

**TECHNOLOGY & COSTS****Biorenewable Insights****Green Ammonia**

## Table of Contents

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

Published Date: October 2022

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

1	Executive Summary .....	1
1.1	Introduction and Scope .....	1
1.2	Technology .....	1
1.3	Economics .....	2
1.4	Carbon Intensity Impact .....	5
1.5	Implications for Conventional Technology.....	6
2	Introduction.....	8
2.1	Introduction .....	8
2.2	Ammonia Value Chain .....	8
2.3	Drivers for the Adoption of Green Ammonia .....	10
2.4	Scope of the Report .....	11
3	Ammonia Conversion Technologies .....	13
3.1	Conventional Ammonia Synthesis (Haber-Bosch Process) .....	13
3.1.1	Chemistry .....	13
3.1.2	Process Description.....	15
3.2	Lithium-Mediated Indirect Electroreduction of Nitrogen .....	18
3.2.1	Chemistry .....	18
3.2.2	Process Description.....	21
3.3	Electrically Promoted Haber Synthesis .....	24
3.3.1	Chemistry .....	24
3.3.2	Process Description.....	28
3.4	Membrane Electroreduction of Nitrogen and Water (Solid State Ammonia Synthesis) .....	31
4	Hydrogen Production Technologies .....	32
4.1	Steam Reforming of Methane .....	32
4.1.1	Chemistry .....	32
4.1.2	Process Description.....	33
4.1.3	Ancillary Processes .....	35
4.1.4	Carbon Capture Potential .....	38

4.2	Autothermal Reforming of Methane.....	39
4.2.1	Chemistry .....	40
4.2.2	Process Description.....	40
4.2.3	Carbon Capture Potential .....	42
4.3	Electrolysis of Water.....	42
4.3.1	Alkaline Electrolysis .....	43
4.3.2	Proton Exchange Membrane (PEM) Electrolysis .....	49
4.3.3	Solid Oxide Electrolysis Cell (SOEC).....	54
4.4	Carbonaceous Feedstock Gasification.....	58
4.4.1	Chemistry .....	59
4.4.2	Process Description.....	60
4.5	Thermolysis and Thermochemical Processes .....	62
4.5.1	Sulfur-Iodine Cycle .....	62
4.5.2	Hybrid-Sulfur Cycle (Westinghouse Cycle).....	63
5	Air Separation Technologies .....	64
5.1	Cryogenic Separation.....	64
5.1.1	Process Technology .....	65
5.2	Adsorption Air Separation .....	74
5.2.1	Pressure-Swing Adsorption Theory .....	74
5.2.2	Process Description.....	75
5.3	Indirect Air Separation in ATR-based Ammonia Production.....	78
6	Carbon Capture and Sequestration .....	79
6.1	Carbon Capture Technology.....	79
6.1.1	Chemical Gas Absorption.....	79
6.1.2	Gas Adsorption .....	85
6.2	Carbon Capture in Ammonia Plants .....	86
6.2.1	Primary Separation from Reforming .....	86
6.2.2	Flue Gas Capture .....	86
6.2.3	Purge Stream Oxidation and Capture.....	86
6.3	Geological Sequestration Technology.....	87
6.3.1	Carbon Dioxide Transportation .....	87
6.3.2	Geological Sequestration .....	92
7	Economics .....	95
7.1	Methodology .....	95
7.1.1	Sources .....	95
7.1.2	Costing Basis .....	95
7.1.3	Investment Basis.....	95
7.1.4	Pricing Basis .....	96
7.1.5	Cost of Production Basis .....	98
7.1.6	Technology Coverage .....	98
7.2	Blue Ammonia .....	100
7.2.1	Introduction .....	100

7.2.2	Summary .....	101
7.2.3	Blue Ammonia from SMR Ammonia Production .....	102
7.2.4	Blue Ammonia from ATR Ammonia Production .....	110
7.3	Green Ammonia .....	120
7.3.1	Introduction .....	120
7.3.2	Summary .....	121
7.3.3	Green Ammonia from PEM Electrolysis Hydrogen and Haber Conversion .....	123
7.3.4	Green Ammonia from Lithium-Mediated Direct Reduction of Nitrogen .....	138
8	Carbon Intensity Impact Comparison .....	152
8.1	Methodology .....	152
8.1.1	Generic Nature of This Analysis .....	152
8.1.2	Carbon Intensity Methodology .....	152
8.2	Results .....	156
9	Green Ammonia Capacity .....	161
9.1	Types of Developments Considered .....	161
9.2	Existing Capacity .....	161
9.3	Planned Major Projects .....	161
10	Implications for Conventional Technology .....	164
10.1	Private Industrial and Regulatory Driver Outlook .....	164
10.1.1	Regulatory and Policy Drivers .....	164
10.1.2	Industry Perspective on Decarbonization .....	164
10.2	Green Ammonia Capacity In Context .....	165
10.2.1	Boundary Case: Requirements for a Favorable Scenario .....	166
10.2.2	Boundary Case: Current Investment is the Limit .....	167

## Appendices

A	Supplemental Techno-Economic Methodologies .....	169
B	References .....	183

## Figures

Figure 1	Summary of Costs of Production of Green Ammonia .....	3
Figure 2	Cash Cost of Green Ammonia Under Intermittent Electricity Optimization .....	4
Figure 3	Ammonia Carbon Intensity Comparison, Implemented Technology Scenarios .....	5
Figure 4	Value Chain of Main Ammonia and Urea Derived Fertilizers .....	9
Figure 5	End Use of Ammonia and Its Derivatives .....	9
Figure 6	Ammonia Sector Carbon Emissions .....	10
Figure 7	Basic Ammonia Converter Design.....	16
Figure 8	Various Ammonia Converter Designs <sup>0</sup> .....	17
Figure 9	Cyclic Reaction of Lithium Mediated Electrosynthesis of Ammonia.....	18
Figure 10	Example Batch Lithium-Mediated Electrosynthesis of Ammonia .....	21
Figure 11	Block Flow Diagram of Jupiter Ionics Lithium-Mediate Indirect Reduction of Nitrogen .....	22
Figure 12	Simplified Flow Diagram of Starfire Energy Ammonia Converter Process Flow .....	29
Figure 13	Diagram of Starfire Energy Converter .....	30
Figure 14	Process Flow Diagram of Steam Methane Reforming .....	34
Figure 15	Process Flow Diagram for Autothermal Reforming of Methane .....	41
Figure 16	Schematic of Unipolar (a) and Bipolar (b) Alkaline Electrolysis Modules.....	46
Figure 17	Basic Flow Diagram of Alkaline Electrolysis System for Hydrogen Production .....	48
Figure 18	Schematic View of a PEM Electrolysis Cell.....	51
Figure 19	Diagram of a PEM Electrolyzer Module .....	51
Figure 20	Basic Flow Diagram of PEM Electrolysis System for Hydrogen Production .....	53
Figure 21	Example of a Solid Oxide Electrolytic Cell (SOEC) Module .....	55
Figure 22	Major Gasification Reactions (of Coal) .....	59
Figure 23	Block Flow Diagram of Major Operations in Coal-Based Production of Hydrogen .....	61
Figure 24	Cryogenic Air Separation Process Warm End .....	66
Figure 25	Cryogenic Air Separation Process Cold End.....	67
Figure 26	Cryogenic Air Separation Process Argon System .....	68
Figure 27	Pressure Swing Adsorption .....	77
Figure 28	Typical Alkanolamines .....	82
Figure 29	Basic Amine Absorption Process for Carbon Capture from Flue Gas .....	84
Figure 30	Phase Diagram for Pure Carbon Dioxide .....	89
Figure 31	Differences in Densities of Pure CO <sub>2</sub> and a CO <sub>2</sub> -Rich Mixture, 100 bar .....	90
Figure 32	Overview of Geological Storage Options for Carbon Dioxide .....	93
Figure 33	Sensitivity of Geological Sequestration Cost for SMR Blue Ammonia in U.S. Midwest to Aboveground Distance and Well Depth (3D Plot) .....	108
Figure 34	Sensitivity of Geological Sequestration Cost for SMR Blue Ammonia in U.S. Midwest to Aboveground Distance and Well Depth (Contour Plot).....	109
Figure 35	Sensitivity of Geological Sequestration Cost for SMR Blue Ammonia in Middle East to Aboveground Distance and Well Depth (3D Plot) .....	109
Figure 36	Sensitivity of Geological Sequestration Cost for SMR Blue Ammonia in Middle East to Aboveground Distance and Well Depth (Contour Plot) .....	110

Figure 37	Sensitivity of Geological Sequestration Cost for ATR Blue Ammonia in U.S. Midwest to Aboveground Distance and Well Depth (3D Plot) .....	118
Figure 38	Sensitivity of Geological Sequestration Cost for ATR Blue Ammonia in U.S. Midwest to Aboveground Distance and Well Depth (Contour Plot).....	118
Figure 39	Sensitivity of Geological Sequestration Cost for ATR Blue Ammonia in Middle East to Aboveground Distance and Well Depth (3D Plot) .....	119
Figure 40	Sensitivity of Geological Sequestration Cost for ATR Blue Ammonia in Middle East to Aboveground Distance and Well Depth (Contour Plot) .....	119
Figure 41	Log-Linear Plot of Unit Production Costs versus Plant Gate Ammonia Price, with Operating Rate and Accessed Power Price, U.S. Midwest.....	128
Figure 42	Intermittent Green Ammonia Production (PEM/Haber/PSA) by Electricity and Ammonia Price, Operational Case Density, U.S. Midwest.....	129
Figure 43	Intermittent Green Ammonia Production (PEM/Haber/PSA) Sensitivity by Electricity and Ammonia Price, Average Cash Cost of Production of Operation, US Midwest .....	130
Figure 44	Histogram of EU Day-Ahead Pricing and US Midwest NAPL .....	131
Figure 45	Log-Linear Plot of Unit Production Costs versus Plant Gate Ammonia Price, with Operating Rate and Accessed Power Price, Western Europe .....	133
Figure 46	Intermittent Green Ammonia Production (PEM/Haber/PSA) by Electricity and Ammonia Price, Operational Case Density, West Europe .....	134
Figure 47	Intermittent Green Ammonia Production (PEM/Haber/PSA) Sensitivity by Electricity and Ammonia Price, Average Cash Cost of Production of Operation, West Europe.....	135
Figure 48	Log-Linear Plot of Ammonia Unit Production Costs (Lithium-Mediated Reduction) vs Plant Gate Ammonia Price, With Operating Rate and Accessed Power Price, U.S. Midwest.....	144
Figure 49	Intermittent Green Ammonia Production (Lithium-Mediated Reduction) by Electricity and Ammonia Price, Operational Case Density, U.S. Midwest .....	145
Figure 50	Intermittent Green Ammonia Production (Lithium-Mediated Reduction) Sensitivity by Electricity and Ammonia Price, Average Cash Cost of Production of Operation, U.S. Midwest.....	146
Figure 51	Log-Linear Plot of Ammonia Unit Production Costs (Lithium-Mediated Reduction) versus Plant Gate Ammonia Price, With Operating Rate and Accessed Power Price, Western Europe .....	147
Figure 52	Intermittent Green Ammonia Production (Lithium-Mediated Reduction) by Electricity and Ammonia Price, Operational Case Density, West Europe.....	148
Figure 53	Intermittent Green Ammonia Production (Lithium-Mediated Reduction) Sensitivity by Electricity and Ammonia Price, Average Cash Cost of Production of Operation, West Europe .....	149
Figure 54	Definitions of Scope Emissions .....	153
Figure 55	Process Carbon Balance.....	153
Figure 56	Utility Emissions Equation .....	155
Figure 57	Ammonia Carbon Intensity Comparison, Grid Power Emissions .....	157
Figure 58	Ammonia Carbon Intensity Comparison, Grid Power Emissions .....	158
Figure 59	Ammonia Carbon Intensity Comparison, Emissions-Free Power .....	159
Figure 60	Ammonia Carbon Intensity Comparison, Implemented Technology Scenarios .....	160
Figure 61	Williston Basin Geological Area.....	170
Figure 62	Areas of Oil and Gas Activity in Williston Basin .....	171
Figure 63	Approximate 1000 km Radius from Williston Basin Oil and Gas Area .....	171

Figure 64	Map of Persian Gulf Oil and Gas Fields .....	173
Figure 65	Map of 300 km Radial Distance from Major Petrochemical Centers in the Middle Eastern Gulf Coast Region.....	174
Figure 66	Sample Performance Curve of Electrochemical Process.....	177
Figure 67	Sample Empirical PEM Energy Efficiency Curve .....	177
Figure 68	Adjusted Pareto Curve of Electricity Pricing.....	179
Figure 69	Monte Carlo Simulation Price Distribution by Number of Model Runs.....	182

## Tables

Table 1	NexantECA Ammonia Technology Coverage .....	2
Table 2	Summary of Green Ammonia Costs of Production .....	3
Table 3	Major Chemical Carbon Dioxide Absorption Systems.....	80
Table 4	Alkanolamine Properties Relative to MEA During Typical Operation.....	81
Table 5	Typical U.S. Carbon Dioxide Pipeline Compositional Specifications .....	88
Table 6	Prices of Raw Materials, Utilities, and Labor .....	97
Table 7	Green Hydrogen Modular Technology Coverage.....	99
Table 8	Key Technoeconomic Assumptions in Blue Ammonia Model .....	100
Table 9	Summary of Cost of Production for Blue Ammonia Processes .....	101
Table 10	Summary of Cost of Production for Blue Ammonia Processes Including Geological Sequestration.....	101
Table 11	Cost of Production Model for SMR Ammonia Production with Flue Gas and Internal Carbon Capture in U.S. Midwest .....	103
Table 12	Cost of Production Model for SMR Ammonia Production with Flue Gas & Internal Carbon Capture in Middle East .....	104
Table 13	Cost of Production Model for Geological Sequestration of SMR Blue Ammonia in the U.S. Midwest.....	106
Table 14	Cost of Production Model for Geological Sequestration of SMR Blue Ammonia in the Middle East.....	107
Table 15	Cost of Production Model for ATR Ammonia Production with Internal Carbon Capture in US Midwest .....	112
Table 16	Cost of Production Model for ATR Ammonia Production with Internal Carbon Capture in Middle East .....	113
Table 17	Cost of Production Model for Geological Sequestration of ATR Blue Ammonia in the U.S. Midwest.....	115
Table 18	Cost of Production Model for Geological Sequestration of ATR Blue Ammonia in the Middle East.....	116
Table 19	Key Technoeconomic Assumptions in Green Ammonia Models .....	121
Table 20	Summary of Cost of Production for Green Ammonia Processes .....	122
Table 21	Cost of Production Estimate for Green Ammonia, PEM Electrolysis Hydrogen and PSA Nitrogen with Haber-Bosch Conversion, Maximal Operating Rate, in the U.S. Midwest.....	124
Table 22	Cost of Production Estimate for Green Ammonia, PEM Electrolysis Hydrogen and PSA Nitrogen with Haber-Bosch Conversion, Maximal Operating Rate, in West Europe .....	125

Table 23	Sensitivity of Intermittent Green Ammonia Production (PEM/Haber/PSA) by Electricity and Ammonia Price, US Midwest .....	127
Table 24	Sensitivity of Intermittent Green Ammonia Production (PEM/Haber/PSA) by Electricity and Ammonia Price, West Europe .....	132
Table 25	Cost of Production Estimate for Green Ammonia, PEM Electrolysis and PSA Nitrogen with Haber-Bosch Conversion, Optimal Operating Rate, in US Midwest .....	136
Table 26	Cost of Production Estimate for Green Ammonia, PEM Electrolysis and PSA Nitrogen with Haber-Bosch Conversion, Optimal Operating Rate, in West Europe .....	137
Table 27	Cost of Production Estimate for Green Ammonia, PSA Nitrogen with Lithium-Mediated Nitrogen Reduction, Maximal Operating Rate, in the U.S. Midwest.....	140
Table 28	Cost of Production Estimate for Green Ammonia, PSA Nitrogen with Lithium-Mediated Reduction of Nitrogen, Maximal Operating Rate, in West Europe .....	141
Table 29	Sensitivity of Intermittent Green Ammonia Production (Lithium-Mediated Reduction) by Electricity and Ammonia Price, U.S. Midwest .....	143
Table 30	Sensitivity of Intermittent Green Ammonia Production (Lithium-Mediated Reduction) by Electricity and Ammonia Price, West Europe .....	147
Table 31	Cost of Production Estimate for Green Ammonia, Lithium-Mediated Direct Reduction of Nitrogen, Optimal Operating Rate, in U.S. Midwest.....	150
Table 32	Cost of Production Estimate for Green Ammonia, Lithium-Mediated Direct Reduction of Nitrogen, Optimal Operating Rate, in West Europe .....	151
Table 33	Scope 1 & Scope 2 Utility Emissions Factors .....	155
Table 34	Ammonia Carbon Intensity Comparison, Grid Power Emissions .....	157
Table 35	Ammonia Carbon Intensity Comparison, Emissions-Free Power .....	158
Table 36	Announced Green Ammonia Projects .....	162



## TECHNOLOGY & COSTS

# Biorenewable Insights

The NexantECA 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 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