 31 | USGC CO ₂ Utilization Potential | 64 |

Tables

| | | |
|----------|---|----|
| Table 1 | Current Developers of Carbon Dioxide to Chemicals Technologies | 2 |
| Table 2 | Current Developers of Carbon Dioxide to Chemicals Technologies | 5 |
| Table 3 | Non-Transformative Uses of Carbon Dioxide..... | 7 |
| Table 4 | Current Developers of Carbon Dioxide to Chemicals Technologies | 8 |
| Table 5 | Typical Characteristic Syngas Composition | 11 |
| Table 6 | Biochemical Carbon Fixation Pathways | 23 |
| Table 7 | Theoretical Yields of Ethanol Production Using Reductive Acetyl-CoA Pathway | 24 |
| Table 8 | LanzaTech Key Patent Activity..... | 31 |
| Table 9 | Urea Synthesis and Finishing Technology Licensors..... | 34 |
| Table 10 | Non-Transformative Uses of Carbon Dioxide..... | 56 |
| Table 11 | Prices for Main Feedstock, Byproduct, and Utilities Inputs to Models | 58 |
| Table 12 | Western Europe CAPEX Table, 2020 | 58 |
| Table 13 | China CAPEX Table, 2025 | 59 |
| Table 14 | CO ₂ to Chemicals and Fuels WE Economic Competitiveness..... | 59 |
| Table 15 | CO ₂ to Chemicals and Fuels Asia Economic Competitiveness..... | 60 |



TECHNOLOGY & COSTS

Biorenewable Insights

The NexantECA Subscriptions' Biorenewable Insights program is recognized globally as the industry standard source for information relevant to the chemical process and refining industries. Biorenewable Insights reports are available as a subscription program or on a single report basis.

Contact Details:

Americas:

Marcos Nogueira Cesar, Vice President, Global Products, E&CA: NexantECA Subscriptions
Phone: + 1-914-609-0324, e-mail: mcesar@nexant.com

Erica Hill, Client Services Coordinator, E&CA-Products
Phone: + 1-914-609-0386, e-mail: ehill@nexant.com

EMEA:

Anna Ibbotson, Director, NexantECA Subscriptions
Phone: +44-207-950-1528, aibbotson@nexant.com

Asia:

Chommanad Thammanayakatip, Managing Consultant, Energy & Chemicals Advisory
Phone: +66-2793-4606, email: chommanadt@nexant.com

E&CA Americas, LLC, a subsidiary of Nexant, Inc. (www.nexant.com) is a leading management consultancy to the global energy, chemical, and related industries. For over 38 years, Nexant has helped clients increase business value through assistance in all aspects of business strategy, including business intelligence, project feasibility and implementation, operational improvement, portfolio planning, and growth through M&A activities. Nexant has its main offices in San Francisco (California), White Plains (New York), and London (UK), and satellite offices worldwide.

Copyright © by E&CA Americas, LLC, 2020. All Rights Reserved.