Supplementary Information for

The Economic Outlook for Converting CO_2 and Electrons to Molecules

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Complementary Website: Interactive visualizations of the cost breakdown information reported in this manuscript can be found at: https://www.nrel.gov/bioenergy/co2-utilization-economics/.

Table of Contents

1. Process Flow Diagram and System Boundary of Studied CO_2 Reduction Processes

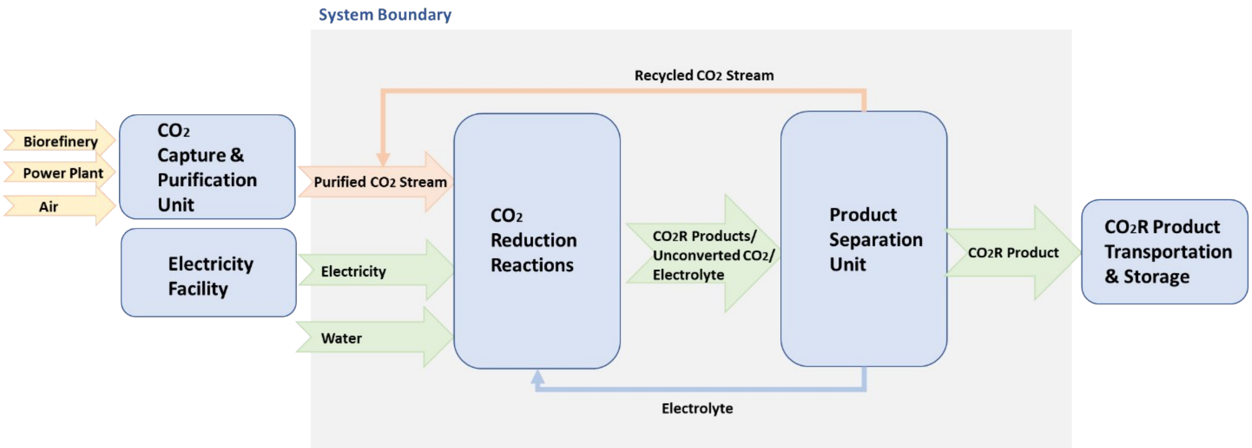

Figure S1. Process flow diagram of the CO_2 reduction processes. The system boundary in this study is shown by shaded are including the CO_2 reduction, recycle of unconverted feedstocks, and product purification stages. Adapted from ref [21].

2. Material Unit Prices

Table S1: Raw material unit prices inflated to 2016$

Components	Cost (2016$)	Ref
Sulfuric acid	$0.09kg^{-1}	IHS Market Connect[1]
Lime	$0.15kg^{-1}	IHS Market Connect[1]
Monopotassium phosphate	$1.76kg^{-1}	IHS Market Connect[1]
Dipotassium phosphate	$1.49kg^{-1}	IHS Market Connect[1]
Ammonium sulfate	$0.26kg^{-1}	IHS Market Connect[1]
Magnesium sulfate heptahydrate	$0.64kg^{-1}	IHS Market Connect[1]
Sodium chloride	$0.06kg^{-1}	IHS Market Connect[1]
Magnesium chloride hexahydrate	$0.37kg^{-1}	IHS Market Connect[1]
Ferrous sulfate	$0.17kg^{-1}	IHS Market Connect[1]
Sodium sulfide	$0.60kg^{-1}	IHS Market Connect[1]
Calcium chloride	$0.36kg^{-1}	IHS Market Connect[1]
Ammonium chloride	$0.09kg^{-1}	IHS Market Connect[1]
Yeast extract	$1.33kg^{-1}	IHS Market Connect[1]
CO (sold)	$0.18kg^{-1}	IHS Market Connect[1]
Hydrogen (sold)	$1.47kg^{-1}	IHS Market Connect[1]
Acetic acid (sold)	$0.61kg^{-1}	IHS Market Connect[1]
Ethylene (sold)	$0.71kg^{-1}	IHS Market Connect[1]
Cu-Zn Catalyst	$20.38kg^{-1}	2010 NREL Report[2]
Cobalt Catalyst	$38.21kg^{-1}	2010 NREL Report[2]
$CuZnOAl_2O_3$ Catalyst	$22.75kg^{-1}	2015 NREL Report[3]
$CuZnOAl_2O_3/HZM_5$ Catalyst	$24.18kg^{-1}	2015 NREL Report[3]
23%Ni/Al_2O_3/5%CaO Catalyst	$10.00kg^{-1}	Alibaba[4]
Fresh water	$0.00022kg^{-1}	2015 NREL Report[3]
Amine	$823.00kg^{-1}	Mar Perez-Fortes, 2016[5]
Natural gas	$3.00MMBTU^{-1}	2019 EIA Data[6]

Cost from IHS Market Connect is 5 year (2014-2018) average U.S. market price in 2016$

Table S2: U.S. market price for studied CO_2R products in 2016$[1, 7].

Species	US Market Price [a] (2016$)	High Bar [b]	Low Bar [b]
Carbon monoxide	$0.18kg^{-1}	$0.23kg^{-1}	$0.14kg^{-1}
Formic acid	$0.66kg^{-1}	$0.70kg^{-1}	$0.63kg^{-1}
Methanol	$0.35kg^{-1}	$0.46kg^{-1}	$0.23kg^{-1}
Methane [c]	$0.15kg^{-1}	$0.22kg^{-1}	$0.12kg^{-1}
Acetic acid	$0.61kg^{-1}	$0.71kg^{-1}	$0.50kg^{-1}
Oxalic acid	$1.73kg^{-1}	n.a.	n.a.
Ethanol	$0.52kg^{-1}	$0.73kg^{-1}	$0.43kg^{-1}
Ethylene	$0.71kg^{-1}	$1.29kg^{-1}	$0.38kg^{-1}
Polyhydroxybutyrate	$1.50kg^{-1}	n.a.	n.a.
Dimethyl ether	$0.65kg^{-1}	$0.76kg^{-1}	$0.53kg^{-1}
Fischer-Tropsch liquids	$0.97kg^{-1}	$1.27kg^{-1}	$0.80kg^{-1}

a: 2014-2018 average market price in United States.

b: High/Low bars reflect the upper and lower bounds of the observed market price in the 2008-2018 period.

c: Renewable natural gas (RNG) has higher market price of $0.37-$1.31/kg compared with reported natural gas market price[8].

3. Capital and Operating Cost Assumptions

Table S3: Cost assumptions for LTE/HTE/MES CO_2 Electrolyzers

From the DOE H2A analysis for central electrolysis, the reported capital costs for PEM, SOEC and Alkaline water electrolyzers are used to estimate the CO_2 Electrolyzer capital costs for LTE, HTE and MES pathways, respectively. The equation below is used to calculate CO_2 electrolyzer capital costs on the basis of $/m^2.

CO_2 Electrolyzer installed capital cost ($/m^2) = Uninstalled capital cost ($/kW) × Cell voltage (V) × Current Density (mA/cm^2) × (1000mA/A) × (1kW/1000W) × (10000cm^2/m^2) × Installation Factor

Parameter	Uninstalled Capital Cost ($2016/kW)	Cell Voltage (V)	Current Density (mA/cm2)	Installation Factor	Justification and Reference
PEM Electrolyzer					
Current	460	1.9	2000	1.12	From DOE H2A analysis model[9]. Pt group metal is assumed 16% of uninstalled capital with Anode/Cathode loading ratio 7/4[10].
Future	233	1.8	3000	1.1	From DOE H2A analysis model[11]. Pt group metal is assumed 13% of uninstalled capital with Anode/Cathode loading ratio 7/4[10].
Theoretical	100	1.8	3000	1.1	From DOE H2A technical report[12]. Pt group metal is assumed 13% of uninstalled capital with Anode/Cathode loading ratio 7/4[10].
SOEC Electrolyzer					
Current	523	1.285	1000	1.12	From DOE H2A analysis model[13]
Future	357	1.285	1200	1.1	From DOE H2A analysis model[14]
Theoretical	150	1.285	2000	1.1	From DOE H2A analysis model[12]
Alkaline Electrolyzer					
Current	378	1.75	175	1.2	From DOE H2A analysis model[15, 16]

Future	295	1.65	200	1.1	From DOE H2A analysis model[15, 16]
Theoretical	197	1.65	200	1.1	From DOE H2A analysis model[15, 16]

Table S4: Cost assumptions for Bio- and Thermo- reactor.

Parameter	**Assumption**	**Year of Quote**	**Installation Factor**	**Justification and Reference**
Capital Cost (CAPEX)				
Bioreactor	[X/ (5.00E +5)] ^ 1.0*($782,600)	2013	1.6	From 2011 NREL design report[17]. (x in unit of Liter per hour)
Thermo-reactor	[X/ (12.5)] ^ 0.6*($872,300)	2011	2.6	From 2011 NREL design report[18]. (x in unit of mmscf per hour)

Table S5: Cost assumptions for separation processes

Parameter	**Assumption**	**Year of Quote**	**Installation Factor**	**Justification and Reference**
Capital Cost (CAPEX)				
CO_2 Separation Cost ($/Metric Ton CO_2 separated)	[271.3(X)]^-0.245	2016	1.0	From IHS potassium carbonate CO_2 separation system based on the total recycled CO_2 amount. (x in unit of million lb per year)
Pressure Swing Adsorption (PSA)	[X/ (4.40 E +6)] ^ 0.65*($10,800,000)	2010	1.0	From Joshua Spurgeon et al. 2018[19], Xuping Li et al. 2016[20]. (x in unit of mol per hour)
Liquid/Gas Flash Tank	[X/ (2.64E +5)] ^ 0.70*($511,000)	2009	2.0	From 2011 NREL design report[17]. (x in unit of kg per hour)
Ethanol Distillation	[X/ (2.27E +4)] ^ 0.60*($6,008,000)	2009	2.1	From 2011 NREL design report[17]. (x in unit of kg per hour)
Methanol Distillation	[X/ (2.27E +4)] ^ 0.60*($3,407,000)	2009	2.1	From 2011 NREL design report[18]. (x in unit of kg per hour)
Formic Acid Reactive Distillation	[X/ (1500)] ^ 0.60*($834,000)	2014	1.7	From ChemCAD Model and Mar Perez-Fortes, 2016[21]. (x in unit of kg per hour)
Base/Acid Mixer Tank Agitator	[X/ (1.40E+5)] ^ 0.60*($9,000)	2007	3.0	From 2011 NREL design report[17]. (x in unit of kg per hour)
Base/Acid Mixer Tank	[X/ (1.40E+5)] ^ 0.60*($131,000)	2007	3.0	From 2011 NREL design report[17]. (x in unit of kg per hour)
Liquid/Solid Separator	[X/ (3.20E+4)] ^ 0.80*($293,000)	2009	3.0	From 2011 NREL design report[17]. (x in unit of kg per hour)
Acetate Membrane Separator	[X/ (3.62E+5)] ^ 0.70*($8,000,000)	2010	2.0	Estimated in Aspen Capital Cost Estimator. (x in unit of kg per hour)
PHB Separator	[X/ (1.60E+4)] ^ 0.80*($27,500,000)	2011	1.0	Estimated in Aspen Capital Cost Estimator. (x in unit of kg per hour)
Operating Cost (OPEX)				
CO_2 Recycle Stream Compressor Power (kWh)	Calculated			The CO_2 compressor power is modeled in Aspen Plus under different scenarios based on the total recycled CO_2 amount.
Pressure Swing Adsorption (PSA) Power (kWh)	0.25 kWh/m^3 gas in			From Jouny et al., 2018[22]
Distillation Reboiler Duty (Btu)	6750 Btu/kg product produced			From 2011 NREL design report[18].
Amine for Formic Acid Reactive Distillation (kg)	5.8g Amine/g Formic acid produced			From Mar Perez-Fortes, 2016[5]
Lime for Oxalic Acid precipitation	0.6 g Lime/g Oxalic acid produced			Based on reaction stoichiometry
Sulfuric acid for oxalic acid separation	1.1 g Sulfuric acid/g Oxalic acid produced			Based on reaction stoichiometry

4. Major Economic Assumptions

Table S6: Major economic assumptions for discounted cash flow analysis

Economic parameters	Assumed basis
Basis year for analysis	2016
Debt/equity for plant financing	60%/40%
Interest rate and term for debt financing	8%/10 years
Internal rate of return for equity financing	10%
Total income tax rate	21%
Plant life	20 years
Construction period	3 year
Fixed capital expenditure schedule	32% in year 1
	60% in year 2
	8% in year 3
Start-up time	0.5 year
Revenues during start-up	50%
Variable costs during start-up	75%
Fixed costs during start-up	100%
Site development cost	9% of ISBL, total installed cost
Warehouse	1.5% of ISBL
Working capital	5% of fixed capital investment
Indirect costs	% of total direct costs
Prorated expenses	10
Home office and construction fees	20
Field expenses	10
Project contingency	10
Other costs (start-up and permitting)	10
Fixed operating cost	Assumed Basis
Plant operators' salaries	5.24 Operators / Shift
Maintenance salaries	1% of fixed capital investment
Supervision & administration	40% of operators & maintenance labor
Fringe benefits	30% of total labor
Supplies	1.75% of fixed capital investment
Insurance and local tax	0.8% of fixed capital investment
ISBL=inside battery limits (of the plant)	

Table S7: Major Technical Parameters for Future and Theoretical Scenarios

LTE Pathway			
	Future Scenario	Theoretical Scenario	Justification and Reference
Current Density (mA/cm^2)	1500	2000	Quote from reported current density values for PEM water electrolyzer in DOE H2A model[9].
Cell Voltage (V)	Theoretical +0.6V	Theoretical	Future scenario applies +0.6V cell overpotential on the theoretical voltage based on the reported overpotential values for PEM water electrolyzer[23].
Faradaic Efficiency (%)	95	100	Quote from current CO_2-to-CO faradaic efficiency that is reported ~100%[24].
Single-pass CO_2 Conversion (%)	90	100	Future projection of 90% single-pass CO_2 conversion is made by assuming ongoing technologies such as direct electrolytic conversion of carbon capture solutions[25, 26] can potentially

			address the low CO_2 conversion issue.
HTE Pathway			
Current Density (mA/cm²)	2,500	3,000	Quote from reported current density values for SOEC system[27].
Cell Voltage (V)	Avg of SOT and Theoretical Cell Voltages	Theoretical	This assumption is based on engineering judgement. Other major technical parameter assumptions such as faradaic efficiency and single-pass CO_2 conversion are consistent with LTE pathway.
MES Pathway			
Current Density (mA/cm²)	100	200	Quote from reported current density values for alkaline water electrolyzer[15, 16]. Other major technical parameter assumptions such as cell voltage, faradaic efficiency and single-pass CO_2 conversion are consistent with LTE pathway.
BC Pathway			
Feedstock (H_2/CO_2) Ratio	Stoichiometry	Stoichiometry	Stoichiometry has the optimistic H_2: CO_2 ratio and excess H_2 feedstock is needed in some SOT cases to enhance the production rate of final product.
Product Titer (g/L)	Highest reported value in Batch	Bacteria death limit	These assumptions are based on subject matter expert interviews and engineering judgement.
Productivity (g/L/hr)	Highest reported value in Batch	10	Theoretical productivity projection is made based on the reported commercialized ethanol productivity~10g/L/hr[28].
Single-pass CO_2 Conversion (%)	90	98	Future project of 90% single-pass CO_2 conversion is made to be consistent with LTE pathway. 2% CO_2 loss to cell growth is assumed in theoretical scenario[29].
TC Pathway			
Feedstock (H_2/CO_2) Ratio	Stoichiometry	Stoichiometry	Consistent assumptions with BC pathway.
Single-pass CO_2 Conversion (%)	90	Theoretical	Theoretical is calculated using ASPENPlus Gibbs Reactor. Future project of 90% single-pass CO_2 conversion is made to be consistent with LTE pathway. Future single-pass CO_2 conversion equals theoretical value if <90%
Product Selectivity (%)	95	100	Future project of 95% product selectivity is made to be consistent with LTE pathway faradaic efficiency.

5. Cost Breakdown Analysis

Table S8: Cost breakdown of selected products for LTE pathway

Scenarios	Current	Future	Theoretical
CO			
PEM Electrolyzer Capital	37%	20%	26%
Separation Capital	1%	2%	0%
CO_2 Cost	4%	13%	0%
Electrolysis Cost	37%	56%	73%
Utility &Supplies	1%	3%	0%
CO_2 Separation	20%	6%	0%
Minimum Selling Price ($/kg)	1.55	0.23	0.07
Formic Acid			
PEM Electrolyzer Capital	40%	28%	25%
Separation Capital	1%	5%	0%
CO_2 Cost	3%	10%	0%
Electrolysis Cost	34%	45%	75%
Utility &Supplies	4%	7%	0%
CO_2 Separation	16%	5%	0%
Minimum Selling Price ($/kg)	1.36	0.23	0.05
Oxalic Acid			
PEM Electrolyzer Capital	42%	15%	23%
Separation Capital	1%	2%	0%
CO_2 Cost	2%	5%	0%
Electrolysis Cost	34%	13%	77%
Utility &Supplies	11%	62%	0%
CO_2 Separation	10%	2%	0%
Minimum Selling Price ($/kg)	2.23	0.33	0.03
Ethylene			
PEM Electrolyzer Capital	13%	29%	28%
Separation Capital	1%	1%	0%
CO_2 Cost	3%	5%	0%
Electrolysis Cost	66%	61%	71%
Utility &Supplies	1%	1%	1%
CO_2 Separation	16%	2%	0%
Minimum Selling Price ($/kg)	6.39	1.20	0.42
Ethanol			
PEM Electrolyzer Capital	47%	29%	25%
Separation Capital	1%	2%	6%
CO_2 Cost	2%	5%	0%
Electrolysis Cost	41%	57%	59%
Utility &Supplies	1%	4%	10%
CO_2 Separation	9%	2%	0%
Minimum Selling Price ($/kg)	6.07	0.74	0.30
Methanol			
PEM Electrolyzer Capital	74%	34%	26%
Separation Capital	0%	2%	4%
CO_2 Cost	0%	5%	0%
Electrolysis Cost	23%	53%	60%
Utility &Supplies	1%	4%	10%
CO_2 Separation	2%	2%	0%
Minimum Selling Price ($/kg)	14.82	0.54	0.22
Methane			
PEM Electrolyzer Capital	53%	31%	33%
Separation Capital	1%	2%	0%
CO_2 Cost	1%	3%	0%

Electrolysis Cost	37%	46%	67%
Utility &Supplies	2%	16%	0%
CO_2 Separation	5%	1%	0%
Minimum Selling Price ($/kg)	16.97	1.74	0.47

Table S9: Cost breakdown of selected products for HTE pathway

Scenarios	**Current**	**Future**	**Theoretical**
CO			
SOEC Electrolyzer Capital	24%	14%	19%
Separation Capital	3%	2%	2%
CO_2 Cost	16%	22%	0%
Electrolysis Cost	48%	52%	70%
Utility &Supplies	2%	6%	8%
CO_2 Separation	6%	5%	0%
Minimum Selling Price ($/kg)	0.38	0.15	0.05
CH_4			
SOEC Electrolyzer Capital	15%	19%	17%
Separation Capital	2%	2%	2%
CO_2 Cost	1%	7%	0%
Electrolysis Cost	66%	64%	77%
Utility &Supplies	5%	4%	3%
CO_2 Separation	11%	3%	0%
Minimum Selling Price ($/kg)	11.15	0.77	0.36

Table S10: Cost breakdown of selected products for MES pathway

Scenarios	**Current**	**Future**	**Theoretical**
CH_4			
MES Reactor Capital	74%	44%	41%
Separation Capital	0%	0%	0%
CO_2 Cost	0%	4%	0%
Electrolysis Cost	25%	47%	51%
Utility &Supplies	0%	3%	7%
CO_2 Separation	1%	2%	0%
Minimum Selling Price ($/kg)	107.76	1.90	0.76
Formic Acid			
MES Reactor Capital	71%	54%	45%
Separation Capital	1%	5%	10%
CO_2 Cost	1%	5%	0%
Electrolysis Cost	23%	22%	30%
Utility &Supplies	1%	11%	15%
CO_2 Separation	3%	2%	1%
Minimum Selling Price ($/kg)	26.42	0.29	0.21
Acetic Acid			
MES Reactor Capital	66%	50%	52%
Separation Capital	2%	7%	6%
CO_2 Cost	1%	5%	0%
Electrolysis Cost	23%	32%	35%
Utility &Supplies	1%	3%	6%
CO_2 Separation	7%	2%	0%
Minimum Selling Price ($/kg)	5.32	0.57	0.22
Ethanol			
MES Reactor Capital	76%	55%	58%
Separation Capital	0%	2%	3%

CO_2 Cost	0%	3%	0%
Electrolysis Cost	22%	34%	29%
Utility &Supplies	0%	5%	9%
CO_2 Separation	1%	2%	0%
Minimum Selling Price ($/kg)	441.01	1.10	0.54

Table S11: Cost breakdown of selected products for BC pathway

Scenarios	Current	Future	Theoretical
CH_4			
Bioreactor Capital	5%	5%	3%
Separation Capital	0%	0%	0%
CO_2 Cost	5%	5%	0%
H_2 Cost	89%	88%	96%
Nutrient Cost	0%	1%	1%
Utility &Supplies	0%	1%	1%
Minimum Selling Price ($/kg)	2.22	1.04	0.64
Acetic Acid			
Bioreactor Capital	11%	5%	5%
Separation Capital	6%	7%	7%
CO_2 Cost	6%	9%	0%
H_2 Cost	55%	70%	78%
Nutrient Cost	13%	7%	7%
Utility &Supplies	9%	3%	3%
Minimum Selling Price ($/kg)	0.95	0.34	0.21
Ethanol			
Bioreactor Capital	3%	3%	8%
Separation Capital	3%	3%	9%
CO_2 Cost	5%	9%	0%
H_2 Cost	79%	64%	75%
CO and Nutrient Cost	7%	13%	0%
Utility &Supplies	3%	8%	9%
Minimum Selling Price ($/kg)	1.27	0.64	0.39
PHB			
Bioreactor Capital	12%	10%	15%
Separation Capital	9%	12%	17%
CO_2 Cost	5%	6%	0%
H_2 Cost	61%	59%	50%
Nutrient Cost	3%	3%	4%
Utility &Supplies	9%	10%	14%
CO_2 Separation	1%	2%	0%
Minimum Selling Price ($/kg)	1.36	0.64	0.37

Table S12: Cost breakdown of selected products for TC pathway

Scenarios	Current	Future	Theoretical
CO			
Thermo Capital	1%	1%	1%
Product Separation	3%	5%	2%
CO_2 Cost	14%	13%	0%
H_2 Cost	63%	52%	53%
CO_2 Separation	10%	18%	28%
Utilities	9%	11%	15%
Minimum Selling Price ($/kg)	0.45	0.25	0.16
CH_4			

Thermo Capital	1%	1%	1%
Product Separation	2%	3%	2%
CO_2 Cost	5%	5%	0%
H_2 Cost	86%	84%	88%
CO_2 Separation	1%	1%	5%
Utilities	4%	4%	4%
Minimum Selling Price ($/kg)	2.28	1.08	0.68
Methanol			
Thermo Capital	1%	1%	1%
Product Separation	6%	9%	6%
CO_2 Cost	5%	4%	0%
H_2 Cost	48%	43%	44%
CO_2 Separation	16%	25%	36%
Utilities	24%	19%	13%
Minimum Selling Price ($/kg)	1.66	0.80	0.52
DME			
Thermo Capital	1%	1%	1%
Product Separation	6%	8%	4%
CO_2 Cost	5%	4%	0%
H_2 Cost	58%	55%	53%
CO_2 Separation	15%	22%	29%
Utilities	15%	10%	13%
Minimum Selling Price ($/kg)	1.89	0.87	0.58
FT-hydrocarbon (HC)			
Thermo Capital	17%	21%	28%
Product Separation	2%	3%	2%
CO_2 Cost	4%	5%	0%
H_2 Cost	55%	66%	67%
CO_2 Separation	11%	2%	0%
Utilities	11%	4%	2%
Minimum Selling Price ($/kg)	4.52	1.31	0.81

6. Sensitivity Analysis

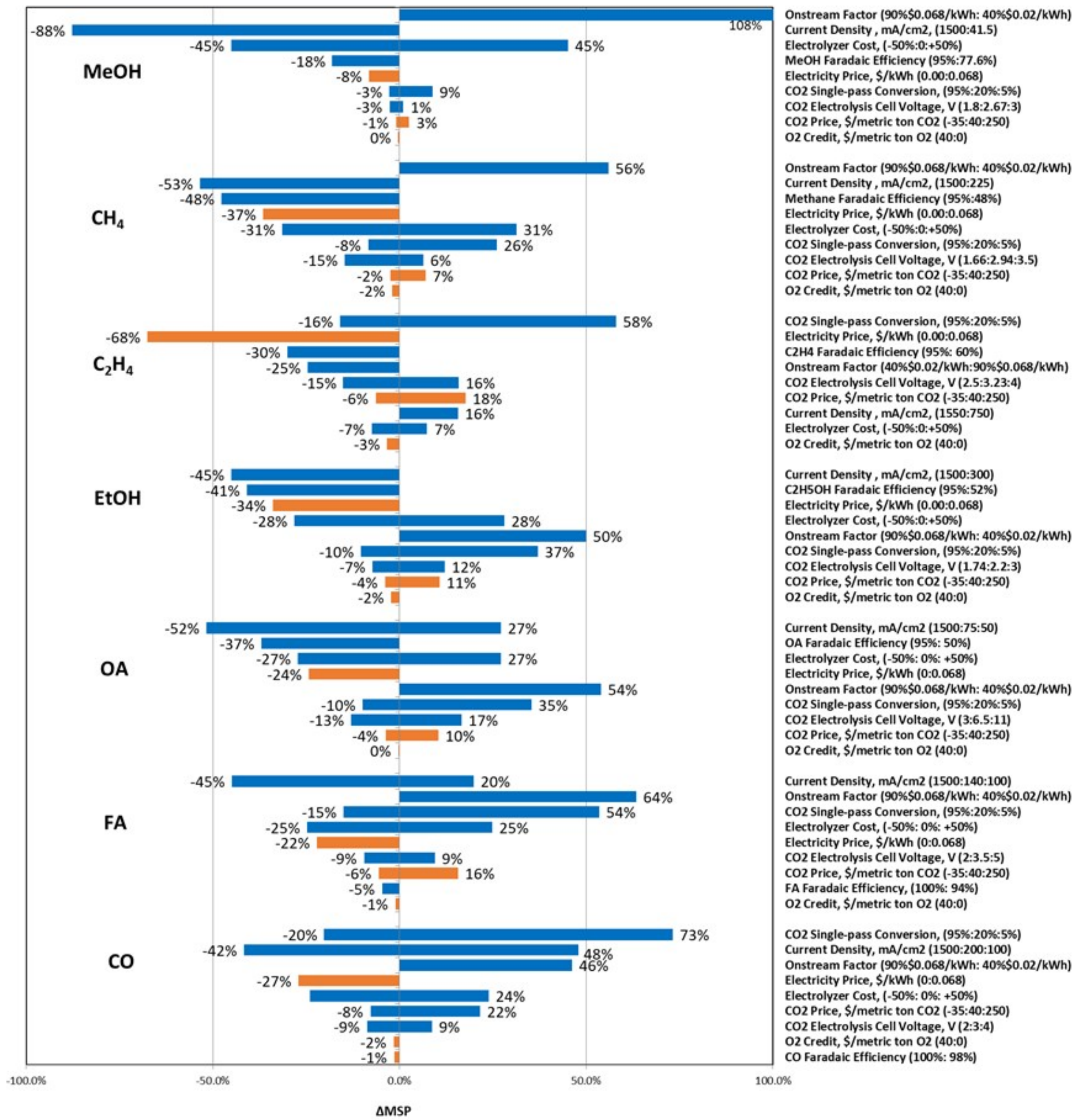

Figure S2. Sensitivity analysis of selected products in LTE pathway. Key cost drivers include current density, onstream factor and electrolyzer cost. Blue and orange bars reflect technical and market parameters respectively.

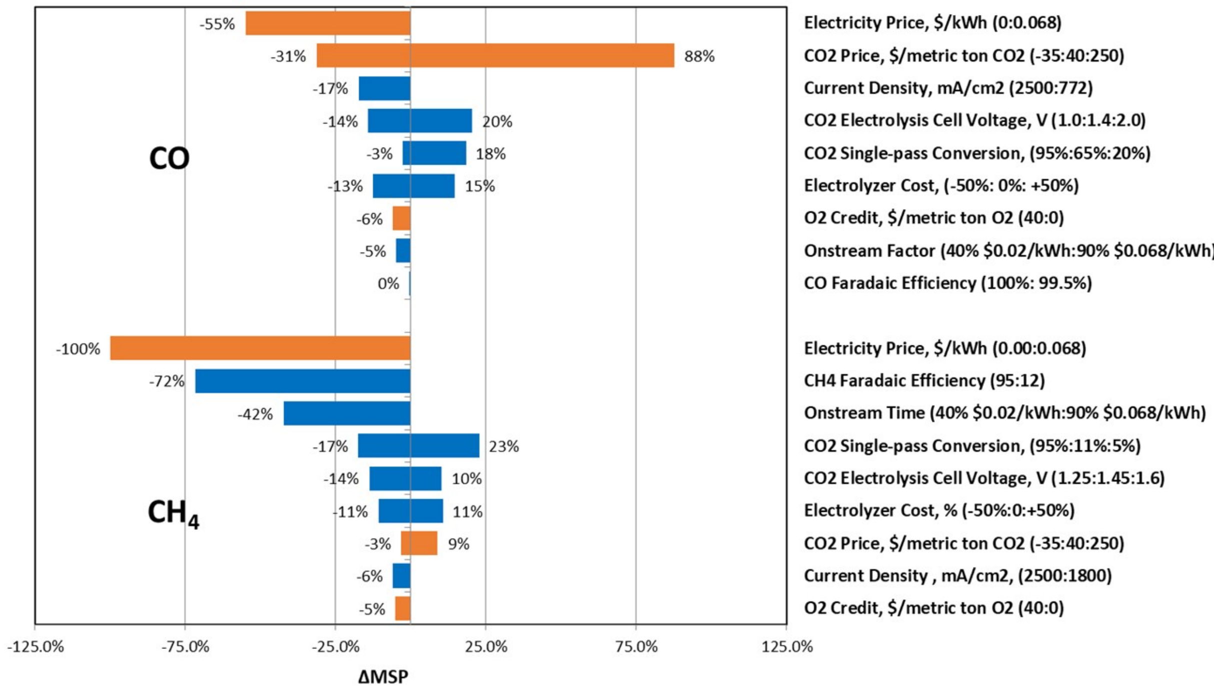

Figure S3. Sensitivity analysis of selected products in HTE pathway. Key cost drivers include electricity, CO_2 single-pass conversion and CO_2 cost. Blue and orange bars reflect technical and market parameters respectively.

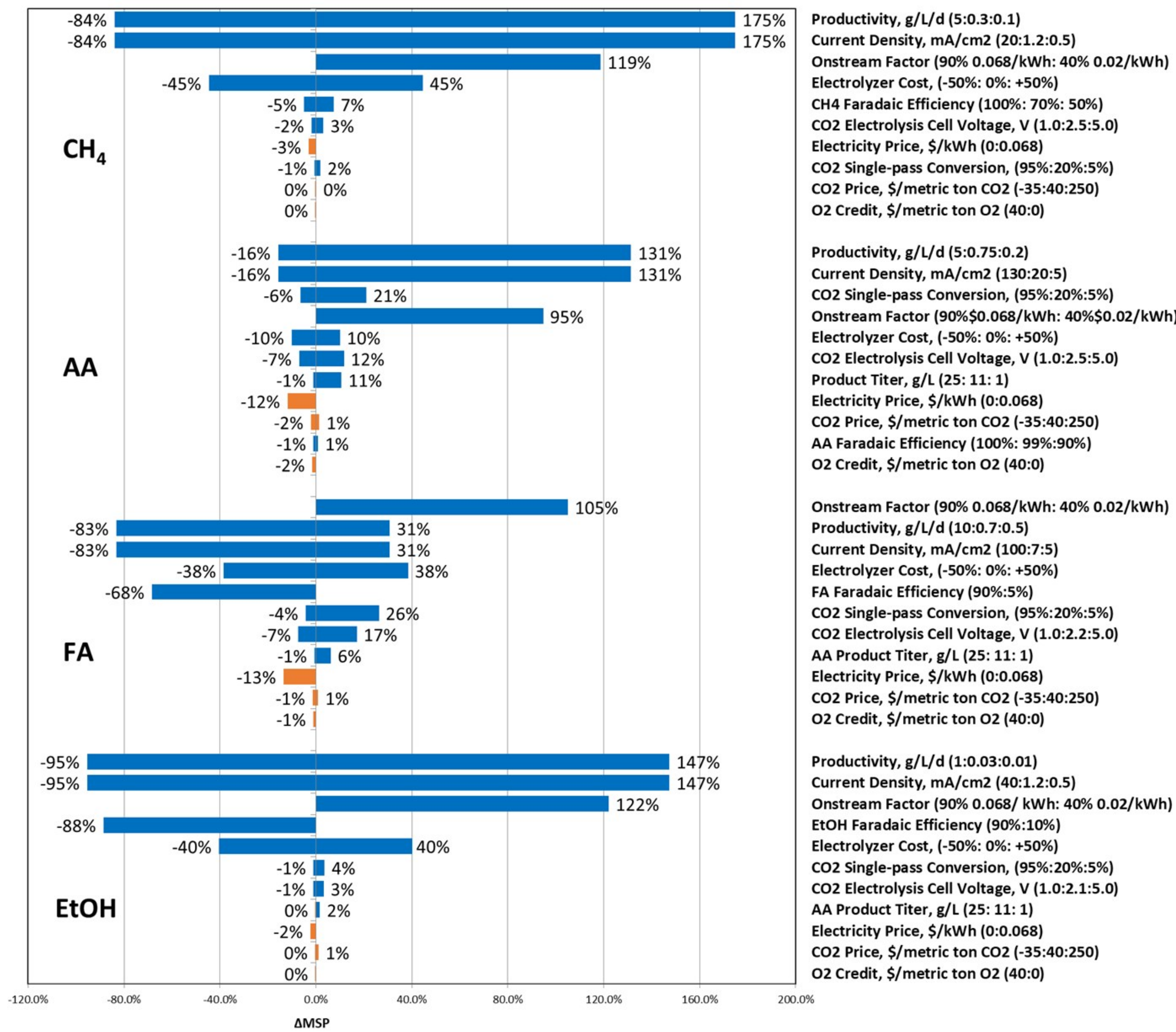

Figure S4. Sensitivity analysis of selected products in MES pathway. Key cost drivers include productivity, current density and onstream factor. Blue and orange bars reflect technical and market parameters respectively.

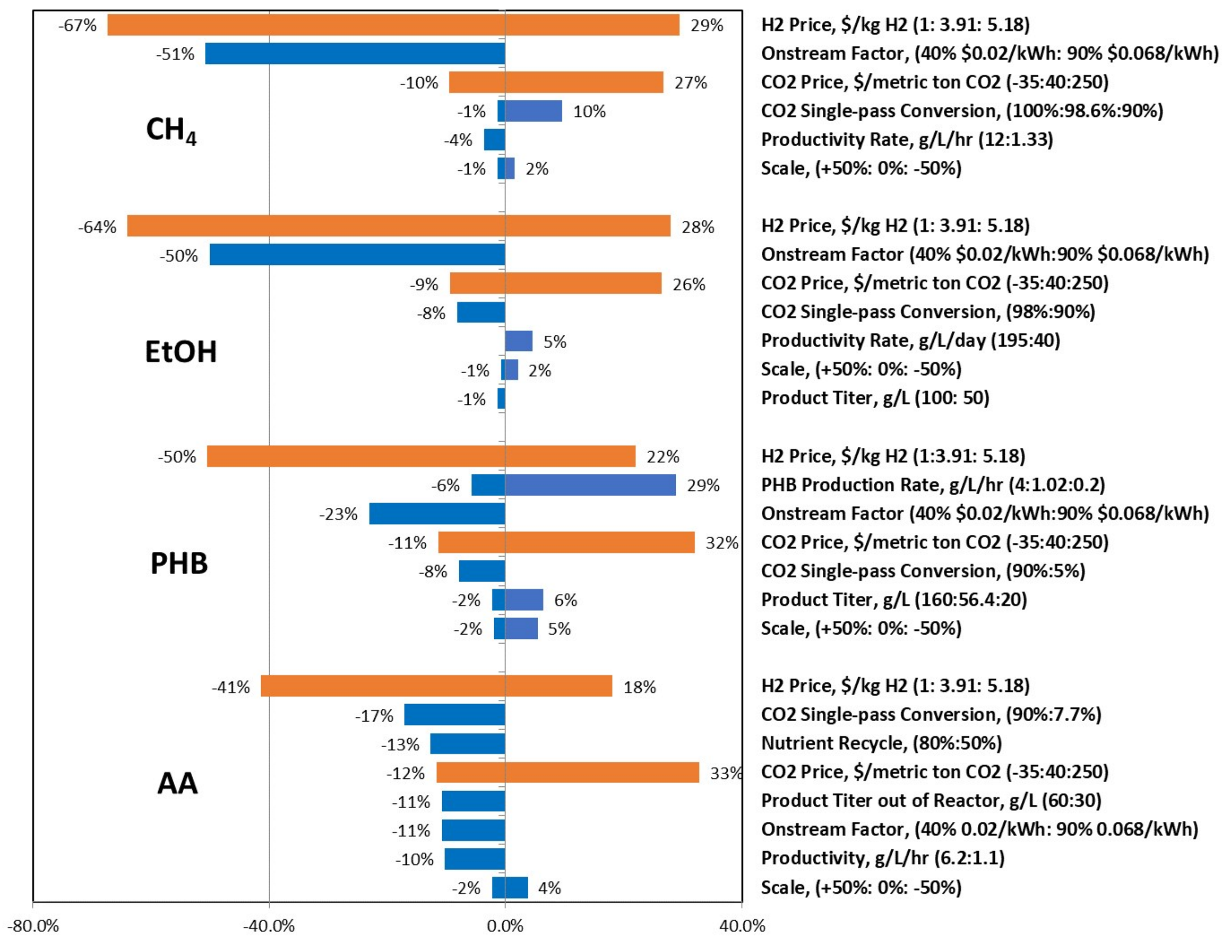

Figure S5. Sensitivity analysis of selected products in BC pathway. Key cost drivers include electrolytic H_2 cost, production rate and onstream factor. Blue and orange bars reflect technical and market parameters respectively.

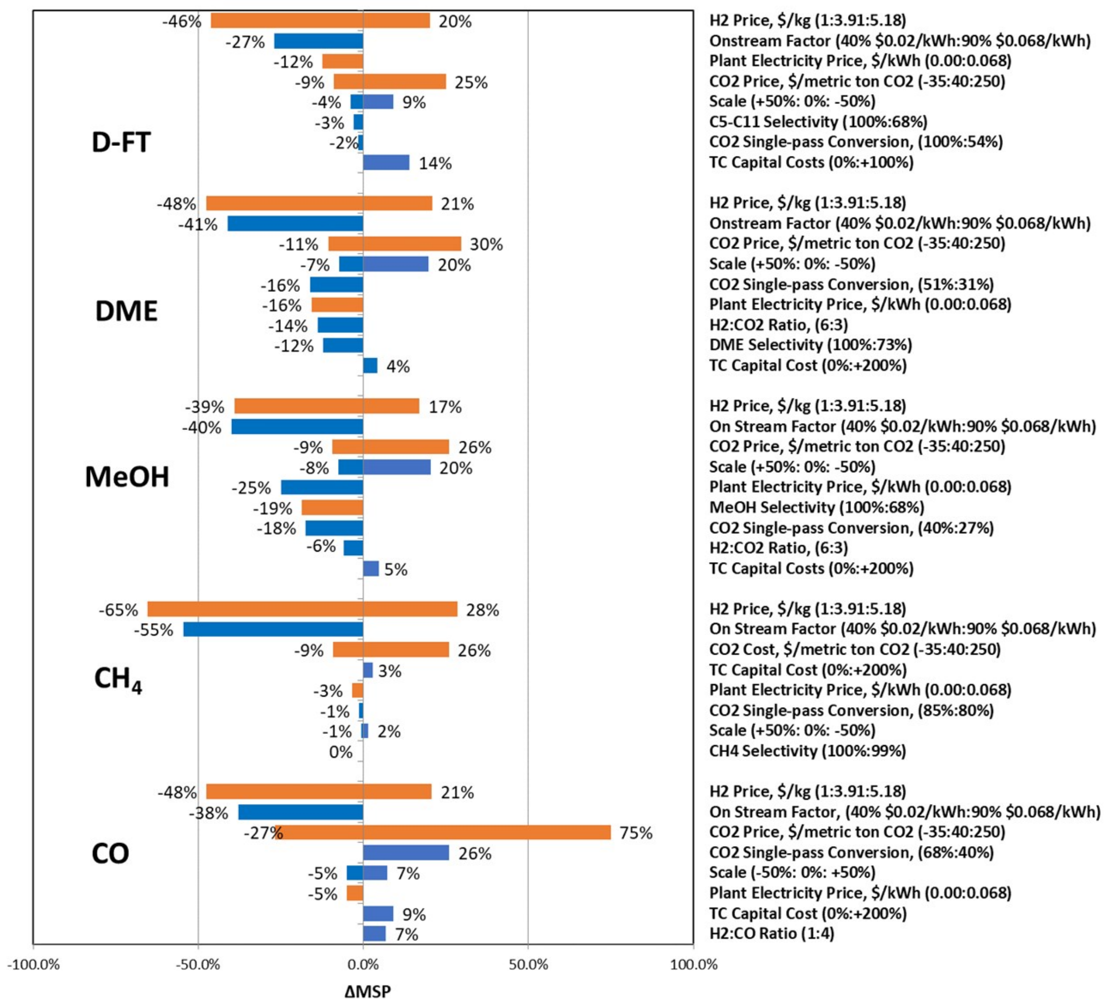

Figure S6. Sensitivity analysis of selected products in TC pathway. Key cost drivers include electrolytic H_2 cost, onstream factor and CO_2 cost. Blue and orange bars reflect technical and market parameters respectively.

7. CO_2 Price Sensitivity under Current Scenario

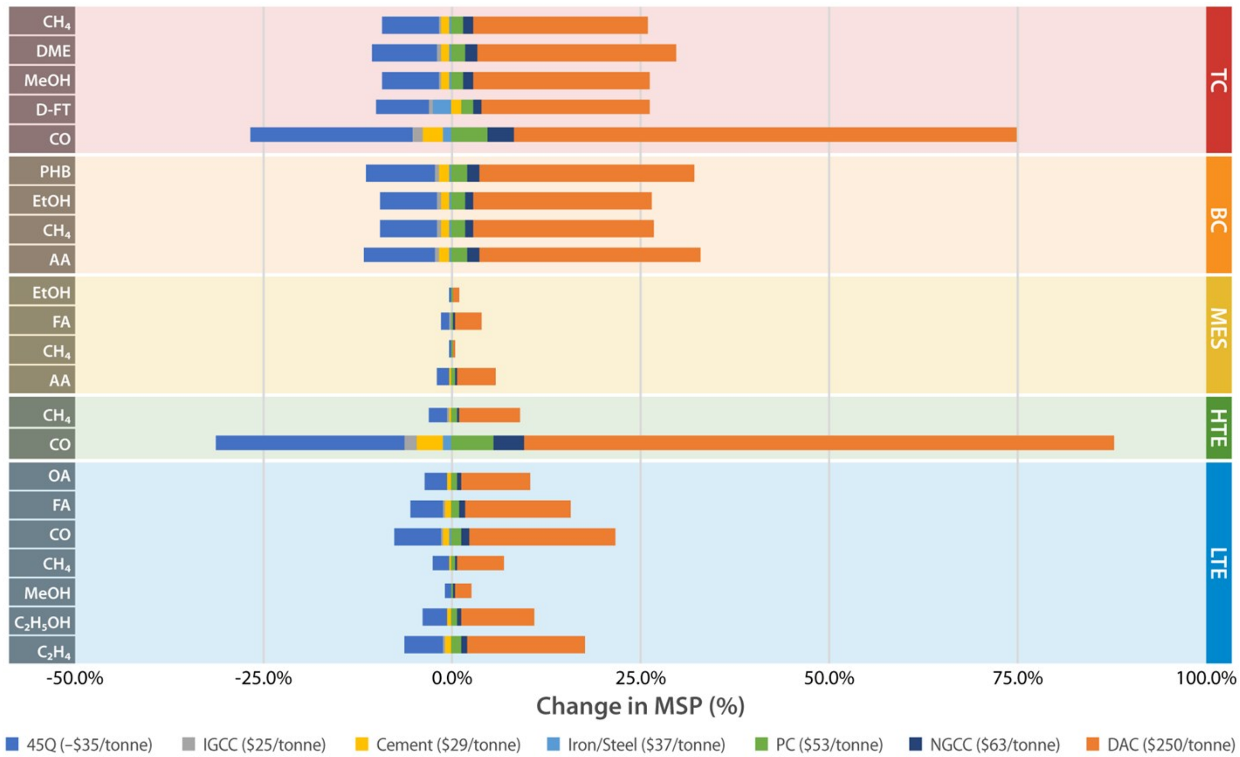

Figure S7. The percent change in product minimum selling price (MSP) as a function of CO_2 capture cost assuming current scenario conditions and an initial capture cost of $40/tonne. Assumed capture costs of -$35/tonne (45Q), $25/tonne (IGCC), $29/tonne (cement), $37/tonne (iron/steel), $53/tonne (PC), $63/tonne (NGCC), and $250/tonne (DAC) are based on published literature reports[22-24].

8. Reference

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