

Biorenewable Insights

Butadiene

Table of Contents

A Report by NexantThinking™

Published December 2014

www.nexantthinking.com

Section	Page
1 Executive Summary	1
1.1 OVERVIEW	1
1.2 TECHNOLOGIES.....	1
1.3 ECONOMICS	1
1.4 CAPACITY ANALYSIS.....	3
1.4.1 Announced Capacity	3
1.4.2 Adjusted Capacity	4
1.5 IMPLICATIONS FOR CONVENTIONAL TECHNOLOGY	5
1.5.1 Strategic and Technical Implications.....	6
1.6 PATENT ANALYSIS.....	6
2 Introduction.....	7
2.1 BACKGROUND.....	7
2.1.1 Conventional Petrochemical Source of Butadiene as a Byproduct Olefin ...	7
2.2 TECHNOLOGIES INVESTIGATED	9
3 Technologies	10
3.1 DIRECT FERMENTATION TO BUTADIENE.....	10
3.1.1 Company Profiles	10
3.1.2 Technology	11
3.2 SUGAR FERMENTATION TO BDO AND DEHYDRATION TO BUTADIENE	15
3.2.1 Sugar Fermentation to BDO.....	15
3.2.2 BDO Dehydration to Butadiene	20
3.3 SUGAR FERMENTATION TO SUCCINIC ACID AND HYDROGENATION TO BDO, FOLLOWED BY DEHYDROGENATION TO BUTADIENE.....	23
3.3.1 Sugar Fermentation to Succinic Acid	23

3.3.2	Succinic Acid Hydrogenation to BDO.....	28
3.3.3	Technology.....	29
3.4	CO RICH WASTE GAS / SYNGAS FERMENTATION TO BDO	30
3.4.1	Company Profiles	30
3.4.2	Technology.....	30
3.5	FERMENTATION TO BUTANOL, DEHYDRATION TO BUTENES, AND OXIDATIVE DEHYDROGENATION TO BUTADIENE.....	33
3.5.1	Fermentation to <i>n</i> -Butanol.....	33
3.5.2	<i>n</i> -Butanol Dehydration.....	43
3.5.3	Oxidative Dehydrogenation Process	44
3.6	LEBEDEV PROCESS	61
3.6.1	Commercial History.....	61
3.6.2	Chemistry	62
3.6.3	Process	64
3.7	COPERBO PROCESS.....	66
3.7.1	Commercial History.....	66
3.7.2	Chemistry	66
3.7.3	Process Description	66
4	Economics	70
4.1	BASIS OF ECONOMICS.....	70
4.2	METHODOLOGY	70
4.2.1	Capital Cost Elements.....	70
4.2.2	Operating Cost Elements	74
4.3	COMPETITIVE ECONOMICS.....	77
4.3.1	Comparison by Region.....	77
4.3.2	Comparison by Process	82
4.3.3	Comparison to Conventional On-Purpose Butadiene Technologies	90
4.4	BIO-BUTADIENE TECHNOLOGIES.....	91
4.4.1	Direct Fermentation.....	91
4.4.2	Sugar Fermentation to BDO and Dehydration	96
4.4.3	Sugar Fermentation to Succinic, Hydrogenation to BDO, and Dehydration	96
4.4.4	LanzaTech CO/Syngas Fermentation to BDO and Dehydration	105
4.4.5	Fermentation to Butanol, Dehydration, and OXO-D	105
4.4.6	Lebedev Process.....	114
4.4.7	Coperbo Process.....	114

4.5	SENSITIVITIES	123
4.5.1	Net Raw Materials	123
4.5.2	Capital Sensitivity	125
5	Capacity Analysis	127
5.1	OVERVIEW	127
5.1.1	Types of Developments Considered	127
5.2	METHODOLOGY	127
5.3	EXISTING CAPACITY.....	130
5.4	ANNOUNCED PROJECT LISTING	130
5.5	PROJECT ANALYSIS	131
5.5.1	Global Bioenergies	131
5.5.2	Genomatica	132
5.5.3	LanzaTech.....	132
5.5.4	Cobalt Technologies.....	133
5.6	ADJUSTED PROJECT LISTING	134
6	Implications for Conventional Technology	136
6.1	SCALES AND MARKETS	136
6.1.1	Scales.....	136
6.1.2	Markets.....	136
6.2	PRICES AND MARGINS.....	137
6.2.1	Prices	137
6.2.2	Margins.....	138
6.3	STRATEGIC AND TECHNICAL IMPLICATIONS	139
6.3.1	Strategic Implications	139
6.3.2	Technical Implications	139
7	Patent Analysis.....	140
7.1.1	OVERVIEW	140
7.2	GRANTED PATENTS	141
7.2.1	Global	141
7.2.2	North America	143
7.2.3	ROW	145
7.3	PATENT APPLICATIONS.....	146
7.3.1	Global	146
7.3.1	Japan.....	149
7.3.1	Other Asia Pacific	151

7.3.2	North America	157
7.3.3	ROW.....	161

Figure	Page
1.1 Comparative Economics by Region	2
1.2 Comparative Economics by Process	3
1.3 Biobutadiene Announced Project Capacities	4
1.4 Biobutadiene Adjusted Project Capacities	5
1.5 Overall Patent Activity by Region	6
2.1 U.S. Natural Gas and Crude Oil Pricing.....	7
2.2 U.S. Ethylene Feedstock Sources	8
2.3 Steam Cracker Products Naphtha versus Ethane	9
3.1 Global Bioenergies Reactions	12
3.2 Global Bioenergies Direct Butadiene Production by Fermentation.....	14
3.3 Genomatica BDO Pathway()	16
3.4 Genomatica Pathway to 4-HB and BDO ().....	17
3.5 Genomatica BDO Block Flow Diagram	18
3.6 BDO to Butadiene Fixed Bed Dehydration.....	22
3.7 Biosuccinic Acid Process Overview	25
3.8 Wood Ljundahl Pathway from CO to 2,3-BDO	31
3.9 Simplified Process flow of the LanzaTech Technology.....	32
3.10 Cobalt's Simplified Process Schematic()	37
3.11 Cobalt Simplified Process Flow Diagram from U.S. 20100330633.....	38
3.12 Green Biologics' Flow Scheme for Producing n-Butanol	40
3.13 Green Biologics Ethanol Retrofit Process Flow Diagram.....	42
3.14 Butadiene Production by n-Butane Dehydrogenation (Catadiene®)	48
3.15 Production of Butadiene by Oxo-D™ Process	53
3.16 Block Flow Diagram for U.S. Patent 7 495 138.....	56
3.17 Block Flow Diagram, U.S. Patent Application 2011/0040134	58
3.18 Lebedev Process – One Step Ethanol to Butadiene.....	65
3.19 Coperbo Process – Ethanol to Acetaldehyde plus Ethanol	67
4.1 Comparative Economics by Region	82
4.2 Comparative Economics by Process	90
4.3 Comparison to Conventional On-Purpose Butadiene Technologies	91
4.4 Biobutadiene Cash Cost Sensitivity to Net Raw Material Costs	123

4.5	Biobutadiene Cost of Production Sensitivity to Net Raw Material Costs	124
4.6	Biobutadiene Cost Plus 10 Percent Return Sensitivity to Net Raw Material Costs	125
4.7	Biobutadiene Cost of Production Sensitivity to Capital Costs	126
4.8	Biobutadiene Cost Plus 10 Percent Return Sensitivity to Capital Costs.....	126
5.1	Biobutadiene Announced Project Capacities	131
5.2	Biobutadiene Adjusted Project Capacities	135
6.1	Global Butadiene Price Forecast	138
7.1	Overall Patent Activity by Region.....	140
7.2	Granted Patents by Region	141
7.3	Granted Patents by Assignee.....	142
7.4	North American Granted Patents by Assignee	143
7.5	ROW Granted Patents by Assignee.....	145
7.6	Patent Applications by Region	147
7.7	Patent Applications by Assignee	147
7.8	Japanese Patent Applications by Assignee	149
7.9	Other Asia Pacific Patent Applications by Assignee	152
7.10	North American Patent Applications by Assignee.....	157
7.11	ROW Patent Applications by Assignee	161

Table	Page
1.1 CO/Syngas Fermentation to BDO and Dehydration Comparative Economics	5
3.1 Butane Feed.....	49
3.2 1,3-Butadiene Product.....	49
3.3 Catadiene® Material Balance	51
3.4 Yields for U.S. Patent 7 488 858	54
3.5 Material Balance for U.S. Patent 7 495 138.....	57
3.6 Feed Composition	60
3.7 Performance and Efficiency Improvement Arc of the Lebedev Process.....	62
3.8 Typical Butadiene and Byproduct Yields from Reaction Radicals	63
4.1 North American Comparative Economics	78
4.2 South American Comparative Economics.....	79
4.3 Western Europe Comparative Economics	80
4.4 Asia Comparative Economics	81
4.5 Direct Fermentation Comparative Economics.....	83
4.6 Sugar Fermentation to BDO and Dehydration Comparative Economics	84
4.7 Sugar Fermentation to Succinic Acid, Hydrogenation to BDO, and Dehydration Comparative Economics	85
4.8 CO/Syngas Fermentation to BDO and Dehydration Comparative Economics.....	86
4.9 Fermentation Butanol, Dehydration, and OXO-D Comparative Economics	87
4.10 Lebedev Process Comparative Economics	88
4.11 Coperbo Process Comparative Economics	89
4.12 Cost of Production Model for Direct Fermentation, North America.....	92
4.13 Cost of Production Model for Direct Fermentation, South America	93
4.14 Cost of Production Model for Direct Fermentation, Western Europe	94
4.15 Cost of Production Model for Direct Fermentation, Asia	95
4.16 Cost of Production Model for Sugar Fermentation to BDO and Dehydration, North America	97
4.17 Cost of Production Model for Sugar Fermentation to BDO and Dehydration, South America	98
4.18 Cost of Production Model for Sugar Fermentation to BDO and Dehydration, Western Europe	99
4.19 Cost of Production Model for Sugar Fermentation to BDO and Dehydration, Asia	100
4.20 Cost of Production Model for Sugar Fermentation to Succinic Acid, Dehydration to BDO, and Dehydration, North America	101
4.21 Cost of Production Model for Sugar Fermentation to Succinic Acid, Dehydration to BDO, and Dehydration, South America	102

4.22 Cost of Production Model for Sugar Fermentation to Succinic Acid, Dehydration to BDO, and Dehydration, Western Europe	103
4.23 Cost of Production Model for Sugar Fermentation to Succinic Acid, Dehydration to BDO, and Dehydration, Asia	104
4.24 Cost of Production Model for LanzaTech CO Fermentation to BDO and Dehydration, North America	106
4.25 Cost of Production Model for LanzaTech CO Fermentation to BDO and Dehydration, South America	107
4.26 Cost of Production Model for LanzaTech CO Fermentation to BDO and Dehydration, Western Europe	108
4.27 Cost of Production Model for LanzaTech CO Fermentation to BDO and Dehydration, Asia	109
4.28 Cost of Production Model for Corn Fermentation to n-Butanol, Dehydration to 1-Butene, and OXO-D, North America	110
4.29 Cost of Production Model for Sugarcane Fermentation to n-Butanol, Dehydration to 1-Butene, and OXO-D, South America	111
4.30 Cost of Production Model for Corn Fermentation to n-Butanol, Dehydration to 1-Butene, and OXO-D, Western Europe	112
4.31 Cost of Production Model for Corn Fermentation to n-Butanol, Dehydration to 1-Butene, and OXO-D, Western Europe	113
4.32 Cost of Production Model for Lebedev, North America	115
4.33 Cost of Production Model for Lebedev, South America	116
4.34 Cost of Production Model for Lebedev, Western Europe	117
4.35 Cost of Production Model for Lebedev, Asia	118
4.36 Cost of Production Model for Coperbo, North America	119
4.37 Cost of Production Model for Coperbo, South America	120
4.38 Cost of Production Model for Coperbo, Western Europe	121
4.39 Cost of Production Model for Coperbo, Asia	122
5.1 Project Scoring Methodology	127
5.2 Biobutadiene Announced Project Capacity Listing	130
5.3 Global Bioenergies Project Scoring	131
5.4 Genomatica Project Scoring	132
5.5 LanzaTech Project Scoring	133
5.6 Cobalt Technologies Project Scoring	133
5.7 Biobutadiene Adjusted Project Capacity Listing	134
6.1 CO/Syngas Fermentation to BDO and Dehydration Comparative Economics	138
7.1 Key Global Granted Patents	142
7.2 Key North American Granted Patents	143

7.3	North American Granted Patents	144
7.4	Key ROW Granted Patents	145
7.5	ROW Granted Patents	146
7.6	Key Global Patent Applications	148
7.7	Key Japanese Patent Applications.....	149
7.8	Japanese Patent Applications	150
7.9	Key Asia Pacific Granted Patents	152
7.10	All Other Asia Pacific Patent Applications.....	153
7.11	Key North American Patent Applications	158
7.12	Canadian Patent Applications	158
7.13	Mexican Patent Applications	159
7.14	U.S. Patent Applications.....	159
7.15	ROW Patent Applications.....	162

NexantThinking™

Biorenewable Insights



Nexant, Inc. (www.nexanthing.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 .

Contact Details:

New York: Steven Slome
Phone: + 1-914-609-0379, e-mail: sslome@nexant.com

New York: Heidi Junker Coleman, Global Programs Support Manager
Phone: + 1-914-609-0381, e-mail: hcoleman@nexant.com

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 Nexant Inc. 2014. All Rights Reserved.