

Biorenewable Insights

Adipic Acid

Table of Contents

A Report by NexantThinking™

Published December 2015

www.nexantthinking.com

Section	Page
1 Executive Summary	1
1.1 OVERVIEW AND APPLICATIONS	1
1.2 DRIVERS IMPACTING BIORENEWABLE ADIPIC ACID PRODUCTION	1
1.3 TECHNOLOGY OVERVIEW	2
1.3.1 Rennovia	2
1.3.2 Genomatica	4
1.3.3 Verdezyne	6
1.3.4 BioAmber	8
1.4 ECONOMICS	8
1.5 CAPACITY ANALYSIS	10
1.6 IMPLICATIONS FOR CONVENTIONAL TECHNOLOGY	10
1.7 PATENT ANALYSIS	10
2 Introduction	11
2.1 OVERVIEW AND PROPERTIES	11
2.1.1 Properties	11
2.1.2 Health Hazards	11
2.1.3 Storage and Transportation	11
2.1.4 Applications and Market	12
2.2 ADIPIC ACID APPLICATIONS	12
2.2.1 Polyamide 6,6	12
2.2.2 Polyurethanes	14
2.2.3 Other	15
2.3 CONVENTIONAL TECHNOLOGIES	15

2.3.1	NOx Generation	16
2.4	BIO-BASED ADIPIC ACID DEMAND DRIVERS	17
2.4.1	Sustainability	18
2.4.2	Consumer Desirability and Bio-Based Premiums	18
2.4.3	Feedstock Price Volatility	19
2.4.4	Food versus Fuel/Chemicals.....	19
2.4.5	Emissions Reductions and Tightening Governmental Regulation	20
2.4.6	Chinese Overcapacity and Pricing Implications	20
2.4.7	Development of Novel Bio-Dicarboxylic Acids Targeting Polyamide and Polyurethane Markets	21
3	Technology	22
3.1	CHEMICAL CATALYTIC	22
3.1.1	Rennovia	22
3.2	DIRECT FERMENTATION.....	28
3.2.1	Genomatica GENO™	28
3.2.2	Verdezyne	35
3.3	FERMENTATION AND CATALYSIS	43
3.3.1	BioAmber Inc.....	43
3.4	MINOR DEVELOPERS	48
3.4.1	Joule Unlimited	48
3.4.2	INVISTA	48
4	Economics	49
4.1	METHODOLOGY	49
4.1.1	Sources	49
4.1.2	Capital Cost Elements.....	49
4.1.3	Operating Cost Elements	53
4.2	COST OF PRODUCTION ESTIMATES.....	56
4.2.1	Rennovia	56
4.2.2	Genomatica	58
4.2.3	Verdezyne	60
4.2.4	By Region	62
4.2.5	By Process	64
4.3	SENSITIVITY ANALYSIS.....	66
5	Capacity Analysis	69
5.1	OVERVIEW AND METHODOLOGY	69

5.1.1	Types of Developments Considered	69
5.1.2	Capacity Analysis Methodology	69
5.2	EXISTING CAPACITY.....	73
5.3	PROJECTS	73
5.3.1	Rennovia	73
5.3.2	Genomatica	74
5.4	CONCLUSIONS	74
5.4.1	Unadjusted Capacities	74
5.4.2	Risk-Adjusted Capacities	75
6	Implications for Conventional Technology	77
6.1	SCALE AND MARKET PENETRATION	77
6.2	PRICES AND MARGINS.....	78
6.3	STRATEGIC IMPLICATIONS	80
7	Patent Analysis.....	81
7.1	OVERVIEW	81
7.1.1	Types of Patents Considered	81
7.1.2	Overall Patent Activity by Region	81
7.2	GRANTED PATENTS	82
7.2.1	Global	82
7.2.2	North America	84
7.2.3	Asia Pacific.....	87
7.2.4	Europe	88
7.3	PATENT APPLICATIONS	90
7.3.1	Global	90
7.3.2	North America	92
7.3.3	Asia Pacific.....	98
7.3.4	Europe.....	104
7.3.5	ROW.....	106
8	References	108

Appendix	Page
A Cost of Production Estimates (Other Regions)	A-1

Figure	Page
1.1 Structure of Adipic Acid	1
1.2 Synthesis of Adipic Acid via Glucaric Acid	2
1.3 Rennovia Block Flow Diagram	3
1.4 Genomatica Block Flow Diagram	5
1.5 Verdezyne Block Flow Diagram	7
1.6 Regional Economic Comparison by Process	9
1.7 Economic Comparison by Region	9
1.8 Overall Patent Activity by Region	10
2.1 Structure of Adipic Acid	11
2.2 Molecular Structure of Polyamide 6 and Polyamide 6,6	13
2.3 Polyamide 6,6 Value Chain	14
2.4 Illustration of a Polyurethane Systems House	14
2.5 Routes to Adipic Acid	16
2.6 United States Historical Corn and Crude Prices	19
2.7 Regional Distribution of Conventional Capacity, 2015	20
2.8 Adipic Acid Prices	21
3.1 Synthesis of Adipic Acid via Glucaric Acid	23
3.2 Oxidation of Glucose to Glucaric Acid	23
3.3 Hydrodeoxygenation of Glucaric Acid to Adipic Acid	25
3.4 Rennovia Block Flow Diagram	26
3.5 Pathways for Adipic Acid Production	30
3.6 Genomatica Block Flow Diagram	32
3.7 β -Oxidation of Fatty Acids	37
3.8 Fatty Acid Structure	37
3.9 Carbonization and Fatty Acid Synthesis	38
3.10 ω -Oxidation of Hexanoic Acid	38
3.11 Verdezyne Block Flow Diagram	40
3.12 Glycolysis Pathway	45
3.13 TCA Cycle to (R)-Homocitrate	46
3.14 Catalytic Routes from Homocitrate to Adipate	47
4.1 North American Comparative Economics	62
4.2 South American Comparative Economics	63
4.3 Comparative Economics	63
4.4 Comparative Economics	64

4.5	Rennovia Regional Economic Comparison.....	65
4.6	Genomatica Regional Economic Comparison	65
4.7	Verdezyne Regional Economic Comparison.....	66
4.8	Sensitivity to Feedstock Price	67
4.9	Sensitivity to Operating Rate.....	67
4.10	Capital Cost Sensitivity.....	68
5.1	Risk Adjustment Methodology.....	72
5.2	Announced Bio-Adipic Acid Capacity.....	75
5.3	Risk-Adjusted Bio-Adipic Acid Capacity.....	76
6.1	Conventional versus Bio - Adipic Acid Capacity	78
6.2	Adipic Acid Prices and Cost of Production(6,7,8)	79
6.3	Margins and Returns for Bio-Adipic Acid Developers	80
7.1	Patent Activity over Time.....	81
7.2	Overall Patent Activity by Region	82
7.3	Granted Patents by Region	83
7.4	Granted Patents by Assignee.....	83
7.5	Breakdown of North American Granted Patents by Assignee	84
7.6	Asia Pacific Granted Patents by Assignee	87
7.7	European Granted Patents by Assignee	88
7.8	Global Patent Applications by Region	90
7.9	Global Patent Applications by Assignee	91
7.10	North American Patent Applications by Assignee.....	92
7.11	Asia Pacific Patent Applications by Assignee	98
7.12	European Patent Applications by Assignee	104
7.13	ROW Patent Applications by Assignee	107

Table	Page
2.1 Physical Properties of Adipic Acid	11
2.2 Typical Molecular Structure and Physical Properties of Polyester Polyols	15
3.1 Adipic Acid Pathway Stoichiometry	31
4.1 Rennovia Cost of Production Estimate, USGC	57
4.2 Genomatica Cost of Production Estimate, USGC	59
4.3 Verdezyne Cost of Production Estimate, USGC	61
5.1 Project Scoring Methodology	69
5.2 Calculation Chart for Capacity Factor	70
5.3 Rennovia Commercial Facility Project Scoring	73
5.4 Genomatica Commercial Facility Project Scoring	74
5.5 Announced Bio-Adipic Acid Capacity	75
5.6 Risk-Adjusted Bio-Adipic Acid Capacity	75
7.1 Key Global Granted Patents	84
7.2 Key North American Granted Patents	85
7.3 North American Granted Patents	85
7.3 North American Granted Patents	86
7.4 Key Asia Pacific Granted Patents	87
7.5 Asia Pacific Granted Patents	88
7.6 European Granted Patents	89
7.7 Key Global Patent Applications	91
7.8 Key North American Patent Applications	93
7.9 Canadian Patent Applications	94
7.10 Mexican Patent Applications	95
7.11 United States Patent Applications	95
7.12 Key Asia Pacific Patent Applications	98
7.13 Australian Patent Applications	99
7.14 Chinese Patent Applications	100
7.15 Japanese Patent Applications	102
7.16 Other Asia Pacific Patent Applications	102
7.17 Key European Patent Applications	105
7.18 European Patent Office Patent Applications	105
7.19 Other European Patent Applications	106
7.20 All ROW Patent Applications	107

NexantThinking™

Biorenewable Insights



Nexant, Inc. (www.nexantthinking.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. 2015. All Rights Reserved.