

# Biorenewable Insights Butanediol (BDO)

## Table of Contents

A Report by NexantThinking™

Published April 2015

[www.nexantthinking.com](http://www.nexantthinking.com)

Section	Page
1 Executive Summary .....	1
1.1 OVERVIEW .....	1
1.2 TECHNOLOGY .....	1
1.2.1 1, 4 BDO.....	1
1.2.2 2,3-BDO .....	3
1.3 ECONOMICS .....	4
1.3.1 Overall Comparative Economics by Region .....	4
1.3.2 Overall Comparative Economics by Process .....	4
1.4 CAPACITY ANALYSIS.....	5
1.5 IMPACTS ON CONVENTIONAL INDUSTRY .....	7
1.5.1 Strategic Implications .....	7
1.5.2 Commercial Implications .....	7
1.6 PATENT ANALYSIS.....	8
2 Introduction.....	9
2.1 OVERVIEW .....	9
2.1.1 Market Size .....	10
2.1.2 Incentives .....	11
2.2 PRODUCT SPECIFICATIONS .....	12
2.3 TRANSPORTATION AND STORAGE .....	12
2.4 HEALTH HAZARDS .....	13
2.5 SCOPE OF STUDY.....	13
3 Technology .....	14
3.1 OVERVIEW .....	14

3.2	1,4-BDO.....	15
	3.2.1 Direct Fermentation of Sugars .....	15
	3.2.2 Succinic Acid Hydrogenation .....	26
	3.2.3 PHA Depolymerization .....	33
3.3	2,3-BDO.....	36
	3.3.1 CO/Syngas Fermentation.....	36
4	Economics .....	40
4.1	BASIS OF ECONOMICS.....	40
4.2	METHODOLOGY .....	40
	4.2.1 Capital Cost Elements.....	40
	4.2.2 Operating Cost Elements .....	44
4.3	COMPARATIVE ECONOMICS .....	47
	4.3.1 Comparison by Region.....	47
	4.3.2 Comparative Economics by Process .....	51
4.4	COST OF PRODUCTION MODELS .....	54
	4.4.1 North America .....	54
	4.4.2 South America.....	58
	4.4.3 Western Europe .....	62
	4.4.4 Asia.....	66
4.5	SENSITIVITIES .....	70
	4.5.1 Feedstock Price.....	70
	4.5.2 Byproduct Price .....	70
	4.5.3 Economy of Scale .....	71
	4.5.4 Investment.....	72
	4.5.5 ROCE .....	72
5	Capacity Analysis .....	74
5.1	OVERVIEW .....	74
5.2	EXISTING COMMERCIAL CAPACITY .....	74
5.3	PROJECT CAPACITY ANALYSIS .....	74
	5.3.1 Methodology.....	74
	5.3.2 BioAmber.....	78
	5.3.3 Myriant.....	79
	5.3.4 BASF .....	80
	5.3.5 Genomatica .....	80
	5.3.6 LanzaTech.....	81

5.4	CONCLUSION .....	81
6	Impact on the Conventional Industry.....	83
6.1	SCALES AND MARKETS .....	83
6.1.1	Scale of Production .....	83
6.1.2	Market Penetration .....	83
6.2	PRICE AND MARGINS .....	84
6.2.1	Prices .....	84
6.2.2	Margins.....	84
6.3	STRATEGIC AND TECHNICAL IMPLICATIONS .....	85
6.3.1	Strategic Implications .....	85
6.3.2	Technical Implications .....	85
6.3.3	Technology Implications.....	86
7	Patent Analysis.....	87
7.1	OVERVIEW .....	87
7.2	GRANTED PATENTS .....	88
7.2.1	Global .....	88
7.2.2	North America .....	89
7.2.3	Europe .....	93
7.2.4	Asia.....	94
7.2.5	ROW .....	95
7.3	PATENT APPLICATIONS .....	96
7.3.1	Global .....	96
7.3.2	North America .....	98
7.3.3	Europe .....	104
7.3.4	Asia.....	108
7.3.5	ROW .....	116
8	References .....	120

<b>Figure</b>	<b>Page</b>
1.1 Engineered Metabolic Pathways to 4-HB and BDO in <i>E. coli</i> .....	1
1.2 Succinic Acid Hydrogenation.....	2
1.3 PH4B-Based 1,4-BDO Process Chemistry .....	3
1.4 Simplified Process Flow of LanzaTech's Technology .....	3
1.5 Comparative Economics by Region .....	4
1.6 Comparative Economics by Process .....	5
1.7 Potential Bio-based Share of 1,4-BDO Production Capacities .....	7
1.8 Overall Patent Activity by Region .....	8
2.1 Global 1,4-BDO Demand Distribution (2012).....	10
2.2 1,4-BDO Value Chain.....	11
3.1 Some Developers of Bio-Based 1,4-BDO Routes.....	14
3.2 Engineered Metabolic Pathways to 4-HB and BDO in <i>E. coli</i> .....	16
3.3 Genomatica's BDO Fermentation Process (Simple Flow Diagram) .....	21
3.4 Genomatica's BDO Recovery Process (Simple Flow Diagram) .....	23
3.5 Process Chemistry for Succinic Acid Hydrogenation .....	27
3.6 Davy Process Succinic Acid Esterification and Hydrogenation .....	28
3.7 Davy Process Bio-BDO Separation and Purification .....	29
3.8 DuPont Succinic Acid to THF Process .....	31
3.9 PH4B-Based 1,4-BDO Process Chemistry .....	33
3.10 Metabolix GBL Recovery from Biomass with Residual Converted to Solid Fuel .....	34
3.11 Metabolix FAST™ Process for Industrial Chemicals .....	36
3.12 Wood Ljungdahl Pathway from CO to 2,3-BDO.....	37
3.13 Simplified Process Flow of the LanzaTech Technology .....	38
4.1 Comparative Economics by Region .....	50
4.2 Comparative Economics by Process .....	53
4.3 Feedstock Price Sensitivity .....	70
4.4 Byproduct Price Sensitivity.....	71
4.5 Economy of Scale Sensitivity .....	71
4.6 Capital Investment Sensitivity .....	72
4.7 ROCE Sensitivity.....	73
5.1 Risk Adjustment Methodology.....	78
6.1 Potential Bio-based Share of BDO Production Capacities .....	83

6.2	Regional Potential Bio-based Share of 1,4-BDO Production Capacities by 2020 .....	84
7.1	Overall Patent Activity by Region .....	87
7.2	Granted Patents by Region .....	88
7.3	Granted Patents by Assignee.....	88
7.4	North American Granted Patents by Assignee .....	89
7.5	European Granted Patents by Assignee .....	93
7.6	Asian Granted Patents by Assignee .....	94
7.7	ROW Granted Patents .....	95
7.8	Patent Applications by Region .....	96
7.9	Patent Applications by Assignee .....	97
7.10	North American Patent Applications by Assignee.....	99
7.11	Europe Applications by Assignee.....	105
7.12	Asian Patent Applications by Assignee.....	108
7.13	ROW Patent Applications by Assignee .....	117

<b>Table</b>	<b>Page</b>
1.1 Announced Bio-BDO Capacities .....	6
1.2 Adjusted Bio-BDO Capacities .....	6
2.1 Typical Commercial Specifications for 1,4-BDO .....	12
3.1 Genomatica’s Assumed Biocatalyst Genetic Modifications .....	17
4.1 North American Comparative Economics .....	47
4.2 South America Comparative Economics.....	48
4.3 Asia Comparative Economics .....	49
4.4 Western Europe Comparative Economics .....	50
4.5 Direct Fermentation Comparative Economics.....	51
4.6 Succinic Acid Process Comparative Economics.....	52
4.7 PHAs Polymerization Process Comparative Economics .....	52
4.8 CO Fermentation Process Comparative Economics .....	53
4.9 Cost of Production Model for Genomatica Direct Sugar Fermentation to BDO, North America .....	54
4.10 Cost of Production Model for BDO Production via Bio-Succinic Acid Route, North America .....	55
4.11 Cost of Production Model for BDO Production via PHA Polymerization, North America.....	56
4.12 Cost of Production Model for LanzaTech’s CO Fermentation to BDO, North America .....	57
4.13 Cost of Production Model for Genomatica Direct Sugar Fermentation to BDO, South America.....	58
4.14 Cost of Production Model for BDO Production via Bio-Succinic Acid Route, South America.....	59
4.15 Cost of Production Model for BDO Production via PHA Polymerization Route, South America.....	60
4.16 Cost of Production Model for LanzaTech’s CO Fermentation to BDO, South America.....	61
4.17 Cost of Production Model for Genomatica Direct Sugar Fermentation to BDO, Western Europe .....	62
4.18 Cost of Production Model for BDO Production via Bio-Succinic Acid Route, Western Europe .....	63
4.19 Cost of Production Model for BDO Production via PHA Polymerization Route, Western Europe .....	64
4.20 Cost of Production Model for LanzaTech’s CO Fermentation to BDO, Western Europe .....	65
4.21 Cost of Production Model for Genomatica Direct Sugar Fermentation to BDO, Asia.....	66
4.22 Cost of Production Model for BDO Production via Bio-Succinic Acid Route, Asia .....	67

4.23	Cost of Production Model for BDO Production via PHA Polymerization Route, Asia .....	68
4.24	Cost of Production Model for LanzaTech's CO Fermentation to BDO, Asia .....	69
5.1	Project Scoring Methodology .....	74
5.2	Calculation Chart for Capacity Factor .....	75
5.3	BioAmber Project Scoring (Sarnia, Ontario) .....	78
5.4	BioAmber Project Scoring (North America, 2017).....	79
5.5	BioAmber Project Scoring (2022).....	79
5.6	Myriant Project Scoring .....	80
5.7	BASF Project Scoring.....	80
5.8	Genomatica Project Scoring.....	81
5.9	LanzaTech Project Scoring .....	81
5.10	Announced Bio-BDO Capacity .....	82
5.11	Adjusted Bio-BDO Capacity .....	82
6.1	CO/Syngas Fermentation to BDO Comparative Economics.....	85
6.2	Direct Fermentation to BDO Comparative Economics.....	85
7.1	Key Global Granted Patents.....	89
7.2	Key North American Granted Patents .....	90
7.3	All North American Granted Patents .....	91
7.4	List of All European Granted Patents .....	94
7.5	List of All Asian Granted Patents .....	95
7.6	List of All ROW Patents.....	96
7.7	Key Global Patent Applications .....	98
7.8	Key North American Patent Applications .....	99
7.9	All North American Patent Applications .....	100
7.10	Key European Patents .....	105
7.11	All European Patent Applications .....	106
7.12	Key Asian Patent Applications .....	109
7.13	All Asian Patent Applications.....	110
7.14	All ROW Patent Applications.....	118

# NexantThinking™

## Biorenewable Insights



Nexant, Inc. ([www.nexant.com](http://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 .

### Contact Details:

**New York:** Steven Slome

Phone: + 1-914-609-0379, e-mail: [sslome@nexant.com](mailto:sslome@nexant.com)

**New York:** Heidi Junker Coleman, Global Programs Support Manager

Phone: + 1-914-609-0381, e-mail: [hcoleman@nexant.com](mailto:hcoleman@nexant.com)

Nexant, Inc. ([www.nexant.com](http://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. 2015. All Rights Reserved.