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A comparative technoeconomic analysis of pathways for commercial electrochemical CO₂ reduction to liquid products

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Technoeconomic assumptions

CO₂ capture

Table S1. CO₂ capture and storage (CCS) technoeconomic assumption parameters.¹

Parameter	Value
Basis power plant size	500 MW
Power plant overnight w/ CCS cost, 2011 \$	3808 \$/kW
Power plant overnight w/o CCS cost, 2011 \$	2162 \$/kW
Power plant overnight carbon capture cost, 2011 \$	1646 \$/kW
Power plant overnight w/ CCS cost, 2018 \$	4344 \$/kW
Power plant overnight w/o CCS cost, 2018 \$	2466 \$/kW
Power plant overnight carbon capture cost, 2018 \$	1878 \$/kW
Carbon capture capital expense, 2018 \$	\$939,000,000
Efficiency loss for CO ₂ capture	25%
Effective power plant generation needed w/ CCS	666.7 MW
CCS operating energy	166.7 MW
CCS annual operating energy	1.46 x 10 ⁹ kWh/yr
CO ₂ emissions w/ CCS	111 kg/MWh
CO ₂ emissions w/o CCS	820 kg/MWh
CO ₂ capture rate	7.056 x 10 ⁸ kmol/yr

CO₂ electrolyzers**Table S2.** CO₂ electrolyzer techno-economic assumption parameters.^{2,3}

Parameter	Value
Reference PEM electrolyzer basis H ₂ production (mass)	50,000 kg/day
Reference PEM electrolyzer basis H ₂ production (molar)	24,752 kmol/day
Reference PEM electrolyzer current density	1.50 A/cm ²
Reference PEM electrolyzer H ₂ faradaic efficiency	100%
Reference PEM electrolyzer electrode area	3685 m ²
Reference PEM electrolyzer stack cost (uninstalled), 2012 \$	\$47,851,875
Reference PEM electrolyzer BOP cost (uninstalled), 2012 \$	\$53,960,625
Reference PEM electrolyzer stack cost per area (uninstalled), 2012 \$	\$12,984/m ²
Reference PEM electrolyzer BOP cost per area (uninstalled), 2012 \$	\$14,640/m ²
Reference PEM electrolyzer total cost per area (uninstalled), 2012 \$	\$27,624/m ²
Reference PEM electrolyzer stack cost (uninstalled), 2018 \$	\$53,572,765
Reference PEM electrolyzer BOP cost (uninstalled), 2018 \$	\$60,411,841
Reference PEM electrolyzer stack cost per area (uninstalled), 2018 \$	\$14,536/m ²
Reference PEM electrolyzer BOP cost per area (uninstalled), 2018 \$	\$16,391/m ²
Reference PEM electrolyzer total cost per area (uninstalled), 2018 \$	\$30,927/m ²
Installation costs	12% of equipment (stack+BOP)
Contingency costs	15% of installed capital cost
Site preparation cost	2% of installed capital cost
Engineering and design	8% of installed capital cost
Up-front permitting	15% of installed capital cost
Reference PEM electrolyzer total overnight cost per area, 2018 \$	\$48,493/m ²
Electrolyzer capacity factor	97%
Replacement costs (every 7 years)	15% of installed electrolyzer capital cost

Gas separation**Table S3.** CO₂/CO gas separation and recycle techno-economic assumption parameters.⁴

Parameter	Value
Reference total gas flow to separator	4.40 x 10 ⁶ mol/h
Reference separator/recycle cost, 2016 \$	\$10,800,000
Reference separator/recycle cost, 2018 \$	\$11,214,299
Scaling exponent	0.65
CO ₂ recycling efficiency	97%
CO loss to recycle	0%
Case-dependent total gas flow to separator	X mol/h
CO ₂ /CO separator/recycle scaled capital expense	$[X/(4.40 \times 10^6)]^{0.65} * (\$11,214,299)$
Reference power to operate separator/recycle	10 kW
Reference annual energy usage to operate separator/recycle	8.76 x 10 ⁴ kWh/yr

Fischer-Tropsch system**Table S4.** Fischer-Tropsch system reference case technoeconomic assumptions.⁵

Parameter	Value
Reference basis diesel fuel produced	50,000 bbl/day
Reference Fischer-Tropsch island capital cost, 2007 \$	\$882,000,000
Reference naphtha upgrade unit capital cost, 2007 \$	\$86,000,000
Reference topping power unit capital cost, 2007 \$	\$35,000,000
Reference heat recovery + steam cycle capital cost, 2007 \$	\$723,000,000
Reference Fischer-Tropsch island capital cost, 2018 \$	\$1,084,887,260
Reference naphtha upgrade unit capital cost, 2018 \$	\$105,782,658
Reference topping power unit capital cost, 2018 \$	\$43,051,082
Reference heat recovery + steam cycle capital cost, 2018 \$	\$889,312,346
Reference steam turbine output	783 MW
Reference export electricity	66 MW
Reference recycle compressor energy consumption	16 MW
Reference Fischer-Tropsch synthesis energy consumption	22 MW
Reference Fischer-Tropsch refining energy consumption	11 MW

Byproduct value**Table S5.** Byproduct market value technoeconomic assumptions.

Parameter	Value
Hydrogen [a]	\$1.90/kg
Ethylene [b]	\$0.989/kg
Carbon monoxide [c]	\$0.60/kg
Acetic acid [d]	\$0.60/kg

[a] - Energy Information Administration estimate for commercial price steam methane reforming (SMR) for 2017⁶

[b] - Based on May to September average price, S&P Global Platts Petrochemical Index 2017⁷

[c] – Based on bulk carbon monoxide price, Alibaba

[d] – Based on bulk acetic acid price by metric ton, Alibaba

CO₂ reduction systemsCO₂ to CO to Fischer-Tropsch diesel**Table S6.** CO₂-CO-FTL system values under base case operating parameters.

Parameter	Value
CO ₂ feed rate to electrolyzer (capture + recycle)	1.37x10 ⁸ kmol/yr
CO ₂ rate exiting the electrolyzer	6.85x10 ⁷ kmol/yr
CO ₂ recycle rate	6.64x10 ⁷ kmol/yr
CO production rate from electrolyzer	6.85x10 ⁷ kmol/yr
H ₂ production rate from electrolyzer	1.40x10 ⁶ kmol/yr
H ₂ rate supplied to Fischer-Tropsch	6.71x10 ⁷ kmol/yr
Diesel fuel (C ₁₀ H ₂₂) production rate	2.33x10 ⁶ kmol/yr
Diesel fuel (C ₁₀ H ₂₂) production rate	3.31x10 ⁸ kg/yr
Diesel fuel (C ₁₀ H ₂₂) production rate	1.17x10 ⁸ gge/yr
Diesel fuel (C ₁₀ H ₂₂) production rate	9279 bbl/day
CO ₂ sequestered in the diesel fuel	1.03x10 ⁶ ton/yr
Gas flow rate to the separator	1.38x10 ⁸ kmol/yr
Gas flow rate to the separator (X mol/h)	1.58x10 ⁷ mol/h
CO ₂ /CO separator/recycle scaled capital expense, 2018 \$	\$25,743,126
CO ₂ /CO separator/recycle electricity usage	3.15x10 ⁵ kWh/yr
Total electrolyzer current	4.28x10 ⁸ A
Total electrolyzer power	769.9 MW
Total electrode area	106,937 m ²
Capacity-factor-adjusted total electrode area	110,245 m ²
Electrolyzer total capital expense, 2018 \$	\$5,346,209,520
Electrolyzer electricity usage	6.74x10 ⁹ kWh/yr
Scaled Fischer-Tropsch island capital cost, 2018 \$	\$201,328,546
Scaled naphtha upgrade unit capital cost, 2018 \$	\$19,630,675
Scaled topping power unit capital cost, 2018 \$	\$7,989,228
Scaled heat recovery + steam cycle capital cost, 2018 \$	\$165,034,625
Total Fischer-Tropsch capital expense, 2018 \$	\$393,983,073
Scaled steam turbine output	145.3 MW
Scaled export electricity	12.2 MW
Scaled recycle compressor	3.0 MW
Scaled Fischer-Tropsch synthesis	4.1 MW
Scaled Fischer-Tropsch refining	2.0 MW
Scaled total Fischer-Tropsch power generation	148.5 MW
Electricity credit from byproducts	1.30x10 ⁹ kWh/yr
CO ₂ -CO-FTL system capital expense, 2018 \$	\$6,704,835,252

CO₂ to C₂H₅OH one-step electrolysis**Table S7.** CO₂-C₂H₅OH system values under base case operating parameters.⁸

Parameter	Value
CO ₂ feed rate to electrolyzer (capture + recycle)	1.37x10 ⁸ kmol/yr
CO ₂ rate exiting the electrolyzer	6.85x10 ⁷ kmol/yr
CO ₂ recycle rate	6.64x10 ⁷ kmol/yr
Base case CO faradaic efficiency	13%
Base case H ₂ faradaic efficiency	25%
Base case C ₂ H ₄ faradaic efficiency	34%
Base case C ₂ H ₅ OH faradaic efficiency	28%
CO production rate from electrolyzer	2.59x10 ⁷ kmol/yr
H ₂ production rate from electrolyzer	5.18x10 ⁷ kmol/yr
C ₂ H ₄ production rate from electrolyzer	1.17x10 ⁷ kmol/yr
C ₂ H ₅ OH production rate from electrolyzer	9.59x10 ⁶ kmol/yr
C ₂ H ₅ OH production rate from electrolyzer	4.42x10 ⁸ kg/yr
C ₂ H ₅ OH production rate from electrolyzer	9.01x10 ⁷ gge/yr
CO ₂ sequestered in the C ₂ H ₅ OH, C ₂ H ₄ , CO	3.01x10 ⁶ ton/yr
Gas flow rate to the separator	1.68x10 ⁸ kmol/yr
Gas flow rate to the separator (X mol/h)	1.80x10 ⁷ mol/h
CO ₂ /CO separator/recycle scaled capital expense, 2018 \$	\$28,045,421
CO ₂ /CO separator/recycle electricity usage	3.59x10 ⁵ kWh/yr
Total electrolyzer current	1.26x10 ⁹ A
Total electrolyzer power	2892 MW
Total electrode area	503,033 m ²
Capacity-factor-adjusted total electrode area	518,590 m ²
Electrolyzer total capital expense, 2018 \$	\$25,148,569,580
Electrolyzer electricity usage	2.53x10 ¹⁰ kWh/yr
CO ₂ -C ₂ H ₅ OH system capital expense, 2018 \$	\$26,115,514,534

CO₂ to CO to C₂H₅OH two-step electrolysis**Table S8.** CO₂-CO-C₂H₅OH system values under base case operating parameters.^{9, 10}

Parameter	Value
CO ₂ feed rate to electrolyzer 1 (capture + recycle)	1.37x10 ⁸ kmol/yr
CO ₂ rate exiting electrolyzer 1	6.85x10 ⁷ kmol/yr
CO ₂ recycle rate	6.64x10 ⁷ kmol/yr
Base case electrolyzer 1 CO faradaic efficiency	98%
Base case electrolyzer 1 H ₂ faradaic efficiency	2%
CO production rate from electrolyzer 1	6.85x10 ⁷ kmol/yr
H ₂ production rate from electrolyzer 1	1.40x10 ⁶ kmol/yr
CO feed rate to electrolyzer 2 (capture + recycle)	1.33x10 ⁸ kmol/yr
CO rate exiting electrolyzer 2	6.65x10 ⁷ kmol/yr
CO recycle rate	6.45x10 ⁷ kmol/yr
Base case electrolyzer 2 H ₂ faradaic efficiency	41%
Base case electrolyzer 2 C ₂ H ₄ faradaic efficiency	2%
Base case electrolyzer 2 CH ₃ COOH faradaic efficiency	12%
Base case electrolyzer 2 C ₂ H ₅ OH faradaic efficiency	45%
CO rate exiting final separator	2.00x10 ⁶ kmol/yr
H ₂ production rate from electrolyzer 2	7.68x10 ⁷ kmol/yr
Total H ₂ rate exiting final separator	7.82x10 ⁷ kmol/yr
C ₂ H ₄ production rate from electrolyzer 2	9.37x10 ⁵ kmol/yr
CH ₃ COOH production rate from electrolyzer 2	1.12x10 ⁷ kmol/yr
C ₂ H ₅ OH production rate from electrolyzer 2	2.11x10 ⁷ kmol/yr
C ₂ H ₅ OH production rate from electrolyzer 2	9.71x10 ⁸ kg/yr
C ₂ H ₅ OH production rate from electrolyzer 2	1.98x10 ⁸ gge/yr
CO ₂ sequestered in the C ₂ H ₅ OH, C ₂ H ₄ , CO, CH ₃ COOH	3.01x10 ⁶ ton/yr
Gas flow rate to separator 1	1.38x10 ⁸ kmol/yr
Gas flow rate to separator 1 (X mol/h)	1.58x10 ⁷ mol/h
CO ₂ /CO separator/recycle 1 scaled capital expense, 2018 \$	\$25,743,126
CO ₂ /CO separator/recycle 1 electricity usage	3.15x10 ⁵ kWh/yr
Gas flow rate to separator 2	1.48x10 ⁸ kmol/yr
Gas flow rate to separator 2 (X mol/h)	1.69x10 ⁷ mol/h
CO separator/recycle 2 scaled capital expense, 2018 \$	\$26,855,293
CO separator/recycle 2 electricity usage	3.36x10 ⁵ kWh/yr
Electrolyzer 1 current	4.28x10 ⁸ A
Electrolyzer 1 power	769.9 MW
Electrolyzer 1 electrode area	106,937 m ²
Capacity-factor-adjusted electrolyzer 1 electrode area	110,245 m ²
Electrolyzer 1 total capital expense, 2018 \$	\$5,346,209,520

Electrolyzer 1 electricity usage	6.74x10 ⁹ kWh/yr
Electrolyzer 2 current	1.15x10 ⁹ A
Electrolyzer 2 power	2178 MW
Electrolyzer 2 electrode area	955,362 m ²
Capacity-factor-adjusted electrolyzer 2 electrode area	984,910 m ²
Electrolyzer 2 total capital expense, 2018 \$	\$47,762,298,456
Electrolyzer 2 electricity usage	1.91x10 ¹⁰ kWh/yr
CO ₂ -CO-C ₂ H ₅ OH system capital expense, 2018 \$	\$54,100,005,928

CO₂ to HCOOH**Table S9.** CO₂-HCOOH system values under base case operating parameters.¹¹

Parameter	Value
CO ₂ feed rate to electrolyzer (capture + recycle)	1.37x10 ⁸ kmol/yr
CO ₂ rate exiting the electrolyzer	6.85x10 ⁷ kmol/yr
CO ₂ recycle rate	6.64x10 ⁷ kmol/yr
Base case CO faradaic efficiency	4%
Base case H ₂ faradaic efficiency	2%
Base case HCOOH faradaic efficiency	94%
CO production rate from electrolyzer	2.80x10 ⁶ kmol/yr
H ₂ production rate from electrolyzer	1.40x10 ⁶ kmol/yr
HCOOH production rate from electrolyzer	6.57x10 ⁷ kmol/yr
HCOOH production rate from electrolyzer	3.02x10 ⁹ kg/yr
HCOOH production rate from electrolyzer	1.22x10 ⁸ gge/yr
CO ₂ sequestered in the HCOOH	3.01x10 ⁶ ton/yr
Gas flow rate to the separator	7.27x10 ⁷ kmol/yr
Gas flow rate to the separator (X mol/h)	8.30x10 ⁶ mol/h
CO ₂ /CO separator/recycle scaled capital expense, 2018 \$	\$16,939,500
CO ₂ /CO separator/recycle electricity usage	1.65x10 ⁵ kWh/yr
Total electrolyzer current	4.28x10 ⁸ A
Total electrolyzer power	1497.1 MW
Total electrode area	305,535 m ²
Capacity-factor-adjusted total electrode area	314,984 m ²
Electrolyzer total capital expense, 2018 \$	\$15,274,884,341
Electrolyzer electricity usage	1.31x10 ¹⁰ kWh/yr
CO ₂ -HCOOH system capital expense, 2018 \$	\$16,230,723,374

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