CARBON CONVERSION EXAMPLE TECHNO-ECONOMIC ANALYSIS: ELECTROCHEMICAL CONVERSION

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ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius
°F	Degrees Fahrenheit
Ar	Argon
Aspen	Aspen Plus®
atm	Atmosphere
BEC	Bare erected cost
BFD	Block flow diagram
BOP	Balance of plant
Btu	British thermal unit
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	Butane
CCF	Capital charge factor
CF	Capacity factor
CH_4	Methane
CH_4S	Methanethiol
CO	Carbon monoxide
CO_2	Carbon dioxide
DME_2	Dimethyl ether
DOE	Department of Energy
ECC	Electrochemical catalyst
Eng’g CM H.O & Fee	Engineering construction management home office and fees
EPCC	Engineering, procurement, and construction cost
ETOH	Ethanol
FCF	Fixed charge factor
FE	Faradaic efficiency
FECM	Office of Fossil Energy and Carbon Management
ft^3	Cubic foot
gal	Gallon
gpm	Gallons per minute
gpy	Gallons per year
h, hr	Hour
H_2	Hydrogen
H_2O	Water
I&C	Instrumentation and control
ISO	International Organization for Standardization

kg	Kilogram
kW, kWe	Kilowatt electric
kWh	Kilowatt-hour
lb	Pound
LCOP	Levelized cost of production
m^3/min	Cubic meters per minute
mA/cm^2	Milliampere per square centimeter
MeOH	Methanol
MM	Million
MPa	Megapascal
MW	Megawatt electric
MWh	Megawatt-hour
N_2	Nitrogen
NETL	National Energy Technology Laboratory
O&M	Operation and maintenance
O_2	Oxygen
O-H	Overhead
OP	Overpotential
psia	Pound per square inch absolute
QGESS	Quality Guidelines for Energy System Studies
SCPC	Supercritical pulverized coal
SO_2	Sulfur dioxide
syngas	Synthesis gas
T&S	Transport and storage
TASC	Total as-spent cost
TEA	Techno-economic analysis
TFOM	Total annual fixed operation and maintenance
TOC	Total overnight cost
tonne	Metric ton
TPC	Total plant cost
TVOM	Total annual variable operation and maintenance
U.S.	United States
V-L	Vapor-liquid
V	Volt
y, yr	Year

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EXECUTIVE SUMMARY

The Carbon Conversion Techno-Economic Analysis (TEA) Toolkit is a web-based toolkit developed by the United States (U.S.) Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM) and the National Energy Technology Laboratory (NETL) to support TEA of carbon conversion technologies. The TEA described herein was developed as part of the Carbon Conversion TEA Toolkit and is one of a series of example TEA on established carbon conversion pathways. Example TEA were developed based on prior screening analyses on specific technologies using real data. However, performance data for the underlying carbon conversion technology is often proprietary and has been made generic where necessary by altering values sourced from real data. Generic values are assumed to fall within a range of plus or minus 50 percent from real data.

The example TEA described here was developed using the ECC-MeOH (electrochemical catalyst + methanol production) case from NETL's 2018 report, "Metrics Assessment for an Electrochemical CO_2 Conversion Catalyst" [1]. This case and the subsequently developed example TEA evaluate an electrochemical conversion pathway. In this pathway, an electrochemical catalyst (ECC) is used to efficiently convert carbon dioxide (CO_2) to synthesis gas (syngas) via electrochemical reduction of CO_2 using hydrogen (H_2) ions and electrons, which are simultaneously generated via water splitting. Specifications for the ECC cell (e.g., cell voltage, faradaic efficiency, current density) are consistent with default parameters used in the NETL Electrochemical Conversion of CO_2 Sensitivity Analysis Tool [2]. The resulting syngas is subsequently fed to a conventional methanol (MeOH) synthesis process. The system model of the carbon conversion and MeOH synthesis process was developed at a capacity of 61 million (MM) gallons per year (gpy) representing a new, small-scale MeOH plant in the United States. A summary of the case developed for the example TEA is shown in Exhibit ES-1.

Exhibit ES-1. Electrochemical conversion example TEA summary

	Electrochemical Conversion Example TEA
Technology	Electrochemical CO_2 Reduction + MeOH Synthesis
Feedstocks	CO_2, Water
MeOH Production (MMgpy)	61

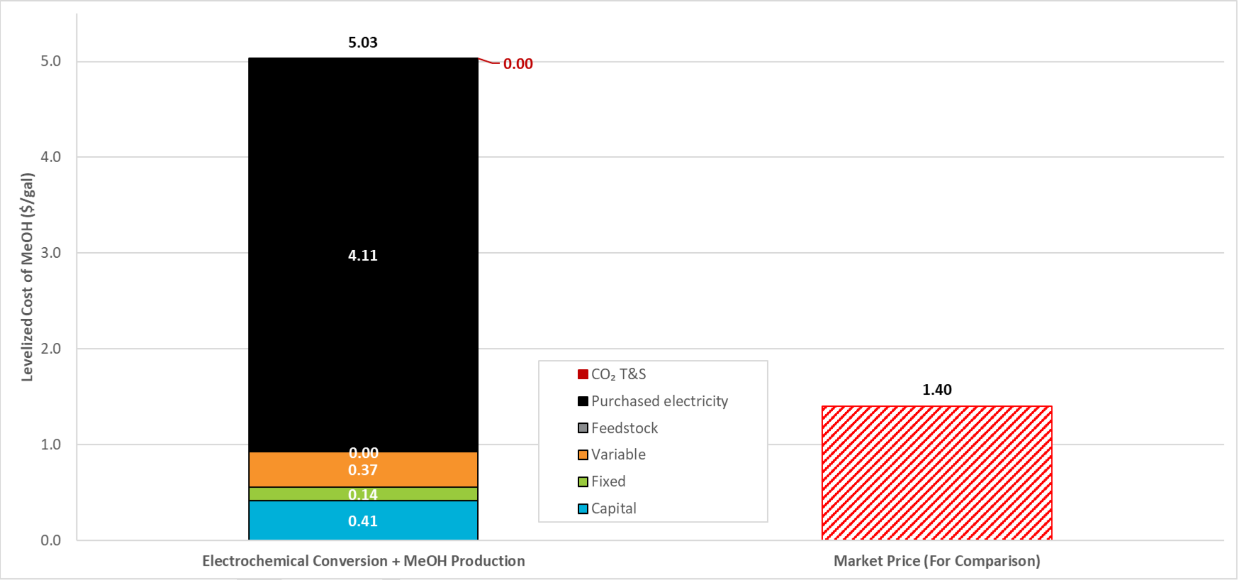
The cost metric of interest is the levelized cost of production (LCOP), in $/gallon (gal) of MeOH. The resulting LCOP for this analysis, along with capital, variable and fixed operation and maintenance (O&M), purchased electricity, and feedstock cost components, is presented in Exhibit ES-2 and Exhibit ES-3.

Exhibit ES-2. Electrochemical conversion example TEA results, table

Levelized Cost of Product ($/gal MeOH)	
Capital	0.41
Fixed	0.14
Variable	0.37
Feedstock	0.00
Purchased Electricity	4.11
Total LCOP	5.03

Note: All dollar figures are expressed as Real December 2018 U.S. dollars

Exhibit ES-3. Electrochemical conversion example TEA results, graph



Note: All dollar figures are expressed as Real December 2018 U.S. dollars

The results show that the electrochemical conversion process with MeOH production results in an LCOP that is 3.6 times greater than the market price of MeOH [3]. The cost of purchased electricity is the largest economic constraint representing 81.7 percent of the LCOP. Sensitivity analyses on key performance parameters of the electrochemical conversion system, as well as general financial assumptions, were completed. Reducing ECC cell voltage was shown to be particularly impactful with a 41.9 percent reduction in LCOP realized when voltage drops from 4 volts (V) to 2V. As such, significant improvements to the ECC technology can be realized with reduced electricity consumption and increased performance of the ECC.

1 INTRODUCTION

The Carbon Conversion TEA Toolkit is a web-based toolkit developed by the United States (U.S.) Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM) and the National Energy Technology Laboratory (NETL) to support techno-economic analysis (TEA) of carbon conversion technologies. The TEA described herein was developed as part of the Carbon Conversion TEA Toolkit and is one of a series of example TEA on established carbon conversion pathways. Example TEA were developed based on prior screening analyses on specific technologies using real data. However, performance data for the underlying carbon conversion technology is often proprietary and has been made generic where necessary by altering values sourced from real data. Generic values are assumed to fall within a range of plus or minus 50 percent from real data.

The example TEA described here was developed using the ECC-MeOH (electrochemical catalyst + methanol production) case from NETL's 2018 internal report, "Metrics Assessment for an Electrochemical CO_2 Conversion Catalyst" (reference screening analysis) [1]. This case and the subsequently developed example TEA evaluate an electrochemical conversion pathway. In this pathway, an electrochemical catalyst (ECC) is used to efficiently convert carbon dioxide (CO_2) to synthesis gas (syngas) via electrochemical reduction of CO_2 using hydrogen (H_2) ions and electrons, which are simultaneously generated via water splitting. Specifications for the ECC cell (e.g., cell voltage, faradaic efficiency, current density) are consistent with default parameters used in the NETL Electrochemical Conversion of CO_2 Sensitivity Analysis Tool [2]. The resulting syngas is subsequently fed to a conventional methanol (MeOH) synthesis process. The system model of the carbon conversion and MeOH synthesis process was developed at a capacity of 61 million (MM) gallons per year (gpy) representing a new, small-scale MeOH plant in the United States. A summary of the case developed for the example TEA is shown in Exhibit 1-1.

Exhibit 1-1. Electrochemical conversion example TEA summary

	Electrochemical Conversion Example TEA
Technology	Electrochemical CO_2 Reduction + MeOH Synthesis
Feedstocks	CO_2, Water
MeOH Production (MMgpy)	61

2 NOVEL TECHNOLOGY BASIS

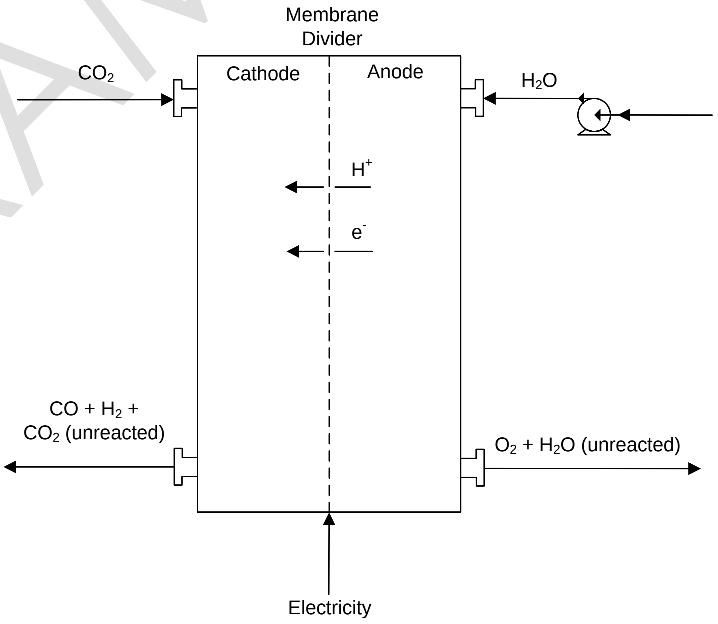
The ECC system electrochemically reduces CO_2 using H_2 ions and electrons to create the desired product while simultaneously splitting water to generate the required H_2 and electrons. These reactions occur with the assistance of catalysts at the cathode and anode, respectively. While the ECC can produce a variety of different products, the electricity required to complete the electrolysis reactions can greatly increase the operating costs of the plant. Exhibit 2-1 shows the formal potentials, E^0, (minimum potentials) for several common CO_2 reduction reactions and the water splitting reaction, referenced against the reversible hydrogen electrode.

Exhibit 2-1. Formal potentials for several common CO_2 reduction and water splitting reactions [4]

Electrode	Reaction	E^0 (V)	Reaction
Cathode	$CO_2 + 2H^+ + 2e^- \rightarrow CO + H_2O$	-0.10	(1)
	$CO_2 + 2H^+ + 2e^- \rightarrow HCOOH$	-0.18	(2)
	$CO_2 + 4H^+ + 4e^- \rightarrow HCOH + H_2O$	-0.15	(3)
	$CO_2 + 6H^+ + 6e^- \rightarrow CH_3OH + H_2O$	-0.15	(4)
	$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$	0.00	(5)
	$CO_2 + 8H^+ + 12e^- \rightarrow C_2H_4 + 2H_2O$	0.07	(6)
	$2H^+ + 2e^- \rightarrow H_2$	0.00	(7)
Anode	$2H_2O + 4e^- \rightarrow O_2 + 4H^+$	1.23	(8)

Carbon monoxide (CO), one of two components in syngas, results in the lowest electrical requirement per metric ton (tonne) of CO_2 converted. A flow diagram of one ECC cell is shown in Exhibit 2-2.

Exhibit 2-2. ECC cell diagram



The total number of cells required by a commercial system will depend on several variables, including desired production rate, catalyst activity, future scalability, and others. CO_2 is fed to the cathode side of the cell and water is fed to the anode side where it is split. The splitting of water provides the electrons and protons necessary to drive the CO_2 reduction reaction, shown in the reaction equation below:

$$\boldsymbol{CO_2 + 2H^+ + 2e^- \xrightarrow{yields} CO + H_2O}$$

Equation 2-1: CO_2 reduction reaction

The anode outlet stream contains unreacted water as well as oxygen (O_2) resulting from water splitting. This O_2 is a secondary product of the ECC system and would require separation and compression to ready it for sale. The cathode product stream will contain, at a minimum, unreacted CO_2 as well as the CO product. For this example TEA, all product streams exiting the ECC system are assumed to be completely pure and it is assumed that no separations or recycle will be required.

To produce 1 ton of CO, the ECC system requires 6,944 kilowatt-hours (kWh) of power input. This value assumes a cell voltage of 4V, 98 percent Faradaic efficiency (FE) or transfer of electrons to the product, and 0V of overpotential. All systems experience losses in FE when electrons are utilized in side reactions, so excess electricity will likely be required to supplement the loss of electrons. Additionally, the theoretical minimum is rarely observed experimentally and the application of overpotential (OP) is required to ensure that the redox reaction will occur. Sensitivities on ECC cell parameters are available in Section 5.2.2.

To produce syngas with a 2:1 ratio of H_2:CO, the power input must be increased to 20,833 kWh per ton CO, which results in additional water being split on the anode side; the excess H^+ will diffuse to the cathode side and recombine to form H_2. Therefore, H_2 can also be present as a product from the cathode. This is an attractive aspect of the ECC system because the resulting H_2/CO syngas product can be tuned to meet downstream processing synthesis requirements by adjusting the applied power, catalyst loading, or CO_2 flow rate. H_2 can also be purchased over the fence to lower electrical auxiliary requirements.

3 EXAMPLE TEA DEVELOPMENT

The example TEA was developed using the performance calculations and cost estimates for the ECC-MeOH case from the reference screening analysis. However, the performance model for the conventional MeOH synthesis process was based on Case 6A from NETL's 2023 internal report, "CO_2 Conversion: Screening Technoeconomic Analysis of NETL Microwave-Assisted Carbon Conversion Technology." [5] The capacity was set at 61 MMgpy, consistent with Case 6A, to represent a new, small-scale MeOH plant in the United States. Specifications for the ECC cell (e.g., cell voltage, FE, current density) are consistent with default parameters used in the NETL Electrochemical Conversion of CO_2 Sensitivity Analysis Tool [2]. Select financial assumptions were adjusted from the reference screening analysis to conform with assumptions used throughout the example TEA series.

3.1 METHANOL SYNTHESIS

Methanol was chosen as the end-use product as syngas is mostly generated as an intermediate product and existing data is available for MeOH production from syngas. The MeOH synthesis process used in Case 6A and the subsequently developed example TEA is based on AspenTech's Aspen Plus® MeOH Synthesis Model [6]. AspenTech's model is based on the ICI Synetix low pressure MeOH process, which is the most common industrial MeOH process worldwide [6].

Most MeOH production in the United States utilizes a natural gas feedstock, which is reformed into syngas with small amounts of CO_2. The syngas proportions are described by the module, or M, number [7]. An M number of approximately 2 is most desirable for MeOH synthesis and the power supplied to the ECC cell is set to achieve the appropriate syngas proportions [7]. The M number is defined by Equation 3-1.

$$\boldsymbol{M} = (\boldsymbol{H_2} + \boldsymbol{CO_2})/(\boldsymbol{CO} + \boldsymbol{CO_2})$$

Equation 3-1: Module number

4 GENERAL EVALUATION BASIS

4.1 SITE CHARACTERISTICS

The plant evaluated in the example TEA is assumed to be located at a generic plant site in the midwestern United States, with site characteristics and ambient conditions as presented in Exhibit 4-1 and Exhibit 4-2. The ambient conditions are the same as International Organization for Standardization (ISO) conditions.

Exhibit 4-1. Site characteristics

Parameter	Value
Location	Greenfield, Midwestern U.S.
Topography	Level
Size, acres	Variable per Plant Capacity/Size
Transportation	Rail or Highway
Water	50% Municipal and 50% Ground Water

Exhibit 4-2. Site ambient conditions

Parameter	Value
Elevation, meters (feet)	0 (0)
Barometric Pressure, MPa (psia)	0.101 (14.696)
Average Ambient Dry Bulb Temperature, °C (°F)	15 (59)
Average Ambient Wet Bulb Temperature, °C (°F)	10.8 (51.5)
Design Ambient Relative Humidity, %	60
Cooling Water Temperature, °C (°F)[A]	15.6 (60)
Air composition based on published psychrometric data, mass %	
N_2	75.055
O_2	22.998
Ar	1.280
H_2O	0.616
CO_2	0.050
Total	100.00

[A] The cooling water temperature is the cooling tower cooling water exit temperature. This is set to 4.8°C (8.5°F) above ambient wet bulb conditions in ISO cases.

4.2 STUDY ASSUMPTIONS

Assumptions were made as necessary for the development of the performance model and for calculations regarding consumables, waste disposal, and other operation and maintenance

(O&M) costs. Select considerations are included in Exhibit 4-3—this table is not considered exhaustive.

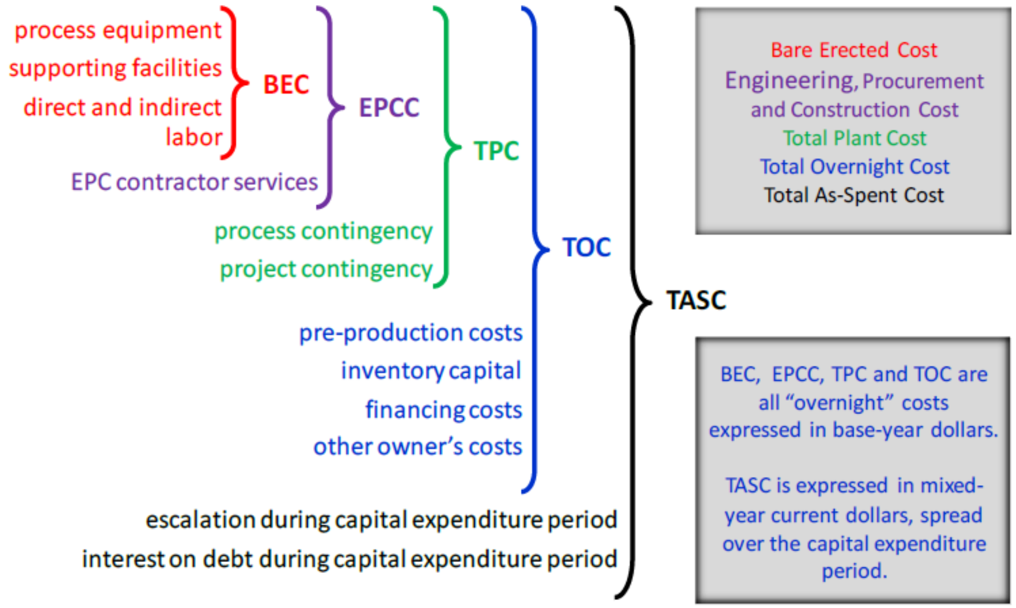
Exhibit 4-3. Select study assumptions

Parameter	Temperature	Pressure
Makeup Water Conditions	15°C (59°F)	0.101 MPa (14.7 psia)
ECC Syngas Product Conditions	38°C (100°F)	0.101 MPa (14.7 psia)
Capacity Factor	85 percent	

4.3 COST ESTIMATING METHODOLOGY

Cost estimates were developed using those from Case 6A, which, in turn, uses costs obtainable from other NETL studies and literature sources. Cost and/or consumption estimates were estimated using Aspen Economic Analyzer, or best engineering judgement, as appropriate. Proprietary cost data was made generic and labeled as such in the example TEA templates. To the extent possible, guidance from NETL's Quality Guidelines for Energy System Studies (QGESS) publications was employed to estimate and scale costs for capital and O&M costs. Consistent with guidance in the QGESS document "Cost Estimation Methodology for NETL Assessments of Power Plant Performance" [8], capital costs were estimated from bare erected cost (BEC) to total as-spent cost (TASC) as shown in Exhibit 4-4.

Exhibit 4-4. Capital cost levels and their elements



The resulting calculation for each case is the annual levelized cost of production (LCOP) (i.e., dollars per gallon of MeOH), which includes factors for variable and fixed O&M and purchased power and feedstock, along with the levelized capital costs. The TASC/total overnight cost (TOC) ratio and the fixed charge factor (FCF)—1.047 and 6.64 percent, respectively, expressed in real dollar terms—are consistent with that of an ethanol plant, with a 1-year capital expenditure period and a 30-year operating life. Equation 4-1 shows the calculation of the LCOP.

$$\boldsymbol{LCOP = \left(\frac{TVOM + TFOM + TOC * TASC/TOC * FCF}{CF * gallons\ of\ product\ per\ year}\right)}$$

Equation 4-1: Levelized cost of production

Where

LCOP – Levelized cost of production
TVOM – Total annual variable O&M
TFOM – Total annual fixed O&M
TOC – Total overnight costs of all equipment
TASC/TOC – Total overnight cost to total as-spent cost basis multiplier
FCF – Fixed charge factor
CF – Capacity factor

5 RESULTS, ANALYSIS, AND DISCUSSION

5.1 PERFORMANCE RESULTS

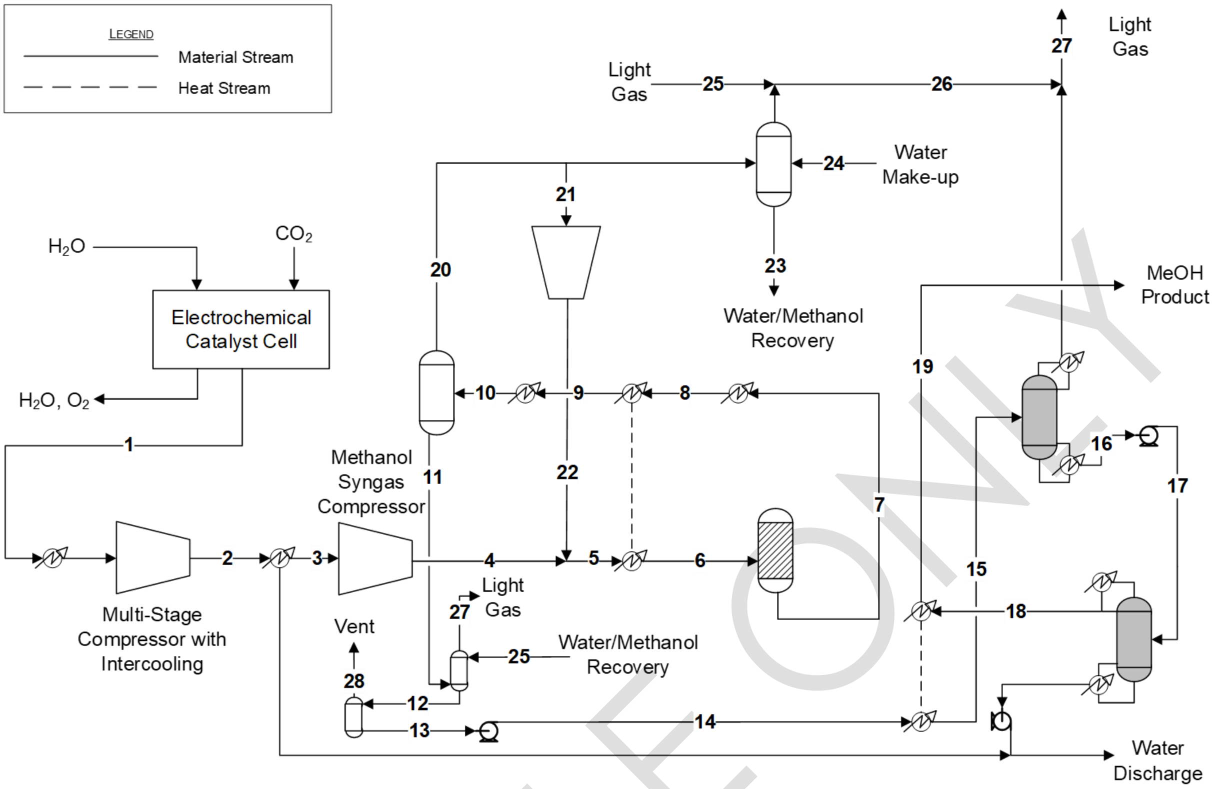
The performance results for the ECC cell + MeOH synthesis system are presented Exhibit 5-1 and the block flow diagram (BFD) is shown in Exhibit 5-2. The stream table is available in Appendix A: Stream Tables.

Exhibit 5-1. Performance summary for ECC cell + MeOH synthesis

Performance Summary	
Parameter	**Value**
MeOH Production Rate, MMgpy (100% CF)	61
Total Auxiliaries, MW	429
CO Feed From ECC, lb/hr	39,281
H_2 Feed From ECC, lb/hr	5,654
CO_2 Required, lb/hr	61,718
Total CO_2 Emissions, ton/yr	672
Auxiliary Loads	
ECC Power Requirement, kWe	417,517
MeOH Process Compression, kWe	10,510
MeOH Pumps, kWe	20
Cooling Tower Fans, kWe	200
Circulating Water Pumps, kWe	390
Miscellaneous Balance of Plant,[A] kWe	240
Power Generated	
MeOH Water Turbine, kWe	30

[A] Includes plant control systems; lighting; heating, ventilation, and air conditioning; and miscellaneous low voltage loads

Exhibit 5-2. BFD for ECC cell + MeOH synthesis



5.1.1 Carbon Conversion Metrics Analysis

The goal of evaluating carbon conversion technologies is to provide a reasonable comparison between developing technologies and traditional technologies. As such, NETL developed carbon conversion metrics, detailed in the QGESS "Performing a Techno-economic Analysis for Carbon Conversion Technologies," published in 2023 [9]. Applicable carbon conversion metrics are summarized for the example TEA in Exhibit 5-3.

Exhibit 5-3. Carbon conversion metrics

Carbon Conversion Metrics Summary	
CO_2 Conversion Efficiency, %	100
CO_2 Conversion Potential (SCPC Plant), %	283
CO_2 Conversion Intensity, %	140
Required Purchase Price, \$/ton CO_2	-903.66

Note: Calculation of CO_2 conversion potential requires selection of reference emitters to compare to the process being evaluated. In the example TEA, a standalone supercritical pulverized coal (SCPC) power plant serves as the default reference emitter.

As CO_2 conversion efficiency and potential is positive, considering MeOH production as a utilization technology for an existing CO_2 emitter (i.e., utilizing the CO_2 from flue gas at a power plant) would offer beneficial CO_2 use. The cost of producing MeOH with electrochemical syngas production would require that CO_2 producers pay for processing CO_2 emissions into beneficial products (i.e., negative required purchase price).

5.2 COST RESULTS

The economic results for MeOH synthesis using syngas produced by electrochemical conversion are presented in Exhibit 5-4. Owner's costs, capital costs, and O&M costs are available in Appendix B: Detailed Cost Estimates.

Exhibit 5-4. Cost summary for ECC cell + MeOH synthesis

Parameter	Value
MeOH Production Rate, Mgpy (100% CF)	61
Annual Purchased Power, $/1,000 (100% CF)	$250,764
Total Overnight Cost, $/1,000	$307,708
First Year Variable O&M Cost, $/1,000 (100% CF)	$22,578
Levelized Cost of Methanol ($/gal)	
Capital	0.41
Fixed	0.14
Variable	0.37
Feedstock	0.00
Purchased Electricity	4.11
Total LCOP	**5.03**

Note: All dollar figures are expressed as Real December 2018 U.S. dollars

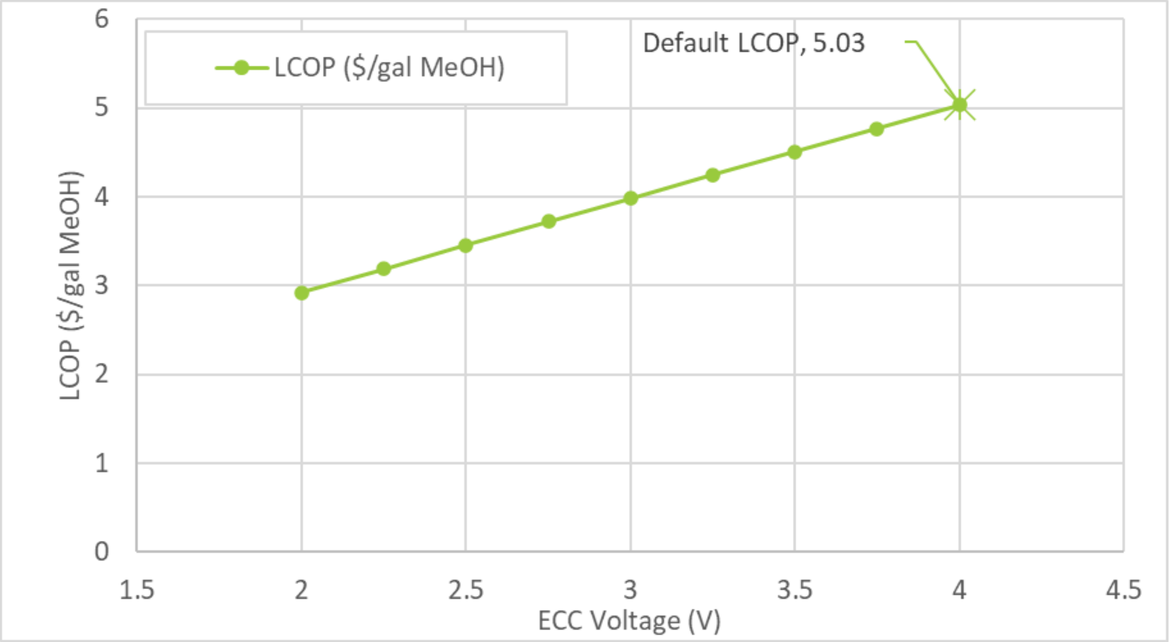
5.2.1 Electrochemical Conversion Sensitivity Analyses

Many costs associated with the electrochemical conversion system are unknown. As such, the effects that varying assumptions regarding the cost and performance of the ECC cell might have on the LCOPs were estimated for the example TEA.

5.2.1.1 ECC Voltage

An ECC voltage of 4V was considered for the example TEA, based on the default specifications from the NETL Electrochemical Conversion Sensitivity Analysis Tool. However, with further development of the ECC technology, the required voltage could be considerably lower. Decreasing the ECC voltage by 50 percent provided a 42 percent LCOP decrease (Exhibit 5-5).

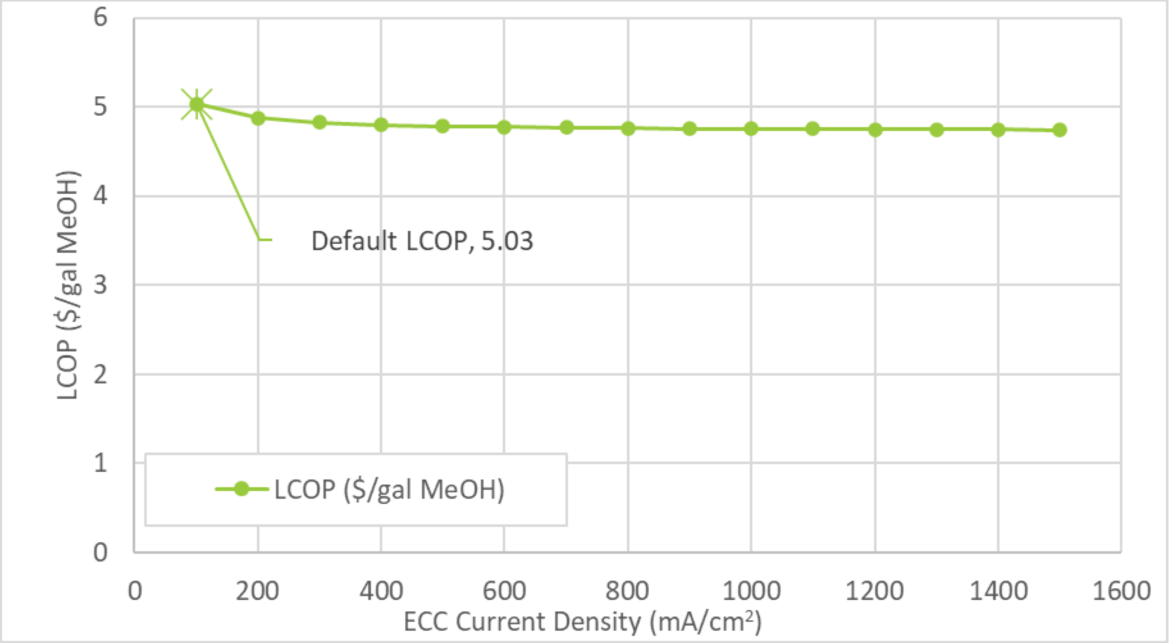
Exhibit 5-5. LCOP versus ECC voltage



5.2.1.2 ECC Current Density

An ECC current density of 100 mA/cm^2 was considered for the example TEA, based on the default specifications from the NETL Electrochemical Conversion Sensitivity Analysis Tool. With further development of the ECC technology, the current density could increase considerably. Increasing the ECC current density by 15 times provided a 6 percent LCOP decrease (Exhibit 5-6).

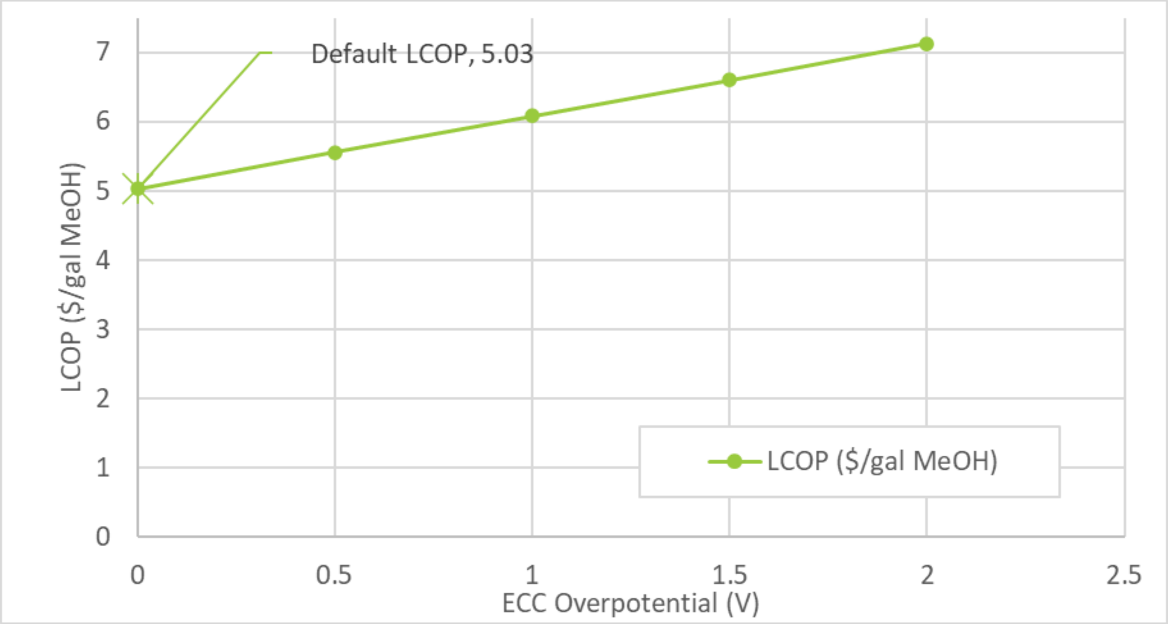
Exhibit 5-6. LCOP versus ECC current density



5.2.1.3 ECC Overpotential

An ECC overpotential of 0V was considered for the example TEA, based on the default specifications from the NETL Electrochemical Conversion Sensitivity Analysis Tool. Zero overpotential corresponds to the theoretical minimum voltage required for the CO_2 reduction reaction to occur. The theoretical minimum is rarely observed experimentally and overpotential will likely be required to ensure the desired reaction extent. Increasing overpotential from 0V to 2V provided a 42 percent LCOP increase (Exhibit 5-7).

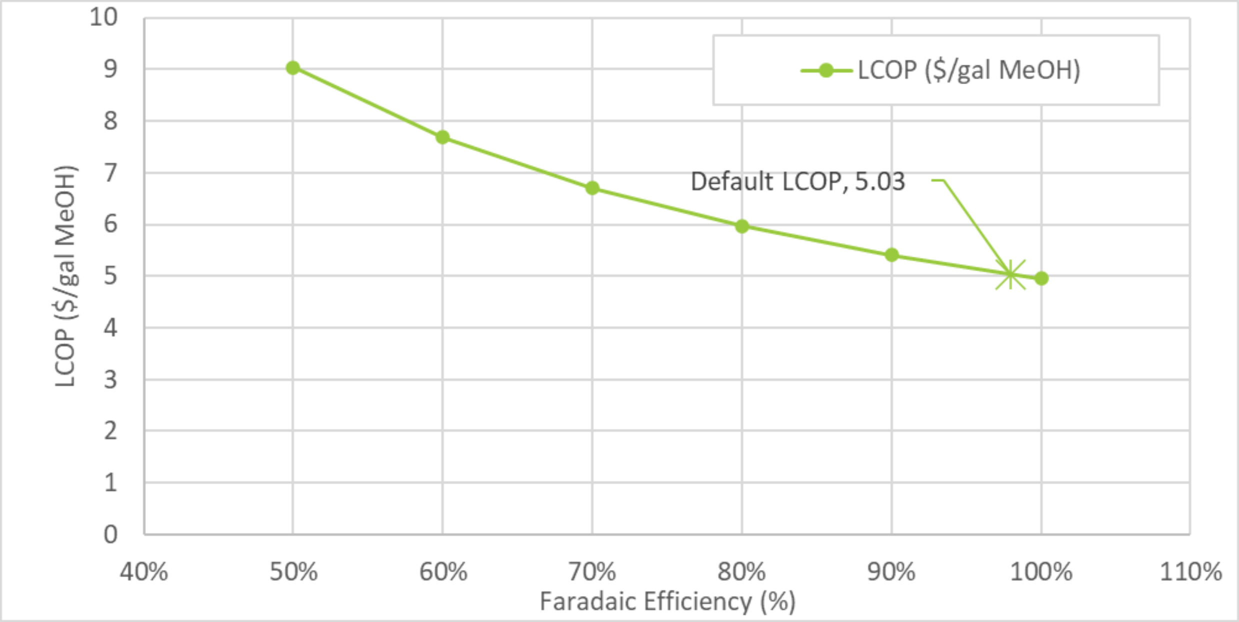
Exhibit 5-7. LCOP versus ECC overpotential



5.2.1.4 Faradaic Efficiency

A FE of 98 percent was considered for the example TEA, based on the default specifications from the NETL Electrochemical Conversion Sensitivity Analysis Tool. All systems experience losses in FE when electrons are utilized in side reactions, requiring excess electricity to supplement the loss of electrons. FE shows a significant effect on LCOP, with a drop to 50 percent efficiency resulting in an LCOP increase of 80 percent (Exhibit 5-8).

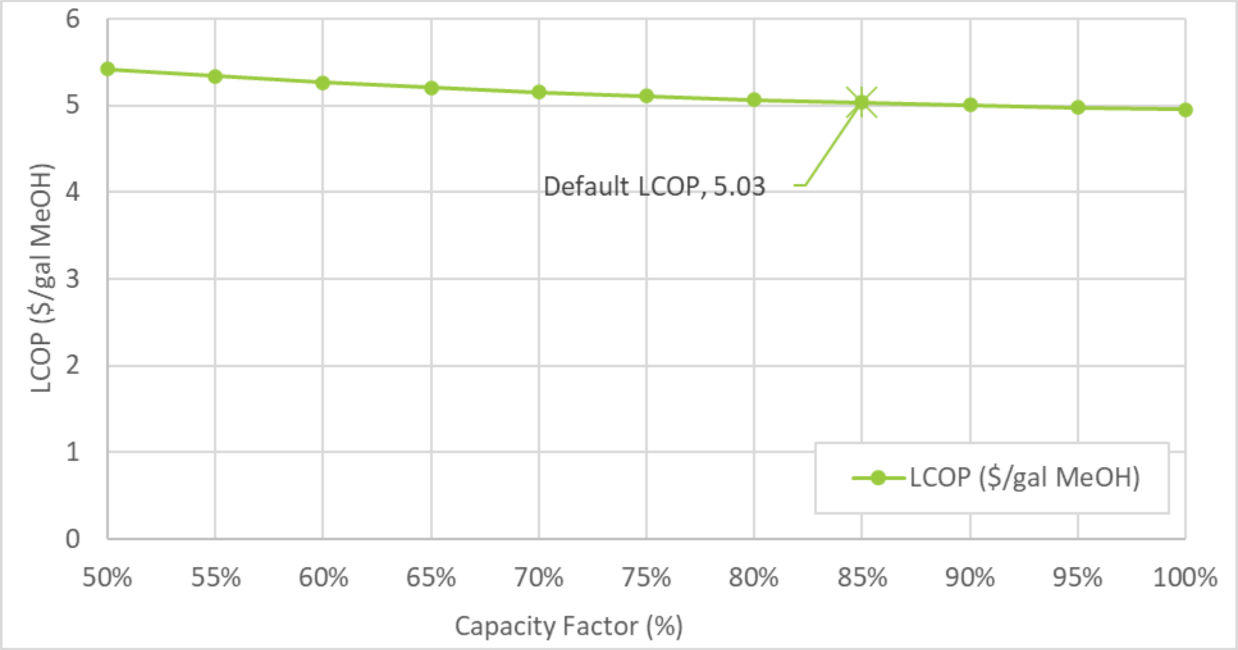
Exhibit 5-8. LCOP versus FE



5.2.1.5 Capacity Factor

The capacity factor (CF) is assumed to be 85 percent, the standard value assumed for NETL studies. CF can vary depending on numerous factors including the availability of renewable energy. As such, the LCOP was evaluated across a range of CFs of 50–100 percent (Exhibit 5-9).

Exhibit 5-9. LCOP versus CF



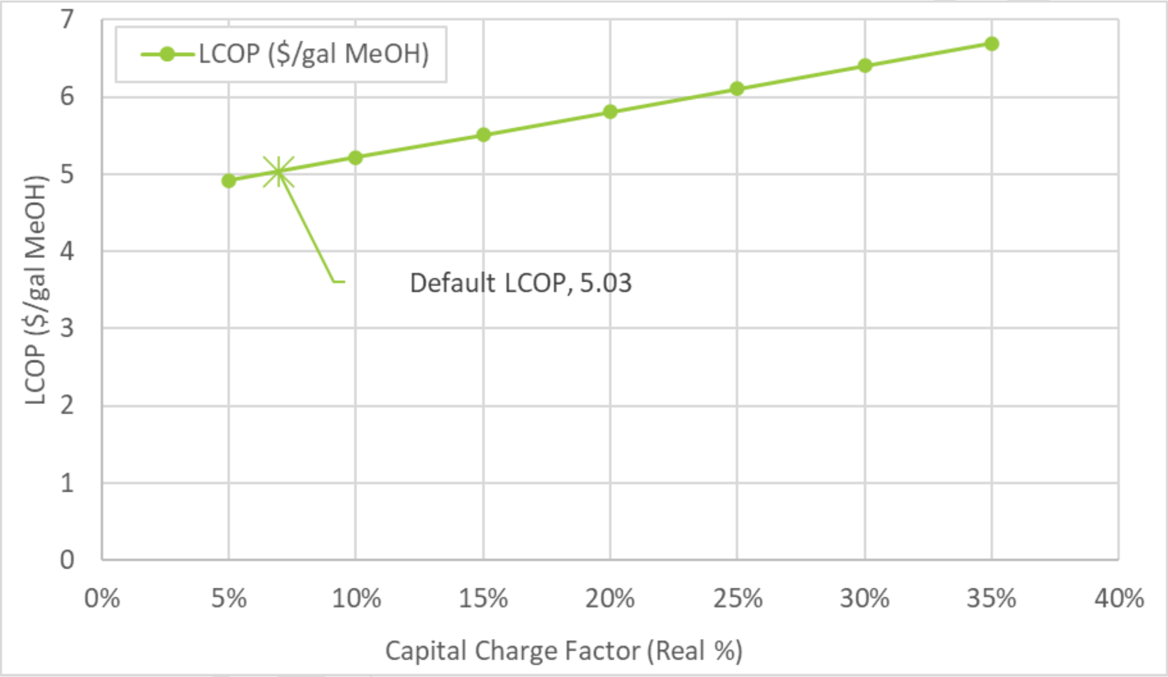
5.2.2 Financial Assumptions Sensitivity Analyses

Evaluations of the effects that varying financial assumptions might have on the LCOPs are presented in this section.

5.2.2.1 *Capital Charge Factor*

The capital charge factor (CCF) used to estimate the capital component of the LCOP is a market-dependent value; it is the product of the FCF and the TASC/TOC ratio. For this analysis, values for FCF and TASC/TOC ratio applicable to ethanol plants were applied to the TOC to determine the capital portion of the LCOP. As the CCF would vary in real applications, the LCOP was evaluated across a range of CCFs of 5–35 percent (Exhibit 5-10).

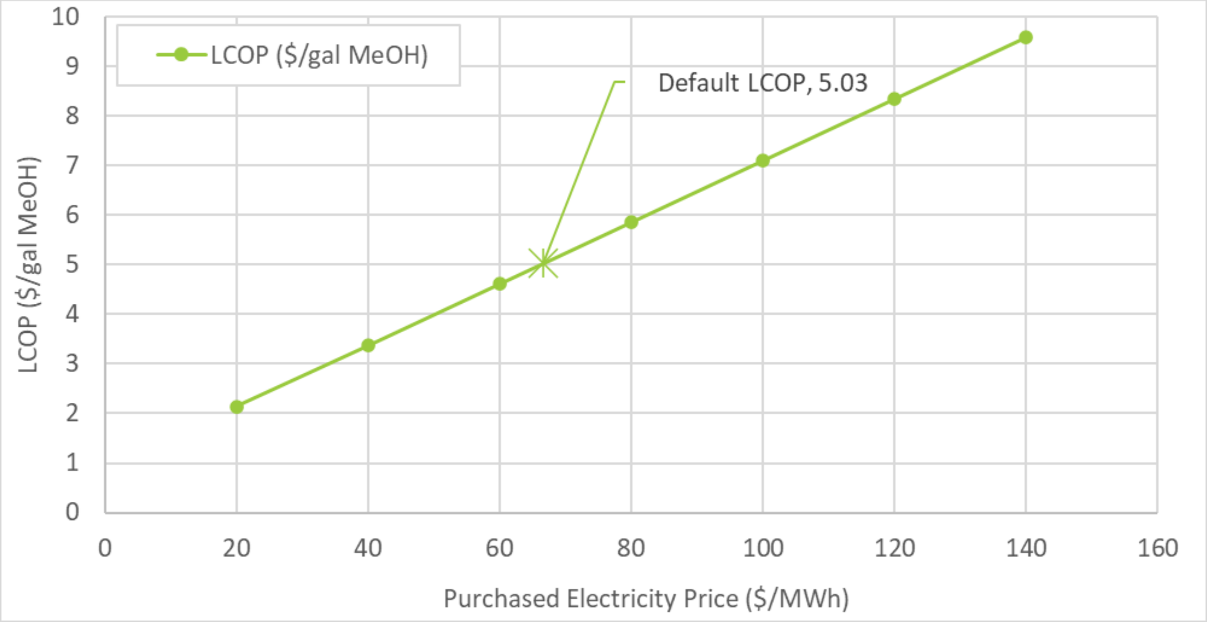
Exhibit 5-10. LCOP versus CCF



5.2.2.2 *Purchased Electricity Price*

The purchased electricity cost for each case is directly dependent upon the price of electricity assumed. For the example TEA, a $66.7/ megawatt-hour (MWh) price was used to estimate the purchased electricity costs but purchased electricity price can vary widely depending upon market scenario, location, economic conditions, fuel pricing, on-site power production, and more. As such, the LCOP was estimated across a range of $20–140/MWh purchased electricity cost (Exhibit 5-11).

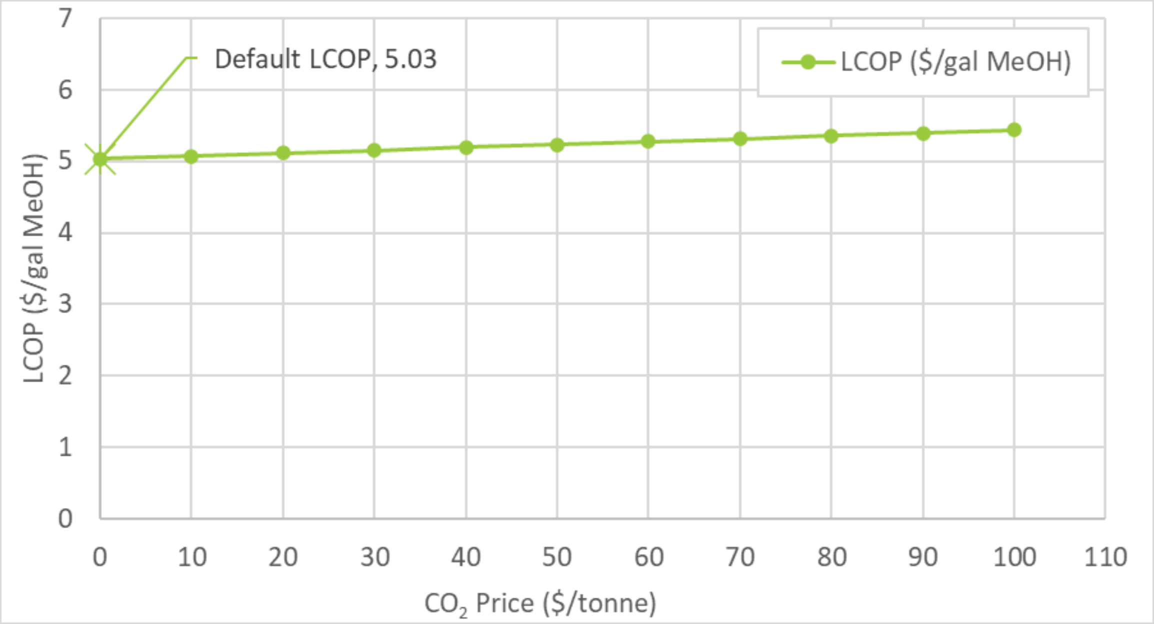
Exhibit 5-11. LCOP versus purchased electricity price



5.2.2.3 CO_2 Price

CO_2 is a feedstock for electrochemical conversion and the cost of the CO_2 feedstock is dependent upon the price assumed. For this example TEA, CO_2 is assumed to be free but CO_2 price can vary depending on the CO_2 source and location. As such, the LCOP for each case was estimated across a range of $0–100/tonne CO_2 (Exhibit 5-12).

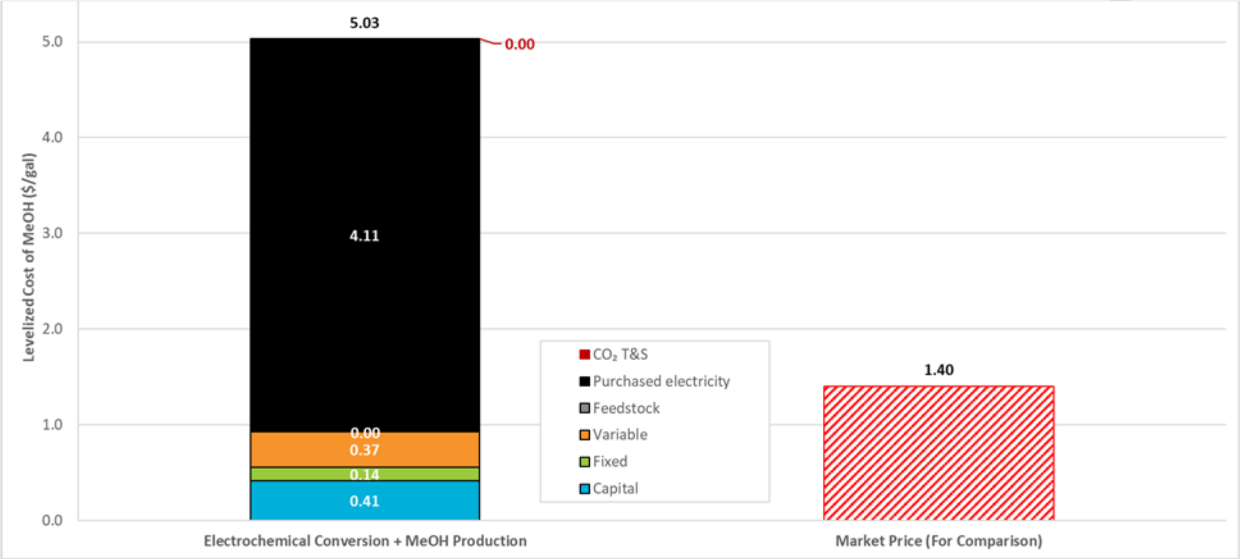
Exhibit 5-12. LCOP versus CO_2 price



6 CONCLUSION

This example TEA evaluated an electrochemical conversion pathway producing syngas from CO_2 and water via the use of an ECC. Syngas is subsequently used as the feedstock for a conventional MeOH synthesis process. Performance and costs for the system were evaluated by scaling up the system to a capacity of 61 MMgpy representing a new, small-scale MeOH plant in the United States and comparing the resulting LCOP to the market price of MeOH (Exhibit 6-1).

Exhibit 6-1. Cost results summary



Note: All dollar figures are expressed as Real December 2018 U.S. dollars

The results of this analysis show that MeOH production with syngas generated via electrochemical conversion is less economically favorable than MeOH production with conventional syngas production methods. For MeOH production, the electrochemical conversion process results in an LCOP 3.6 times greater than the market price of MeOH. The cost of purchased electricity is the largest economic constraint representing 81.7 percent of LCOP.

The example TEA shows favorable CO_2 utilization efficiency and intensity. However, the cost of producing MeOH via electrochemical conversion would require that CO_2 producers pay for processing CO_2 emissions into beneficial products.

Sensitivity analyses on ECC parameters (i.e., voltage, current density, overpotential, FE, and CF) were completed to quantify uncertainty of the ECC technology. The sensitivity analyses on ECC voltage, overpotential, and FE were shown to have a substantial impact on LCOP due to the sensitivity of power consumption to these parameters. Decreasing ECC voltage from 4V to 2V showed a 42 percent decrease in LCOP. Furthermore, increasing overpotential from 0V to 2V and decreasing FE by 50 percent showed LCOP increases of 42 and 80 percent, respectively. The results of these analyses further highlight the impact of purchased electricity cost on the economic viability of the electrochemical conversion technology.

7 REFERENCES

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APPENDIX A: STREAM TABLES

Exhibit A-1. Stream table

	1	2	3	4	5	6	7	8	9	10
V-L Mole Fraction										
H_2	0.6667	0.6667	0.6667	0.6667	0.7222	0.7222	0.5710	0.5710	0.5710	0.5710
CO	0.3333	0.3333	0.3333	0.3333	0.2725	0.2725	0.1472	0.1472	0.1472	0.1472
CO_2	0.0000	0.0000	0.0000	0.0000	0.0027	0.0027	0.0050	0.0050	0.0050	0.0050
H_2O	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0004	0.0004	0.0004	0.0004
N_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MeOH	0.0000	0.0000	0.0000	0.0000	0.0025	0.0025	0.2752	0.2752	0.2752	0.2752
ETOH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0012	0.0012	0.0012	0.0012
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DME_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Molecular Weight	10.681	10.681	10.681	10.681	9.291	9.291	14.376	14.376	14.376	14.376
V-L Flowrate (lb_{mole}/hr)	4,207	4,207	4,207	4,207	7,846	7,846	5,070	5,070	5,070	5,070
V-L Flowrate (lb/hr)	44,935	44,935	44,935	44,935	72,893	72,893	72,892	72,892	72,892	72,892
Temperature (°F)	100	100	100	197	154	360	530	390	156	100
Pressure (psia)	14.7	772.6	772.6	1,159.7	1,159.7	1,154.7	1,154.7	1,149.7	1,144.7	1,139.7
Steam Table Enthalpy (Btu/lb)[A]	43.9	42.7	42.7	107.3	90.7	249.1	285.3	190.7	32.2	-282.6
AspenPlus® Enthalpy (Btu/lb)[B]	-1,468.2	-1,469.3	-1,469.3	-1,404.7	-1,409.8	-1,251.3	-1,950.4	-2,044.9	-2,203.4	-2,518.3
Density (lb/ft^3)	0.026	1.345	1.343	1.697	1.580	1.182	1.549	1.825	2.729	3.474

[A] Steam table reference conditions are 32.02 °F & 0.089 psia

[B] Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-1. Stream table (cont'd)

	11	12	13	14	15	16	17	18	19	20
V-L Mole Fraction										
H_2	0.0034	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7864
CO	0.0023	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2023
CO_2	0.0028	0.0012	0.0012	0.0012	0.0012	0.0000	0.0000	0.0000	0.0000	0.0059
H_2O	0.0014	0.2710	0.2710	0.2710	0.2710	0.2717	0.2717	0.0333	0.0333	0.0000
N_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MeOH	0.9858	0.7245	0.7246	0.7246	0.7246	0.7251	0.7251	0.9625	0.9625	0.0054
ETOH	0.0043	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032	0.0042	0.0042	0.0000
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DME_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Molecular Weight	32.005	28.299	28.299	28.299	28.299	28.276	28.276	31.634	31.634	7.684
V-L Flowrate (lb_{mole}/hr)	1,395	1,898	1,897	1,897	1,897	1,893	1,893	1,426	1,426	3,675
V-L Flowrate (lb/hr)	44,653	53,702	53,697	53,697	53,697	53,516	53,516	45,099	45,099	28,240
Temperature (°F)	100	85	85	85	130	181	181	162	106	100
Pressure (psia)	1,139.7	34.7	14.6	26.7	23.8	24.7	29.7	19.7	16.8	1,139.7
Steam Table Enthalpy (Btu/lb)[A]	-499.5	-423.4	-423.5	-423.4	-383.0	-336.9	-336.9	-442.7	-490.8	60.4
AspenPlus® Enthalpy (Btu/lb)[B]	-3,212.0	-3,850.5	-3,850.6	-3,850.5	-3,810.1	-3,764.4	-3,764.3	-3,229.0	-3,277.2	-1,421.4
Density (lb/ft^3)	48.305	50.735	50.734	50.733	48.872	46.666	46.665	46.007	48.436	1.408

[A] Steam table reference conditions are 32.02 °F & 0.089 psia

[B] Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

Exhibit A-1. Stream table (cont'd)

	21	22	23	24	25	26	27	28
V-L Mole Fraction								
H_2	0.7864	0.7864	0.0000	0.0000	0.4649	0.7200	0.6529	0.2150
CO	0.2023	0.2023	0.0000	0.0000	0.3142	0.2274	0.2067	0.2739
CO_2	0.0059	0.0059	0.0000	0.0000	0.1508	0.0373	0.0785	0.3463
H_2O	0.0000	0.0000	0.9996	1.0000	0.0060	0.0014	0.0013	0.0141
N_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MeOH	0.0054	0.0054	0.0004	0.0000	0.0638	0.0138	0.0606	0.1499
ETOH	0.0000	0.0000	0.0000	0.0000	0.0003	0.0001	0.0001	0.0007
CH_4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_2H_6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3H_8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4H_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DME_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Molecular Weight	7.684	7.684	18.021	18.015	18.541	9.935	12.528	28.440
V-L Flowrate (lb_{mole}/hr)	3,638	3,638	513	512	10	47	51	0
V-L Flowrate (lb/hr)	27,957	27,957	9,237	9,231	188	464	645	5
Temperature (°F)	100	104	45	59	85	53	62	85
Pressure (psia)	1,139.7	1,159.7	1,058.8	14.7	34.7	34.7	19.7	14.6
Steam Table Enthalpy (Btu/lb)[A]	60.4	63.9	-32.0	27.0	26.8	17.0	19.0	24.2
AspenPlus® Enthalpy (Btu/lb)[B]	-1,421.4	-1,417.9	-6,895.6	-6,925.5	-2,511.3	-1,876.2	-2,281.8	-3,025.7
Density (lb/ft^3)	1.408	1.422	63.092	62.650	0.110	0.063	0.044	0.072

[A] Steam table reference conditions are 32.02 °F & 0.089 psia

[B] Aspen thermodynamic reference state is the component's constituent elements in an ideal gas state at 25°C and 1 atm

APPENDIX B: DETAILED COST ESTIMATES

Exhibit B-1. Owner's costs

Description	$/1,000	$/gallon MeOH
Pre-Production Costs		
6 Months All Labor	$1,282	$0.02
1-Month Maintenance Materials	$261	$0.00
1-Month Non-Fuel Consumables	$22,518	$0.37
1-Month Waste Disposal	$0	$0.00
25% of 1-Month Fuel Cost at 100% CF	$0	$0.00
2% of TPC	$4,666	$0.08
Total	**$28,727**	**$0.47**
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	$3,151	$0.05
0.5% of TPC (spare parts)	$1,167	$0.02
Total	**$4,317**	**$0.07**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0.00
Land	$55	$0.00
Other Owner's Costs	$34,997	$0.57
Financing Costs	$6,299	$0.10
TOC	**$307,708**	**$5.04**
TASC Multiplier (ethanol plant, 30 year)	1.047	
TASC	**$322,171**	**$5.28**

Exhibit B-2. Capital costs

Case:		Electrochemical conversion + MeOH					Estimate Type:			Conceptual	
Representative Plant Size:		61 MM gallons/year					Cost Base:			Dec 2018	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/gallon MeOH
3		Feedwater & Miscellaneous BOP Systems									
3.2	Water Makeup & Pretreating	$1,098	$110	$622	$0	$1,830	$366	$0	$439	$2,635	$0.04
3.7	Waste Water Treatment Equipment	$1,364	$0	$836	$0	$2,199	$440	$0	$528	$3,167	$0.05
3.8	Miscellaneous Plant Equipment	$4,344	$570	$2,208	$0	$7,121	$1,424	$0	$1,709	$10,254	$0.17
	Subtotal	**$6,805**	**$679**	**$3,665**	**$0**	**$11,150**	**$2,230**	**$0**	**$2,676**	**$16,056**	**$0.26**
4		Electrochemical Conversion System									
4.3	ECC Cell	$11,020	w/ equip	w/ equip	w/ equip	$11,020	$2,204	$0	$2,645	$15,869	$0.26
	Subtotal	**$11,020**	**$0**	**$0**	**$0**	**$11,020**	**$2,204**	**$0**	**$2,645**	**$15,869**	**$0.26**
9		Cooling Water System									
9.1	Cooling Towers	$1,823	$0	$552	$0	$2,374	$475	$0	$570	$3,419	$0.06
9.2	Circulating Water Pumps	$255	$0	$16	$0	$271	$54	$0	$65	$390	$0.01
9.3	Circulating Water System Aux.	$2,428	$0	$320	$0	$2,748	$550	$0	$660	$3,957	$0.06
9.4	Circulating Water Piping	$0	$699	$633	$0	$1,331	$266	$0	$319	$1,917	$0.03
9.5	Make-up Water System	$105	$0	$135	$0	$240	$48	$0	$58	$346	$0.01
9.6	Component Cooling Water System	$103	$0	$79	$0	$182	$36	$0	$44	$262	$0.00
9.7	Circulating Water System Foundations	$0	$162	$268	$0	$430	$86	$0	$103	$619	$0.01
	Subtotal	**$4,714**	**$860**	**$2,003**	**$0**	**$7,577**	**$1,515**	**$0**	**$1,818**	**$10,911**	**$0.18**
12		Instrumentation & Control									
12.6	Control Boards, Panels & Racks	$0	$769	$90	$70	$929	$186	$0	$223	$1,337	$0.02
12.7	Computer & Accessories	$20,676	$0	$632	$0	$21,308	$4,262	$0	$5,114	$30,684	$0.50
12.8	Instrument Wiring & Tubing	$0	$539	$923	$720	$2,182	$436	$0	$524	$3,141	$0.05
12.9	Other I&C Equipment	$0	$3,330	$872	$680	$4,882	$976	$0	$1,172	$7,030	$0.12
	Subtotal	**$20,676**	**$4,638**	**$2,517**	**$1,470**	**$29,300**	**$5,860**	**$0**	**$7,032**	**$42,193**	**$0.69**
13		Improvements to Site									
13.1	Site Preparations	$0	$1,204	$25,561	$0	$26,765	$5,353	$0	$6,424	$38,541	$0.63
13.2	Site Improvements	$0	$656	$2,629	$2,051	$5,335	$1,067	$0	$1,281	$7,683	$0.13
13.3	Site Facilities	$3,716	$0	$3,899	$0	$7,615	$1,523	$0	$1,828	$10,966	$0.18

	Case:	Electrochemical conversion + MeOH						Estimate Type:		Conceptual	
	Representative Plant Size:	61 MM gallons/year						Cost Base:		Dec 2018	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O. & Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/gallon MeOH
	Subtotal	**$3,716**	**$1,859**	**$32,089**	**$2,051**	**$39,715**	**$7,943**	**$0**	**$9,532**	**$57,190**	**$0.94**
14						**Buildings & Structures**					
14.3	Administration Building	$0	$823	$556	$0	$1,379	$276	$0	$331	$1,986	$0.03
14.4	Circulation Water Pumphouse	$0	$17	$9	$0	$26	$5	$0	$6	$38	$0.00
14.5	Water Treatment Buildings	$0	$103	$94	$0	$197	$39	$0	$47	$283	$0.00
14.6	Machine Shop	$0	$1,230	$787	$0	$2,017	$403	$0	$484	$2,905	$0.05
14.7	Warehouse	$0	$958	$577	$0	$1,535	$307	$0	$368	$2,210	$0.04
14.8	Other Buildings & Structures	$0	$3,902	$2,219	$1,731	$7,852	$1,570	$0	$1,885	$11,308	$0.19
14.9	Waste Treating Building & Str.	$0	$600	$1,072	$0	$1,672	$334	$0	$401	$2,408	$0.04
	Subtotal	**$0**	**$7,633**	**$5,315**	**$1,731**	**$14,679**	**$2,936**	**$0**	**$3,523**	**$21,138**	**$0.35**
15						**Methanol Production**					
15.1	Heat exchangers	$17,803	w/ equip	w/ equip	w/ equip	$17,803	$3,561	$0	$4,273	$25,636	$0.42
15.2	Compressors/turbines	$26,078	w/ equip	w/ equip	w/ equip	$26,078	$5,216	$0	$6,259	$37,552	$0.62
15.3	Reactors	$1,484	w/ equip	w/ equip	w/ equip	$1,484	$297	$0	$356	$2,136	$0.04
15.4	Columns/vessels	$3,199	w/ equip	w/ equip	w/ equip	$3,199	$640	$0	$768	$4,606	$0.08
15.5	Pumps	$17	w/ equip	w/ equip	w/ equip	$17	$3	$0	$4	$25	$0.00
	Subtotal	**$48,580**	**$0**	**$0**	**$0**	**$48,580**	**$9,716**	**$0**	**$11,659**	**$69,956**	**$1.15**
	Total	**$95,512**	**$15,670**	**$45,589**	**$5,251**	**$162,023**	**$32,405**	**$0**	**$38,885**	**$233,313**	**$3.82**

Exhibit B-3. Initial and annual O&M costs

Case:	**Electrochemical conversion + MeOH**				**Cost Base:**	**Dec 2018**
Representative Plant Size:	**61 M gallons/year MeOH**				**Capacity Factor (%):**	**85**
O&M Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:	0.1	
Operating Labor Burden:		30.00	**% of base**	Operator:	0.3	
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:	0.1	
				Lab Techs, etc.:	0.1	
				Total:	**0.6**	
Fixed Operating Costs						
					Annual Cost	
					($)	**($/gallon MeOH)**
Annual Operating Labor:					$278,347	$0.005
Maintenance Labor:					$1,773,175	$0.029
Administrative & Support Labor:					$512,881	$0.008
Property Taxes and Insurance:					$4,666,251	$0.076
Total:					**$7,230,655**	**$0.119**
Variable Operating Costs						
					($)	**($/gallon MeOH)**
Maintenance Material:					$2,659,763	$0.04
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	0	786	$1.90	$0	$463,493	$0.8937
Makeup and Waste Water Treatment Chemicals (ton):	0	1.6	$550	$0	$277,078	$0.5343
Methanol Production Catalyst (ft³):	w/ equip	0.5	$280.00	$0	$46,827	$0.0903
Electrode Assembly Replacement (m³):	0	13.6	$3,724.00	$0	$15,744,420	$30.3580
Electricity (MWh):	0	10,293	$66.70	$0	$213,149,693	$410.9893
Subtotal:				**$0**	**$229,681,511**	**$442.8655**
Variable Operating Costs Total:				**$0**	**$232,341,274**	**$442.90911**
Fuel/Feedstock Cost						
CO_2 (tonne):	0	661	$0.00	$0	$0	$0.00000
Total:				**$0**	**$0**	**$0**

Exhibit B-4. LCOP results

Component	**LCOP, $/gallon MeOH**
Capital	0.41
Fixed	0.14
Variable	0.37
Feedstock	0.00
Purchased Power	4.11
Total	**5.03**

APPENDIX C: COMPONENT BALANCES

Exhibit C-1. Water balance

Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m³/min (gpm)	m³/min (gpm)	m³/min (gpm)	m³/min (gpm)	m³/min (gpm)
MeOH Synthesis Water	0.07 (18)	0.07 (18)	–	–	–
Waste Water	–	–	–	0.06 (17)	-0.06 (-17)
ECC Water	0.57 (152)	–	0.57 (152)	–	0.57 (152)
Cooling Tower	1.49 (394)	–	1.49 (394)	0.34 (89)	1.16 (305)
Total	**2.14 (564)**	**0.07 (18)**	**2.07 (546)**	**0.40 (105)**	**1.67 (440)**

Exhibit C-2. Carbon balance

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
Syngas	7,640 (16,844)	Methanol Product	7,541 (16,625)
		Light Gas	97 (214)
		Vent	1 (2)
		Waste Water	1 (3)
Total	**7,640 (16,844)**	**Total**	**7,640 (16,844)**

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