Dii Desert Energy

Green Hydrogen:
The Rise of Green Molecules!
Innovative Financial Model Toolkit for Analyzing Levelized Costs (LCOH & LCOA)

Fadi Maalouf
Dubai 10th Nov 2021

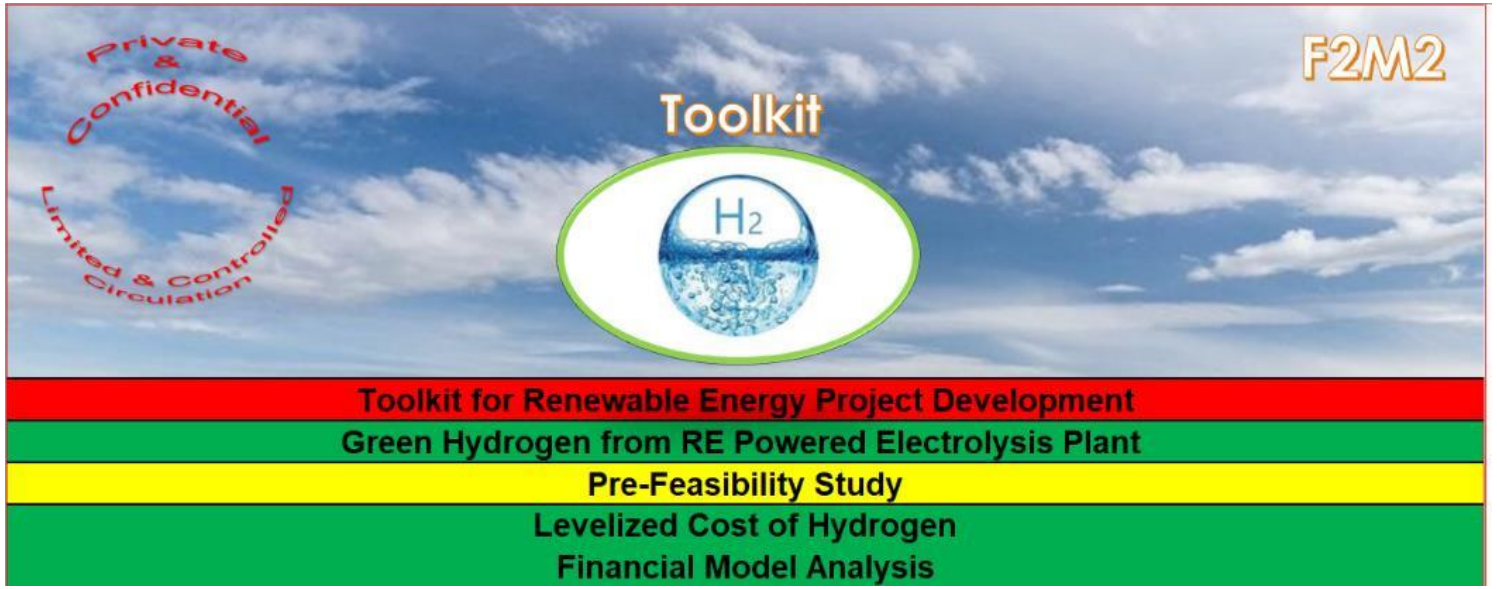
Document History

DOCUMENT CHANGE HISTORY RECORD SHEET			
Document Title / Number	**Rev.**	**Description Of Change**	**Effective Date**
Green Hydrogen Financial Model Toolkit Hydrogen-Financial-Model-Toolkit-R1-fm200722	1	Initial Release – For Information	22-Jul-2020
Green Hydrogen Financial Model Toolkit Hydrogen-Financial-Model-Toolkit-R2-fm200922	2	Updated for Toolkit Model V4 – For Information	22-Sep-2020
Green Hydrogen Financial Model Toolkit Green-Hydrogen-Financial-Model-Toolkit-R3-fm210112	3	Updated for Toolkit Model V5 – For Information	12-Jan-2021
Green Hydrogen Financial Model Toolkit Green-Hydrogen-Financial-Model-Toolkit-R4-fm210209	4	Updated for Toolkit Model V6 & V7 – For Information	9-Feb-2021
Green Hydrogen Financial Model Toolkit Green-Hydrogen-Financial-Model-Toolkit-R5-fm211110	5	Updated Business Cases – For Information	10-Nov-2021

Category	**Name**	**Designation**	**Signature**	**Date**
Author	Fadi Maalouf	CTO - Director IPP & EPC	F2M2	10-Nov-2021

Outline

- Introduction
- Background & Context
- Toolkit Versions
- Toolkit Features
- How Does It Work?
- Toolkit Content
- Toolkit Inputs Form
- Toolkit Direct Outputs
- Toolkit Analytical Outputs
- Grey vs. Green Ammonia
- Takeaways
- Contact



Introduction

- In the Global Energy Transition context and decarbonization, all hands must be on deck!
- There is no magic quick fix or silver bullet solution. It is a collaborative effort across all stakeholders and industries.
- A double win can be achieved: accelerated energy transition driven by sustainable economic recovery.
- An important element of this double win is Green Hydrogen, i.e. hydrogen produced from electrolyzers powered by renewable energy resources.
- Hydrogen is a versatile energy carrier with a wide range of uses and unique attributes, especially for energy sectors that are hard to electrify with renewable resources but can be made greener through sector coupling.
- So, if Green Hydrogen is technically a key enabler of decarbonization, then the next step or barrier to break is economics.
- This translates to: how much does Green Hydrogen costs to produce and how to calculate that as well as analyze pathways of cost reduction?
- A financial model toolkit for analyzing levelized cost of Hydrogen becomes necessary.

Background & Context: Why Hydrogen ?

Net Zero by 2050 – IEA Scenario - Role of Hydrogen & Its Derivatives

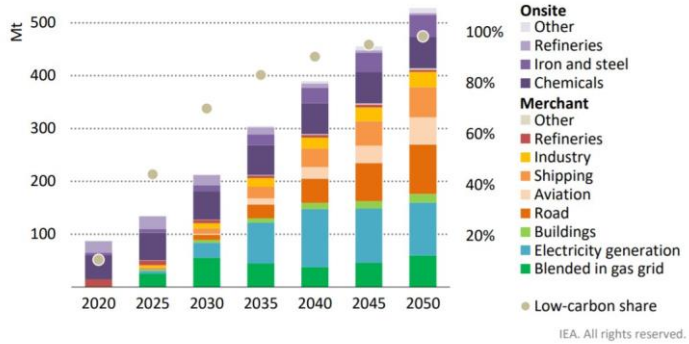
Hydrogen Demand

- *H_2 & its derivative should meet 13% of final energy use in 2050*
- *2020 demand is around 90 Mt per annum*
- *2050 demand forecast is around 528 Mt per annum*
- *Majority of Future demand is heavy transport, H_2 derivative fuel for shipping & aviation, & flexible power generation*
- *H_2 and NH_3 could meet 60% of energy demand in shipping*
- *Synthetic fuels could meet third of energy demand in aviation*

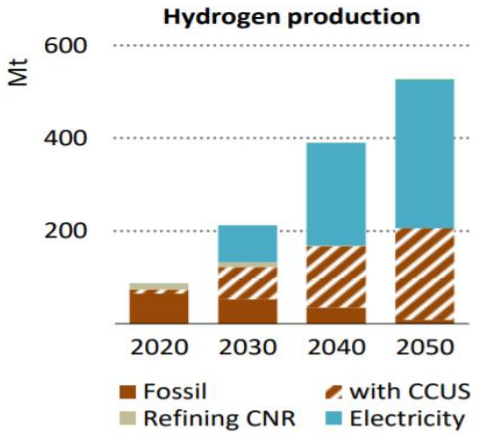
Hydrogen Supply

- *Decarbonizing fossil based H_2 is vital*
- *Low carbon based H_2 supply will increase from today till 2050*
- *Electricity based H_2 represents 62% of supply by 2050*
- *Electrolysis capacity should reach 850 GW by 2030*
- *Electrolysis capacity should reach 3000 GW by 2045*
- *Scaling up & innovation are critical for electrolysis cost reduction*

Figure 2.19 ▷ Global hydrogen and hydrogen-based fuel use in the NZE



The initial focus for hydrogen is to convert existing uses to low-carbon hydrogen; hydrogen and hydrogen-based fuels then expand across all end-uses



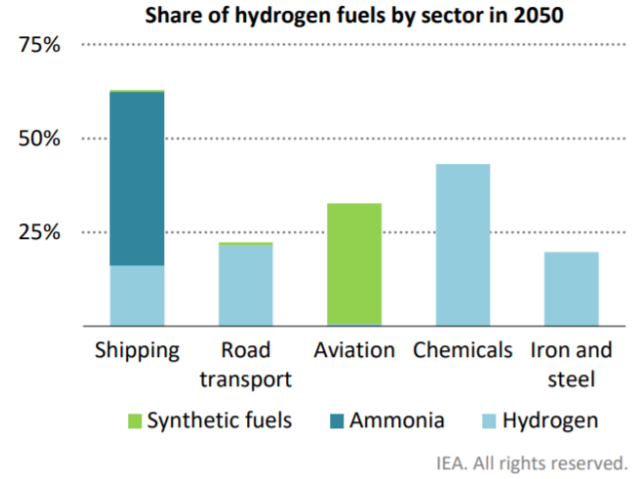


Table 2.7 ▷ Key deployment milestones for hydrogen and hydrogen-based fuels

Sector	2020	2030	2050
Total production hydrogen-based fuels (Mt)	87	212	528
Low-carbon hydrogen production	9	150	520
share of fossil-based with CCUS	*95%*	*46%*	*38%*
share of electrolysis-based	*5%*	*54%*	*62%*
Merchant production	15	127	414
Onsite production	73	85	114
Total consumption hydrogen-based fuels (Mt)	87	212	528
Electricity	0	52	102
of which hydrogen	0	43	88
of which ammonia	0	8	13
Refineries	36	25	8
Buildings and agriculture	0	17	23
Transport	0	25	207
of which hydrogen	0	11	106
of which ammonia	0	5	56
of which synthetic fuels	0	8	44
Industry	51	93	187

Note: Hydrogen-based fuels are reported in million tonnes of hydrogen required to produce them.

Toolkits Versions

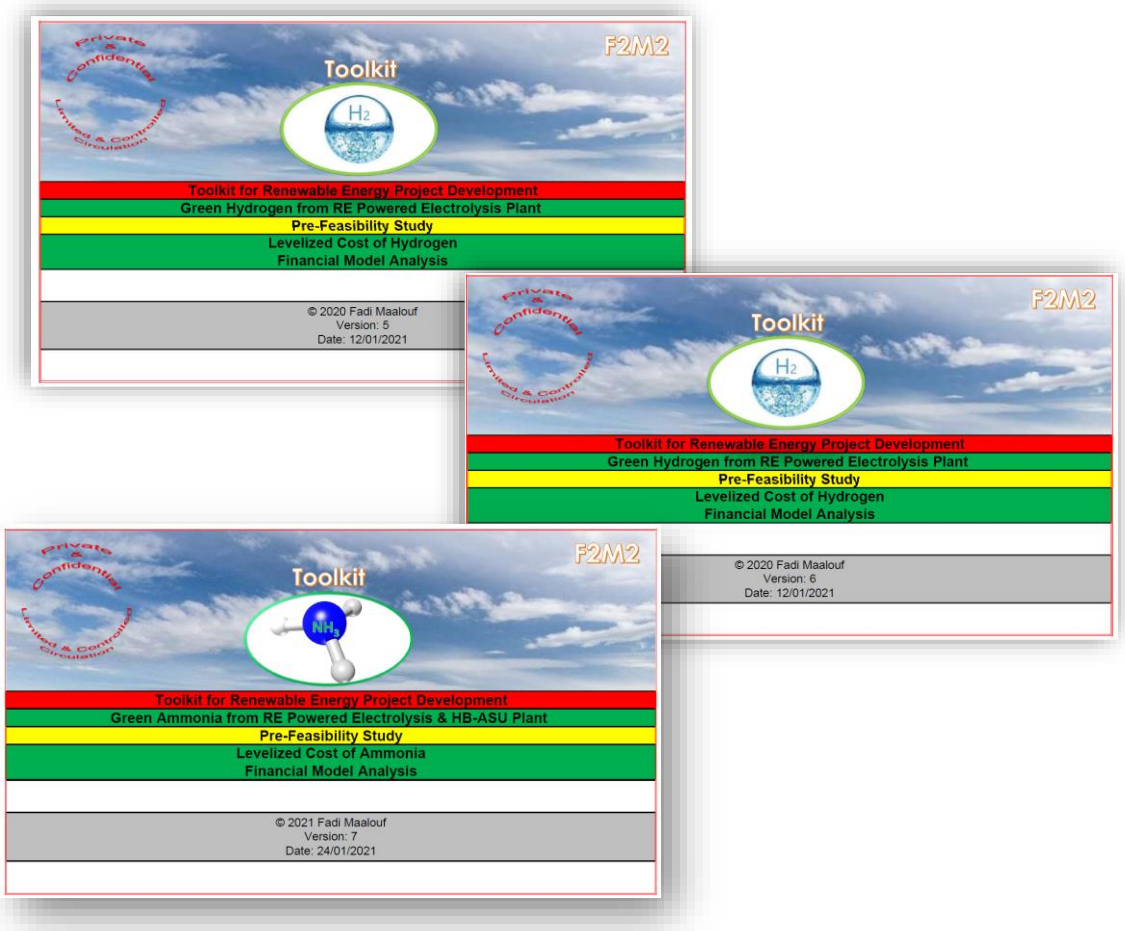
Levelized Cost of Green Hydrogen LCOH & Green Ammonia LCOA

Three Versions:

- *LCOH Financial Model Toolkit V5*
  Green H_2 Production

- *LCOH Financial Model Toolkit V6*
  Green H_2 Production & Delivery Infra Pathways

- *LCOA Financial Model Toolkit V7*
  Green NH_3 Production & Storage



Three versions Modular approach to:

- *Verify costs at each stage of the process*
- *Identify cost optimization priorities & opportunities*

Toolkits Feautures

Levelized Cost of Green Hydrogen LCOH & Green Ammonia LCOA

Features:

- *Get exclusive market analysis and benchmarking data about the Levelized Cost of Green Hydrogen and Green Ammonia.*
- *Obtain the best of all worlds assembled from over 50 best in class models for LCOH/LCOA in the market.*
- *A quick yet very effective holistic approach methodology to determine levelized costs of green molecules.*
- *Capture all life cycle costs and assess project feasibility.*
- *A detailed analytical dive into optimizing costs as well as performance parameters.*
- *Utilize powerful and comprehensive sensitivity analysis scenarios.*
- *User-friendly design with guideline, rich visuals & charts, printable 16-page report.*
- *A free Software as a Service (SaaS) basis for Dii network members and partners.*
- *Native model toolkits files (xls) are available as commercial product.*
- *Download sample pdf reports at: www.dii-desertenergy.org*

Toolkits Features

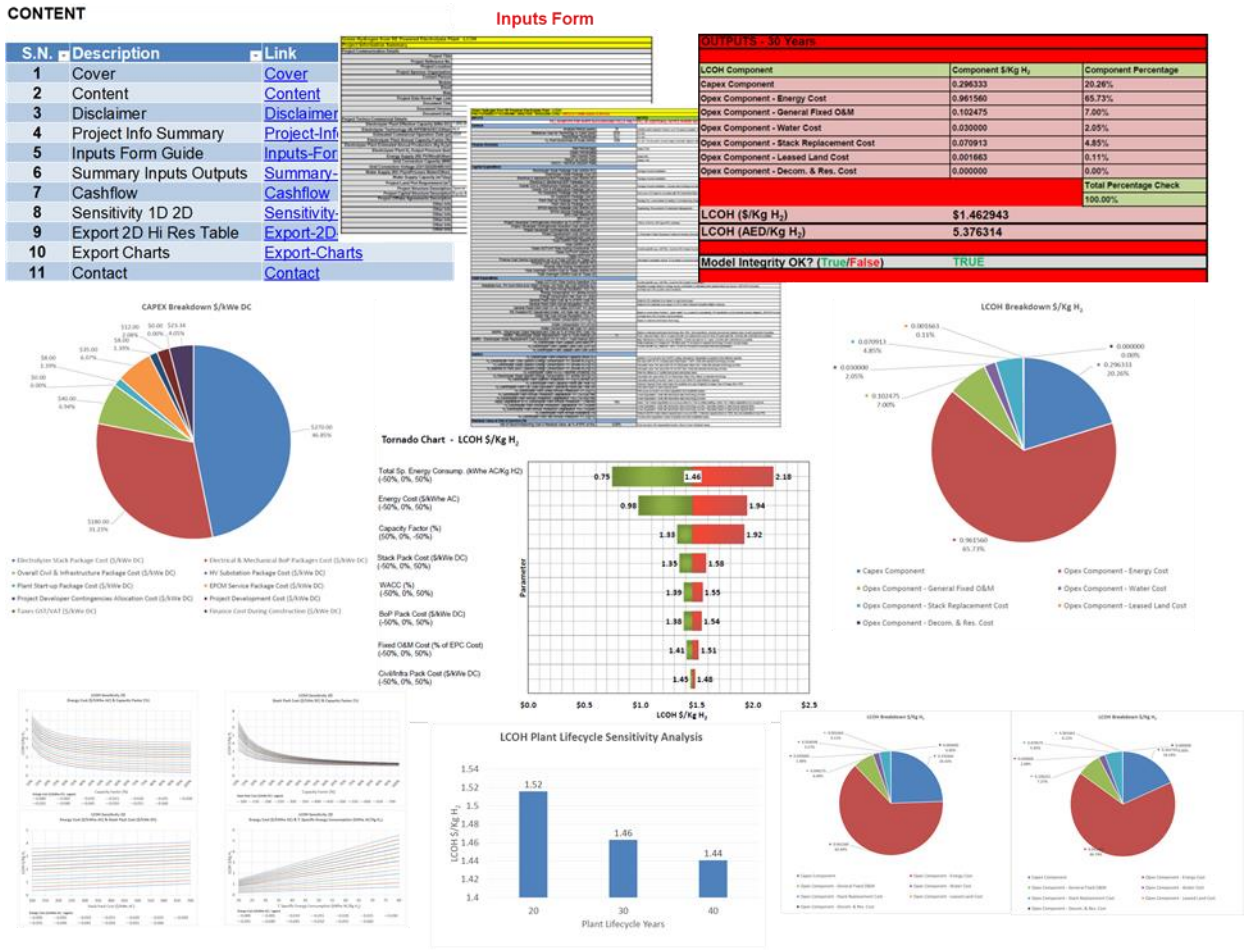
Levelized Cost of Green Hydrogen LCOH & Green Ammonia LCOA

Financial Model Toolkit Features: Zoom In!

- *Very Well-Structured Content & Workflow*
- *Project Information Data Capturing Full Scope of Work & Limits*
- *Detailed Input Parameters Form with Guideline Notes*
- *Tabular LCOH/LCOA Outputs*
- *Breakdown CAPEX & LCOH/LCOA Output Charts*
- *Up to 16 Parameters Sensitivity Tornado Chart*
- *Up to 8 Two-Dimensional Sensitivity Charts*
- *Multi-Lifecycle Analysis Chart*
- *Export Data/Charts Feature*
- *GIS Interface Feature*

Sample Case Studies Forecast for GWe Scale Plants LCOH/LCOA in 2025

- *Morocco Green Hydrogen (PV+Wind) LCOH: < $1.6//Kg H_2*
- *Oman Green Ammonia (PV+Wind) LCOA: < $475/ tNH_3*
- *UAE Green Hydrogen (PV) LCOH: < $2.1//Kg H_2*
- *KSA Green Ammonia (PV+Wind) LCOA: < $450/ tNH_3*



How Does It Work? V5

- The financial model toolkit is a discounted cashflow model coupled with visual representation in charts and graphs, and analytical features of one- and two-dimensional sensitivity analysis.

- Basically, the toolkit is a calculation engine that feeds on user supplied input parameters and provides calculated outputs of LCOH in $/Kg H_2 plus plenty of charts for easier analytical what-If-scenarios representation.

- To run the model and provide a report, the user (desktop researcher) provides Dii with the required “input parameters”.

- This is a two-page Inputs Form that covers the attributes of Green Hydrogen/Ammonia . Dii runs the model and provides a report. Service Done!

Toolkit Content V5

- The financial model toolkit is an XLS file with 11 sheets.
- The integrity of the toolkit structure and calculation engine is secured and protected against unintended formulae edits.
- A content sheet provides quick navigation hyperlinks to all sheets.
- By providing a list of input parameters, a model run will generate a 14-page pdf report.

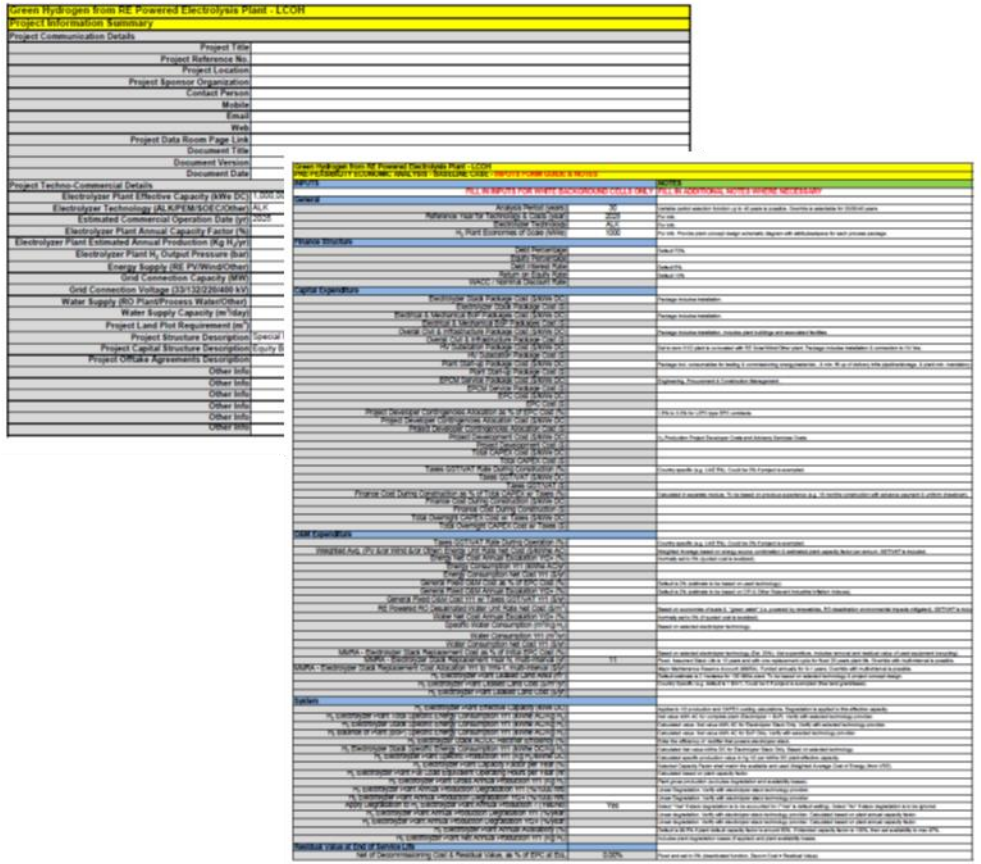
CONTENT

S.N.	Description	Link
1	Cover	Cover
2	Content	Content
3	Disclaimer	Disclaimer
4	Project Info Summary	Project-Info-Summary
5	Inputs Form Guide	Inputs-Form-Guide
6	Summary Inputs Outputs	Summary-Inputs-Outputs
7	Cashflow	Cashflow
8	Sensitivity 1D 2D	Sensitivity-1D-2D
9	Export 2D Hi Res Table	Export-2D-HiRes
10	Export Charts	Export-Charts
11	Contact	Contact

Toolkit Inputs Form V5

- The Inputs Form (xls file) data set is in six categories:
  1. General (Lifecycle up to 40 years, economies of scale, technology & costs ref. years)
  2. Finance Structure (gearing, equity & debt rates)
  3. CAPEX (breakdown required)
  4. OPEX (fixed & variable, energy & water, land lease, escalation rates, stack replacement intervals)
  5. System (capacity, efficiency, degradation, capacity factor)
  6. Decommissioning & Residual Value
- For each input parameter, a few notes and remarks are provided. The user can also add his/her special notes as well. It is worth noting that quality and validity of input data is key.

Inputs Form

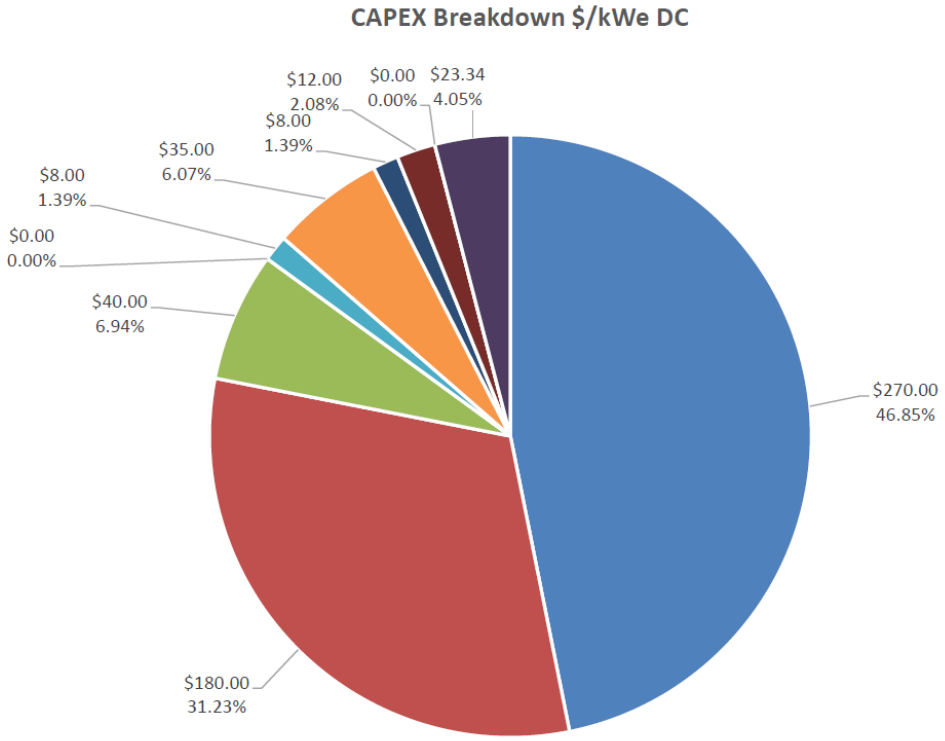


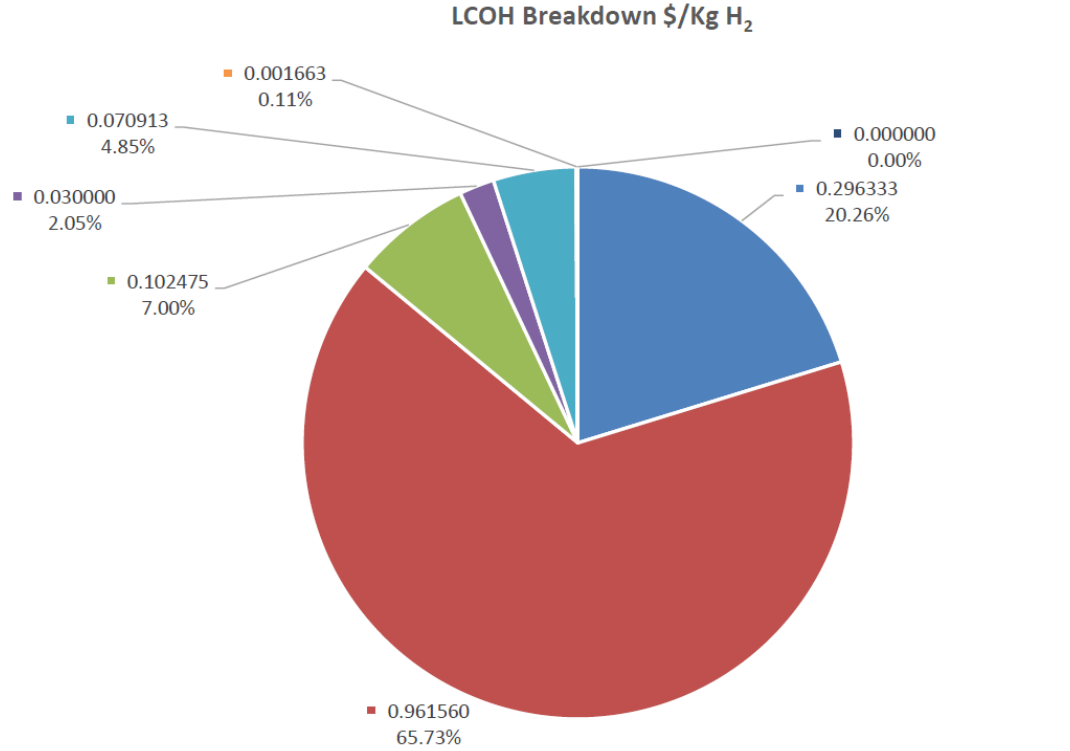
Toolkit Direct Outputs V5

- The toolkit direct outputs are in three categories:
  1. Direct calculation outputs, LCOH baseline case
  2. CAPEX breakdown with chart
  3. LCOH breakdown chart

OUTPUTS - 30 Years		
LCOH Component	Component $/Kg H_2	Component Percentage
Capex Component	0.296333	20.26%
Opex Component - Energy Cost	0.961560	65.73%
Opex Component - General Fixed O&M	0.102475	7.00%
Opex Component - Water Cost	0.030000	2.05%
Opex Component - Stack Replacement Cost	0.070913	4.85%
Opex Component - Leased Land Cost	0.001663	0.11%
Opex Component - Decom. & Res. Cost	0.000000	0.00%
		Total Percentage Check
		100.00%
LCOH ($/Kg H_2)	$1.462943	
LCOH (AED/Kg H_2)	5.376314	
Model Integrity OK? (True/False)	TRUE	

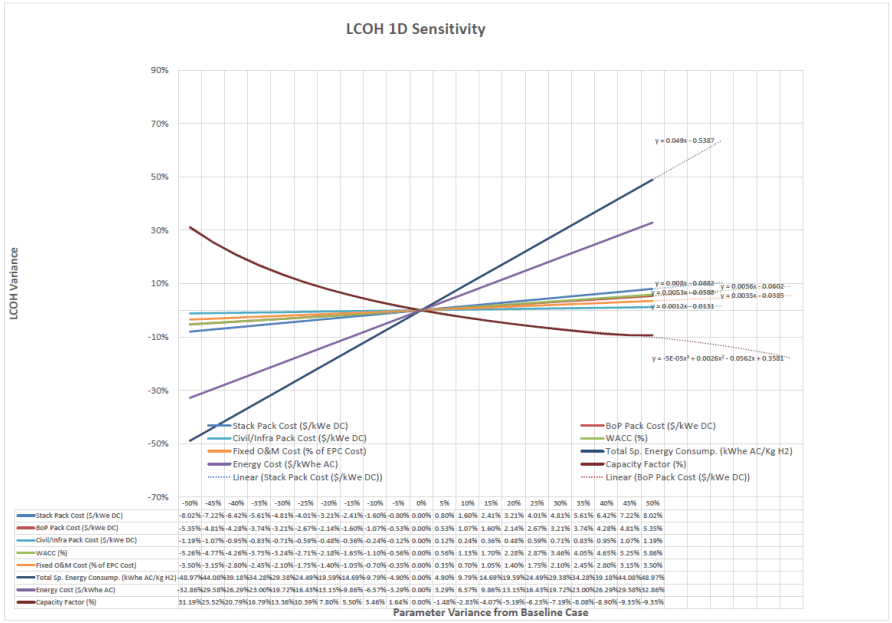
Toolkit Direct Outputs V5





Toolkit Analytical Outputs V5

- Analytical what-if scenarios one-dimensional LCOH calculation outputs
  - Eight input parameters variances +/- 50%
  - Tornado chart



Tornado Chart - LCOH $/Kg H_2

Total Sp. Energy Consump. (kWhe AC/Kg H2) (-50%, 0%, 50%)

Energy Cost ($/kWhe AC) (-50%, 0%, 50%)

Capacity Factor (%) (50%, 0%, -50%)

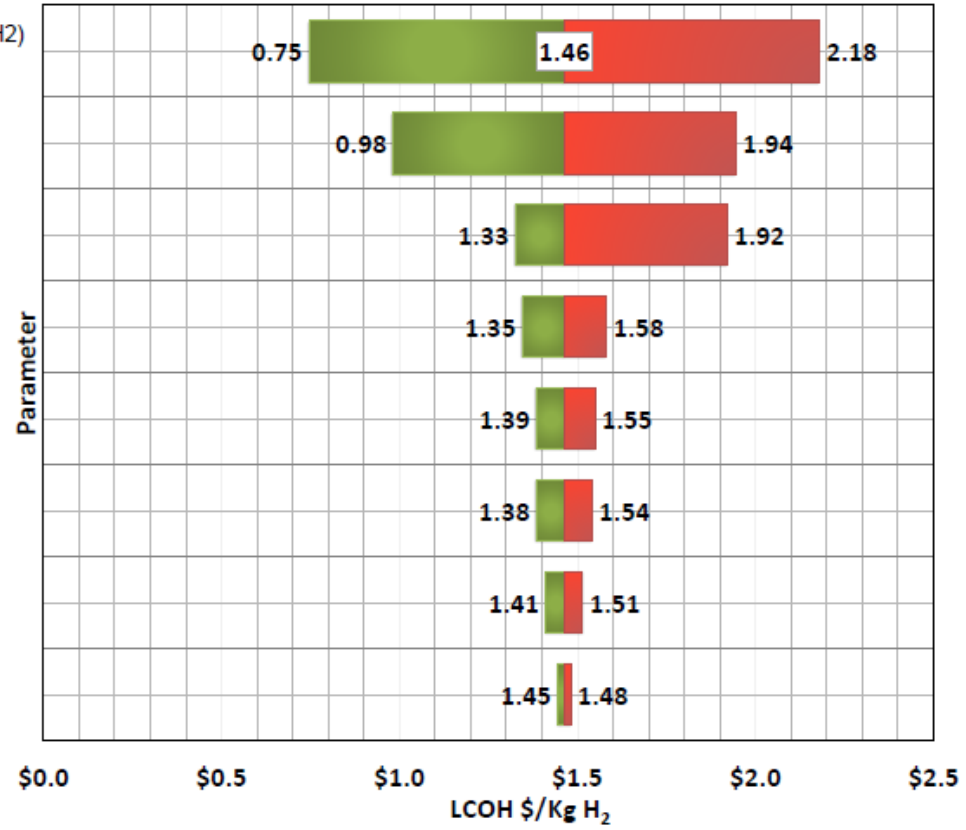
Stack Pack Cost ($/kWe DC) (-50%, 0%, 50%)

WACC (%) (-50%, 0%, 50%)

BoP Pack Cost ($/kWe DC) (-50%, 0%, 50%)

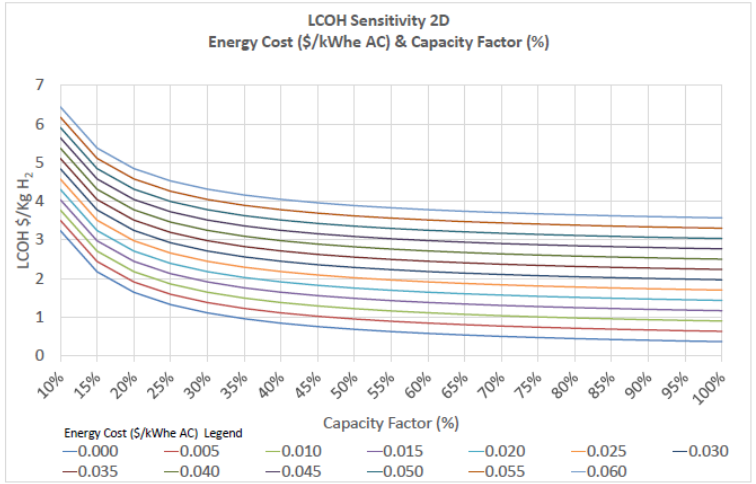
Fixed O&M Cost (% of EPC Cost) (-50%, 0%, 50%)

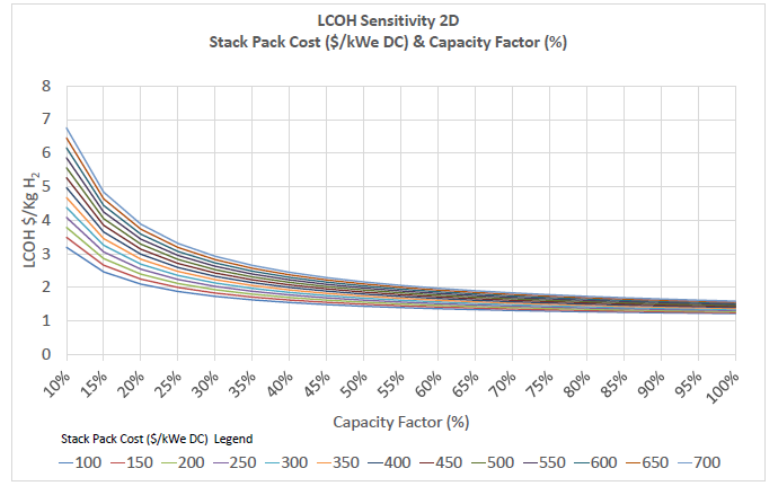
Civil/Infra Pack Cost ($/kWe DC) (-50%, 0%, 50%)

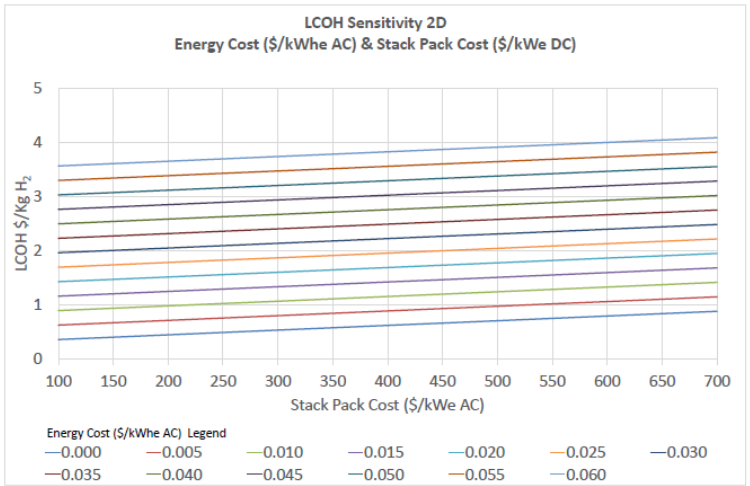


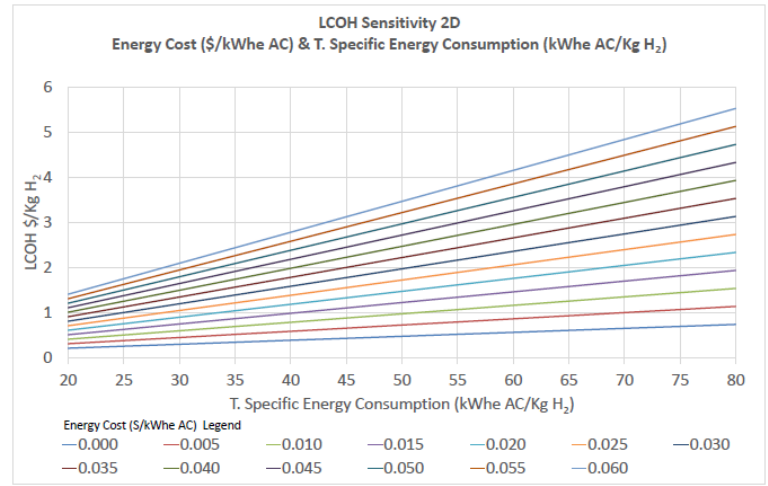
Toolkit Analytical Outputs V5

- Analytical what-if scenarios two-dimensional LCOH calculation outputs









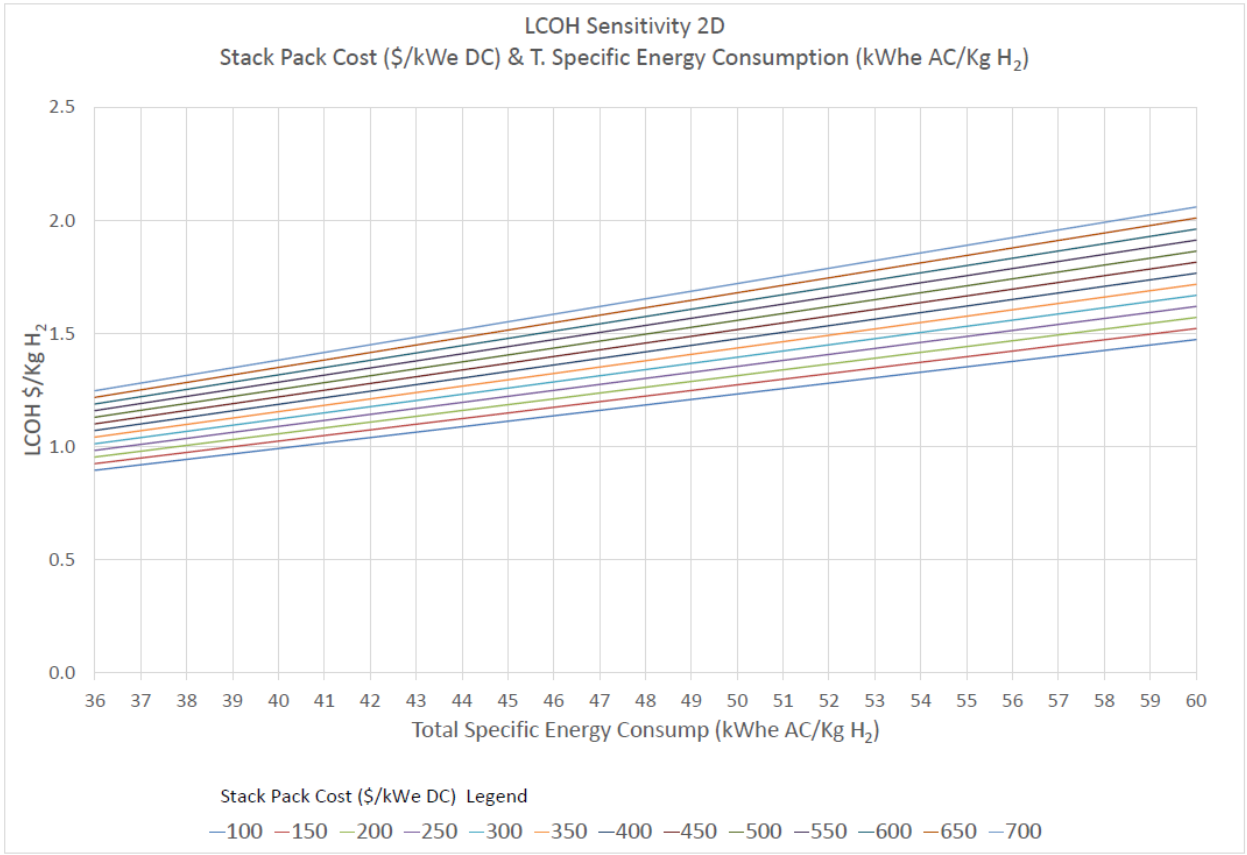
Toolkit Analytical Outputs V5

- Analytical what-if scenarios two-dimensional LCOH calculation outputs for Electrolyzer Development Roadmap (Eff. vs. Cost)

Electrolyzer Development Roadmap Analysis

LCOH 2D Sensitivity for Efficiency and Cost

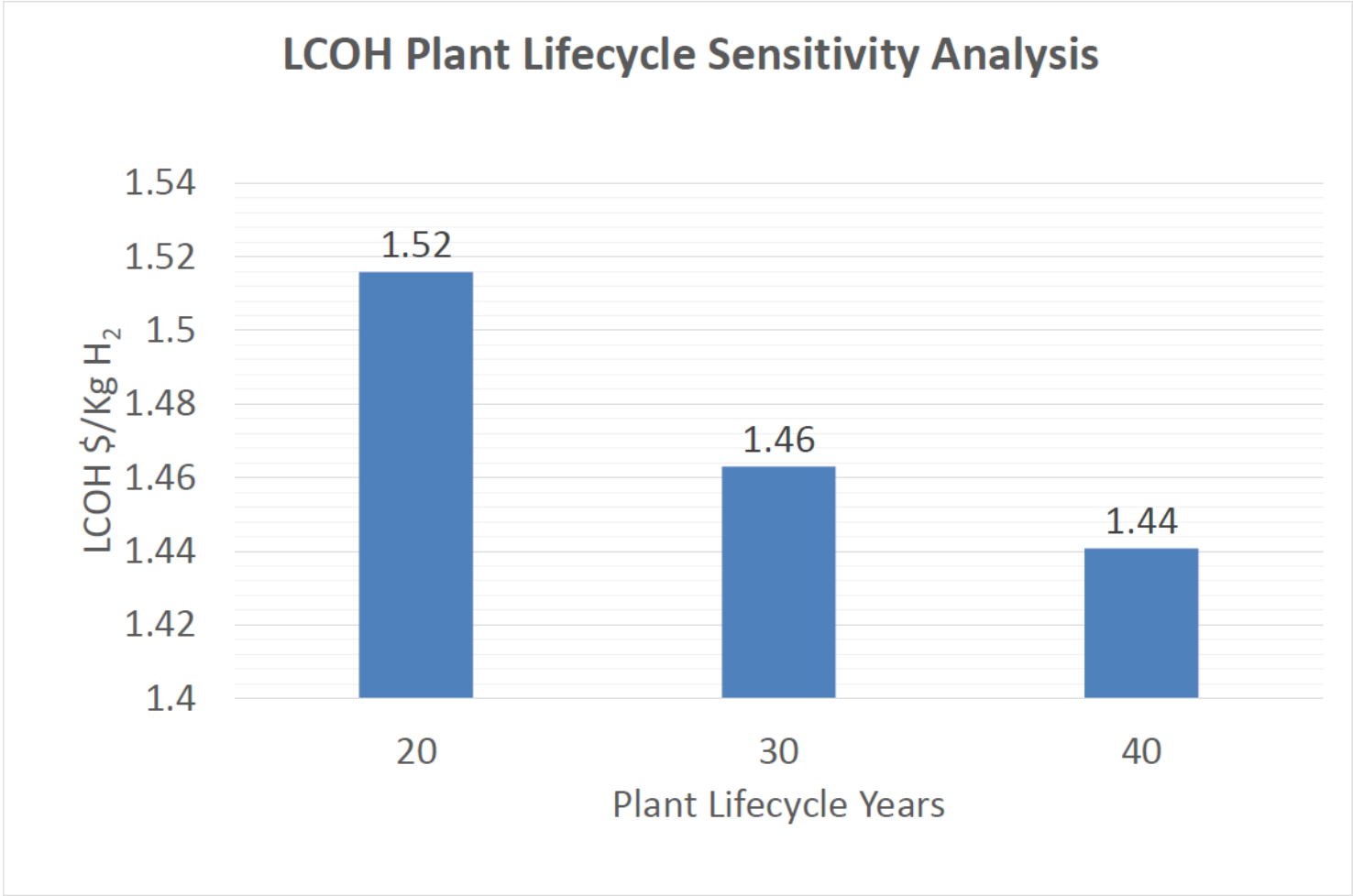
Electrolyzer Total Specific Energy Consumption kWhe AC/Kg H_2 & Stack Pack Cost $/kWe DC Impact on LCOH



Toolkit Analytical Outputs V5

- Impact of Plant Lifecycle on LCOH:

  20 years vs. 30 years vs. 40 years



Toolkit Analytical Outputs V5

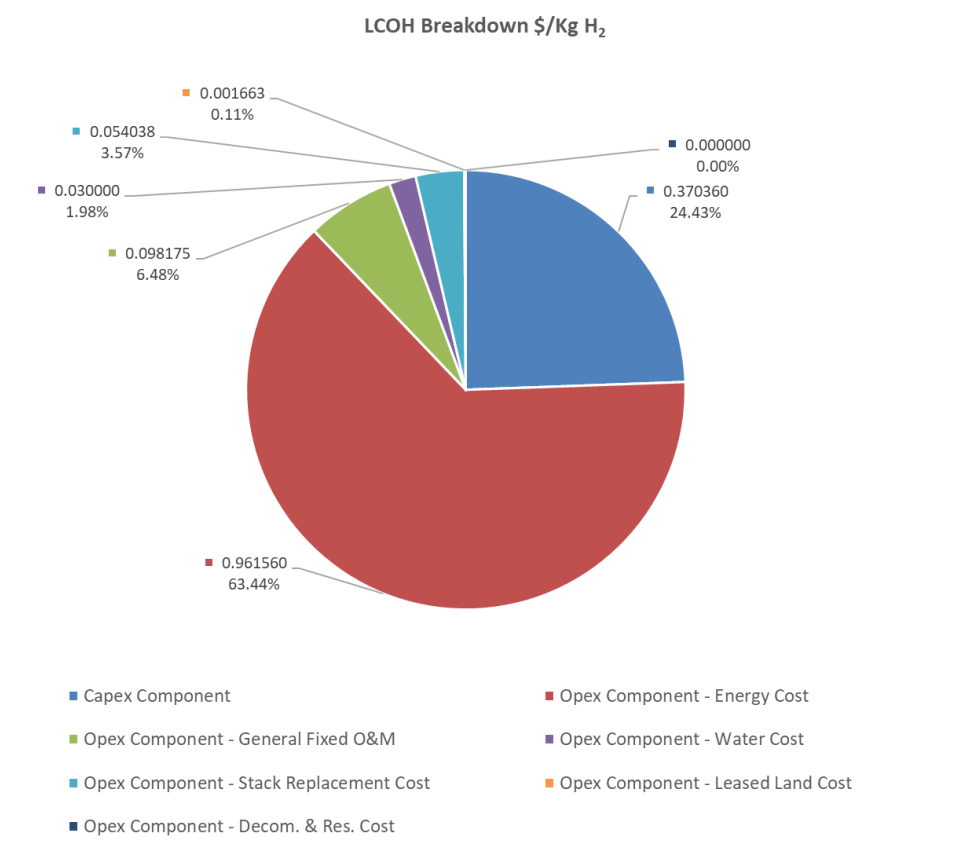
- Impact of Plant Lifecycle on LCOH Breakdown:

20 years

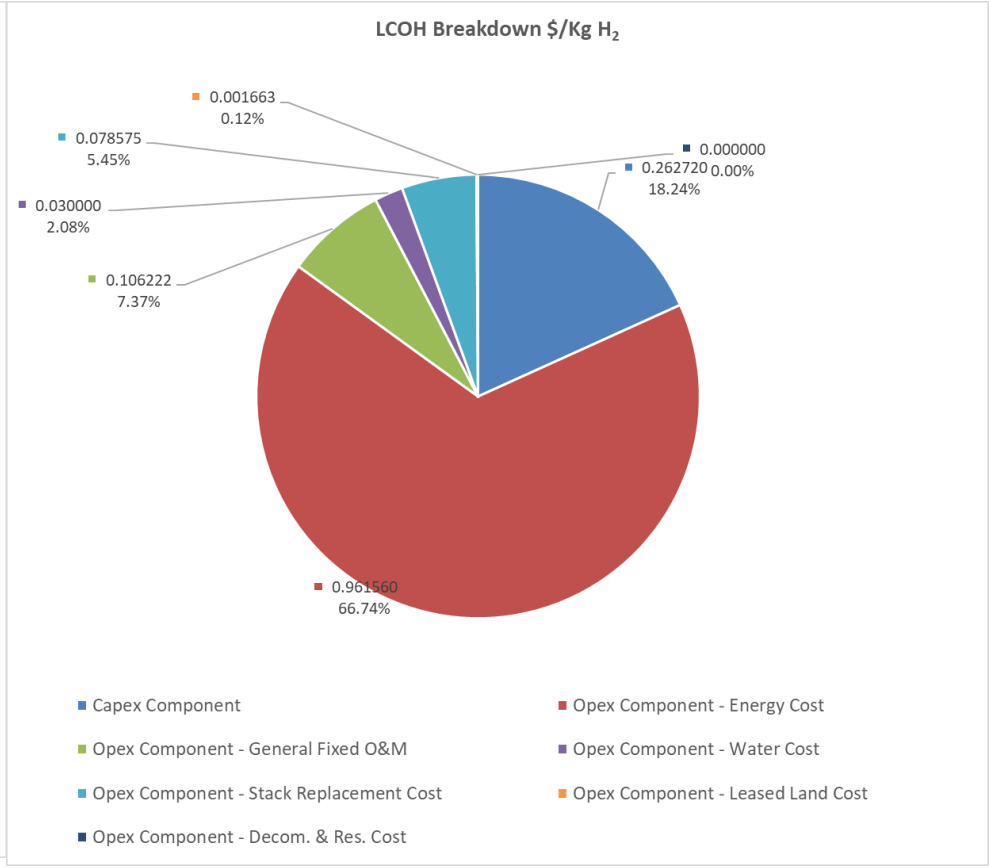
vs.

40 years

20 Years



40 Years



Toolkit Analytical Outputs V5

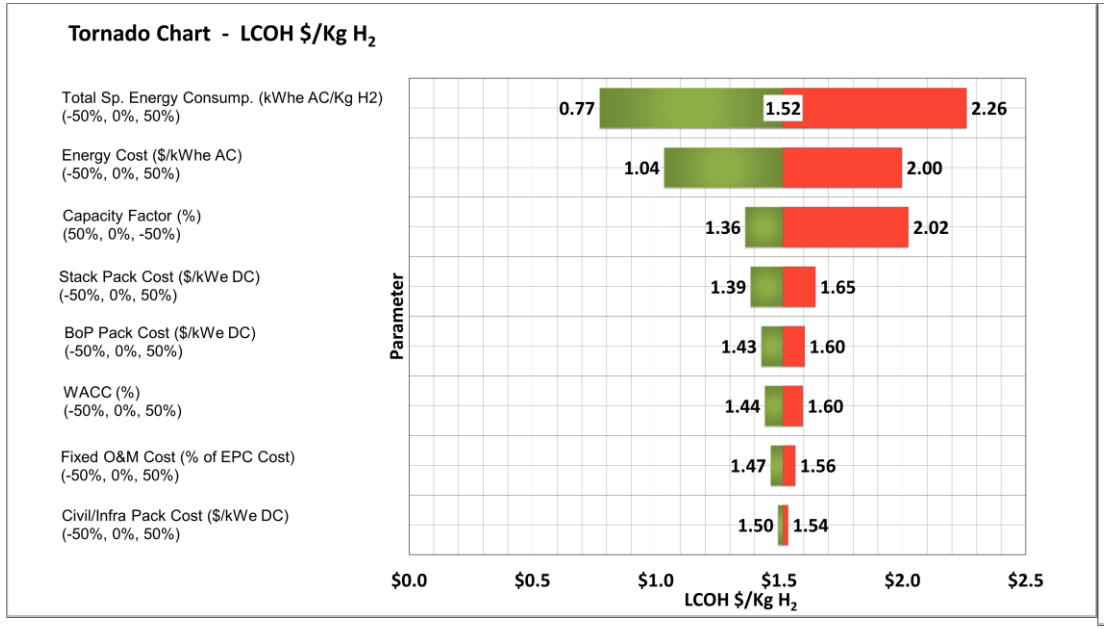
- Impact of Plant Lifecycle on LCOH:

20 years

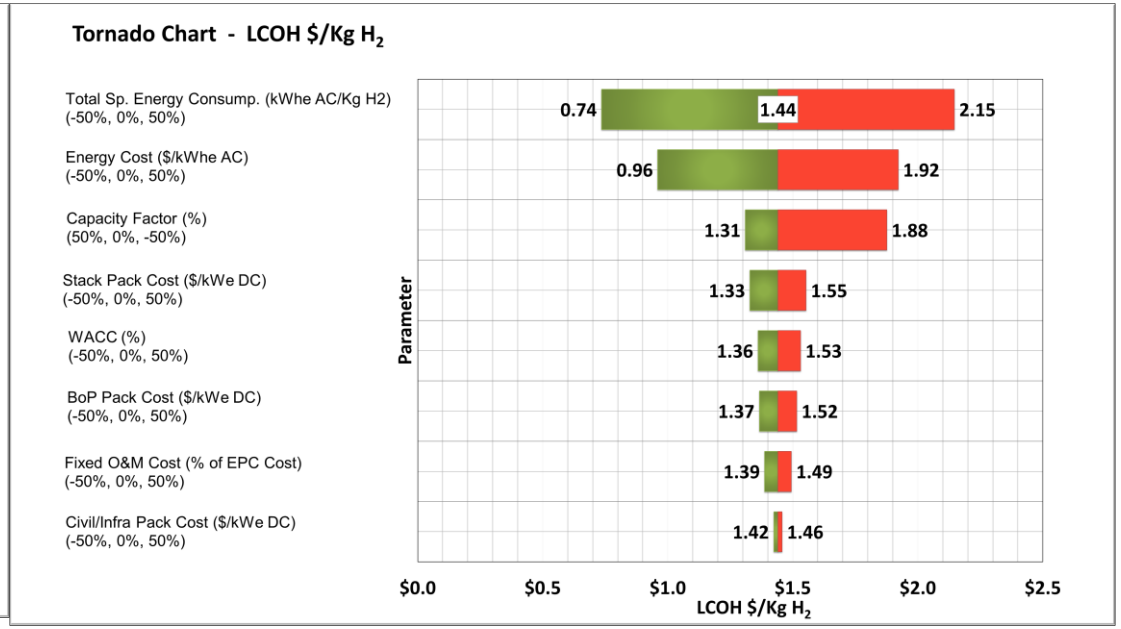
vs.

40 years

20 Years



40 Years



Grey Ammonia vs Green Ammonia LCOA Case Study Toolkit V7

- Green Ammonia Levelized Cost:

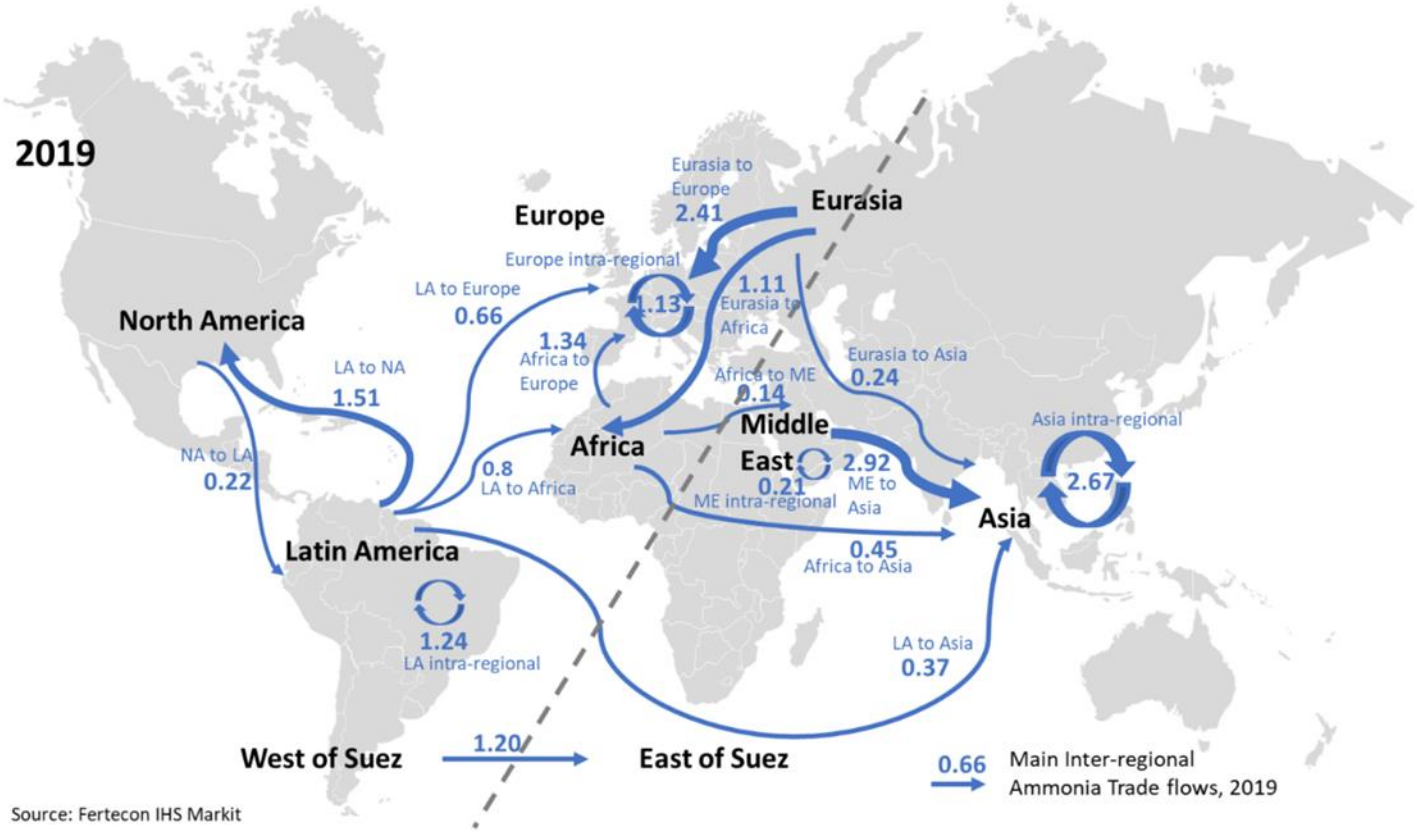
  Is a Competitive Alternative to Volatile Grey Ammonia Markets ?

  - Ammonia is a globally traded commodity
  - Grey ammonia global historical prices review
  - Green ammonia LCOA case study 2025

Green Ammonia Levelized Cost

Competitive Alternative to Volatile Grey Ammonia Markets

Grey Ammonia Global Trade Flow 2019



Map of global ammonia trade flows. Source Fertecon IHS Markit.

Green Ammonia Levelized Cost

Competitive Alternative to Volatile Grey Ammonia Markets

Grey Ammonia Price in China

One Year Period:
Sep-2020 to Sep 2021

Price Range:
$450 to $740/ton

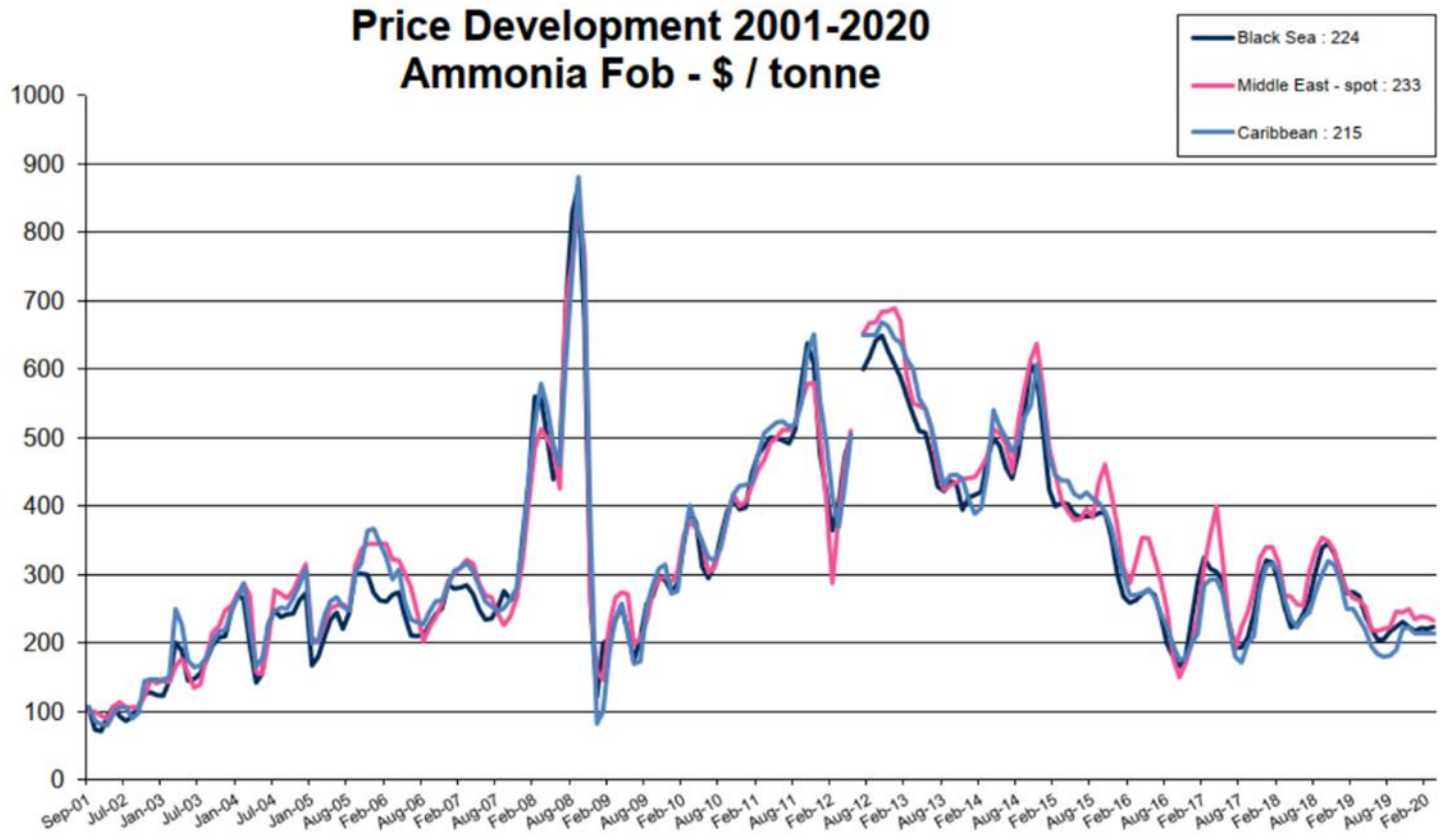
Green Ammonia Levelized Cost

Competitive Alternative to Volatile Grey Ammonia Markets

Grey Ammonia FOB Price in Middle East, Caribbean, Black See

20 Years Period:
Sep-2001 to Feb-2020

Price Range:
$100 to $850/ton



Ammonia price development. (Source: CRU - Fertilizer week)

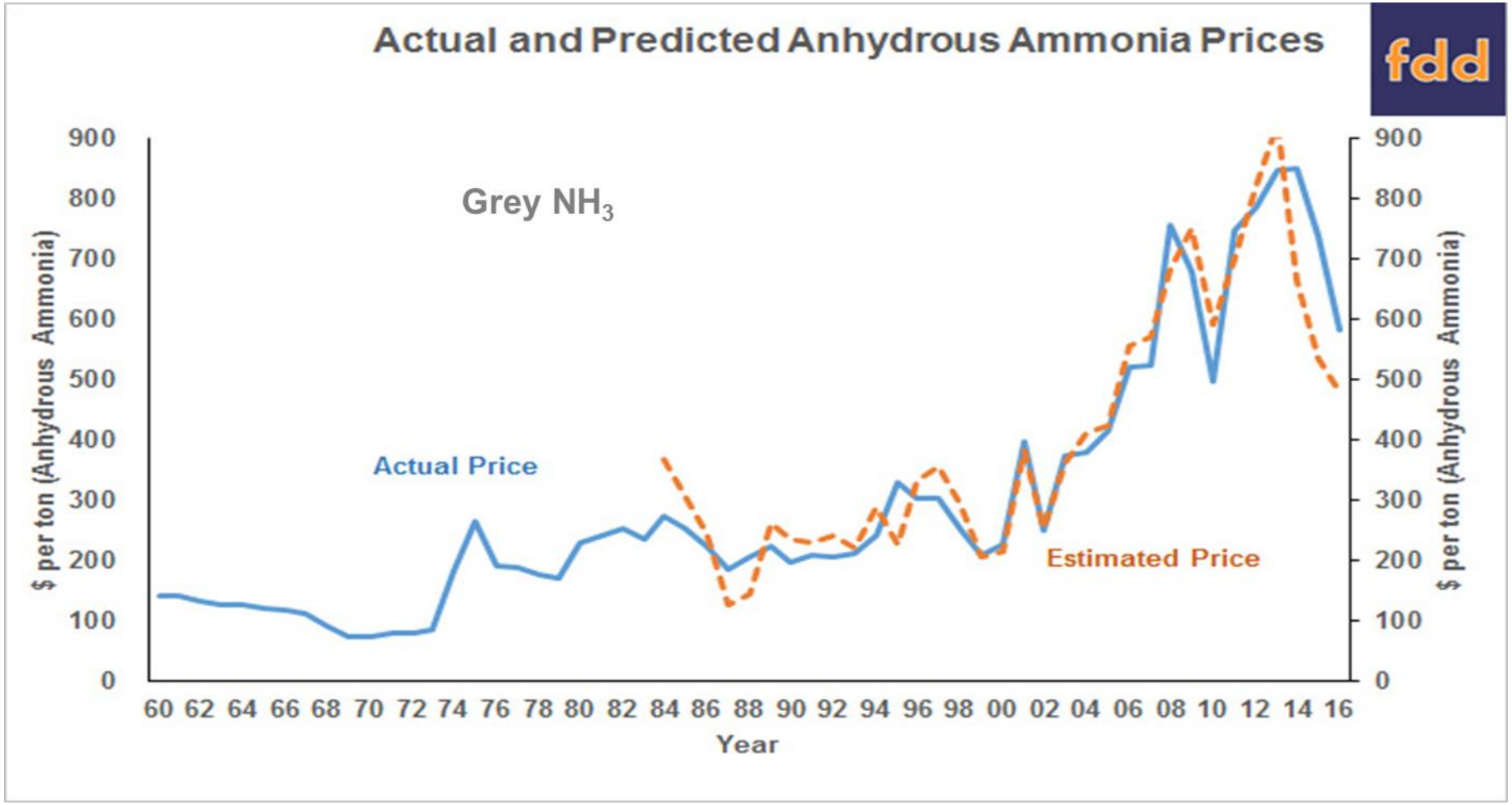
Green Ammonia Levelized Cost

Competitive Alternative to Volatile Grey Ammonia Markets

Grey Ammonia Price in USA

56 Years Period:
1960 to 2016

Price Range:
$100 to $850/ton



Green Ammonia Levelized Cost

Competitive Alternative to Volatile Grey Ammonia Markets

Grey Ammonia Price in USA

31 Years Period:
1990 to Oct 2021

Price Peak Oct-2021:
$1030/ton

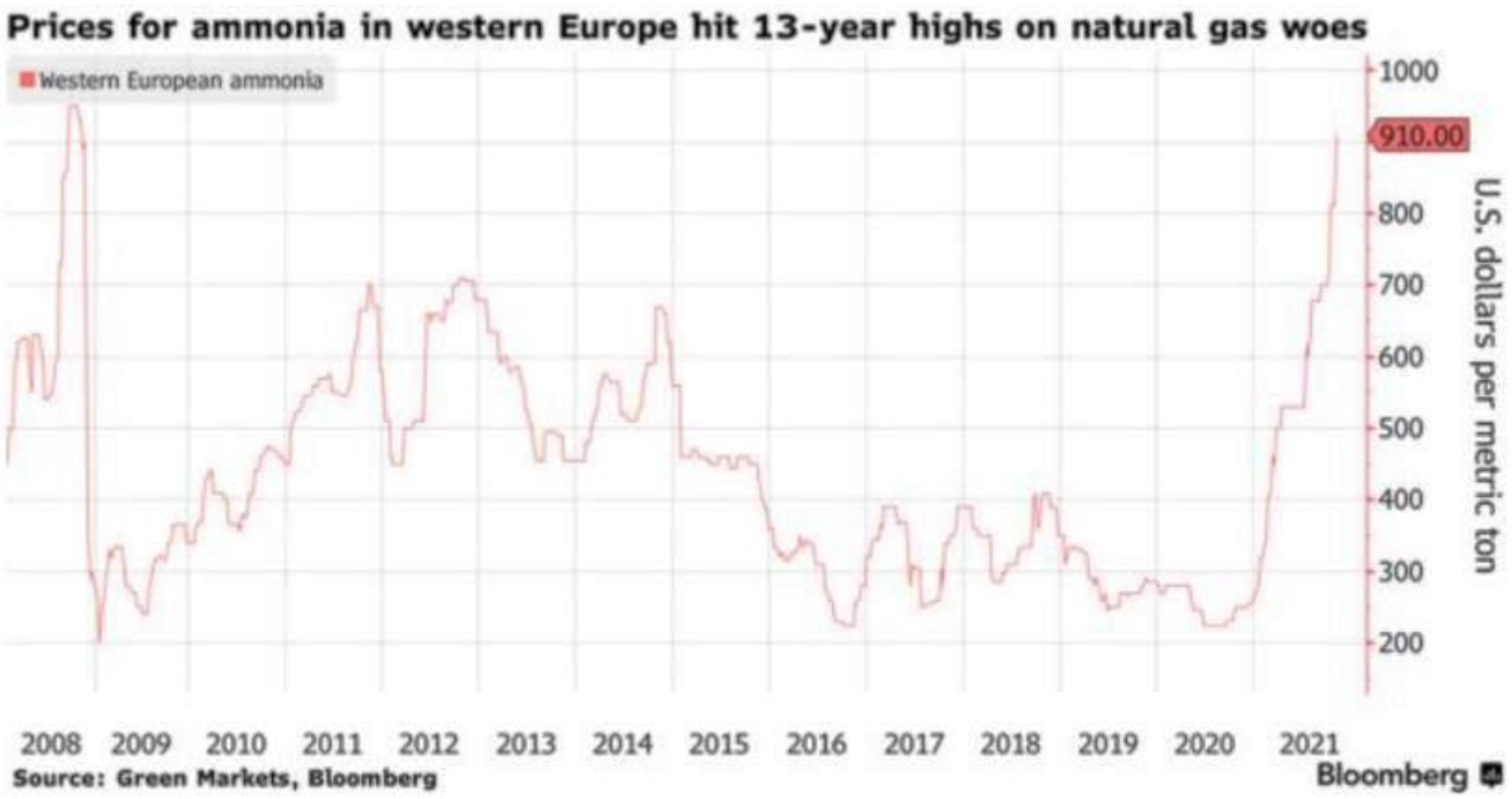
Green Ammonia Levelized Cost

Competitive Alternative to Volatile Grey Ammonia Markets

Grey Ammonia Price in Western Europe

13 Years Period:
2008 to Nov-2021

Price Peak Nov-2021:
$910/ton



Green Ammonia Levelized Cost

Competitive Alternative to Volatile Grey Ammonia Markets

- ***Green Ammonia Offers fixed price contract for 30 years***
- ***Business Case Key Assumptions Under Favorable & Optimum Conditions (e.g., Morocco, Chile, Oman)***
  - *Technology: Water Electrolysis with Haber Bosch Synthesis & ASU*
  - *Plant Size & Capacity Factor: 1 GWe DC, 70% PV+Wind*
  - *CAPEX & OPEX: $1.39 Billion & 3.11% p.a*
  - *Energy Weighted Average Cost : $18/MWh*
  - *RE Powered RO Water Feedstock Cost: $3/$m^{3,}$, WACC: 4.56%*
  - *MMRA: cashflow funded for 10-yr stack replacement cycle (degradation calcs % per khr is considered)*
  - *Plant Lifecycle: 30 years*
  - *Business Case Estimated LCOA for 2025: $414/ton*
  - *2025 estimated Green Ammonia Levelized Cost 375-450 $/ton under favorable & optimum conditions*

Green Ammonia Levelized Cost

Competitive Alternative to Volatile Grey Ammonia Markets

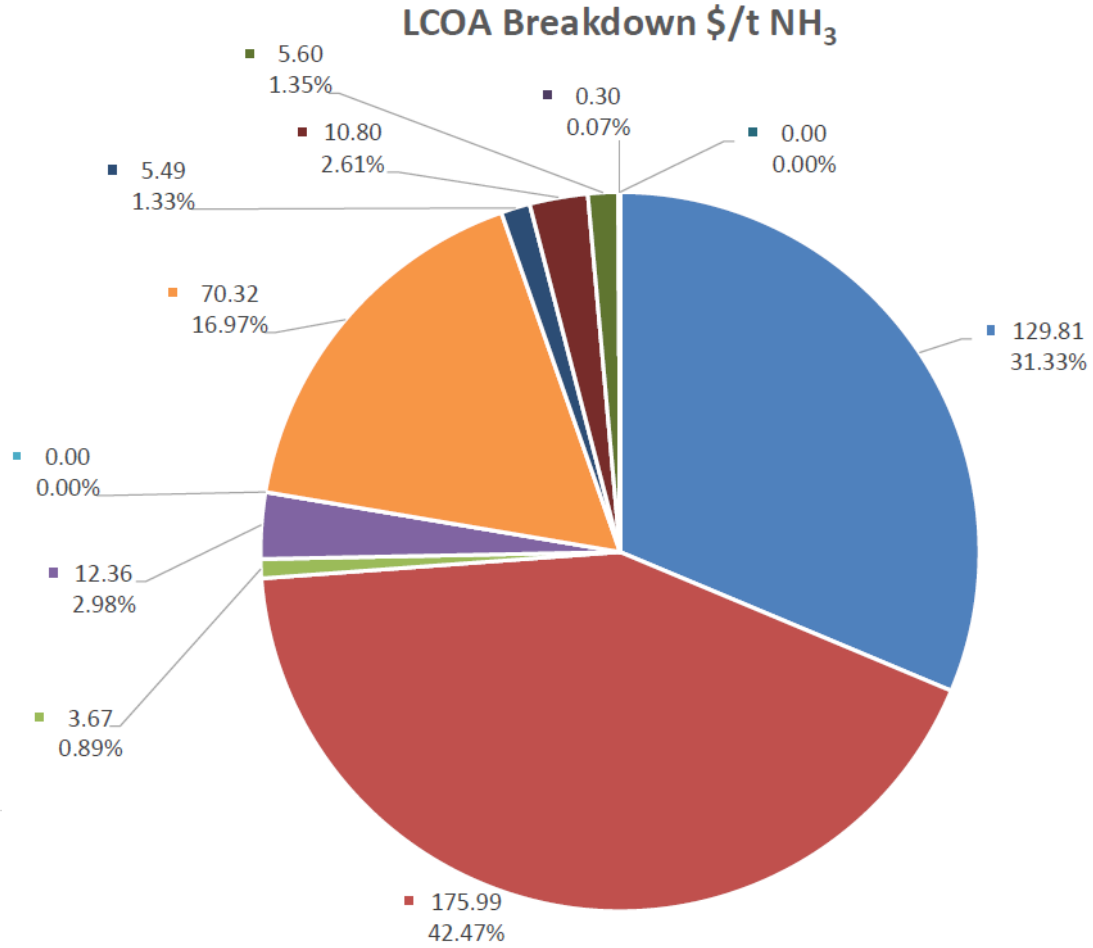
Typical Green Ammonia LCOA Breakdown: Business Case 2025 Under Favorable Conditions @ $414/ton Toolkit V7

OUTPUTS - 30 Years		
LCOA Component	Component $/t NH_3	Component Percentage
Capex Component	129.81	31.33%
Opex Component - Electrolysis Energy Cost	175.99	42.47%
Opex Component - H_2 Pre-Compression Energy Cost	3.67	0.89%
Opex Component - NH_3 Synthesis Energy Cost	12.36	2.98%
Opex Component - Other infra Energy Cost	0.00	0.00%
Opex Component - General Fixed O&M	70.32	16.97%
Opex Component - Water Cost	5.49	1.33%
Opex Component - Stack Replacement Cost	10.80	2.61%
Opex Component - HB-ASU Major Overhaul Cost	5.60	1.35%
Opex Component - Leased Land Cost	0.30	0.07%
Opex Component - Decom. & Res. Cost	0.00	0.00%
		Total Percentage Check
		100.00%
LCOA ($/t NH_3)	414.35	
LCOA (AED/t NH_3)	1,522.74	

Green Ammonia Levelized Cost

Competitive Alternative to Volatile Grey Ammonia Markets

Typical Green Ammonia LCOA Breakdown: Business Case 2025 Under Favorable Conditions @ $414/ton Toolkit V7



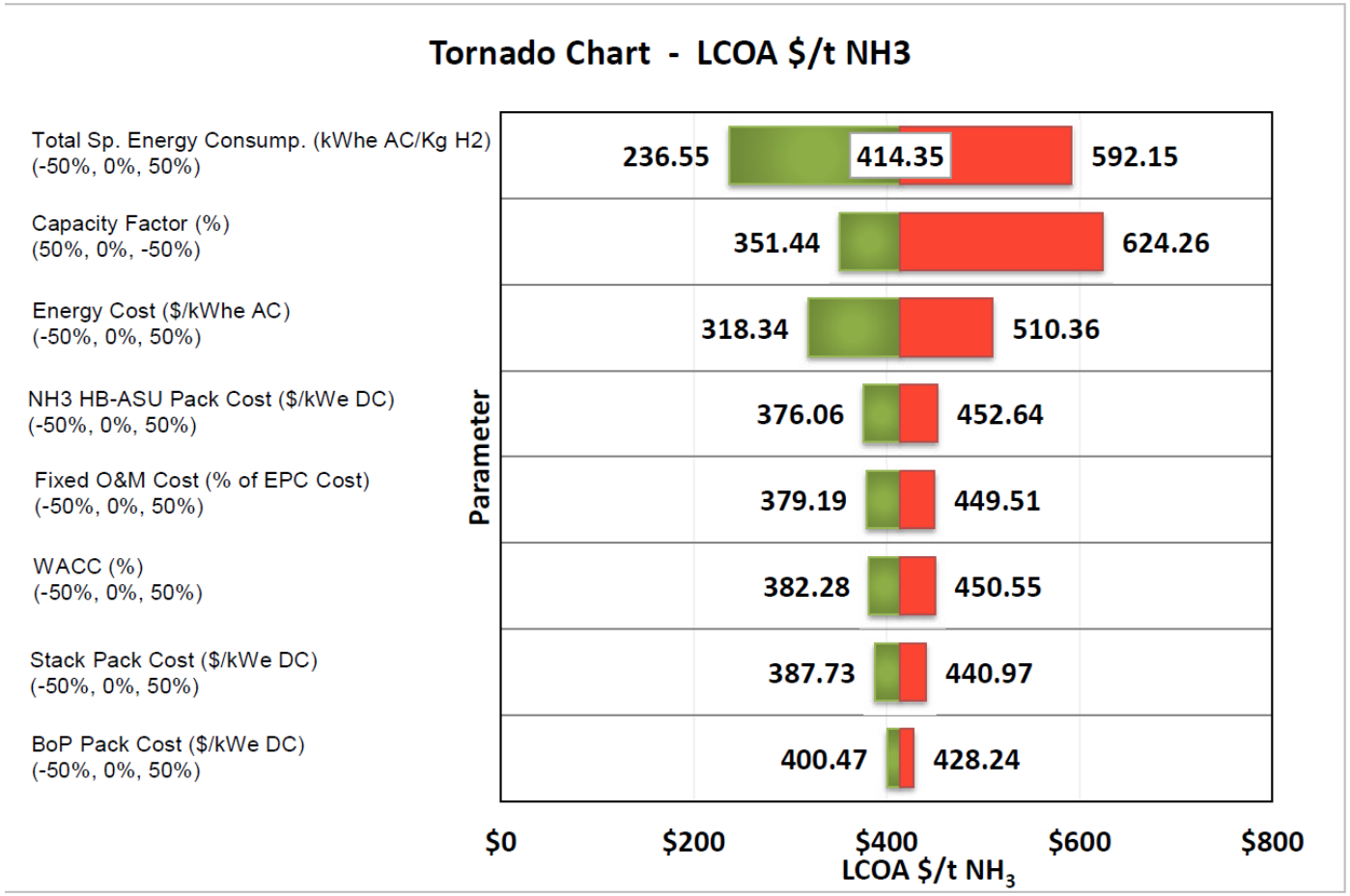
Green Ammonia Levelized Cost

Competitive Alternative to Volatile Grey Ammonia Markets

Green Ammonia LCOA Sensitivity Analysis
2025 Business Case
Significant Room for Improvement by 2050
Toolkit V7

LCOA Key Improvement Drivers:

- *Cumulative learning rates across the board*
- *Maintaining high annual capacity factors*
- *Electrolyzer efficiency increase*
- *Renewable energy cost decrease*
- *CAPEX cost decrease*
- *By 2050, Green Ammonia LCOA could fall to as low as $300/ton*



Takeaways

- The green molecules era has arrived.
- Their contribution to the energy transition will rise and accelerate.
- Balancing the technical solutions with sound economics will be critical to the success.
- Clear long-term standards / policy / regulatory environments w/ risk-balanced offtake agreements are vital for bankable projects development.
- Again, all hands must be on deck!

Thank You For Your Attention!

Contact:
Fadi Maalouf
CTO - Director IPP & EPC
+971 50 624 6126
fadi@dii-desertenergy.org
www.dii-desertenergy.org