

**TECHNOLOGY & COSTS****Technoeconomics - Energy & Chemicals (TECH)****TECH 2021S12 Blue Hydrogen**

## Table of Contents

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

Published Date: December 2021

[www.nexanteca.com/subscriptions-and-reports](http://www.nexanteca.com/subscriptions-and-reports)**Contents**

1	Executive Summary .....	1
1.1	Introduction.....	1
1.2	Viable Pathways.....	2
1.3	Technologies and Processes .....	4
1.4	Costs and Techno-Economics .....	7
1.4.1	NexantECA COP Estimates.....	9
1.4.2	Comparative Techno-Economics for LCOH.....	11
1.5	Case Studies .....	13
1.6	Market Roadmap.....	14
1.7	Conclusion.....	15
2	Introduction.....	17
2.1	Objective.....	17
2.1.1	Abstract .....	17
2.1.2	The Main Focus.....	17
2.1.3	Specific Objectives .....	18
2.1.4	Structure of Report .....	18
2.1.5	Approach and Methodology .....	19
2.2	Increased Focus on Decarbonization.....	20
2.2.1	Reducing GHG Emissions.....	20
2.2.2	Emphasis on Hydrogen .....	22
2.3	Different Colors of Hydrogen.....	25
2.4	Potential Barriers for Hydrogen Production.....	26
2.5	Hydrogen Production Costs – A Key Driver .....	27
2.6	Main Drivers for Successful Blue Hydrogen Projects .....	28
2.7	Conclusions .....	28
3	Viable Pathways .....	30
3.1	Overview Pathways and Routes for Low Carbon Hydrogen .....	30
3.1.1	Terminology for Hydrogen Technologies .....	31
3.2	Qualitative Comparison of Grey, Blue, and Green Blue Hydrogen.....	33
3.2.1	Are Grey, Blue, and Green Hydrogen So Different? .....	34
3.2.2	Potential Sensitivities for Blue Versus Green Hydrogen.....	34

	3.2.3 Blue Hydrogen Process Supply/Value Chain.....	35
3.3	Conclusions .....	36
4	Technologies and Processes .....	37
4.1	Basics of Hydrogen .....	37
4.1.1	Production .....	37
4.1.2	Applications .....	37
4.1.3	Physical and Chemical Properties .....	38
4.1.4	Hydrogen Conversions and Equivalents .....	38
4.1.5	Flammability .....	39
4.1.6	Transport and Logistics .....	39
4.1.7	Health Effects .....	39
4.1.8	Safety Considerations .....	40
4.2	Current Technologies for Hydrogen Production.....	40
4.2.1	Background .....	40
4.2.2	Hydrogen - Key Role in Refining.....	40
4.3	Conventional Processes for Blue Hydrogen .....	43
4.3.1	Overview .....	43
4.3.2	Reforming.....	43
4.3.3	Main Difference Between SMR and ATR Process.....	54
4.3.4	Gasification.....	55
4.4	Specific Blue Hydrogen Processes .....	60
4.4.1	Linde AG .....	61
4.4.2	Linde's Definition of Blue Hydrogen .....	61
4.4.3	Linde's Blue Hydrogen and CO <sub>2</sub> Capture Options .....	62
4.4.4	Matheson Gas .....	68
4.4.5	Air Liquide .....	78
4.4.6	Johnson Matthey .....	84
4.5	Challenges in Estimating GHG Emissions .....	85
4.5.1	Overview .....	85
4.5.2	Comparison of Grey Hydrogen and Blue Hydrogen .....	85
4.5.3	Sensitivities of GHG Emissions with Respect to Global Warming Potential .....	88
4.5.4	Key Takeaways .....	90
4.6	Conclusions .....	91
5	Costs and Techno-Economics .....	93
5.1	The Meaning of These Analyses.....	93
5.1.1	Paradigm Shift.....	93
5.1.2	The "Black Box" .....	93
5.2	Industry Approach and Methodology .....	94
5.2.1	Challenges to Analysis .....	94
5.2.2	Quantifying Costs .....	94
5.3	NexantECA's Approach and Methodology .....	95
5.3.1	Overview .....	95
5.3.2	Sources .....	95
5.3.3	Costing Basis .....	95

5.3.4	Investment Basis .....	96
5.3.5	Technologies Covered .....	96
5.3.6	Pricing Basis.....	97
5.3.7	Cost of Production Basis .....	99
5.4	Cost of Production Analysis .....	100
5.4.1	Syngas via SMR.....	100
5.4.2	Syngas via ATR.....	109
5.4.3	Syngas via POX .....	117
5.5	Region-By Region and Process Comparison.....	125
5.5.1	U.S. Gulf Coast .....	125
5.5.2	China .....	127
5.5.3	Western Europe .....	129
5.6	All Regions and Process Comparison.....	131
5.7	Sensitivity Analysis .....	132
5.7.1	Feedstock Price.....	132
5.7.2	Capital Investment.....	134
5.7.3	Plant Capacity/Economy of Scale .....	135
5.8	Industry Approaches and Methodologies.....	137
5.8.1	Technology Providers and Process Licensors .....	137
5.8.2	U.S. DOE/NREL's H <sub>2</sub> A and H <sub>2</sub> FAST .....	137
5.9	Comparative Techno-Economics .....	139
5.9.1	USDOE .....	139
5.9.2	Comparative Techno-Economics for Grey, Blue, Green Hydrogen versus Industry Targets.....	143
5.9.3	Comparative Techno-Economics for Projects with Grey, Blue, and Green Hydrogen.....	145
5.9.4	Key Takeaways .....	148
5.10	Conclusions .....	148
6	Case Studies .....	150
6.1	Overview of Case Studies .....	150
6.2	Linde Group.....	150
6.2.1	Overview and Highlights.....	150
6.2.2	CO <sub>2</sub> Intensity and Avoidance Cost.....	155
6.2.3	Key Takeaways .....	157
6.3	Matheson.....	158
6.3.1	Overview .....	158
6.3.2	CO <sub>2</sub> Recovery from Syngas .....	158
6.3.3	CO <sub>2</sub> Recovery from Furnace Flue Gas .....	158
6.3.4	Matheson's Findings .....	161
6.4	Hydrogen Hubs and Clusters .....	162
6.4.1	H2H Saltend Project - Decarbonizing Chemicals .....	162
6.4.2	H-Vision Initiative.....	164
6.4.3	Hydrogen to Magnum (H <sub>2</sub> M) .....	164
6.4.4	H <sub>2</sub> 1 NoE .....	164
6.5	Air Products .....	164
6.5.1	Overview and Highlights.....	164

6.5.2	"Net-Zero" Hydrogen Energy Complex in Alberta, Canada .....	164
6.5.3	Blue Hydrogen Project in Louisiana and U.S. Gulf Coast.....	166
6.5.4	Other Low Carbon Initiatives.....	170
6.6	Conclusions .....	173
7	Market Roadmap .....	174
7.1	Overview.....	174
7.2	"Deep-Dive" Market Assessment, Trends, and Outlook .....	174
7.3	Hydrogen Supply and Demand .....	174
7.3.1	Current Supply Sources .....	174
7.3.2	Current Demand.....	175
7.3.3	Government Pledges for Demand Versus "Net-Zero" by 2050.....	176
7.3.4	Hydrogen Production and Supply to 2050 .....	177
7.4	Government Support .....	180
7.4.1	Treaties and Protocols Driving Targets.....	180
7.4.2	Overarching Support .....	180
7.5	Hydrogen Policy Overview .....	181
7.6	Blue Hydrogen Projects.....	183
7.6.1	Key Role for Hydrogen Hubs and Clusters .....	183
7.6.2	Scale of Blue Hydrogen Projects .....	185
7.7	Other Key Market Drivers.....	186
7.7.1	Hydrogen Logistics.....	186
7.7.2	Challenges Based on Hydrogen Form .....	186
7.7.3	Hydrogen Quality Considerations .....	188
7.7.4	Certification of Blue Hydrogen .....	189
7.7.5	Challenges with Blue Hydrogen Blending .....	189
7.7.6	Viable Business Models .....	190
7.8	Conclusions .....	190
C.1	Variable Cost.....	199

## Appendices

A	Glossary .....	192
B	Definitions of Capital Cost Terms Used in Process Economics.....	194
C	Definitions of Operating Cost Terms Used in Process Economics .....	199
D	TECH Program Title Index (2011-2021) .....	202
E	References .....	205

## Figures

Figure 1	Different Colors of Hydrogen .....	1
Figure 2	Blue Hydrogen Production with CO <sub>2</sub> Capture Options .....	5
Figure 3	GHG Footprint for Grey Hydrogen, Blue Hydrogen and Fossil Fuels .....	6
Figure 4	Integrated Costs and Techno-Economic-Financial Analysis .....	8
Figure 5	Regional Cost of Production Comparison for Syngas .....	9
Figure 6	Regional Cost of Production Comparison for CO (and CO <sub>2</sub> )/Hydrogen .....	10
Figure 7	Comparative Techno-Economics of Grey, Blue, Green Hydrogen versus Industry Targets.....	11
Figure 8	Comparative Projects for Grey, Blue, and Green Hydrogen .....	12
Figure 14	Overall Grey, Blue, and Green Hydrogen Scenario .....	15
Figure 15	Focus on Energy Transition.....	21
Figure 16	Share of Total Final Energy Consumption in “Net-Zero” Emissions Scenario .....	23
Figure 17	Sources of Hydrogen Production in “Net-Zero” Emissions Scenario .....	24
Figure 18	Mitigation Measures in “Net-Zero” Emissions Scenario .....	25
Figure 19	Different Colors of Hydrogen .....	26
Figure 20	Overview of Various Pathways and Routes for Low Carbon Hydrogen.....	30
Figure 21	Differentiation of Main Hydrogen Pathways .....	32
Figure 22	Potential Sensitivities for Decarbonized Hydrogen Scenario .....	35
Figure 23	Conventional Pathway for Blue Hydrogen.....	36
Figure 24	Basic Process of a Simple Refinery .....	41
Figure 25	Shift to a Complex Refinery.....	42
Figure 26	SMR, ATR and POX Processes for Syngas Production .....	43
Figure 27	Steam-Methane Reforming .....	45
Figure 28	Process Flow Diagram of Hydrogen via Steam Methane Reforming.....	52
Figure 29	Hydrogen Yield versus Oxygen Content of Various Feedstocks .....	53
Figure 30	Gasification Process Flow Diagram.....	57
Figure 31	Linde’s Visual Guide to the Colors of Hydrogen.....	61
Figure 32	Linde’s Blue Hydrogen Production with CO <sub>2</sub> Capture Options .....	63
Figure 33	Linde’s Option 1: Tail Gas CO <sub>2</sub> PSA Unit.....	63
Figure 34	Linde Operated SMR Plant with CO <sub>2</sub> Capture from PSA Tail Gas Unit .....	64
Figure 35	Linde Option 2: Syngas CO <sub>2</sub> PSA Unit.....	64
Figure 36	Linde Option 3: Syngas CO <sub>2</sub> Wash Unit.....	65
Figure 37	Linde Operated SMR Plant with CO <sub>2</sub> Capture via Amine Wash Unit.....	65
Figure 38	Linde Option 4: Flue Gas CO <sub>2</sub> Wash Unit.....	66
Figure 39	Linde Built Reference Plant with Flue Gas CO <sub>2</sub> Wash Unit .....	66
Figure 40	SMR Based Hydrogen Plant with CO <sub>2</sub> Capture .....	69
Figure 41	Amine Scrubbing System for CO <sub>2</sub> Removal from Syngas .....	72
Figure 42	Amine Scrubbing Unit for CO <sub>2</sub> Removal from Flue Gas .....	75
Figure 43	Typical Air Liquide Hydrogen Plant .....	79
Figure 44	Typical Air Liquide SMR Unit with Food Grade CO <sub>2</sub> Tanks .....	79
Figure 45	Relationship Between Hydrogen Produced and ROG/Natural Gas Ratio .....	81

Figure 46	Variation of Fuel Supplied to Furnace .....	82
Figure 47	Temperature Profile of Pre-reforming Process.....	83
Figure 48	GHG Footprint for Grey Hydrogen, Blue Hydrogen and Fossil Fuels .....	87
Figure 49	Integrated Costs and Techno-Economic-Financial Analysis .....	94
Figure 50	Cost of Production Comparison for Syngas (3:1) via SMR .....	101
Figure 51	Cost of Production Comparison for CO (and CO <sub>2</sub> )/Hydrogen via 3:1 Syngas from SMR .....	102
Figure 52	Cost of Production Comparison for Syngas (2:1) via ATR .....	109
Figure 53	Cost of Production Comparison for CO (and CO <sub>2</sub> )/Hydrogen via 2:1 Syngas from ATR.....	110
Figure 54	Cost of Production Comparison for Syngas (1.7:1) via POX .....	117
Figure 55	Cost of Production Comparison for CO (and CO <sub>2</sub> )/Hydrogen via 1.7:1 Syngas from POX .....	118
Figure 56	Cost of Production Comparision for Syngas, USGC .....	125
Figure 57	Cost of Production Comparison for CO (and CO <sub>2</sub> )/Hydrogen, USGC .....	126
Figure 58	Cost of Production Comparision for Syngas, China .....	127
Figure 59	Cost of Production Comparison for CO (and CO <sub>2</sub> )/Hydrogen, China .....	128
Figure 60	Cost of Production Comparision for Syngas, Western Europe .....	129
Figure 61	Cost of Production Comparison for CO (and CO <sub>2</sub> )/Hydrogen, Western Europe.....	130
Figure 62	Regional Cost of Production Comparison for Syngas .....	131
Figure 63	Regional Cost of Production Comparison for CO (and CO <sub>2</sub> )/Hydrogen .....	131
Figure 64	Sensitivity to Feedstock Price of Syngas Production via SMR versus MSWG .....	133
Figure 65	Sensitivity to Feedstock Price of CO (and CO <sub>2</sub> )/Hydrogen Production via SMR versus MSWG.....	133
Figure 66	Sensitivity to Capital Investment of Syngas Production via SMR versus MSWG .....	134
Figure 67	Sensitivity to Capital Investment of CO (and CO <sub>2</sub> )/Hydrogen Production via SMR versus MSWG.....	135
Figure 68	Sensitivity to Economy of Scale of Syngas Production via SMR versus MSWG .....	136
Figure 69	Sensitivity to Economy of Scale of CO (and CO <sub>2</sub> )/Hydrogen Production via SMR versus MSWG.....	136
Figure 70	Overview of U.S. DOE's H <sub>2</sub> A TEA.....	138
Figure 71	LCOH for SMR and ATR (via Natural Gas) versus POX (via Coal) .....	142
Figure 72	CO <sub>2</sub> Intensity for SMR and ATR (via Natural Gas) versus POX (via Coal).....	143
Figure 73	Comparative Techno-Economics of Grey, Blue, Green Hydrogen versus Industry Targets.....	144
Figure 74	Comparative Projects for Grey, Blue, and Green Hydrogen .....	146
Figure 75	Linde's Plant Configuration.....	151
Figure 76	Linde's SMR Plant without CO <sub>2</sub> Capture.....	151
Figure 77	Linde's SMR Plant with CO <sub>2</sub> Capture.....	152
Figure 78	Linde's SMR Plant with CO <sub>2</sub> Capture from Flue Gas .....	152
Figure 79	Linde's ATR Plant Combined with GHR with CO <sub>2</sub> Capture.....	153
Figure 80	Linde's POX Plant with CO <sub>2</sub> Capture .....	154
Figure 81	Blue Hydrogen Plant and Biofuel Plant with CO <sub>2</sub> Recovery (Source: Matheson) .....	159

Figure 82	Blue Hydrogen Plant and Biofuel Plant with CO <sub>2</sub> Recovery (Prior to Flue Gas Stack).....	160
Figure 83	H2H Saltend Project, UK .....	163
Figure 84	Air Products “Net-Zero” Hydrogen Energy Complex .....	165
Figure 85	Air Product Large-Scale Blue Hydrogen Complex in U.S. Gulf Coast .....	167
Figure 86	Air Products Blue Hydrogen Delivery in U.S. Gulf Coast .....	168
Figure 87	Routing of Air Products Blue Hydrogen Pipeline in U.S. Gulf Coast.....	168
Figure 88	Cross-Section of Proposed Carbon Sequestration Plan .....	169
Figure 89	NEOM Location Map in Saudi Arabia.....	170
Figure 90	Air Products Hybrid Low Carbon Products Process and Distribution.....	171
Figure 91	Air Products Hybrid Green/Blue Hydrogen in Saudi Arabia .....	171
Figure 92	Air Products Supply/Value Chain for Ammonia-Hydrogen .....	172
Figure 93	Air Products Ammonia based HRS .....	172
Figure 94	Agreement Structure for Ammonia-HRS .....	172
Figure 95	Current Sources of Hydrogen Supply.....	175
Figure 96	Aggregate Hydrogen Demand Growth by Sector.....	176
Figure 97	Multilateral Government Announced Pledges versus “Net-Zero” Emissions by 2050 .....	177
Figure 98	Overall Grey, Blue, and Green Hydrogen Scenario .....	179
Figure 99	UK's Largest Hubs and Clusters by Industrial Emissions .....	184
Figure 100	Announced Low Carbon Hydrogen Projects in Europe.....	185

## Tables

Table 1	Qualitative Comparison of Grey, Blue, and Green Hydrogen .....	3
Table 2	Qualitative Comparison of Grey, Blue, and Green Hydrogen .....	33
Table 3	Liquid Hydrogen's Physical and Chemical Properties.....	38
Table 4	Major Syngas Production Technology Holders and Licensors.....	51
Table 5	Major Refinery Gasification/POX Unit .....	55
Table 6	Raw Syngas Characteristics.....	58
Table 7	Technical Evaluation of Linde's Process Options .....	67
Table 8	Economic Evaluation of Linde's Process Options .....	67
Table 9	Summary of Key Streams in CO <sub>2</sub> Recovery from Syngas .....	73
Table 10	Cost of Energy Usage for Large SMR Based Hydrogen Plant.....	76
Table 11	Standard Industry CO <sub>2</sub> Pipeline Specifications .....	78
Table 12	Typical Conditions for ROG Streams .....	80
Table 13	Comparison of GHG Emissions for Grey Hydrogen and Blue Hydrogen.....	86
Table 14	Sensitivities of GHG Emissions for Grey Hydrogen and Blue Hydrogen versus Natural Gas.....	89
Table 15	Sensitivities of GHG Emissions for Blue Hydrogen.....	90
Table 16	Typical Characteristic Syngas Compositions Based on Natural Gas Feedstock.....	97
Table 17	Prices for Raw Materials, Utilities, and Wages.....	98
Table 18	Syngas Plants Modeled.....	100
Table 19	Cost of Production Summary for Syngas (3:1) via SMR .....	101
Table 20	Cost of Production Summary for CO (and CO <sub>2</sub> )/Hydrogen via 3:1 Syngas from SMR .....	102
Table 21	Cost of Production Estimate for: Syngas (3:1) Process: SMR, USGC .....	103
Table 22	Cost of Production Estimate for: CO (and CO <sub>2</sub> ) and Hydrogen Process: Cryogenic Separation of 3:1 Syngas from SMR and PSA, USGC.....	104
Table 23	Cost of Production Estimate for: Syngas (3:1) Process: SMR, China .....	105
Table 24	Cost of Production Estimate for: CO (and CO <sub>2</sub> ) and Hydrogen Process: Cryogenic Separation of 3:1 Syngas from SMR and PSA, China.....	106
Table 25	Cost of Production Estimate for: Syngas (3:1) Process: SMR, Western Europe.....	107
Table 26	Cost of Production Estimate for: CO (and CO <sub>2</sub> ) and Hydrogen Process: Cryogenic Separation of 3:1 Syngas from SMR and PSA, Western Europe.....	108
Table 27	Cost of Production Summary for Syngas (2:1) via ATR .....	109
Table 28	Cost of Production Summary for CO (and CO <sub>2</sub> )/Hydrogen via 2:1 Syngas from ATR.....	110
Table 29	Cost of Production Estimate for: Syngas (2:1) Process: ATR, USGC .....	111
Table 30	Cost of Production Estimate for: CO (and CO <sub>2</sub> ) and Hydrogen Process: Cryogenic Separation of 2:1 Syngas from ATR and PSA, USGC .....	112
Table 31	Cost of Production Estimate for: Syngas (2:1) Process: ATR, China .....	113

Table 32	Cost of Production Estimate for: CO (and CO <sub>2</sub> ) and Hydrogen Process: Cryogenic Separation of 2:1 Syngas from ATR and PSA, China .....	114
Table 33	Cost of Production Estimate for: Syngas (2:1) Process: ATR, Western Europe .....	115
Table 34	Cost of Production Estimate for: CO (and CO <sub>2</sub> ) and Hydrogen Process: Cryogenic Separation of 2:1 Syngas from ATR and PSA, Western Europe.....	116
Table 35	Cost of Production Summary for Syngas (1.7:1) via POX .....	117
Table 36	Cost of Production Summary for CO (and CO <sub>2</sub> )/Hydrogen via 1.7:1 Syngas from POX.....	118
Table 37	Cost of Production Estimate for: Syngas (1.7:1) Process: POX, USGC.....	119
Table 38	Cost of Production Estimate for: CO (and CO <sub>2</sub> ) and Hydrogen Process: Cryogenic Separation of 1.7:1 Syngas from POX and PSA, USGC .....	120
Table 39	Cost of Production Estimate for: Syngas (1.7:1) Process: POX, China.....	121
Table 40	Cost of Production Estimate for: CO (and CO <sub>2</sub> ) and Hydrogen Process: Cryogenic Separation of 1.7:1 Syngas from POX and PSA, China .....	122
Table 41	Cost of Production Estimate for: Syngas (1.7:1) Process: POX, Western Europe .....	123
Table 42	Cost of Production Estimate for: CO (and CO <sub>2</sub> ) and Hydrogen Process: Cryogenic Separation of 1.7:1 Syngas from POX and PSA, Western Europe.....	124
Table 43	Cost of Production Summary for Syngas, USGC .....	125
Table 44	Cost of Production Summary for CO (and CO <sub>2</sub> )/Hydrogen, USGC .....	126
Table 45	Cost of Production Summary for Syngas, China.....	127
Table 46	Cost of Production Summary for CO (and CO <sub>2</sub> )/Hydrogen, China .....	128
Table 47	Cost of Production Summary for Syngas, Western Europe .....	129
Table 48	Cost of Production Summary for CO (and CO <sub>2</sub> )/Hydrogen, Western Europe.....	130
Table 49	Comparative Summary of H <sub>2</sub> A versus H <sub>2</sub> FAST .....	138
Table 50	Case Matrix for Comparison of Hydrogen Production via SMR, ATR, and POX .....	140
Table 51	Hydrogen Purity Specifications.....	141
Table 52	CO <sub>2</sub> Intensity and CO <sub>2</sub> Avoidance Cost .....	155
Table 53	Normalized LCOH for Various Options .....	156
Table 54	Comparative Summary of Grey and Blue Hydrogen Production.....	161
Table 55	Announced Low Carbon Hydrogen Projects in Europe.....	185
Table 56	Challenges and Characteristics by Storage and Transport Pathway.....	187



## TECHNOLOGY & COSTS

# Techneconomics - Energy & Chemicals (TECH)

The NexantECA Subscriptions' Techneconomics - Energy & Chemicals (TECH) program is recognized globally as the industry standard source for information relevant to the chemical process and refining industries. Techneconomics - Energy & Chemicals (TECH) 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](mailto:mcesar@NexantECA.com)

Erica Hill, Client Services Coordinator, Subscriptions and Reports  
Phone: + 1-914-609-0386, e-mail: [ehill@NexantECA.com](mailto:ehill@NexantECA.com)

#### EMEA:

Anna Ibbotson, Vice President, Sales and Marketing  
Phone: +44-207-950-1528, [aibbotson@NexantECA.com](mailto:aibbotson@NexantECA.com)

#### Asia:

Chommanad Thammanayakatip, Managing Consultant  
Phone: +66-2793-4606, email: [chommanadt@NexantECA.com](mailto: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 © 2000-2021 NexantECA (BVI) Limited. All rights reserved