

**TECHNOLOGY & COSTS**

**Biorenewable Insights**

# Hydrogen

## Table of Contents

A Report by **Nexant, Inc.**

Published Date: April 2020

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

## Contents

1	Executive Summary .....	1
1.1	Overview.....	1
1.2	Introduction.....	1
1.3	Technology.....	2
1.4	Economics.....	3
1.5	Implications for the Conventional Technology .....	4
2	Introduction.....	6
2.1	Overview.....	6
2.1.1	End Uses.....	6
2.1.2	Supply Sources .....	10
3	Technology.....	12
3.1	Overview.....	12
3.1.1	Chlor-alkali .....	12
3.2	Conventional Routes to Hydrogen and Potential for Biobased Substitution .....	14
3.2.1	Reforming.....	14
3.2.2	Gasification.....	24
3.2.3	Conventional Electrolysis .....	32
3.3	Developing Processes.....	35
3.3.1	Electrolytic Processes .....	35
3.3.2	Photocatalytic Water Splitting and Artificial Photosynthesis .....	37
3.3.3	Thermocatalytic Processes .....	50
3.3.4	Mechano-catalytic Water Splitting.....	56
3.3.5	Biological Processes .....	58
3.3.6	Other Developments .....	64
3.4	Conclusions.....	64
4	Economics.....	65
4.1	Economic Analysis Methodology .....	65
4.1.1	Sources .....	65
4.1.2	Costing Basis .....	65

4.1.3	Capital Cost Elements.....	65
4.1.4	Operating Cost Elements .....	69
4.1.5	Market Prices .....	72
4.2	Cost of Production (COP) Estimates.....	73
4.2.1	Biogas Reforming.....	74
4.2.2	Biomass Gasification.....	83
4.2.3	Electrolysis .....	90
4.3	Comparative Economics .....	95
4.3.1	Process Competitiveness within a Region .....	95
4.3.2	Regional Competitiveness of Each Process .....	98
5	Capacity Additions.....	101
5.1	Overview.....	101
5.2	Announced Projects .....	102
5.2.1	Biogas Projects .....	102
5.2.2	Electrolysis Projects .....	103
6	Implications.....	106
6.1	Scale and Market Penetration.....	106
6.2	Market Pull and End Uses.....	106
6.2.1	Global Hydrogen Demand.....	106
6.2.2	Global Hydrogen Supply .....	108
6.2.3	Current Hydrogen Station Infrastructure Status .....	110
6.3	Logistics Requirements.....	113
6.3.1	Liquefaction Plants.....	113
6.3.2	Liquid and Gas Terminals .....	115
6.3.3	Hydrogen Delivery Pathways to Refueling Station .....	116
6.3.4	New Developments in Hydrogen Infrastructure .....	123
6.4	Policy Support .....	124
6.4.2	Norway .....	128
6.4.3	China .....	128
6.4.4	Japan.....	129
6.4.5	United States.....	129
6.5	Prices and Margins.....	130
6.5.1	Cost of Production at Current Project Scale .....	131
6.6	Strategic Implications .....	133
<b>Appendices</b>		
A	References .....	134

**Figures**

Figure 1	Major End Uses for Hydrogen .....	2
Figure 2	Commercial and Developmental Routes to Renewable Hydrogen .....	3
Figure 3	United States Cost of Production Comparison .....	3
Figure 4	Comparison of Hydrogen Production Technologies at Current Project Scales with 25 Percent Operating Rate .....	5
Figure 5	Hydrogen Consumption for Hydrotreating of Various Refinery Products .....	7
Figure 6	Major End Uses for Hydrogen .....	8
Figure 7	Sources of Hydrogen .....	10
Figure 8	Anatomy of a Simple Refinery .....	11
Figure 9	Commercial and Developmental Routes to Renewable Hydrogen .....	12
Figure 10	Electricity Generation Matrix in the United States .....	13
Figure 11	Relative Carbon Intensities of Power in Different Regions in the United States .....	13
Figure 12	Steam-Methane Reforming .....	15
Figure 13	Block Flow Diagram of Hydrogen via Steam Methane Reforming .....	22
Figure 14	Hydrogen Yield versus Oxygen Content of Various Feedstocks .....	23
Figure 15	Generic Gasification Process Train .....	25
Figure 16	Schematic Diagram of an Updraft Reactor .....	27
Figure 17	Schematic Diagram of a Downdraft Reactor .....	28
Figure 18	Schematic Diagram of BFB Reactor .....	29
Figure 19	Schematic Diagram of CFB Reactor .....	30
Figure 20	Flow Diagram of MSW Processing Using Plasma Gasification .....	30
Figure 21	Diagram of Hydrogen Production via Electrolysis .....	32
Figure 22	Process Flow Diagram of Hydrogen Production via Electrolysis .....	33
Figure 23	Electrolytic Water Splitting with LNBL's Mo-oxo Metal Complex .....	36
Figure 24	PEC Hydrogen Production of TiO <sub>2</sub> /Pt/SiNW Photocathode .....	39
Figure 25	Photosynthesis of Sunlight in Cyanobacteria .....	41
Figure 26	Ruthenium-based Water Oxidation Catalyst Developed by Jülich Institute .....	42
Figure 27	Proposed Photoelectrolysis Mechanism within a Nafion Membrane .....	46
Figure 28	Nafion-Coated Electrode .....	46
Figure 29	ASU Photoelectrochemical Cell for Water Splitting .....	48
Figure 30	Mechanism of the AIST Photocatalyst-electrolysis Hybrid System .....	50
Figure 31	The Generation-2 CR5 Solar Thermochemical Reactor .....	51
Figure 32	Solar Rotary Reactor Configuration Lined with ZnO Particles .....	52
Figure 33	Solar Thermochemical Reactor Configuration with Cerium-oxide Particles .....	53
Figure 34	FSEC Hybrid S-NH <sub>3</sub> Photothermochemical Water-Splitting Cycle .....	55
Figure 35	H <sub>2</sub> and O <sub>2</sub> Produced by Deformation of ZnO Fibers or BaTiO <sub>3</sub> Dendrites in Water .....	58
Figure 36	ORNL Integrated Pyrolysis-Microbial Electrolysis .....	61
Figure 37	Virent's BioForming Process .....	63
Figure 38	Biomass Gasification-derived Hydrogen Production .....	83
Figure 39	United States Cost of Production Comparison .....	95
Figure 40	China Cost of Production Comparison .....	96

Figure 41	Brazil Cost of Production Comparison.....	96
Figure 42	Western Europe Cost of Production Comparison .....	97
Figure 43	Biogas Reforming – Cost of Production Comparison at Small Scale.....	98
Figure 44	Biogas Reforming – Cost of Production Comparison at Large Scale .....	98
Figure 45	Biomass Gasification – Cost of Production Comparison.....	99
Figure 46	Electrolysis – Cost of Production Comparison .....	100
Figure 47	Global Hydrogen Consumption by Region .....	106
Figure 48	U.S. Hydrogen Demand by Application.....	107
Figure 49	Global Hydrogen Demand by Application, 1975-2019 .....	107
Figure 50	Sources of Hydrogen .....	109
Figure 51	Simplified Flow Diagram for Hydrogen Liquefaction Plant .....	114
Figure 52	Liquid Terminal for Use with Liquid Delivery .....	115
Figure 53	Liquid Terminal for Use with Gas Delivery .....	115
Figure 54	Hydrogen Delivery Costs.....	116
Figure 55	Liquid Hydrogen Distribution Scenario – Pathway 1 .....	117
Figure 56	Liquid Hydrogen Distribution Scenario – Pathway 2 .....	118
Figure 57	Liquid Hydrogen Distribution Scenario – Pathway 3 .....	118
Figure 58	Compressed Hydrogen Distribution Scenario – Pathway 4 .....	119
Figure 59	Compressed Hydrogen Distribution Scenario – Pathway 5 .....	119
Figure 60	Compressed Hydrogen Distribution Scenario – Pathway 6 .....	120
Figure 61	Compressed Hydrogen Distribution Scenario – Pathway 7 .....	120
Figure 62	Transmission and Distribution Pipeline Arrangement .....	121
Figure 63	Pipeline Hydrogen Distribution Scenario – Pathway 8.....	121
Figure 64	Pipeline Hydrogen Distribution Scenario – Pathway 9.....	122
Figure 65	Pipeline Hydrogen Distribution Scenario – Pathway 9.....	122
Figure 66	Comparison of Hydrogen Production Technologies at Current Project Scales .....	132
Figure 67	Comparison of Hydrogen Production Technologies at Current Project Scales with 25 Percent Operating Rate.....	132

**Tables**

Table 1	Margins and Returns of Hydrogen Processes at Industrial Scale in all Regions .....	4
Table 2	Comparison of Hydrogen with Other Renewable Fuel Options .....	9
Table 3	Major Syngas Production Technology Holders and Licensors .....	21
Table 4	Typical Metrics of Various Gasifier Types .....	26
Table 5	Hydrogen Yield per Catalyst, Feedstock, and Gasification Reactor Type .....	31
Table 6	Currently Available Industrial Electrolyzer Hydrogen Generators .....	34
Table 7	Market Prices of Hydrogen .....	72
Table 8	Cost of Production Estimate for: Hydrogen by Biogas Reforming, Small Scale .....	75
Table 9	Cost of Production Estimate for: Hydrogen by Biogas Reforming, World Scale .....	76
Table 10	Cost of Production Estimate for: Hydrogen by Biogas Reforming, Small Scale .....	77
Table 11	Cost of Production Estimate for: Hydrogen by Biogas Reforming, World Scale .....	78
Table 12	Cost of Production Estimate for: Hydrogen by Biogas Reforming, Small Scale .....	79
Table 13	Cost of Production Estimate for: Hydrogen by Biogas Reforming, World Scale .....	80
Table 14	Cost of Production Estimate for: Hydrogen by Biogas Reforming, Small Scale .....	81
Table 15	Cost of Production Estimate for: Hydrogen by Biogas Reforming, World Scale .....	82
Table 16	Feedstock Properties and Value .....	84
Table 17	Cold Gas Efficiencies and Product Yield .....	85
Table 18	Cost of Production Estimate for: Hydrogen by Biomass Gasification of Corn Stover .....	86
Table 19	Cost of Production Estimate for: Hydrogen by Biomass Gasification of Corn Stover .....	87
Table 20	Cost of Production Estimate for: Hydrogen by Biomass Gasification of Sugarcane Trash.....	88
Table 21	Cost of Production Estimate for: Hydrogen by Biomass Gasification of Wheat Straw.....	89
Table 22	Cost of Production Estimate for: Hydrogen by Electrolysis.....	91
Table 23	Cost of Production Estimate for: Hydrogen by Electrolysis .....	92
Table 24	Cost of Production Estimate for: Hydrogen by Electrolysis .....	93
Table 25	Cost of Production Estimate for: Hydrogen by Electrolysis .....	94
Table 26	Global Renewable Hydrogen Biogas Projects Announced Capacity Listing .....	101
Table 27	Global Renewable Hydrogen Electrolysis Projects Announced Capacity Listing .....	101
Table 28	Explicit Hydrogen Support Policies by Country .....	125
Table 29	Emission-thresholds for Light Duty Vehicles .....	126
Table 30	Alternative Fuel Requirements for Heavy Duty Vehicles .....	127
Table 31	Minimum Clean Vehicle Procurement Target per Member States and per Vehicle Segment .....	127
Table 32	Margins and Returns of Hydrogen Processes at Industrial Scale in all Regions .....	131
Table 33	LCFS Credits for Renewable Hydrogen Pathways .....	131

# Nexant Inc.

## TECHNOLOGY & COSTS

# Biorenewable Insights

The Nexant 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: Nexant 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, Nexant 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

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. 2020. All Rights Reserved.