

SPECIAL REPORTS

Low Carbon Intensity Hydrogen

Table of Contents

A Report by **NexantECA**, the Energy and Chemical Advisory company

Published Date: April 2023

www.nexanteca.com/subscriptions-and-reports

Contents

1	Executive Summary	1
1.1	Overview.....	1
1.2	Introduction.....	1
1.3	Technology	3
1.3.1	Green Hydrogen.....	4
1.3.2	Nuclear Hydrogen	4
1.3.3	Hydrogen with Fossil Feedstocks	5
1.4	Carbon Intensity	5
1.5	Economics.....	8
1.5.1	Regional Comparative Economics	8
1.6	Strategic Analysis.....	18
1.6.1	Key Insights.....	18
1.6.2	Emission Baselines	20
1.6.3	Value Chain Emissions Reductions	20
1.6.4	Conclusions and Future Trends	24
2	Introduction.....	25
2.1	Overview.....	25
2.2	Drivers	25
2.2.1	The Current Push: Sustainability.....	25
2.2.2	Downstream Industries.....	26
2.3	Increased Focus on Decarbonization.....	27
2.3.1	Reducing GHG Emissions	27
2.3.2	Emphasis on Hydrogen	29
2.4	Different Colors of Hydrogen.....	32
2.4.1	Hydrogen Color Palette	32
2.4.2	Terminology for Hydrogen Technologies	32
2.5	Potential Barriers for Hydrogen Production.....	33
2.6	Hydrogen Grades	33
2.7	Pricing of Hydrogen.....	34

2.8	Hydrogen End-Use Applications	34
2.9	Market Drivers and Challenges	35
3	Technology Analysis	37
3.1	Overview.....	37
3.2	Green Hydrogen	37
3.2.1	Biomass Gasification	38
3.2.2	Conventional Hydrogen Technologies with Renewable Feedstocks	41
3.2.3	Electrolysis	52
3.2.4	Photocatalytic Water Splitting	62
3.2.5	Thermocatalytic Processes	64
3.2.6	Biological Processes	72
3.3	Nuclear – Red, Purple, and Pink Hydrogen	74
3.4	Hydrogen with Fossil Feedstocks	75
3.4.1	Overview	75
3.4.2	Blue Hydrogen.....	76
3.4.3	Turquoise Hydrogen.....	78
3.5	Other Colors of Hydrogen	82
3.5.1	White Hydrogen.....	82
3.5.2	Yellow Hydrogen	82
3.5.3	Gold Hydrogen	82
4	Carbon Intensity Analysis.....	83
4.1	Methodology	83
4.1.1	Generic Nature of This Analysis.....	83
4.1.2	Carbon Intensity Methodology	83
4.2	Carbon Intensity Model Inputs	86
4.2.1	Raw Material Emission Factors.....	86
4.2.2	Utility Emission Factors	86
4.3	Carbon Intensity Model Results	88
4.3.1	Overview	88
4.3.2	Overall	88
4.3.3	United States.....	91
4.3.4	China	93
4.3.5	Brazil.....	94
4.3.6	Western Europe	95
5	Economic Analysis	96
5.1	Methodology	96
5.1.1	Sources	96
5.1.2	Costing Basis	96
5.1.3	Capital Cost Elements.....	96
5.1.4	Operating Cost Elements	100
5.2	Key Inputs	103
5.2.1	Key modelling Considerations.....	103

5.2.2	Prices	105
5.3	Comparative Economics	106
5.3.1	United States	106
5.3.2	China	108
5.3.3	Brazil.....	111
5.3.4	Western Europe	113
5.4	Cost of Production Models	116
5.5	Ranges of LCOH	131
6	Strategic Analysis	132
6.1	Key Insights	132
6.2	High Level Insights by Technology	134
6.2.1	Electrolysis	134
6.2.2	SMR and ATR	134
6.2.3	Methane Pyrolysis	135
6.2.4	Biomass Gasification	135
6.3	Carbon Intensity Reduction Value Scenarios.....	136
6.3.1	Emission Baselines	136
6.3.2	Value Chain Emissions Reductions	139
6.3.3	Value Chain Carbon Equivalent Values for Economic Breakeven	149
6.4	Conclusions and Future Trends	159
 Appendices		
A	References	161

Figures

Figure 1	Routes to Hydrogen.....	3
Figure 2	Routes to Green Hydrogen.....	4
Figure 3	Routes to Pink, Purple, and Red Hydrogen	4
Figure 4	Routes to Grey, Brown, and Black Hydrogen.....	5
Figure 5	Routes to Blue Hydrogen	5
Figure 6	Route to Turquoise Hydrogen	5
Figure 7	Overall Comparative Carbon Intensities of Low CI Hydrogen.....	6
Figure 8	U.S. Hydrogen Comparative Economics	8
Figure 9	China Hydrogen Comparative Economics	10
Figure 10	Brazil Hydrogen Comparative Economics	13
Figure 11	Western Europe Hydrogen Comparative Economics.....	15
Figure 12	Regional Emissions Baselines	20
Figure 13	Overall Scope 1 Emission Reductions	21
Figure 14	Overall Scope 1 and 2 Breakevens	22
Figure 15	Overall Scope 1, 2, and 3 Breakevens.....	23
Figure 16	Emissions from the Chemical Industry	26
Figure 17	Focus on Energy Transition.....	28
Figure 18	Share of Total Final Energy Consumption in “Net-Zero” Emissions Scenario	30
Figure 19	Sources of Hydrogen Production in “Net-Zero” Emissions Scenario	31
Figure 20	Mitigation Measures in “Net-Zero” Emissions Scenario	31
Figure 21	Major End Use Applications for Hydrogen	35
Figure 22	Routes to Hydrogen.....	37
Figure 23	Routes to Green Hydrogen.....	38
Figure 24	Generic Gasification Process Train	40
Figure 25	Steam-Methane Reforming	42
Figure 26	Block Flow Diagram of Hydrogen via Steam Methane Reforming	50
Figure 27	Hydrogen Yield versus Oxygen Content of Various Feedstocks	51
Figure 28	Diagram of Hydrogen Production via Electrolysis ⁰	52
Figure 29	Electrolyzer Module with (a) Unipolar and (b) Bipolar Cell Configurations ⁰	53
Figure 30	Alkaline, PEM, and SOEC Electrolyzer Configurations.....	54
Figure 31	Process Flow Diagram of Hydrogen Production via Electrolysis ⁰	59
Figure 32	Schematic Diagram of Operating PEC Cell Using Photoanode	63
Figure 33	The Generation-2 CR5 Solar Thermochemical Reactor ⁰	67
Figure 34	Solar Rotary Reactor Configuration Lined with ZnO Particles ⁰	68
Figure 35	Solar Thermochemical Reactor Configuration with Cerium-oxide Particles ⁰	69
Figure 36	FSEC Hybrid S-NH ₃ Photothermochemical Water-Splitting Cycle ⁰	71
Figure 37	Routes to Pink, Purple, and Red Hydrogen	74
Figure 38	Routes to Grey, Brown, and Black Hydrogen.....	75
Figure 39	Routes to Blue Hydrogen	76
Figure 40	Conventional Pathway for Blue Hydrogen.....	77
Figure 41	Route to Turquoise Hydrogen	78

Figure 42	Histogram of Several Methane Pyrolysis Projects	79
Figure 43	Range of Methane Pyrolysis Process Technologies	81
Figure 44	Definitions of Scope Emissions	83
Figure 45	Process Carbon Balance	84
Figure 46	Equation for Raw Material Emissions.....	85
Figure 47	Equation for Utility Emissions	86
Figure 48	Overall Comparative Carbon Intensities of Low CI Hydrogen.....	89
Figure 49	U.S. Comparative Carbon Intensities of Low CI Hydrogen	91
Figure 50	China Comparative Carbon Intensities of Low CI Hydrogen.....	93
Figure 51	Brazil Comparative Carbon Intensities of Low CI Hydrogen	94
Figure 52	Western Europe Comparative Carbon Intensities of Low CI Hydrogen	95
Figure 53	U.S. Hydrogen Comparative Economics	106
Figure 54	China Hydrogen Comparative Economics	108
Figure 55	Brazil Hydrogen Comparative Economics	111
Figure 56	Western Europe Hydrogen Comparative Economics.....	113
Figure 57	Regional Emissions Baselines	136
Figure 58	U.S. Hydrogen Supply by Type	137
Figure 59	China Hydrogen Supply by Type.....	137
Figure 60	Brazil Hydrogen Supply by Type	138
Figure 61	Western Europe Hydrogen Supply by Type	138
Figure 62	Overall Scope 1 Emission Reductions	139
Figure 63	U.S.'s Hydrogen Scope 1 Emissions Reductions.....	140
Figure 64	China's Hydrogen Scope 1 Emissions Reductions	141
Figure 65	Brazil's Hydrogen Scope 1 Emissions Reductions.....	141
Figure 66	Western Europe's Hydrogen Scope 1 Emissions Reductions	142
Figure 67	Overall Scope 1 and 2 Emission Reductions	143
Figure 68	U.S.'s Hydrogen Scope 1 and 2 Emissions Reductions.....	144
Figure 69	China's Hydrogen Scope 1 and 2 Emissions Reductions	144
Figure 70	Brazil's Hydrogen Scope 1 and 2 Emissions Reductions	145
Figure 71	Western Europe's Hydrogen Scope 1 and 2 Emissions Reductions	145
Figure 72	Overall Scope 1, 2, and 3 Emission Reductions	146
Figure 73	U.S.'s Hydrogen Scope 1, 2, and 3 Emissions Reductions	147
Figure 74	China's Hydrogen Scope 1, 2, and 3 Emissions Reductions	147
Figure 75	Brazil's Hydrogen Scope 1, 2, and 3 Emissions Reductions	148
Figure 76	Western Europe's Hydrogen Scope 1, 2, and 3 Emissions Reductions	148
Figure 77	Overall Scope 1 Breakevens.....	149
Figure 78	U.S.'s Hydrogen Scope 1 Breakevens	150
Figure 79	China's Hydrogen Scope 1 Breakevens.....	151
Figure 80	Brazil's Hydrogen Scope 1 Breakevens	151
Figure 81	Western Europe's Hydrogen Scope 1 Breakevens	152
Figure 82	Overall Scope 1 and 2 Breakevens	152
Figure 83	U.S.'s Hydrogen Scope 1 and 2 Breakevens	153
Figure 84	China's Hydrogen Scope 1 and 2 Breakevens.....	154

Figure 85	Brazil's Hydrogen Scope 1 and 2 Breakevens	154
Figure 86	Western Europe's Hydrogen Scope 1 and 2 Breakevens	155
Figure 87	Overall Scope 1, 2, and 3 Breakevens	155
Figure 88	U.S.'s Hydrogen Scope 1, 2, and 3 Breakevens	157
Figure 89	China's Hydrogen Scope 1, 2, and 3 Breakevens	157
Figure 90	Brazil's Hydrogen Scope 1, 2, and 3 Breakevens	158
Figure 91	Western Europe's Hydrogen Scope 1, 2, and 3 Breakevens	158

Tables

Table 1	Overall Comparative Carbon Intensities of Low CI Hydrogen	7
Table 2	U.S. Electrolysis Hydrogen Comparative Economics	9
Table 3	U.S. Other Green Hydrogen Comparative Economics	9
Table 4	U.S. Turquoise Hydrogen Comparative Economics	9
Table 5	U.S. Blue Hydrogen Comparative Economics	10
Table 6	U.S. Grey and Black Hydrogen Comparative Economics	10
Table 7	Electrolysis Hydrogen Comparative Economics China	11
Table 8	Other Green Hydrogen Comparative Economics China	11
Table 9	Turquoise Hydrogen Comparative Economics China	11
Table 10	Blue Hydrogen Comparative Economics China	12
Table 11	Grey and Black Hydrogen Comparative Economics China	12
Table 12	Electrolysis Hydrogen Comparative Economics Brazil	13
Table 13	Other Green Hydrogen Comparative Economics Brazil	14
Table 14	Turquoise Hydrogen Comparative Economics Brazil	14
Table 15	Blue Hydrogen Comparative Economics Brazil	14
Table 16	Grey and Black Hydrogen Comparative Economics Brazil	15
Table 17	Electrolysis Hydrogen Comparative Economics Western Europe	16
Table 18	Other Green Hydrogen Comparative Economics Western Europe	16
Table 19	Turquoise Hydrogen Comparative Economics Western Europe	16
Table 20	Blue Hydrogen Comparative Economics Western Europe	17
Table 21	Grey and Black Hydrogen Comparative Economics Western Europe	17
Table 22	Regional Emissions Baselines	20
Table 23	Overall Scope 1 Breakevens	21
Table 24	Overall Scope 1 and 2 Breakevens	22
Table 25	Overall Scope 1, 2, and 3 Breakevens	23
Table 26	Key Hydrogen Structural Market Parameters	36
Table 27	Typical Metrics of Various Gasifier Types	41
Table 28	Major Syngas Production Technology Holders and Licensors	49
Table 29	The Advantages and Disadvantages of Different Electrolysis Technologies	55
Table 30	Currently Available AEM and PEM Industrial Electrolyzer Hydrogen Generators	57
Table 31	Global Renewable Power Generation by Region	62
Table 32	Global Weighted Average Levelized Cost of Electricity	62

Table 33	Examples of Photocatalyst Performance	63
Table 34	Summary of Methane Pyrolysis Commercialization	79
Table 35	Summary of Range of Process Technologies	81
Table 36	Raw Material Emission Factors	86
Table 37	Utility Emission Factors for all Regions	87
Table 38	Grid Energy Mix across all Regions	88
Table 39	Overall Comparative Carbon Intensities of Low CI Hydrogen.....	90
Table 40	U.S. Comparative Carbon Intensities of Low CI Hydrogen	92
Table 41	China Comparative Carbon Intensities of Low CI Hydrogen.....	93
Table 42	Brazil Comparative Carbon Intensities of Low CI Hydrogen	94
Table 43	Western Europe Comparative Carbon Intensities of Low CI Hydrogen	95
Table 44	Primary Raw Material Costs	105
Table 45	Other Prices.....	105
Table 46	U.S. Electrolysis Hydrogen Comparative Economics.....	106
Table 47	U.S. Other Green Hydrogen Comparative Economics.....	107
Table 48	U.S. Turquoise Hydrogen Comparative Economics.....	107
Table 49	U.S. Blue Hydrogen Comparative Economics.....	107
Table 50	U.S. Grey and Black Hydrogen Comparative Economics	108
Table 51	Electrolysis Hydrogen Comparative Economics China	109
Table 52	Other Green Hydrogen Comparative Economics China	109
Table 53	Turquoise Hydrogen Comparative Economics China	109
Table 54	Blue Hydrogen Comparative Economics China	110
Table 55	Grey and Black Hydrogen Comparative Economics China.....	110
Table 56	Electrolysis Hydrogen Comparative Economics Brazil.....	111
Table 57	Other Green Hydrogen Comparative Economics Brazil.....	112
Table 58	Turquoise Hydrogen Comparative Economics Brazil.....	112
Table 59	Blue Hydrogen Comparative Economics Brazil.....	112
Table 60	Grey and Black Hydrogen Comparative Economics Brazil	113
Table 61	Electrolysis Hydrogen Comparative Economics Western Europe	114
Table 62	Other Green Hydrogen Comparative Economics Western Europe.....	114
Table 63	Turquoise Hydrogen Comparative Economics Western Europe.....	114
Table 64	Blue Hydrogen Comparative Economics Western Europe	115
Table 65	Grey and Black Hydrogen Comparative Economics Western Europe	115
Table 66	Cost of Production Estimate for Green Hydrogen via RNG SMR	116
Table 67	Cost of Production Estimate for Green Hydrogen via RNG ATR	117
Table 68	Cost of Production Estimate for Green-Blue Hydrogen via RNG SMR.....	118
Table 69	Cost of Production Estimate for Green-Blue Hydrogen via RNG ATR.....	119
Table 70	Cost of Production Estimate for Green Hydrogen via Corn Stover Gasification	120
Table 71	Cost of Production Estimate for Green Hydrogen via PEM Electrolysis	121
Table 72	Cost of Production Estimate for Green Hydrogen via Alkaline Electrolysis	122
Table 73	Cost of Production Estimate for Green Turquoise Hydrogen via RNG Pyrolysis	123
Table 74	Cost of Production Estimate for Turquoise Hydrogen via Natural Gas Methane Pyrolysis	124

Table 75	Cost of Production Estimate for Pink Hydrogen via PEM Electrolysis	125
Table 76	Cost of Production Estimate for Pink Hydrogen via Alkaline Electrolysis	126
Table 77	Cost of Production Estimate for Yellow Hydrogen via PEM Electrolysis.....	127
Table 78	Cost of Production Estimate for Yellow Hydrogen via Alkaline Electrolysis.....	128
Table 79	Cost of Production Estimate for Blue Hydrogen via Natural Gas SMR	129
Table 80	Cost of Production Estimate for Blue Hydrogen via Natural Gas ATR.....	130
Table 81	Ranges of Expected Levelized Costs.....	131
Table 82	Regional Emissions Baselines	136
Table 83	Overall Scope 1 Emission Reductions	140
Table 84	Overall Scope 1 and 2 Emission Reductions	143
Table 85	Overall Scope 1, 2, and 3 Emission Reductions	146
Table 86	Overall Scope 1 Breakevens	149
Table 87	Overall Scope 1 and 2 Breakevens	153
Table 88	Overall Scope 1, 2, and 3 Breakevens	156



SPECIAL REPORTS

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

Contact Details:

Americas:

Marcos Nogueira Cesar, Vice President, Global Subscriptions and Reports

Phone: + 1-914-609-0324, e-mail: mcesar@NexantECA.com

Erica Hill, Client Services Coordinator, Subscriptions and Reports

Phone: + 1-914-609-0386, e-mail: ehill@NexantECA.com

EMEA:

Anna Ibbotson, Vice President, Sales and Marketing

Phone: +44-207-950-1528, aibbotson@NexantECA.com

Asia:

Chommanad Thammanayakatip, Managing Consultant

Phone: +66-2793-4606, email: chommanadt@NexantECA.com

NexantECA Subscriptions and Reports provide clients with comprehensive analytics, forecasts and insights for the chemicals, polymers, energy and cleantech industries. Using a combination of business and technical expertise, with deep and broad understanding of markets, technologies and economics, NexantECA provides solutions that our clients have relied upon for over 50 years.

Copyright © 2000-2023. NexantECA (BVI) Limited. All rights reserved