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Supplemental Information

Nurturing the Blossoming Hydrogen Economy Using HBAT: Modelling Every Link in the H_2 Supply Chain

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I. Economic constants and assumptions

HBAT's algorithm has many layers of calculations operating in parallel to produce results. Most of the specific calculations can be seen by downloading the newest version of HBAT and checking the cell equations. Equations 1 through 39 are shown in the main text, but supplementary equations and constants are shown in the following section. Unless otherwise noted, fluid properties were calculated using default user parameters at the equivalent rate of 50,000 kg H_2/day.

Table S1.

Constant	Value	Units	Equation
A_1	0.2016	-	1
A_2	1.9608	-	1
A_3	10000	hr kg^{-1}	1
A_4	0.961	-	1
A_5	19.916	-	1
B_1	-1.3028×10^{-12}	K^{-3} psi^{-1}	3
B_2	1.4×10^{-13}	K^{-3}	3
B_3	1.6873×10^{-9}	K^{-2} psi^{-1}	3
B_4	-1×10^{-10}	K^{-2}	3
B_5	-8.1388×10^{-7}	K^{-1} psi^{-1}	3
B_6	4×10^{-8}	K^{-1}	3
B_7	1.732×10^{-4}	psi^{-1}	3
B_8	1.0001	-	3
C_1	63027	USD	4
C_2	0.0697	in^{-1}	4
C_3	251.737	USD in^{-2}	4
C_4	60848.1	USD in^{-1}	4
C_5	303657	USD	4
P_{in}	1000	psi	1, 3
P_{out}	700	psi	1, 3
ρ_{rel}	0.06897	-	1
T	298.15	K	1, 3
Re_{HCOOH}	53375	-	6
Re_{CH3OH}	56103	-	6
Re_{NH3}	168623	-	6
$Re_{HCOOCH3}$	176294	-	6
ε	4.6×10^{-5}	m	6
x_{mat}	0.75	-	7
$\%R_1$	100	%	24
$\%R_2$	5	%	24, 27

Supplemental equations:

(S1)
$$\dot{W}_{compressor} = Z_{LM} \cdot \frac{\dot{M} \cdot R \cdot T}{36 M_W \cdot \epsilon} \cdot \frac{\gamma}{\gamma - 1} \cdot \left[\left(\frac{P_{in}}{P_0} \right)^{\frac{\gamma-1}{N \cdot \gamma}} - 1 \right]$$

(S2)
$$\dot{W}_{liquefier} = 19.4312 \cdot \dot{M}^{0.9} \cdot N^{0.1}$$

(S3)
$$Break\ Even\ Emissions\ Recovery\ Time\ (t_{leak}\ in\ hrs) = t_{leak} \cdot \frac{GWP \cdot \dot{M}}{\dot{CF}_{net}}$$

(S4)
$$Break\ Even\ Leak\ Rate = \frac{1}{\frac{GWP \cdot \dot{M}}{\dot{CF}_{net}} + 1} \cdot 100\%$$

II. Supply chain specification table

Table S2.

Supply Chain #	Production	Storage	Transport	End Use
1	Biomass Gasification	Gas H2	Pipeline	Fertilizer
2	Biomass Gasification	Gas H2	Pipeline	FCEV vehicle filling
3	Biomass Gasification	Gas H2	Railcar	Fertilizer
4	Biomass Gasification	Gas H2	Railcar	FCEV vehicle filling
5	Biomass Gasification	Formic Acid	Pipeline	Fertilizer
6	Biomass Gasification	Formic Acid	Pipeline	FCEV vehicle filling
7	Biomass Gasification	Formic Acid	Railcar	Fertilizer
8	Biomass Gasification	Formic Acid	Railcar	FCEV vehicle filling
9	Biomass Gasification	Liquid H2	Truck	Fertilizer
10	Biomass Gasification	Liquid H2	Truck	FCEV vehicle filling
11	Biomass Gasification	Liquid H2	Railcar	Fertilizer
12	Biomass Gasification	Liquid H2	Railcar	FCEV vehicle filling
13	CO2 Electrolysis PV Coupled	Methyl Formate	Pipeline	Fertilizer
14	CO2 Electrolysis PV Coupled	Methyl Formate	Pipeline	FCEV vehicle filling
15	CO2 Electrolysis PV Coupled	Methyl Formate	Railcar	Fertilizer

16	CO2 Electrolysis PV Coupled	Methyl Formate	Railcar	FCEV vehicle filling
17	CO2 Electrolysis PV Coupled	Formic Acid	Pipeline	Fertilizer
18	CO2 Electrolysis PV Coupled	Formic Acid	Pipeline	FCEV vehicle filling
19	CO2 Electrolysis PV Coupled	Formic Acid	Railcar	Fertilizer
20	CO2 Electrolysis PV Coupled	Formic Acid	Railcar	FCEV vehicle filling
21	CO2 Electrolysis PV Coupled	Methanol	Pipeline	Fertilizer
22	CO2 Electrolysis PV Coupled	Methanol	Pipeline	FCEV vehicle filling
23	CO2 Electrolysis PV Coupled	Methanol	Railcar	Fertilizer
24	CO2 Electrolysis PV Coupled	Methanol	Railcar	FCEV vehicle filling
25	N2 Electrolysis PV Coupled	Ammonia	Pipeline	Fertilizer
26	N2 Electrolysis PV Coupled	Ammonia	Pipeline	FCEV vehicle filling
27	N2 Electrolysis PV Coupled	Ammonia	Railcar	Fertilizer
28	N2 Electrolysis PV Coupled	Ammonia	Railcar	FCEV vehicle filling
29	H2O electrolysis PV Coupled	Gas H2	Pipeline	Fertilizer
30	H2O electrolysis PV Coupled	Gas H2	Pipeline	FCEV vehicle filling
31	H2O electrolysis PV Coupled	Gas H2	Railcar	Fertilizer
32	H2O electrolysis PV Coupled	Gas H2	Railcar	FCEV vehicle filling
33	H2O electrolysis PV Coupled	Formic Acid	Pipeline	Fertilizer
34	H2O electrolysis PV Coupled	Formic Acid	Pipeline	FCEV vehicle filling
35	H2O electrolysis PV Coupled	Formic Acid	Railcar	Fertilizer
36	H2O electrolysis PV Coupled	Formic Acid	Railcar	FCEV vehicle filling
37	H2O electrolysis PV Coupled	Liquid H2	Truck	Fertilizer
38	H2O electrolysis PV Coupled	Liquid H2	Truck	FCEV vehicle filling
39	H2O electrolysis PV Coupled	Liquid H2	Railcar	Fertilizer
40	H2O electrolysis PV Coupled	Liquid H2	Railcar	FCEV vehicle filling
41	SMR	Gas H2	Pipeline	Fertilizer

42	SMR	Gas H2	Pipeline	FCEV vehicle filling
43	SMR	Gas H2	Railcar	Fertilizer
44	SMR	Gas H2	Railcar	FCEV vehicle filling
45	SMR	Formic Acid	Pipeline	Fertilizer
46	SMR	Formic Acid	Pipeline	FCEV vehicle filling
47	SMR	Formic Acid	Railcar	Fertilizer
48	SMR	Formic Acid	Railcar	FCEV vehicle filling
49	SMR	Liquid H2	Truck	Fertilizer
50	SMR	Liquid H2	Truck	FCEV vehicle filling
51	SMR	Liquid H2	Railcar	Fertilizer
52	SMR	Liquid H2	Railcar	FCEV vehicle filling
53	CO Purchase	Methyl Formate	Pipeline	Fertilizer
54	CO Purchase	Methyl Formate	Pipeline	FCEV vehicle filling
55	CO Purchase	Methyl Formate	Railcar	Fertilizer
56	CO Purchase	Methyl Formate	Railcar	FCEV vehicle filling
57	CO Purchase	Formic Acid	Pipeline	Fertilizer
58	CO Purchase	Formic Acid	Pipeline	FCEV vehicle filling
59	CO Purchase	Formic Acid	Railcar	Fertilizer
60	CO Purchase	Formic Acid	Railcar	FCEV vehicle filling
61	CO Purchase	Methanol	Pipeline	Fertilizer
62	CO Purchase	Methanol	Pipeline	FCEV vehicle filling
63	CO Purchase	Methanol	Railcar	Fertilizer
64	CO Purchase	Methanol	Railcar	FCEV vehicle filling

III. Supplemental Analysis - Feedstock Price Perturbation

The default scenarios, *1* through *64*, utilise commodity price data found in government databases, techno-economic analyses, and market data hubs. Similarly, as discussed in the previous section, the changes in the price of the feedstocks can significantly alter the economic viability of a business case. This section analyses the effect of increasing, and occasionally decreasing, the purchase price of these commodities to visualise how future market fluctuations can potentially disturb the hydrogen business.

Figure SA1 shows key parameters of the 25-year NPV functions for all non-electrolyser supply chains. These NPV functions are derived from at least four feedstock price points (scenarios *1-12*, *41-64*, *129-132*, *161-196*, and *225-248*), starting at zero then low, medium, and high. When segregated by production technology and end-use, there is an interesting linear trend that appears when the maximum NPV is plotted against the break-even feedstock price. This trend correlates supply chains with different storage mediums and transportation methods, indicating that the rate of NPV appreciation depends only on the production method and end-use. The storage medium and transportation method seem to only affect the maximum achievable NPV and does not change the relationship between NPV and feedstock price. This is a peculiar result since there appears to be no obvious connection between those supply chains. Nevertheless, the result makes determining break-even feedstock prices very predictable, as any new supply chain may be classified into any of the six groups in Figure SA1 and the break-even feedstock price can be determined from the NPV of the zero-cost business.

Similarly, the BEHP can also be grouped into the same six groups. Figure SA2 shows the minimum achievable BEHP for each supply chain. Using the feedstock price correlation shown in Figure S6, one can determine the price necessary to reach a BEHP of 2.00 USD kg^{-1} can be determined by the X-intercept. This equivalent feedstock price is plotted on the vertical axis of Figure SA2 to show the linear relationship for each class of supply chains. In plots A, D, and E, most supply chains are not able to reach the desired BEHP. Despite this, they still correlate with the other data to create a strong regression line. The Y-intercept of this line shows the maximum feedstock price for each class that can still break-even selling hydrogen at the aforementioned price. The Y-intercepts

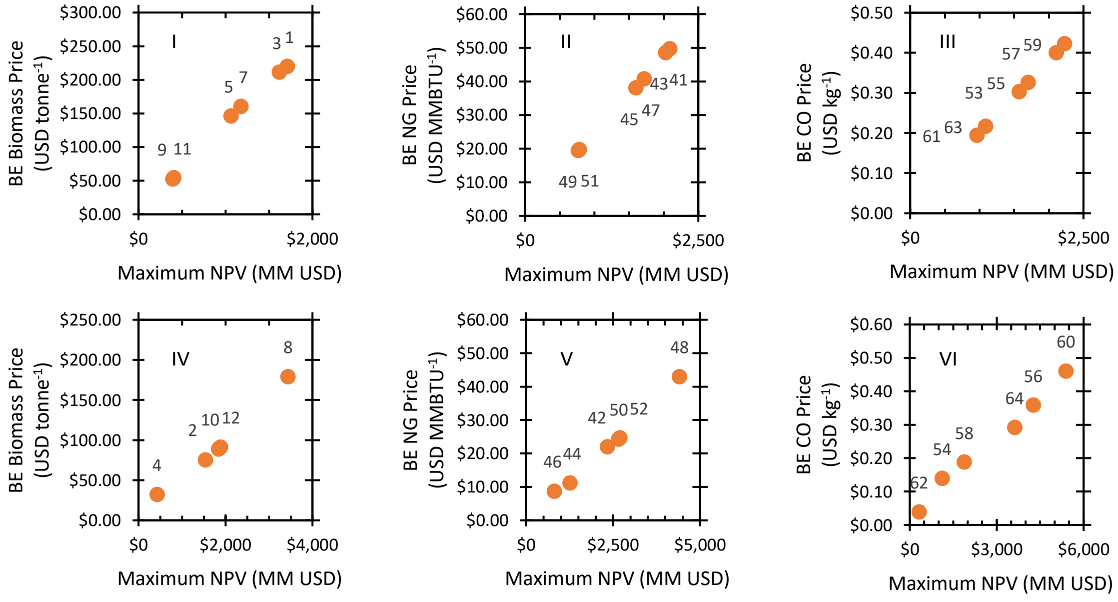


Figure SA1 25-year net present value functions, separated by feedstock type and end-use. A feedstock price of zero provides the maximum achievable NPV, plotted against the break-even feedstock price to achieve a positive NPV. Each point is labelled with the respective supply chain. (A) Wood BG-Fertiliser Manufacturing (B) Wood BG-FCEV Filling (C) SMR-Fertiliser Manufacturing (D) SMR-FCEV Filling (E) CO Purchase-Fertiliser Manufacturing (F) CO Purchase-FCEV Filling. Supply chain 6 is not shown on the B plot because its maximum NPV is negative.

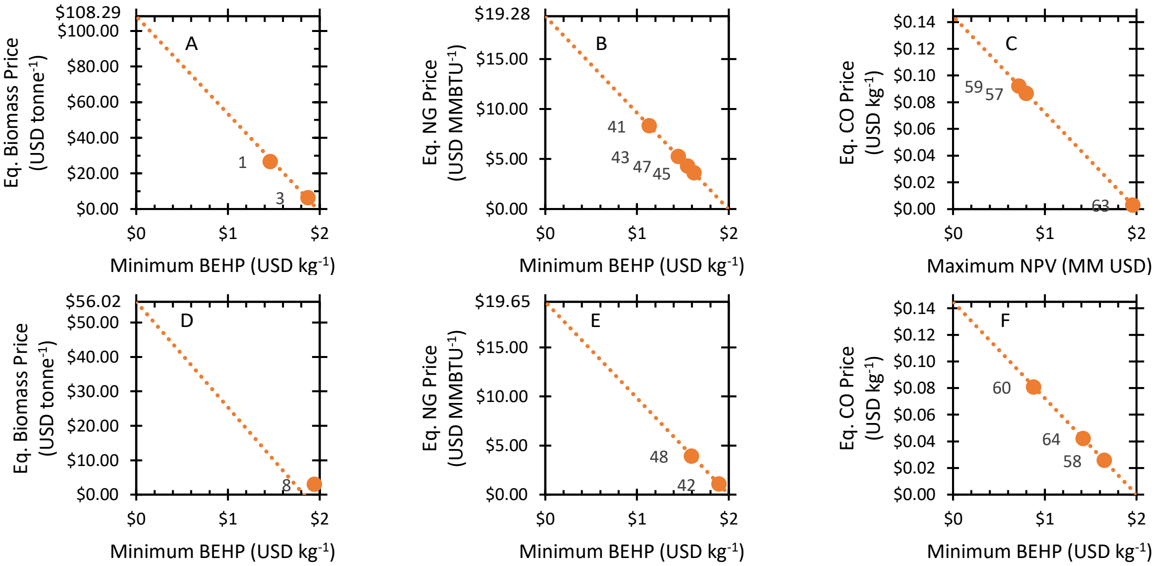


Figure SA2 Break-even hydrogen price functions, separated by feedstock type and end-use. A feedstock price of zero provides the minimum achievable BEHP, plotted against the minimum feedstock price needed to achieve a BEHP of 2.00 USD kg^{-1}. Each point is labelled with the respective supply chain. (A) Wood BG-Fertiliser Manufacturing (B) Wood BG-FCEV Filling (C) SMR-Fertiliser Manufacturing (D) SMR-FCEV Filling (E) CO Purchase-Fertiliser Manufacturing (F) CO Purchase-FCEV Filling. Points not shown on the plot have negative equivalent feedstock prices.

indicate that the change in end-use does not have a significant effect; only plot 21A and 21D display a major difference. Furthermore, the latter's weaker regression ($R^2 = 0.9743$) is significantly more variable than the next sparse regression ($R^2 = 0.9996$), so the difference should be questioned. This is mainly due to an outlier, supply chain 4 at point (5.34, -103.38), which has a high leverage and pulls the Y-intercept of the regression down. Excluding this outlier, the Y-intercept and regression coefficient become 94.84 USD tonne^{-1} and 0.9864 respectively, approaching the regression of plot 21A. Despite the results from a two-sample t-test indicating that only 21C and 21F are statistically identical using 95% confidence, the effect of varying the end-use is negligible in each case.

III. Supplemental Figures

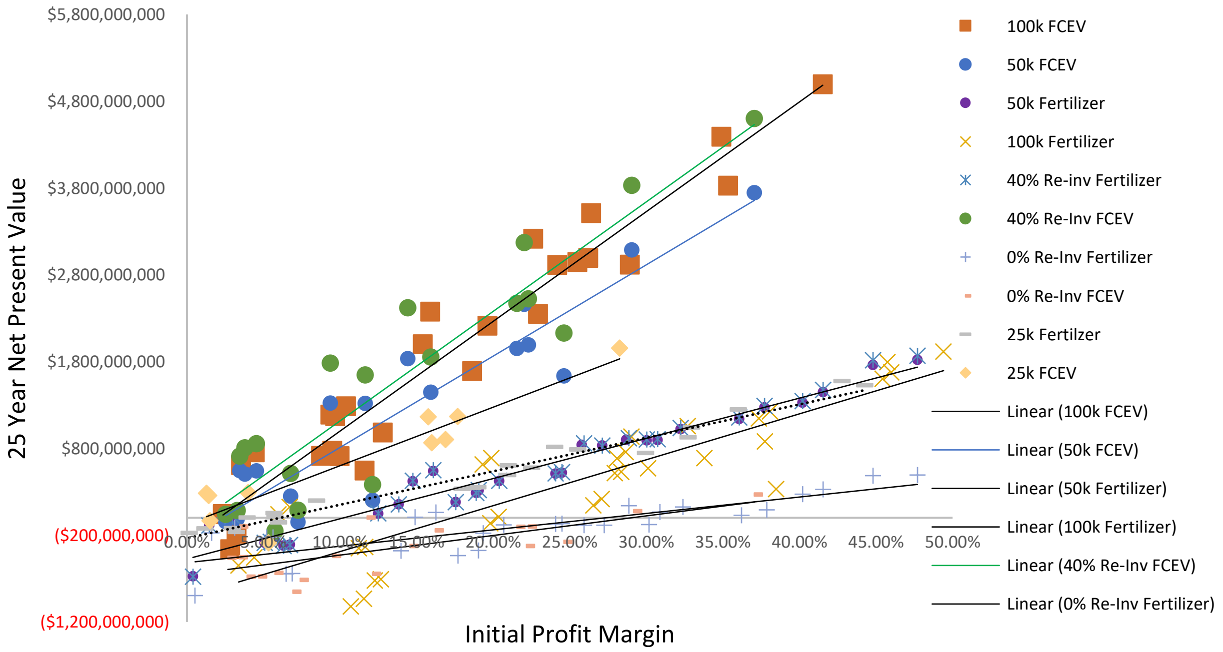


Figure S1. NPV achieved for various scaling strategies, plotted against the respective initial profit margin.

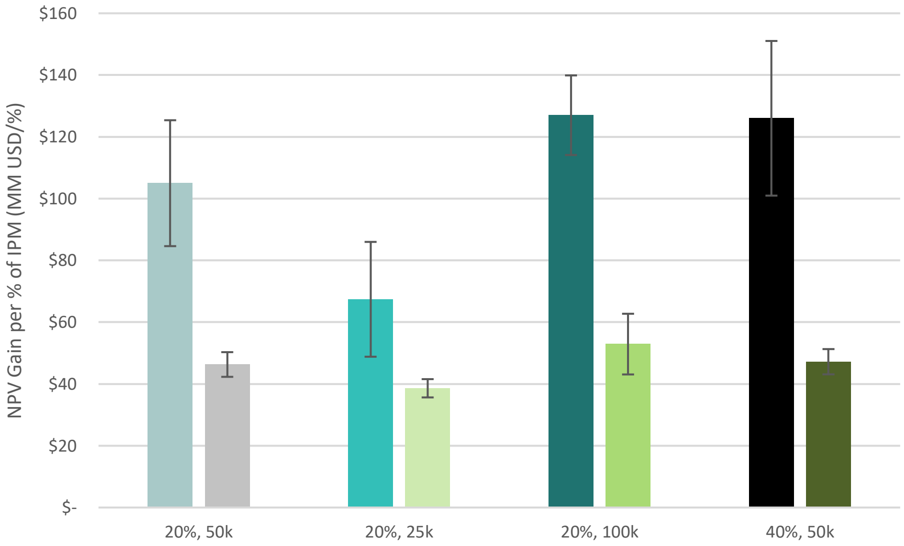


Figure S2. Slope of NPV as a function of Initial Profit Margin (IPM). Shown with regression confidence intervals and split into experimental groups. [end-use, initial daily production, reinvestment rate]: FCEV, 50k, 40% (**olive**); FCEV, 100k, 20% (**green**); FCEV, 50k, 20% (**grey**); FCEV, 25k, 20% (**light green**); Fert., 25k, 20% (**cyan**); Fert., 50k, 20% (**pale blue**); Fert., 50k, 40% (**black**); Fert., 100k, 20% (**dark blue**).

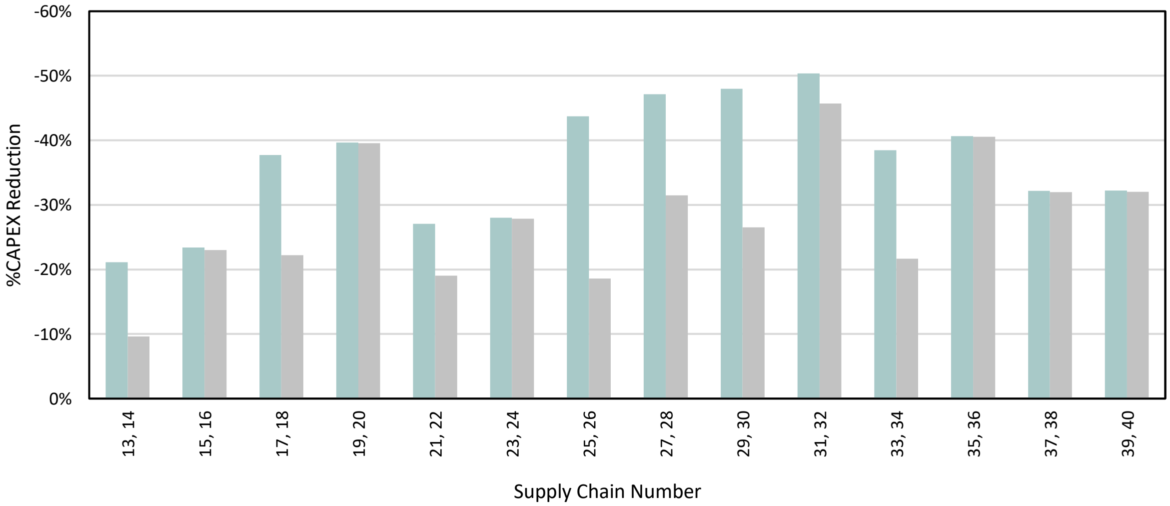


Figure S3. Reduction in total overnight cost for each electrolyser supply chain. Fertiliser supply chains are shown in **pale blue** and FCEV filling supply chains are shown in **grey**.

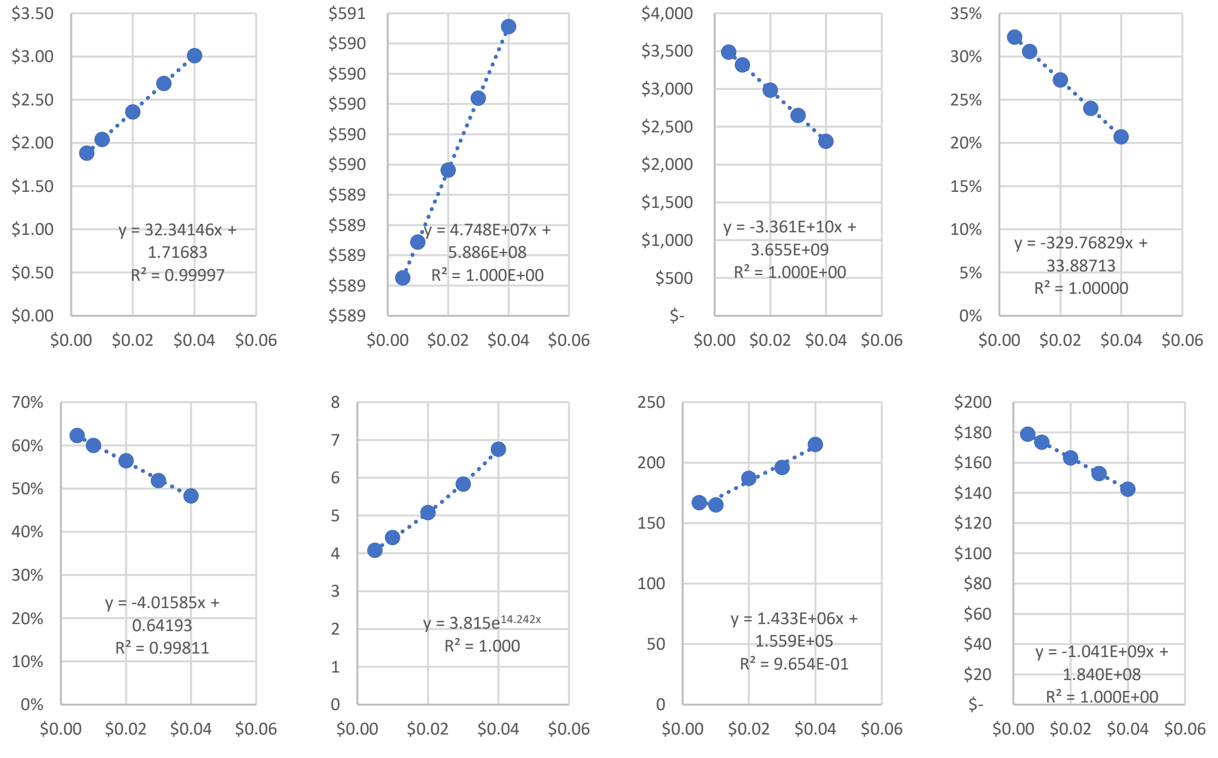


Figure S4. Business properties of supply chain **20** as a function of electricity price during 23-hour operation strategy: **A**. Break-even hydrogen price; **B**. Total overnight cost (MM USD); **C**. Net present value (MM USD); **D**. Initial profit margin; **E**. Max profit margin; **F**. Payback period; **G**. Minimum profitable production scale (x 10^3 kg/day); **H**. Monthly EBITDA at year 25 (MM USD).

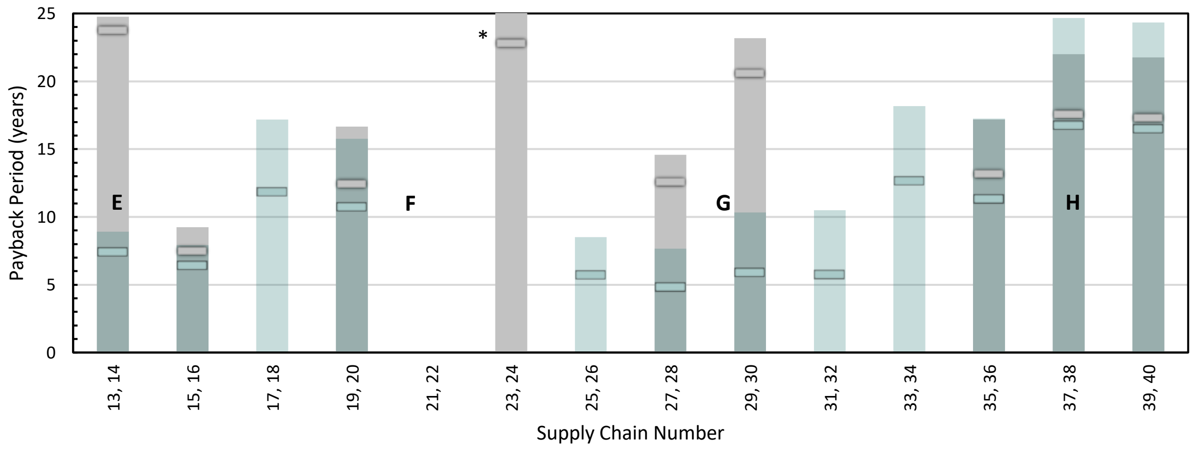


Figure S5. Payback period comparison between the default electrolyser scenarios (bars) and the 0.04 USD/kWh electricity purchasing scenario using the 23-hour strategy. Supply chains that do not achieve a payback period less than 25 years with either strategy are not shown. *PBP for supply chain **24** is greater than 25 years.

Figure S6. Example of linear regression of BEHP vs. price for SMR supply chains.

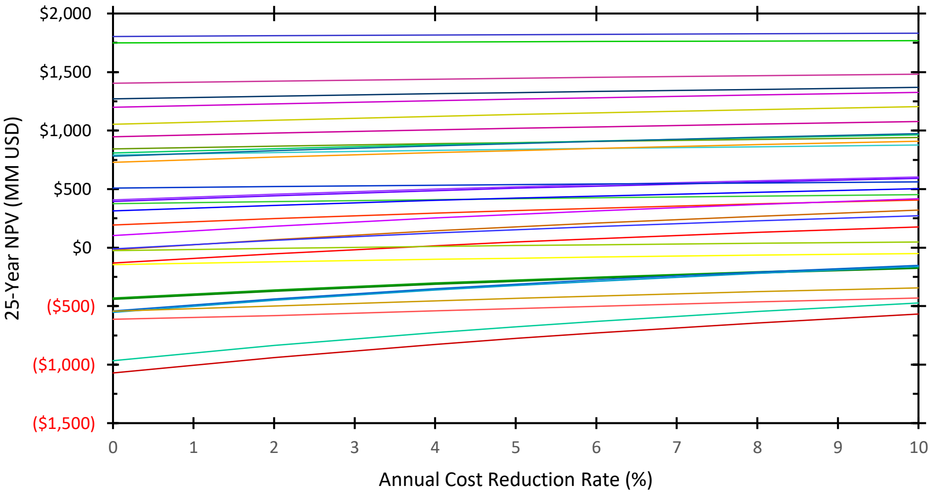


Figure S7. Net present value scaling functions for all 32 fertiliser manufacturing supply chains. Data were collected at ASCR rates of 0%, 2%, 4%, 5%, 6%, 8%, and 10%. List on the right indicates the colour designation of each supply chain and the value of the 10% ASCR rate NPV.

Supply Chain	Fert., FCEV
1,2:	$941, $524
3,4:	$876, N/A
5,6:	$406, -$633
7,8:	$503, $1894
9,10:	-$177, $574
11,12:	-$167, $609
13,14:	$963, $886
15,16:	$1077, $3385
17,18:	$320, -$134
19,20:	$417, $2558
21,22:	-$568, -$1223
23,24:	-$473, $1066
25,26:	$1205, $477
27,28:	$1326, $3111
29,30:	$974, $1337
31,32:	$909, -$311
33,34:	$176, -$644
35,36:	$272, $1982
37,38:	-$163, $1415
39,40:	-$152, $1451
41,42:	$1832, $2316
43,44:	$1768, $713
45,46:	$1369, $1153
47,48:	$1482, $3931
49,50:	$592, $2406
51,52:	$603, $2443
53,54:	-$51, N/A
55,56:	$48, $245
57,58:	$453, N/A
59,60:	$562, $1447
61,62:	$431, N/A
63,64:	$344, $23

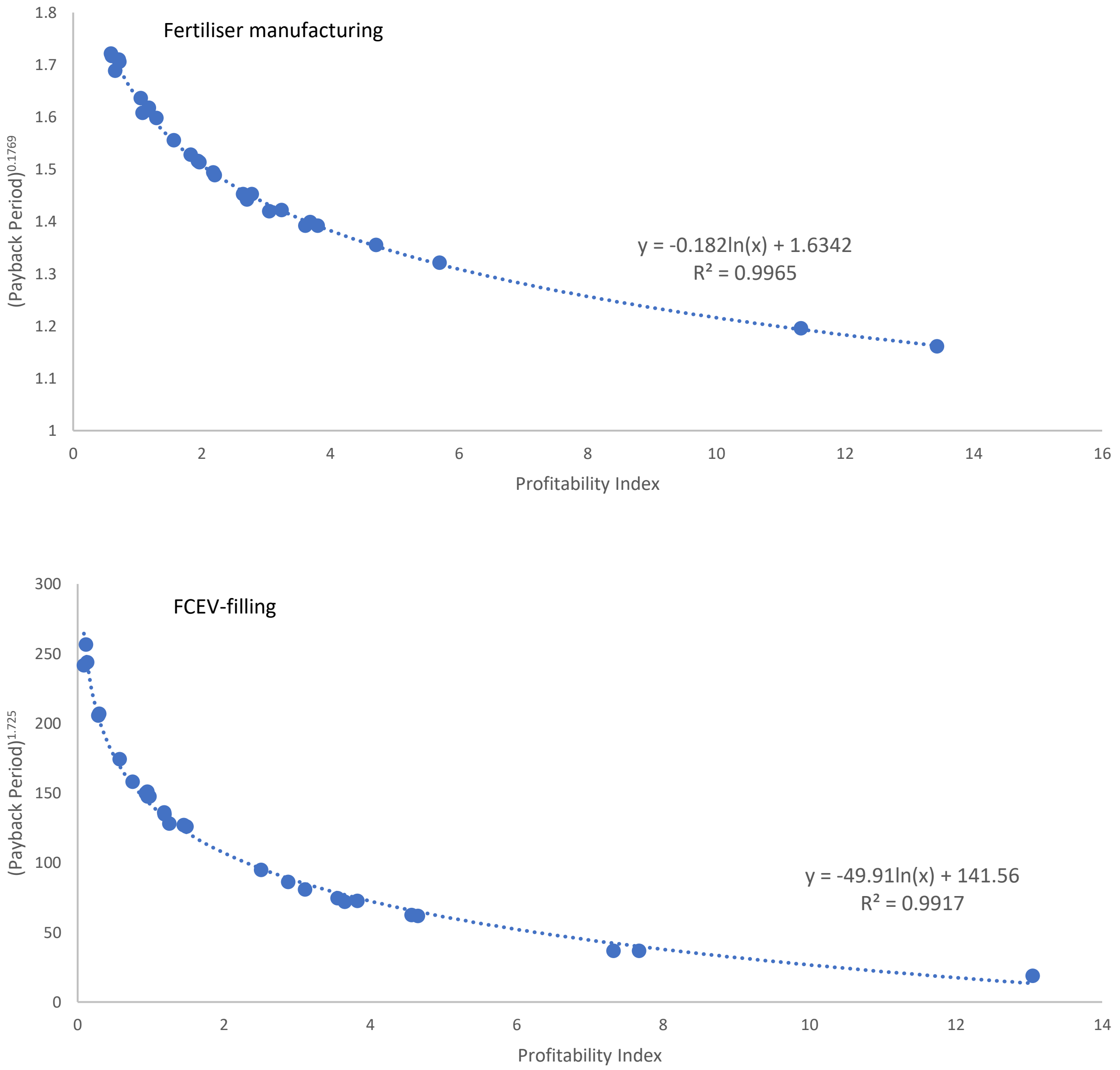


Figure S8. Correlation between profitability index and the supply chain's payback period. The parity between payback period exponents indicates the sensitivity of the payback period to the business case's PI, where fertiliser manufacturing is more sensitive to changes in PI.

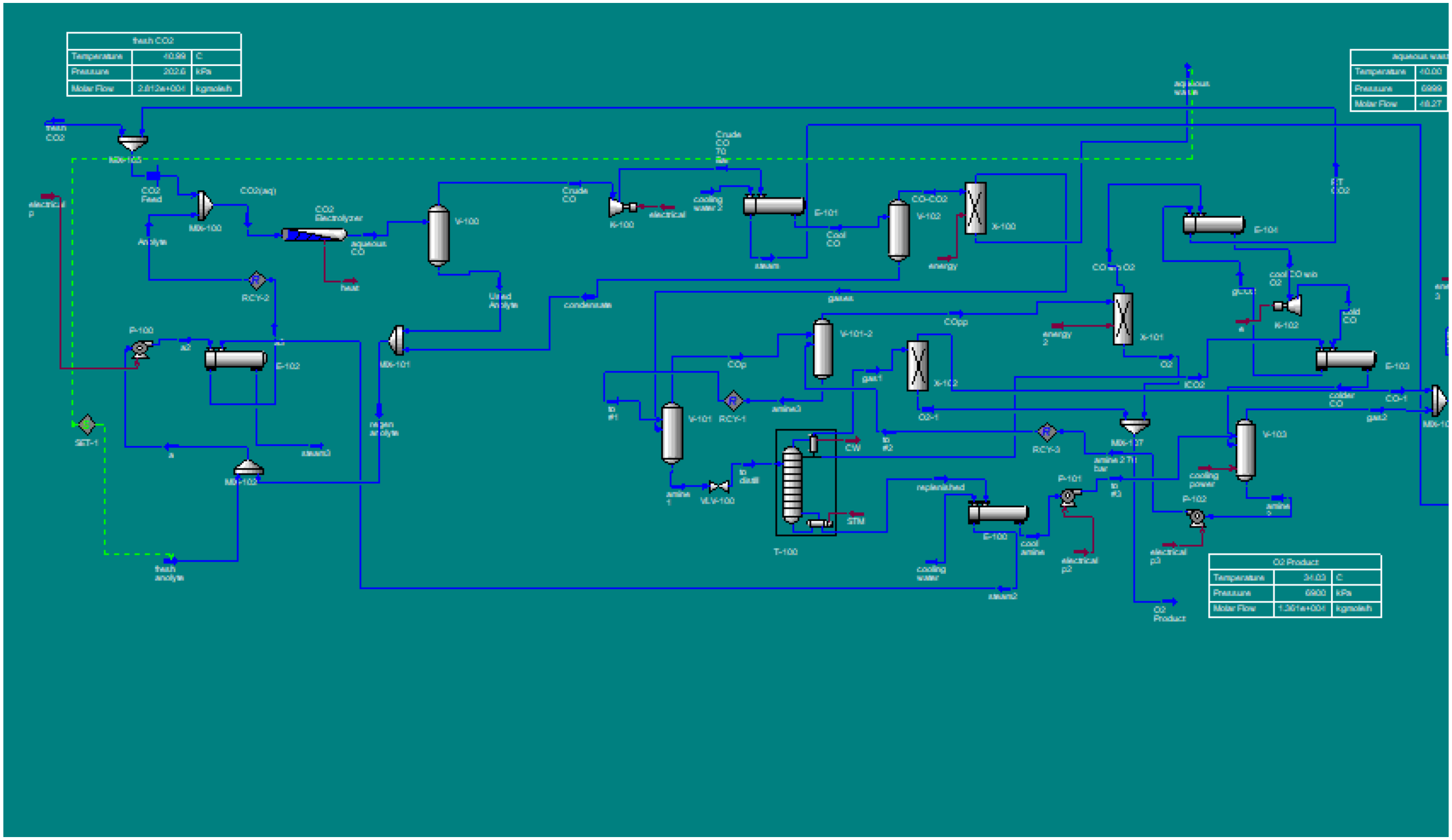
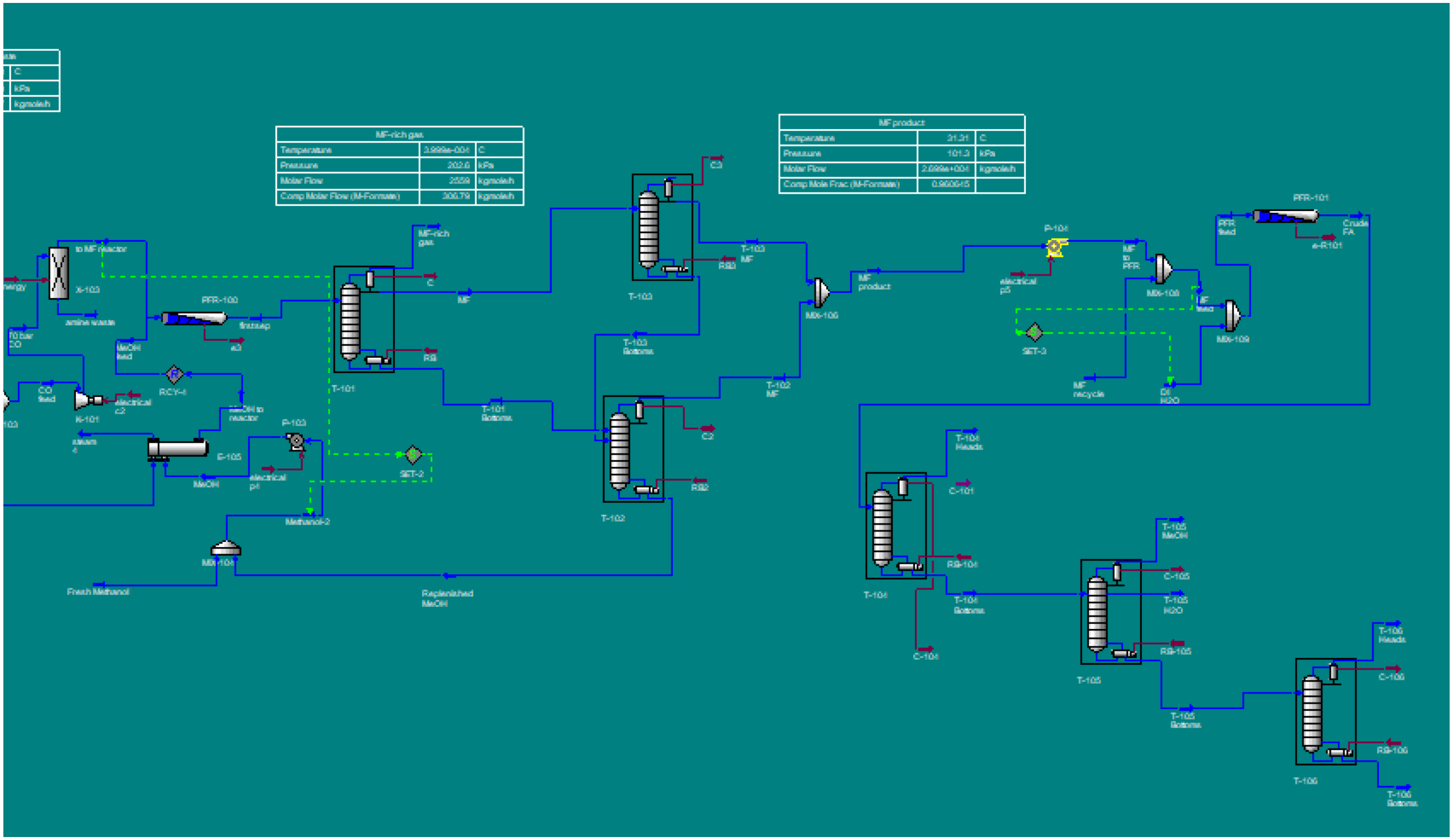


Figure S9. UniSim Design process flow diagram for a CO_2 electrolysis to formic acid supply chain. Electricity generation and transportation equipment not shown. Inlet streams include carbon dioxide, electrolyser analyte, methanol, and water. Outlet streams include aqueous waste, oxygen, methyl formate-rich gas, methanol recycle, and formic acid.



MF-rich gas		
Temperature	3.999e-004	C
Pressure	202.6	kPa
Molar Flow	2559	kgmole/h
Comp Molar Flow (M-Formate)	300.79	kgmole/h

MF product		
Temperature	31.31	C
Pressure	101.3	kPa
Molar Flow	2.699e+004	kgmole/h
Comp Mole Frac (M-Formate)	0.980015	

Figure S9. UniSim Design process flow diagram for a CO_2 electrolysis to formic acid supply chain. Electricity generation and transportation equipment not shown. Inlet streams include carbon dioxide, electrolyser analyte, methanol, and water. Outlet streams include aqueous waste, oxygen, methyl formate-rich gas, methanol recycle, and formic acid.

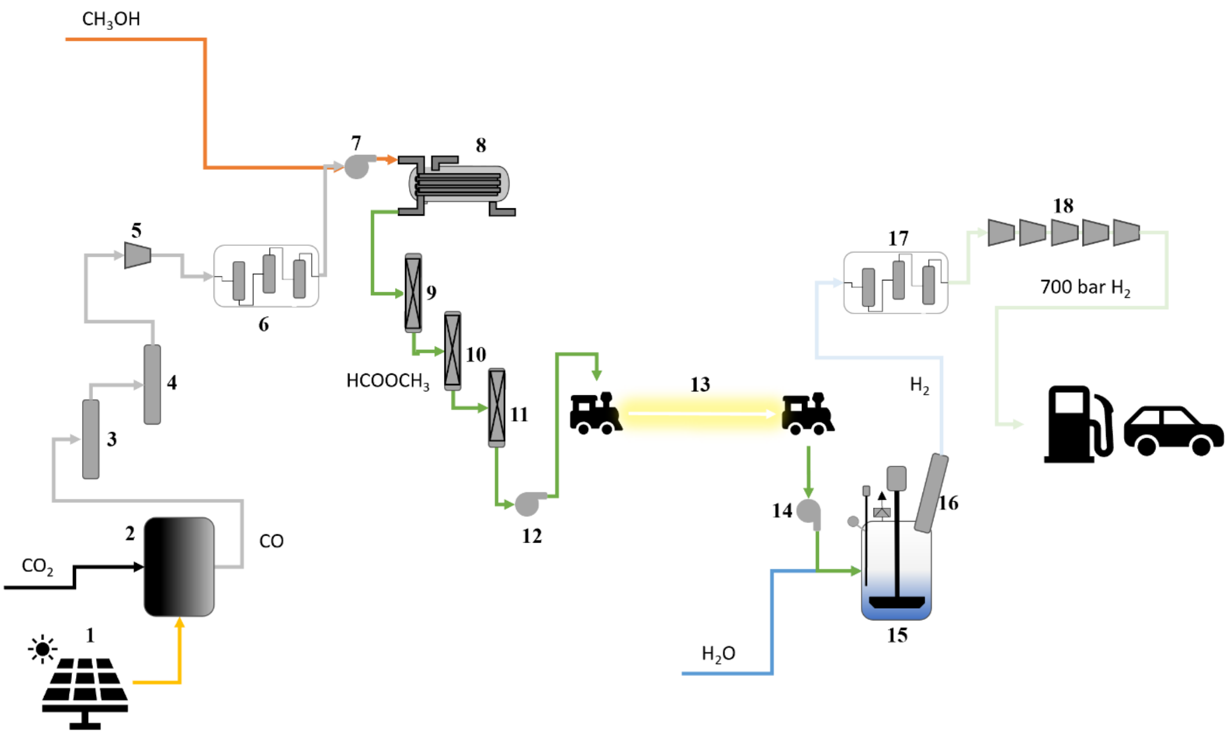


Figure S10. Simplified process flow diagram of supply chain **16**. All equipment items and processes costed in HBAT are listed with exceptions. For simplicity, heat exchangers, storage tanks, and recycle streams are not shown but are also accounted for. Production: PV-coupled CO_2 electrolysis; storage: methyl formate; transportation: railcar; end-use: FCEV filling.

Table S3. Example equipment list for supply chain **16**.

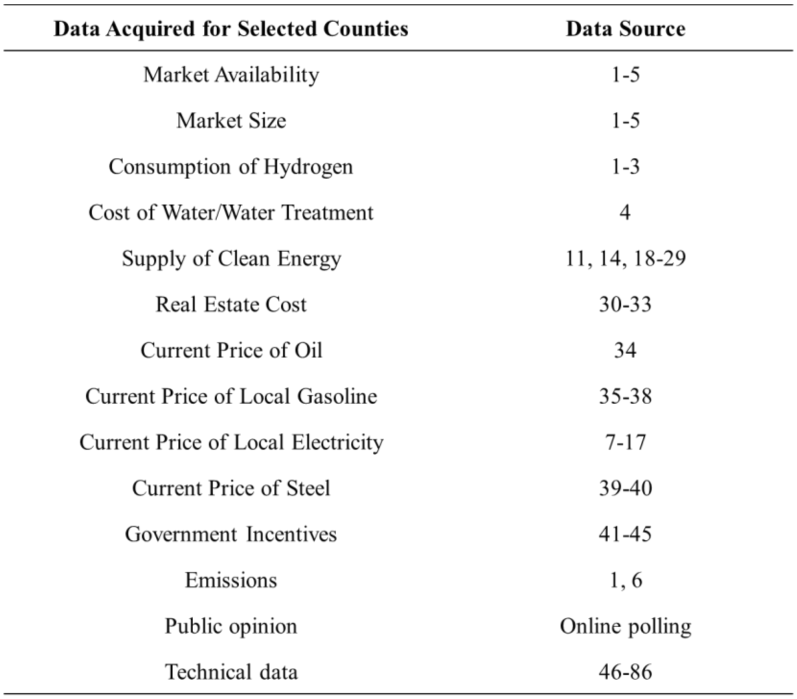
Identifier #	Equipment Item	Bare Module Cost (x10^3 USD)
1	PV Solar Arrays	53,000
2	CO_2 Electrolyser	43,000
3	Flash Vessel	50
4	Flash Vessel	50
5	Generic Compressor	1,703
6	Sweet/Sour Amine Seps.	57,000
7	Positive Displacement Pump	173
8	Plug-Flow Methanol Carbonylation Reactor	4,415
9	Distillation Column	433
10	Distillation Column	433
11	Distillation Column	433
12	Positive Displacement Pump	173
13	Methyl Formate Railcars	280
14	Positive Displacement Pump	173
15	Methyl Formate Dehydrogenation Reactor	107,000
16	Reflux Condenser	253
17	Pressure-Swing Adsorption Seps.	9,962
18	Five-Stage FCEV H_2 Compressors	4,617

Table S4. ASCR optimization results. Red highlight indicates negative NPV scenario.

Supply Chain #	Max R&D Annual Benefit per Point	Optimal ASCR (%)	Total Annual Benefit
1	$ 10,719,677	2	$ 21,439,355
2	$ 49,069,586	10	$ 490,695,858
3	$ 9,333,618	2	$ 18,667,236
4	$ 25,481,437	2	$ 50,962,875
5	$ 53,171,108	10	$ 531,711,077
6	$ 22,361,748	2	$ 44,723,496
7	$ 194,359,253	2	$ 388,718,506
8	$ 32,061,843	2	$ 64,123,687
9	$ 53,774,221	10	$ 537,742,211
10	$ 32,052,356	2	$ 64,104,712
11	$ 57,066,772	10	$ 570,667,720
12	$ 17,446,766	2	$ 34,893,532
13	$ 82,955,333	10	$ 829,553,328
14	$ 14,455,823	2	$ 28,911,647
15	$ 116,283,667	2	$ 232,567,334
16	$ 33,665,922	4	$ 134,663,689
17	$ 137,717,553	10	$ 1,377,175,530
18	$ 37,634,931	2	$ 75,269,862
19	$ 313,592,845	2	$ 627,185,691
20	$ 61,190,095	2	$ 122,380,191
21	$ 72,118,458	10	$ 721,184,579
22	$ 60,544,701	2	$ 121,089,401
23	$ 99,827,371	10	$ 998,273,707
24	$ 16,635,518	2	$ 33,271,037
25	$ 44,651,137	10	$ 446,511,375
26	$ 13,831,835	2	$ 27,663,670
27	$ 283,922,177	2	$ 567,844,353
28	$ 21,839,227	2	$ 43,678,454
29	$ 125,206,062	10	$ 1,252,060,624
30	$ 20,397,915	2	$ 40,795,829
31	$ 45,425,268	10	$ 454,252,679
32	$ 16,512,862	10	$ 165,128,620
33	$ 86,858,150	10	$ 868,581,499
34	$ 29,120,184	4	$ 116,480,737
35	$ 275,801,069	2	$ 551,602,139
36	$ 48,230,851	2	$ 96,461,703
37	$ 132,536,830	10	$ 1,325,368,301
38	$ 48,075,372	2	$ 96,150,744
39	$ 135,913,639	10	$ 1,359,136,387
40	$ 2,860,030	2	$ 5,720,061
41	$ 267,564,565	2	$ 535,129,130
42	$ 1,944,547	2	$ 3,889,094

43	$ 74,174,346	2	$ 148,348,692
44	$ 10,590,074	2	$ 21,180,148
45	$ 108,054,420	10	$ 1,080,544,203
46	$ 8,197,257	2	$ 16,394,513
47	$ 69,692,405	2	$ 139,384,810
48	$ 23,145,056	2	$ 46,290,112
49	$ 197,959,188	2	$ 395,918,376
50	$ 22,949,684	2	$ 45,899,368
51	$ 194,812,158	2	$ 389,624,316
52	$ 11,579,222	2	$ 23,158,444
53			
54	$ 4,456,026	10	$ 44,560,256
55	$ 22,960,153	10	$ 229,601,528
56	$ 8,724,343	2	$ 17,448,686
57			
58	$ 5,802,588	2	$ 11,605,175
59	$ 50,207,512	2	$ 100,415,024
60	$ 17,437,648	6	$ 104,625,889
61			
62	$ 20,920,996	4	$ 83,683,983
63	$ 52,064,201	10	$ 520,642,009
64	$ 10,719,677	2	$ 21,439,355

IV. Data sources and references



Data Acquired for Selected Counties	Data Source
Market Availability	1-5
Market Size	1-5
Consumption of Hydrogen	1-3
Cost of Water/Water Treatment	4
Supply of Clean Energy	11, 14, 18-29
Real Estate Cost	30-33
Current Price of Oil	34
Current Price of Local Gasoline	35-38
Current Price of Local Electricity	7-17
Current Price of Steel	39-40
Government Incentives	41-45
Emissions	1, 6
Public opinion	Online polling
Technical data	46-86

1. A. Elgowainy, M. Mintz, U. Lee, T. Stephens, P. Sun, K. Reddi, Y. Zhou, G. Zang, M. Ruth, P. Jadun, E. Connelly, R. Boardman. Assessment of Potential Future Demands for Hydrogen in the United States. 2020, Argonne National Laboratory.
2. U.S. Department of Energy. 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. doi: 10.2172/1271651. http://energy.gov/eere/bioenergy/2016-billion-ton-report.
3. Annual Energy Outlook 2022. U.S. Energy Information Administration. https://www.eia.gov/outlooks/aeo/
4. Water and Wastewater Annual Price Escalation Rates for Selected Cities Across the United States. U.S. Department of Energy Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/femp/downloads/water-and-wastewater-annual-price-escalation-rates-selected-cities-across-united
5. Kramer, A. Advanced Gasifier and Water Gas Shift Technologies for Low Cost Coal Conversion to High Hydrogen Syngas. 2016. Gas Technology Institute. DE-FE0023577 (DOE NETL)
6. Wang, M., et al., Summary of Expansions and Updates in GREET® 2021. 2021, Argonne National Lab: Argonna, IL.
7. Cost to refill. California Fuel Cell Partnership. https://cafcp.org/content/cost-refill
8. Orange County Electricity Rates. Electricity Local. https://www.electricitylocal.com/states/california/orange/
9. Eudy, L., Post, M. Orange County Transportation Authority Fuel Cell Electric Bus Progress Report. 2020. NREL/PR-5400-78250.
10. Report Confirms Wind Technology Advancements Continue to Drive Down the Cost of Wind Energy. Berkeley Lab. https://newscenter.lbl.gov/2019/08/26/report-confirms-wind-technology-advancements-continue-to-drive-down-the-cost-of-wind-energy/
11. Solar Panels in Orange County. Energy Sage. https://www.energysage.com/local-data/solar-panel-cost/

12. Orange County, California Electric Profile. Find Energy. https://findenergy.com/ca/orange-county-electricity
13. Wind Turbines in Texas. Quick Electricity. https://quickelectricity.com/wind-turbines-in-texas/
14. Solar Panel in Aransas County. Energy Sage. https://www.energysage.com/local-data/solar-panel-cost/tx/aransas-county/
15. Port Aransas Electricity Rates. Energy Bot. https://www.energybot.com/electricity-rates/texas/port-aransas/
16. Volusia County, Florida Electric Profile. Find Energy. https://findenergy.com/fl/volusia-county-electricity/
17. Santa Cruz Electricity Rates. Electricity Local. https://www.electricitylocal.com/states/california/santa-cruz/
18. Clean electricity gains momentum in Orange County despite price hikes. The OC Register. https://www.ocregister.com/2022/02/02/clean-electricity-gains-momentum-in-orange-county-despite-price-hikes/
19. Texas Electricity Resources. Comptroller Texas. https://comptroller.texas.gov/economy/fiscal-notes/2020/august/ercot.php
20. Volusia County Sustainable Action Plan. AECOM.
21. Fact check: The causes for Texas' blackout go well beyond wind turbines. Reuters. https://www.reuters.com/article/uk-factcheck-texas-wind-turbines-explain-idUSKBN2AJ2EI
22. World's Largest Green Hydrogen Project to Launch in California. SG H2 Energy. https://www.sgh2energy.com/worlds-largest-green-hydrogen-project-to-launch-in-california
23. State of Texas Energy Sector Risk Profile. Department of Energy.
24. Green Hydrogen International Announces Hydrogen City, Texas. PR Newswire. https://www.prnewswire.com/news-releases/green-hydrogen-international-announces-hydrogen-city-texas
25. Solar Panels in Chambers County. Energy Sage. https://www.energysage.com/local-data/solar-panel-cost/tx/chambers-county/
26. Manatee County, Florida Electric Profile. Find energy. https://findenergy.com/fl/manatee-county-electricity
27. Solar Panels in Manatee County. Energy Sage. https://www.energysage.com/local-data/solar-panel-cost/fl/manatee-county/
28. Solar Panels in Volusia County. Energy Sage. https://www.energysage.com/local-data/solar-panel-cost/fl/volusia-county/
29. New York Gives Big Boost to Renewable Energy. ERDC. https://www.nrdc.org/experts/cullen-howe/new-york-lays-down-gauntlet-renewable-energy#:~:tex
30. Los Angeles & Orange County Office Markets. Commercial Café. https://www.commercialcafe.com/blog/socal-q3-2019-office-market-report/
31. Port Aransas Commercial Real Estate. Loopnet. https://www.loopnet.com/search/commercial-real-estate/port-aransas-tx/for-sale/
32. Chambers County, TX Real Estate Market. Realtor. https://www.realtor.com/realestateandhomes-search/Chambers-County_TX/overview
33. Manatee Country Commercial Real Estate. Loopnet. https://www.loopnet.com/search/commercial-real-estate/Manatee-county-fl/for-sale/
34. Current West Texas Intermediate Crude Oil (WTI) Prices. UP. https://www.up.com/customers/surcharge/wti/prices/index.htm
35. California Average Gas Prices. Gas Prices. https://gasprices.aaa.com/?state=CA
36. Asian shares extend losess as oil prices push higher. OC Register. https://www.ocregister.com/2022/03/07/asian-shares-extend-losses-as-oil-prices-push-higher/
37. Gas Prices in Port Aransas, TX. Gas Buddy. https://www.gasbuddy.com/gasprices/texas/port-aransas
38. Gas Prices in Chambers, TX. Gas Buddy. https://www.gasbuddy.com/gasprices/texas/1107
39. California Scrap Metal Prices – USA. Price of Scrap Metals. https://www.priceofscrapmetals.com/california/
40. Price of Metal in Manatee County. Metal Supermarkets. https://www.metalsupermarkets.com/location/sarasota/
41. Database of State Incentives for Renewables & Efficiency. DSIRE USA. https://www.dsireusa.org/

42. Hydrogen Laws and Incentives in New York. Alternative Fuels Data Center. https://afdc.energy.gov/fuels/laws/HY?state=ny
43. California Green Energy Incentives. Alternative Fuels Data Center. https://afdc.energy.gov/laws/all?state=CA
44. Texas Solar Incentives. Sun Run. https://www.sunrun.com/solar-by-state/tx/texas-solar-incentives
45. Texas Solar Incentives and Rebates. Freedom Solar Power. https://freedomsolarpower.com/texas-solar-incentives-and-rebates
46. Preuster, P., et al. (2017). "Liquid Organic Hydrogen Carriers (LOHCs): Toward a Hydrogen-free Hydrogen Economy." Acc Chem Res 50(1): 74-85.
47. The Plug 10 MW Electrolyzer. Plug Power. https://www.plugpower.com/
48. Majumdar A, Deutch JM, Prasher RS, Griffin TP. A framework for a hydrogen economy. Joule. 2021;5(8):1905-8.
49. 2021 Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development. California Air Resources Board, September 2021.
50. Assessment of Potential Future Demands for Hydrogen in the United States. Argonne National Laboratory. October 2020.
51. Salkuyeh YK, et al., Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.04.024
52. Segurado R, Pereira S, Correia D, Costa M. Techno-economic analysis of a trigeneration system based on biomass gasification. Renewable and Sustainable Energy Reviews. 2019;103:501-14.
53. Bloom Electrolyzer Data Sheet. Bloom Energy. https://www.bloomenergy.com/
54. Lee D-Y, Elgowainy A, Dai Q. Life cycle greenhouse gas emissions of hydrogen fuel production from chlor-alkali processes in the United States. Applied Energy. 2018;217:467-79.
55. Supekar SD, Skerlos SJ. Market-driven emissions from recovery of carbon dioxide gas. Environ Sci Technol. 2014;48(24):14615-23.
56. Lee J, Lee W, Ryu KH, Park J, Lee H, Lee JH, et al. Catholyte-free electroreduction of CO2 for sustainable production of CO: concept, process development, techno-economic analysis, and CO2 reduction assessment. Green Chemistry. 2021;23(6):2397-410.
57. Ramdin M, De Mot B, Morrison ART, Breugelmans T, van den Broeke LJP, Trusler JPM, et al. Electroreduction of CO2/CO to C2 Products: Process Modeling, Downstream Separation, System Integration, and Economic Analysis. Ind Eng Chem Res. 2021;60(49):17862-80.
58. Source: O.K. Buros, et. al., *The USAID Desalination Manual.* Englewood, N.J., U.S.A., IDEA Publications, 1982.
59. Jing X, Li F, Wang Y. Assessing the economic potential of large-scale carbonate-formation-free CO2 electrolysis. Catalysis Science & Technology. 2022.
60. Hunter CA, Penev MM, Reznicek EP, Eichman J, Rustagi N, Baldwin SF. Techno-economic analysis of long-duration energy storage and flexible power generation technologies to support high-variable renewable energy grids. Joule. 2021;5(8):2077-101.
61. Kurtz, Jennifer, Sam Sprik, Genevieve Saur, and Shaun Onorato. 2019. Fuel Cell Electric Vehicle Driving and Fueling Behavior. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-73010. https://www.nrel.gov/docs/fy19osti/73010.pdf.
62. García-Payo MC, Rivier CA, Marison IW, von Stockar U. Separation of binary mixtures by thermostatic sweeping gas membrane distillation: II. Experimental results with aqueous formic acid solutions. Journal of Membrane Science. 2002;198(2):197-210.
63. Freedman, Y., Hastings, A., Varela. Prepared Direct Testimony of Yuri Freedman, Austin Hastings, and Joseph C. Varela, on behalf of the Southern California Gas Company, San Diego Gas & Electric Company, Pacific Gas and Electric Company, and Southwest Gas Corporation. November 2020.
64. Ball M, Weeda M. The hydrogen economy – Vision or reality? International Journal of Hydrogen Energy. 2015;40(25):7903-19.
65. Zhu Q-L, Xu Q. Liquid organic and inorganic chemical hydrides for high-capacity hydrogen storage. Energy & Environmental Science. 2015;8(2):478-512.

66. Labbaf B, Tabatabaei M, Mostafavi E, Tijani M, Mahinpey N. Methanol production via integrated methane reforming and chemical looping combustion: Process simulation and techno-economic assessment. Process Safety and Environmental Protection. 2021;148:1346-56.
67. He L, Liu H, Xiao C-x, Kou Y. Liquid-phase synthesis of methyl formatevia heterogeneous carbonylation of methanol over a soluble copper nanocluster catalyst. Green Chemistry. 2008;10(6):619-22.
68. Giuliano A, Freda C, Catizzone E. Techno-Economic Assessment of Bio-Syngas Production for Methanol Synthesis: A Focus on the Water–Gas Shift and Carbon Capture Sections. Bioengineering. 2020;7(3).
69. Reymond H, Vitas S, Vernuccio S, von Rohr PR. Reaction Process of Resin-Catalyzed Methyl Formate Hydrolysis in Biphasic Continuous Flow. Industrial & Engineering Chemistry Research. 2017;56(6):1439-49.
70. Kaiser D, Beckmann L, Walter J, Bertau M. Conversion of Green Methanol to Methyl Formate. Catalysts. 2021;11(7).
71. Yang, J., Bai, P., Yin, Kun. Operation and Control of Reactive Distillation of Synthesis of Methyl Formate. Asian Journal of Chemistry. 2013;8:4177-4182.
72. Gomez JR et al., Techno-economic analysis and life cycle assessment for electrochemical ammonia production using proton conducting membrane, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2019.10.174

    J, Park Y, Brigljević B, Lee B, Lim D, Lee T, et al. An efficient process for sustainable and scalable hydrogen production from green ammonia. Renewable and Sustainable Energy Reviews. 2021;152:111562.
73. Ruth, Mark, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simon, Amgad Elgowainy, and Jarett Zuboy. 2020. The Technical and Economic Potential of the H2@Scale Concept within the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP- 6A20-77610. https://www.nrel.gov/docs/fy21osti/77610.pdf.
74. Marcoberardino GD, Vitali D, Spinelli F, Binotti M, Manzolini G. Green Hydrogen Production from Raw Biogas: A Techno-Economic Investigation of Conventional Processes Using Pressure Swing Adsorption Unit. Processes. 2018;6(3).
75. Pump Life Cycle Costs: A Guide to LCC Analysis for Pumping Systems. US Department of Energy's Office of Industrial Technologies (OIT).
76. Yates J, Daiyan R, Patterson R, Egan R, Amal R, Ho-Baille A, et al. Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis. Cell Reports Physical Science. 2020;1(10):100209.
77. Rezaei E, Dzuryk S. Techno-economic comparison of reverse water gas shift reaction to steam and dry methane reforming reactions for syngas production. Chemical Engineering Research and Design. 2019;144:354-69.
78. Byun M, Lee B, Lee H, Jung S, Ji H, Lim H. Techno-economic and environmental assessment of methanol steam reforming for H2 production at various scales. International Journal of Hydrogen Energy. 2020;45(46):24146-58.
79. Tian H, Mancilla-David F, Ellis K, Jenkins P, Muljadi E. A Detailed Performance Model for Photovoltaic Systems. July 2012 National Renewable Energy Laboratory. NREL/JA-5500-54601.
80. Vogl V, Åhman M, Nilsson LJ. Assessment of hydrogen direct reduction for fossil-free steelmaking. Journal of Cleaner Production. 2018;203:736-45.
81. Tremel A, Wasserscheid P, Baldauf M, Hammer T. Techno-economic analysis for the synthesis of liquid and gaseous fuels based on hydrogen production via electrolysis. International Journal of Hydrogen Energy. 2015;40(35):11457-64.
82. Grandholm, J.M. 2021: U.S. Department of Energy Shot Summit.
83. Penev, M., et al., H2A Hydrogen Production Model. 2018: National Renewable Energy Laboratory.
84. Feldman, D., et al., U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020. 2021, National Renewable Energy Laboratory. NREL/TP-6A20-77324: Golden, CO.
85. Elgowainy, A., et al., Impact of Hydrogen Refueling Configurations and Market Parameters on the Refueling Cost of Hydrogen, A.N. Laboratory, Editor. 2017: Argonne, IL.