NATIONAL ENERGY TECHNOLOGY LABORATORY

CARBON CONVERSION EXAMPLE TECHNO-ECONOMIC ANALYSIS: MICROBIAL CONVERSION



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ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius
°F	Degrees Fahrenheit
Ar	Argon
atm	Atmosphere (14.696 psi)
BEC	Bare erected cost
BFD	Block flow diagram
BOP	Balance of plant
Btu	British thermal unit
CCF	Capital charge factor
CF	Capacity factor
CO_2	Carbon dioxide
DOE	Department of Energy
Eng'g CM	
H.O. & Fee	Engineering construction management, home office, and fees
EPCC	Engineering, procurement, and construction cost
FCF	Fixed charge factor
FECM	Office of Fossil Energy and Carbon Management
ft^3	Cubic foot
gpm	Gallons per minute
h, hr	Hour
H_2	Hydrogen
H_2O	Water
I&C	Instrumentation and control
ISO	International Organization for Standardization
kg	Kilogram
kWe	Kilowatt electric
lb	Pound
LCOP	Levelized cost of production
m^3/min	Cubic meters per minute
MPa	Megapascal
MW, MWe	Megawatt electric
MWh	Megawatt-hour
N_2	Nitrogen
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
O-H	Overhead
O&M	Operation and maintenance
O_2	Oxygen
PEM	Polymer electrolyte membrane
psia	Pound per square inch absolute
QGESS	Quality Guidelines for Energy System Studies
RIC	Research and Innovation Center
SCPC	Supercritical pulverized coal
T&S	Transport and storage
TASC	Total as-spent cost
TEA	Techno-economic analysis
TFOM	Total annual fixed O&M
TOC	Total overnight cost
tonne	Metric ton
TPC	Total plant cost
tpy	Tons per year
TVOM	Total annual variable O&M
U.S.	United States
V-L	Vapor-liquid

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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 Case 1C from NETL's 2022 internal report, "CO_2 Conversion: Screening Technoeconomic Analysis of Biological CO_2 Conversion Technology" [1]. This case and the subsequently developed example TEA evaluate a microbial conversion pathway. In this pathway, a biological catalyst is used to efficiently convert a feedstock composed of 20 percent carbon dioxide (CO_2) and 80 percent electrolysis-derived hydrogen (H_2) to dilute acetic acid. Membrane separation is included downstream from the bioreactor to filter impurities from the acetic acid product. A production size of 36,000 tons per year (tpy) of acetic acid was chosen to represent typical gas fermentation plants producing ethanol. A summary of the case developed for the example TEA is shown in Exhibit ES-1.

Exhibit ES-1. Microbial conversion example TEA summary

	Microbial Conversion Example TEA
Technology	Water Electrolysis + Microbial Conversion
Feedstocks	20% CO_2, 80% H_2
Purification Technology	Membrane Separation
Acetic Acid Production (tpy)	36,000

The cost metric of interest is the levelized cost of production (LCOP), in $/kilogram (kg) of acetic acid. 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.

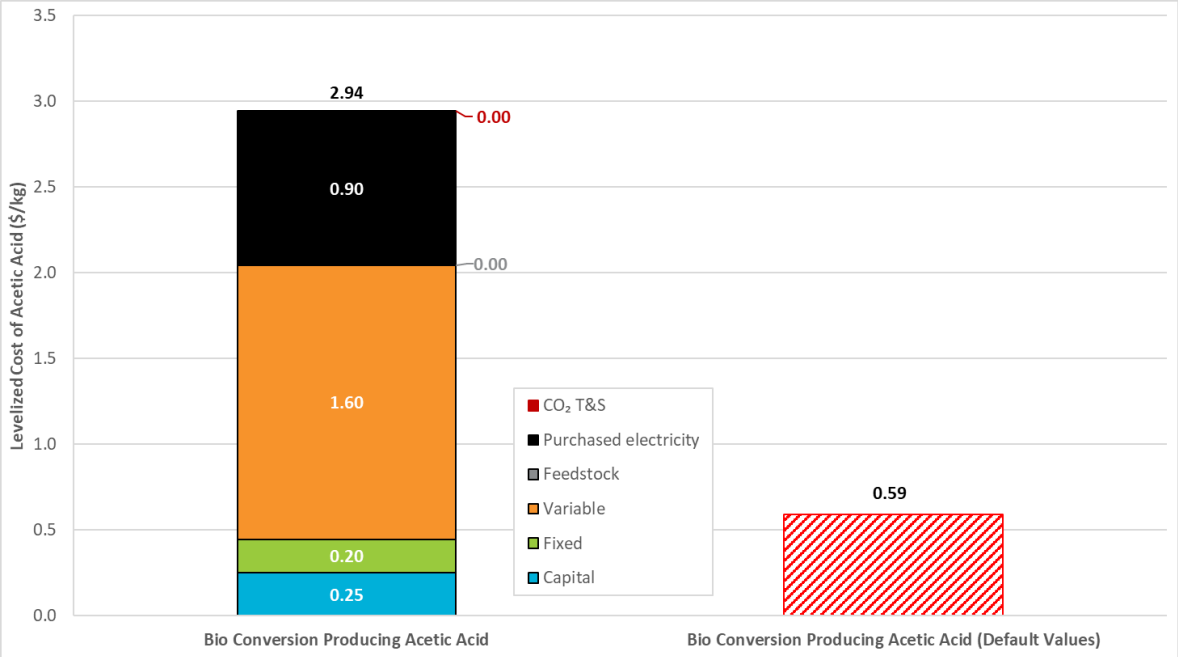
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Exhibit ES-2. Microbial conversion example TEA results, table

Levelized Cost of Product ($/kg Acetic Acid)	
Capital	0.25
Fixed	0.20
Variable	1.60
Feedstock	0.00
Purchased Electricity	0.90
Total LCOP	2.94

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

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



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

The results show that the microbial conversion process results in an LCOP that is 5.0 times greater than the market price of acetic acid [2]. Variable O&M costs, considered separate from the cost of purchased electricity in this analysis, are the largest economic constraint representing 54 percent of the LCOP. The cost of nutrient feed to the microbes in the bioreactor is the largest contributor to variable O&M costs (excluding purchased electricity) accounting for 97 percent of the variable O&M costs. Sensitivity analyses on impactful assumptions associated with the microbial acetic acid production system, as well as general financial assumptions, were completed for all cases considered. Reducing the average nutrient price was shown to be particularly impactful with a 42 percent reduction of LCOP realized when the average nutrient price falls from $4.66/kg to $1/kg.

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 Case 1C from NETL's 2022 internal report, "CO_2 Conversion: Screening Technoeconomic Analysis of Biological CO_2 Conversion Technology" (reference screening analysis) [1]. This case and the subsequently developed example TEA evaluate a microbial conversion pathway. In this pathway, a biological catalyst is used to efficiently convert a feedstock composed of 20 percent carbon dioxide (CO_2) and 80 percent electrolysis-derived hydrogen (H_2) to dilute acetic acid. Membrane separation is included downstream from the bioreactor to filter impurities from the acetic acid product. A production size of 36,000 tons per year (tpy) of acetic acid was chosen to represent typical gas fermentation plants producing ethanol. A summary of the case developed for the example TEA is shown in Exhibit 1-1.

Exhibit 1-1. Microbial conversion example TEA summary

	Microbial Conversion Example TEA
Technology	Water Electrolysis + Microbial Conversion
Feedstocks	20% CO_2, 80% H_2
Purification Technology	Membrane Separation
Acetic Acid Production (tpy)	36,000

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2 NOVEL TECHNOLOGY BASIS

The microbial acetic acid production system comprises microbes suspended in an aqueous medium (i.e., the bioreactor) that consume feedstocks such as CO_2 and H_2 to produce acetic acid through acetogenesis. These microbes, also classified as acetogens, are anaerobic, non-photosynthetic, and autotrophic (i.e., do not require an organic source of carbon) [3]. The strengths exhibited by acetogens include their ability to operate at low temperature and pressure and utilize feedstocks of varying composition [4]. This example TEA does not consider a specific biocatalyst and generic values are used to describe biocatalyst properties. However, the reference screening analysis evaluated a novel biocatalyst developed by the NETL Research and Innovation Center (RIC) [1]. Information on the properties and development of RIC's novel biocatalyst is available in the reference screening analysis [1].

The exact stoichiometry for microbial conversion of CO_2 and H_2 to acetic acid involves numerous potential reaction steps and is prohibitively complex to be considered with full detail in a screening-level analysis. Therefore, the net reaction for microbial conversion of CO_2 and H_2 to acetic acid as reported in literature is used as the stoichiometric basis for this analysis and is shown in Equation 2-1 [3].

$$2CO_2 + 4H_2 \xrightarrow{yields} CH_3COOH + 2H_2O$$

Equation 2-1: Net acetogenic reaction using CO_2 and H_2

In this reaction, CO_2 and H_2 are consumed by microbes to produce acetic acid and water. The stoichiometric ratio of the CO_2 and H_2 feedstocks is 1 mole of CO_2 per 2 moles of H_2. This ratio is inconsistent with the feed ratio used in laboratory tests and assumed for this analysis (i.e., 1 mole of CO_2 per 4 moles of H_2). For the purposes of this example TEA, it is assumed that excess H_2 feed is fully consumed by the microbes for uses other than acetic acid production, such as cell growth, because excess H_2 was not present in the laboratory tests.

The major performance parameters for the bioreactor and the microbes used to produce acetic acid are microbe productivity, microbe titer, and acetic acid selectivity. Microbe productivity refers to the amount of product that can be produced per volume of reaction medium, microbe titer refers to the maximum product concentration that the microbe can produce, and acetic acid selectivity refers to the amount of feedstock that is converted into the target product. Each parameter exhibits uncertainty and is expected to change with scale-up of the microbial acetic acid production system.

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3 EXAMPLE TEA DEVELOPMENT

The example TEA was developed using the performance model, performance calculations, and cost estimates for Case 1C from the reference screening analysis. Case 1C comprises microbial conversion in a bioreactor to produce acetic acid from CO_2 and H_2 feedstocks with a membrane separator to filter impurities. H_2 is produced via a water electrolyzer upstream of the bioreactor. The capacity of Case 1C was set at 36,000 tpy to represent typical gas fermentation plants producing ethanol. The example TEA uses the same configuration and capacity as Case 1C but sensitive data has been replaced with generic values to protect proprietary information. Generic values are primarily used to replace performance data for RIC's novel biocatalyst and proprietary cost references. Furthermore, select financial assumptions were adjusted from the reference screening analysis to conform with assumptions used throughout the example TEA series.

3.1 SELECTION OF FEEDSTOCKS AND HYDROGEN PRODUCTION VIA WATER ELECTROLYSIS

Feedstock selection was influenced by the feedstocks used in laboratory tests that showed the most promise regarding cell growth and acetic acid titer. For this example TEA, one feedstock configuration was considered: 80 percent H_2 with 20 percent CO_2.

To enhance the system's potential to be an impactful CO_2 conversion technology, H_2 is sourced from water electrolysis. Water electrolysis is accomplished by the addition of a polymer electrolyte membrane (PEM) system upstream of the bioreactor. Cost and performance data for the PEM electrolyzer is sourced from the National Renewable Energy Laboratory (NREL) Hydrogen Analysis Production Model, "Current (2015) Hydrogen Production from Central PEM Electrolysis" [5]. This model is based on a standalone, grid-powered PEM electrolyzer system with a total H_2 production of 50,000 kilograms (kg) per day [5]. Input from industry collaborators with experience in commercial PEM electrolysis was utilized for development of the NREL model [5]. The major feeds and utilities required for the electrolyzer are process water and grid electricity for electrolysis.

3.2 SELECTION OF ACETIC ACID PURIFICATION TECHNOLOGY

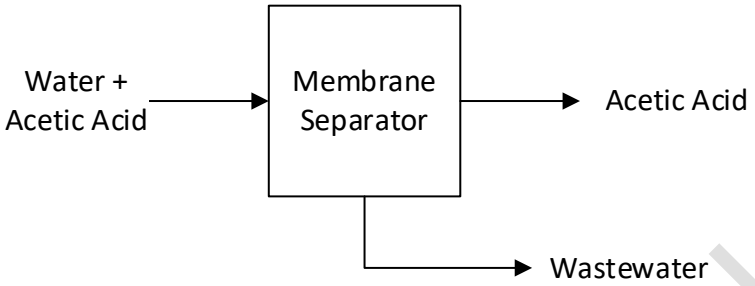
The bioreactor generates heavily dilute acetic acid in water that may be concentrated and purified prior to sale. Separation of acetic acid and water through simple distillation is unfeasible as the mixture demonstrates a small separating factor and the column required for the desired purification would use a prohibitively large number of stages [6]. For this screening analysis, membrane separation was selected as the acetic acid purification technology.

Membrane separation used to filter impurities present in the bioreactor product stream is detailed in the block flow diagram (BFD) in Exhibit 3-1. Specifications for the membrane separator were chosen to mirror the membrane separator used in NREL's 2021 report, "The economic outlook for converting CO_2 and electrons to molecules," so that screening analysis results can be readily compared [7]. The concentration of acetic acid purified with membrane

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separation is unknown, however the acetic acid product is expected to be substantially less pure than glacial acetic acid.

Exhibit 3-1. BFD for membrane separation of acetic acid



Regardless of purification technology, wastewater produced by the biological acetic acid production system must adhere to regulatory guidelines regarding contaminants (e.g., acetic acid) in wastewater streams. These limits may vary by region and should be determined during development of a plant. Because many membrane separators for acetate in water are designed to purify wastewater streams prior to disposal, it is expected that the wastewater streams from cases with membrane separation will meet regulatory limits. The case developed for this analysis does not account for additional wastewater treatment.

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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

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

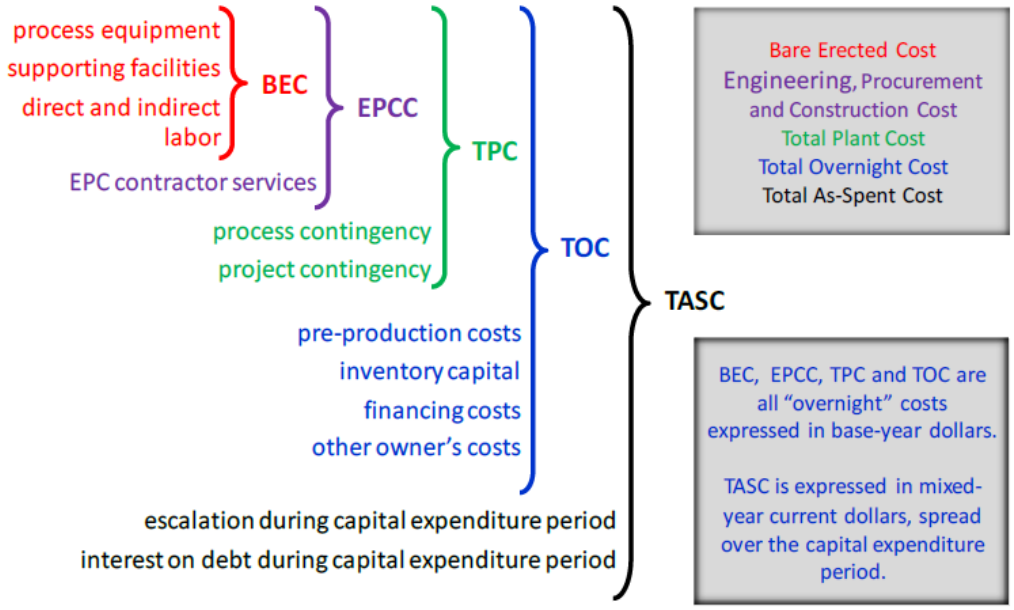
Exhibit 4-3. Select study assumptions

Parameter	Temperature	Pressure
Makeup Water Conditions	15°C (59°F)	0.101 MPa (14.7 psia)
CO_2 Supply Conditions	30°C (86°F)	0.199 MPa (28.9 psia)
H_2 Supply Conditions	80°C (176°F)	0.199 MPa (28.9 psia)
Capacity Factor	85 percent	

4.3 Cost Estimating Methodology

Cost estimates were developed using those from Case 1C, which, in turn, uses costs obtainable from other NETL studies and literature sources. 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" [10], 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., $/kg of acetic acid), which includes factors for variable and fixed O&M, 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

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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.

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

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

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5 Results, Analysis, and Discussion

5.1 Performance Results

The performance results for the microbial acetic acid production system with H_2/CO_2 feedstock and membrane separation for purification are presented Exhibit 5-1 and the BFD is shown in Exhibit 5-2. The stream table is available in Appendix A: Stream Tables.

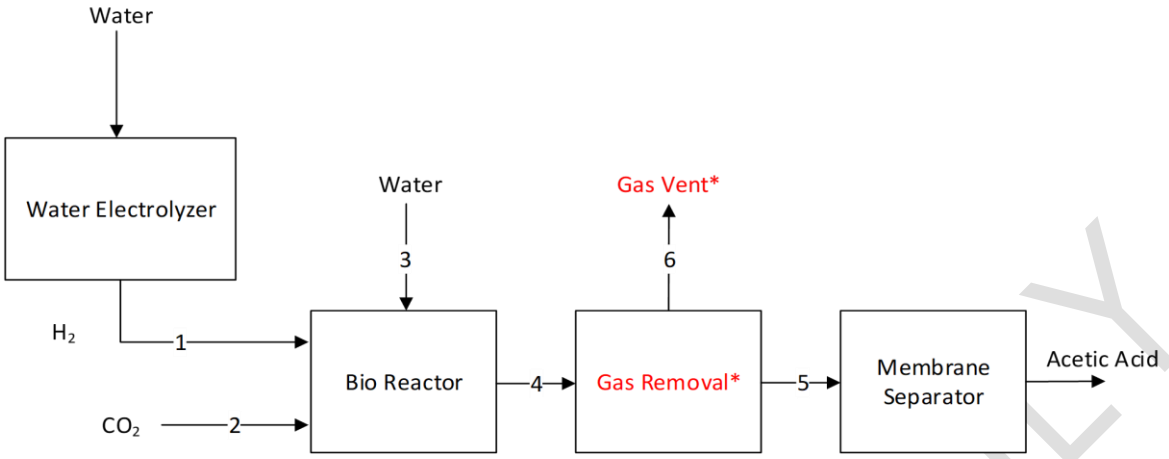
Exhibit 5-1. Performance summary for microbial acetic acid production + H_2/CO_2 feedstock + membrane separation

Performance Summary	
Parameter	**Value**
Acetic Acid Production Rate, tpy (100% CF)	35,975
Total Auxiliaries, MW	50
H_2 Required, lb/hr	2,206
CO_2 Required, lb/hr	12,039
Total Water Demand, lb/hr	355,057
Bioreactor Water Demand, lb/hr	323,542
H_2 Electrolysis Water Demand, lb/hr	31,516
Heating Demand,[A] Btu/hr	7,715,780
Nutrients Required, lb/hr	2,713
Auxiliary Loads	
Water Pump, kWe	10
Water Electrolyzer Power Required, kWe	50,025
Miscellaneous Balance of Plant,[B] kWe	100

[A]The source and cost of the heating demand is not included in this analysis
[B]Includes plant control systems; lighting, heating, ventilation, and air conditioning; and miscellaneous low voltage loads

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Exhibit 5-2. BFD for microbial acetic acid production + H_2/CO_2 feedstock + membrane separation



*Gas vent and gas removal are modeling requirements that remove unreacted feed gas from the process. In a physical system, this feed gas would instead be consumed by the microbes for purposes other than acetic acid production.

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), %	474
CO_2 Conversion Intensity, %	131
Required Purchase Price, $/ton	-1580.94

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.

Carbon conversion efficiency is 100 percent for all cases as the microbial acetic acid production system produces no CO_2 emissions. The cost of producing acetic acid via microbial conversion 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 the microbial acetic acid production system with H_2/CO_2 feedstock are presented in Exhibit 5-4. Owner's costs, capital costs, and O&M costs are available in Appendix B: Detailed Cost Estimates.

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Exhibit 5-4. Cost summary for microbial acetic acid production + H_2/CO_2 feedstock + membrane separation

Parameter	Value
Acetic Acid Production Rate, tpy (100% CF)	36,000
Annual Purchased Power, $/1,000 (100% CF)	$29,294
Total Overnight Cost, $/1,000	$99,623
First Year Variable O&M Cost, $/1,000 (100% CF)	$52,166
Levelized Cost of Acetic Acid ($/kg)	
Capital	0.25
Fixed	0.20
Variable	1.60
Feedstock	0.00
Purchased Electricity	0.90
Total LCOP	**2.94**

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

5.2.1 Financial Assumptions Sensitivity Analyses

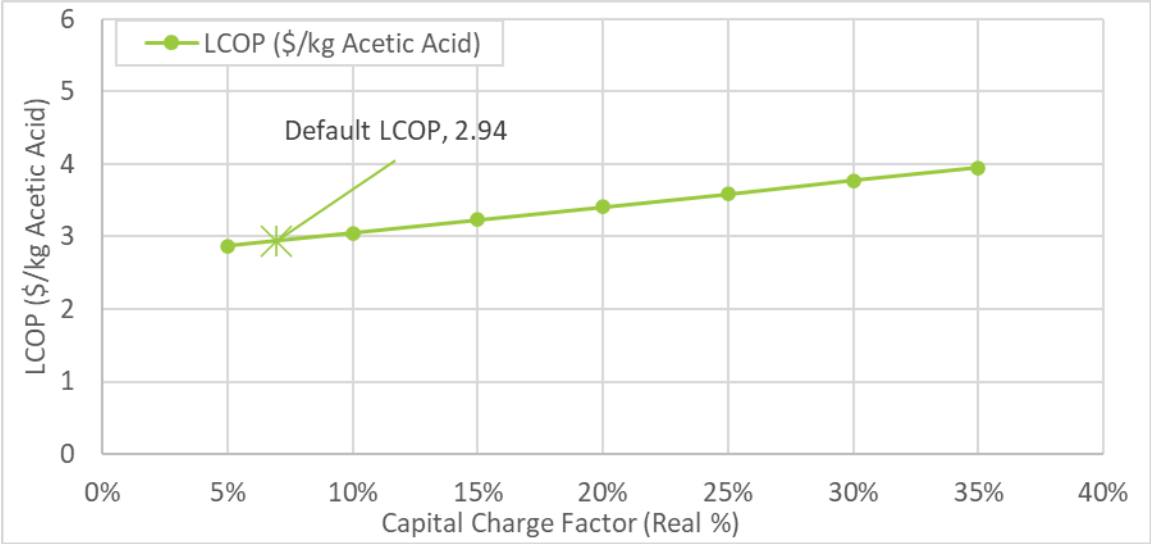
Evaluations of the effects that varying financial assumptions might have on the LCOPs are presented in this section.

5.2.1.1 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 consistent with that of an ethanol plant, with a 1-year capital expenditure period and a 30-year operating life, 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 5-5).

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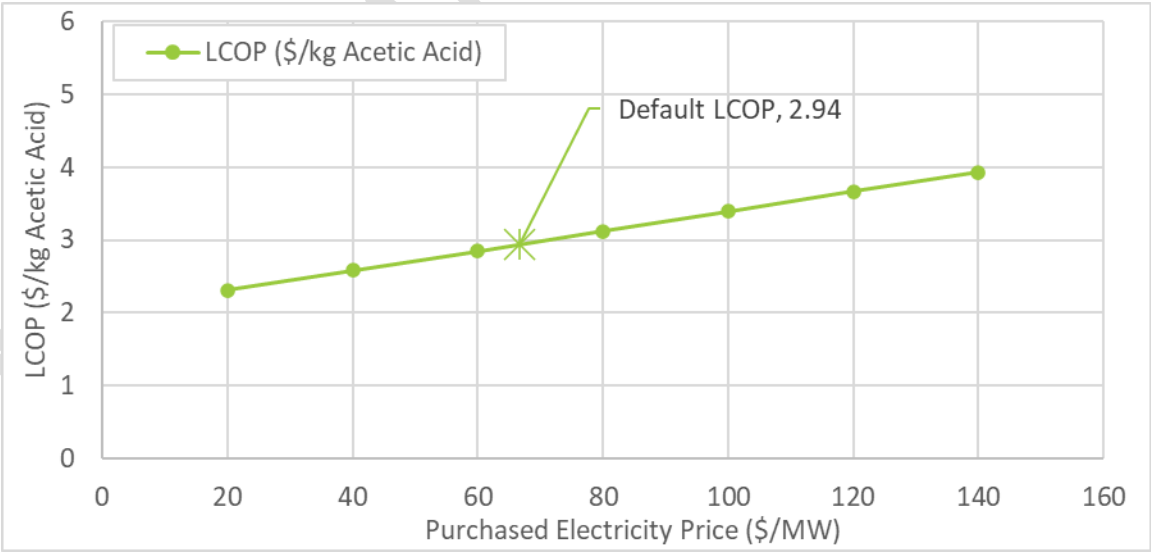
Exhibit 5-5. LCOP versus CCF



5.2.1.2 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 5-6).

Exhibit 5-6. LCOP versus purchased electricity price

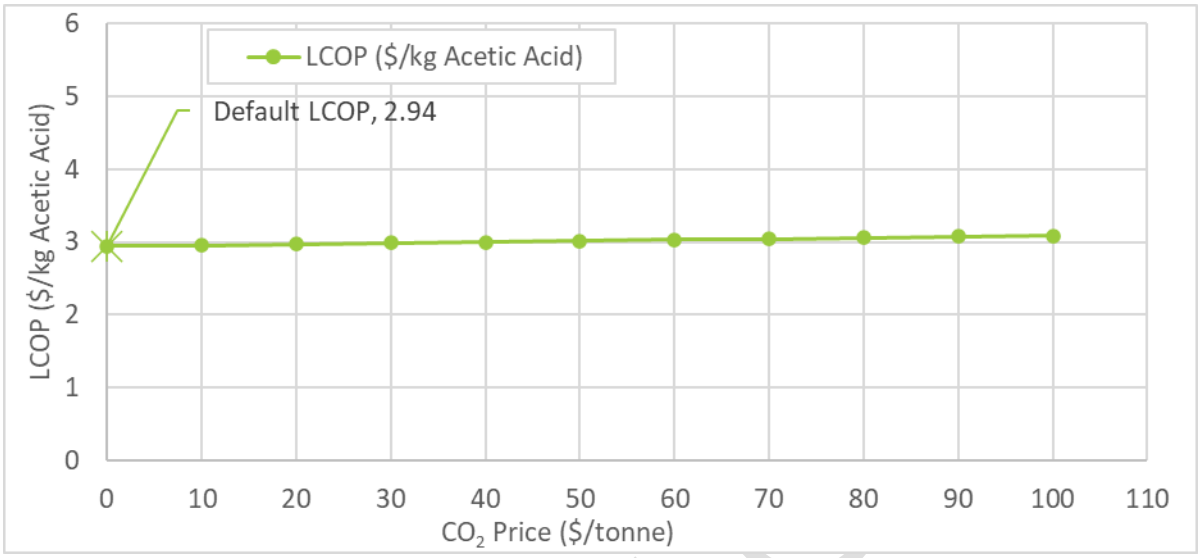


5.2.1.3 CO_2 Price

CO_2 is a feedstock for microbial 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/metric ton (tonne) CO_2 (Exhibit 5-7).

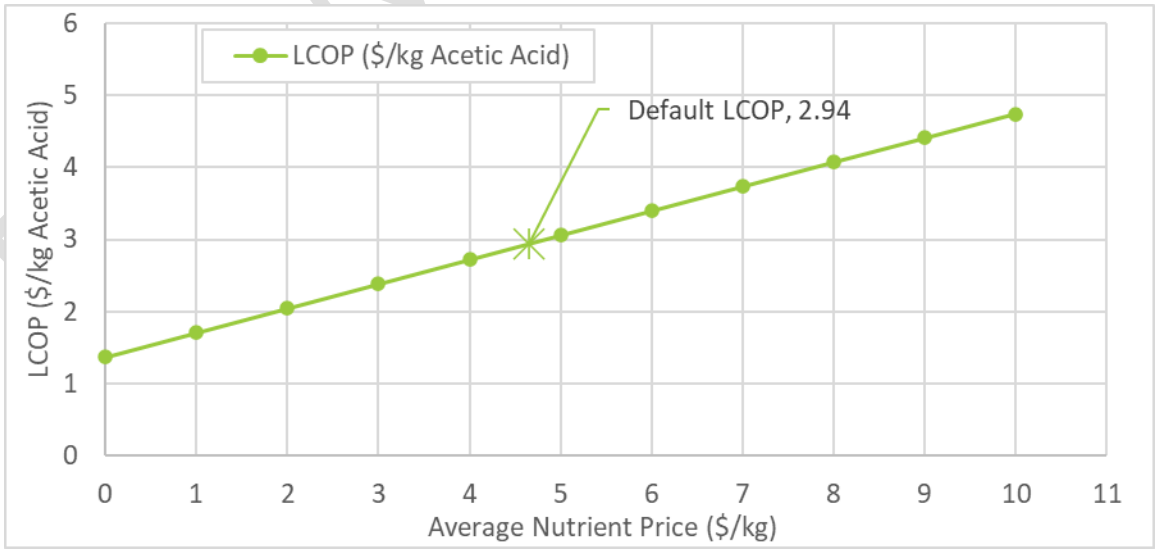
Exhibit 5-7. LCOP versus CO_2 price



5.2.1.4 Average Nutrient Price

The cost of nutrients is based on reported market prices for each nutrient. The weighted average of these prices is $4.66/kg of nutrient mix. Nutrient prices can vary widely depending on market scenario, location, economic conditions, and discounts from bulk purchasing. Nutrient consumption may also vary depending on the characteristics of the biocatalyst. As such, the LCOP for each case was estimated across a range of $0–10/kg of nutrient mix. Decreasing nutrient price by 100 percent provided a 53 percent LCOP decrease (Exhibit 5-8).

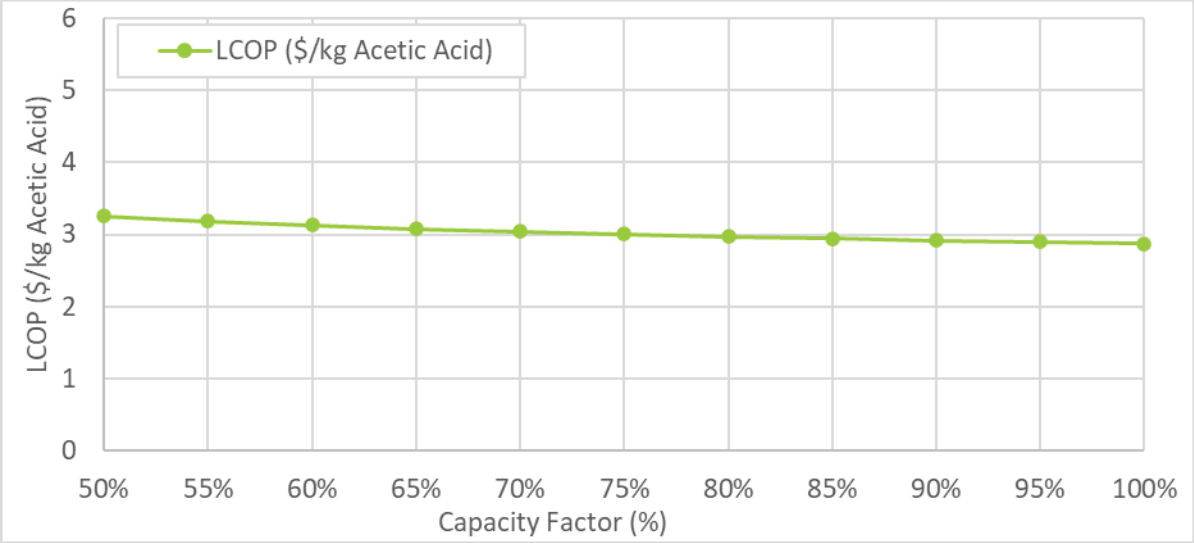
Exhibit 5-8. LCOP versus average nutrient price



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 Cost Uncertainty Sensitivity Analyses

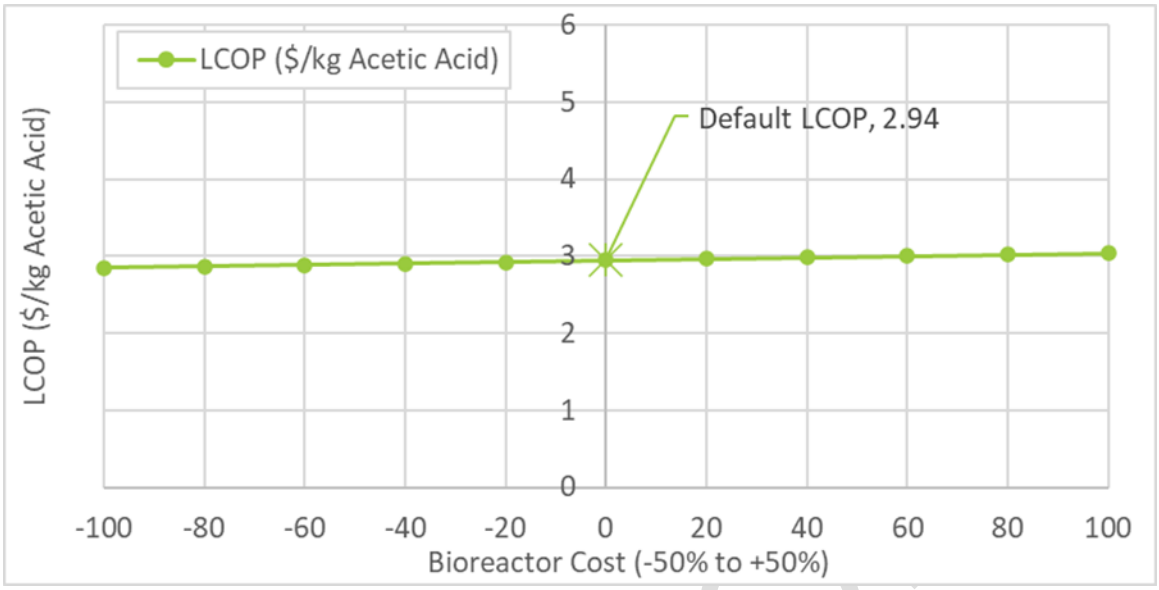
NETL studies typically develop capital cost estimates by scaling on reference costs for similar or analogous equipment or balance of plant (BOP) items. As the microbial acetic acid production system is particularly novel, certain capital costs exhibit increased uncertainty due to the lack of comparable reference costs. Evaluations of the effects that varying cost estimates with significant uncertainty might have on LCOPs are presented in this section.

5.2.2.1 Bioreactor Cost Uncertainty

The capital cost of the bioreactor is dependent on the volume flow of the reactor feed. Improvements to microbe titer will decrease the volume flow leading to a decrease in reactor cost. Similarly, improvements to microbe productivity are expected to decrease reactor cost because of the smaller reactor volume required at higher productivities. To demonstrate the impact of varied reactor costs, the LCOP of each case was estimated across an uncertainty range of -50 to +50 percent for bioreactor capital cost. For this example TEA, changing bioreactor capital cost shows a negligible impact on LCOP (Exhibit 5-10).

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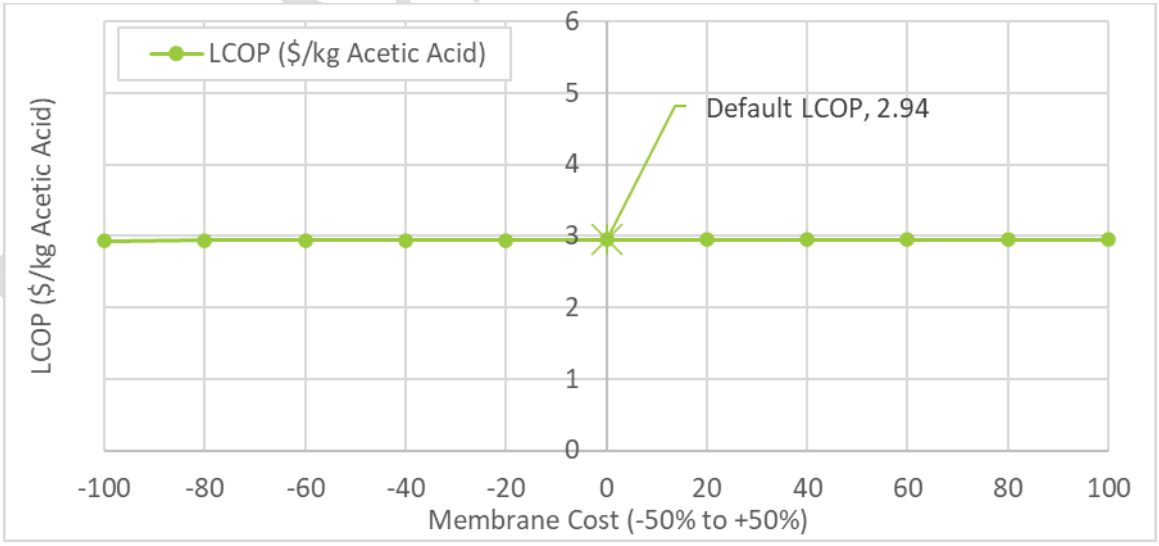
Exhibit 5-10. LCOP versus bioreactor capital cost



5.2.2.2 Membrane Cost Uncertainty

The reference cost for the membrane separator was sourced from NREL's 2021 report, "The economic outlook for converting CO_2 and electrons to molecules" [7]. Because limited cost and background information was available for the membrane separator, the LCOP was estimated across an uncertainty range of -100 to +50 percent for membrane separator capital costs. At the sensitivity bound of -100 percent, the LCOP represents the biological conversion process if no product purification was included. In this example TEA, membrane separator capital costs show a negligible impact on LCOP (Exhibit 5-11).

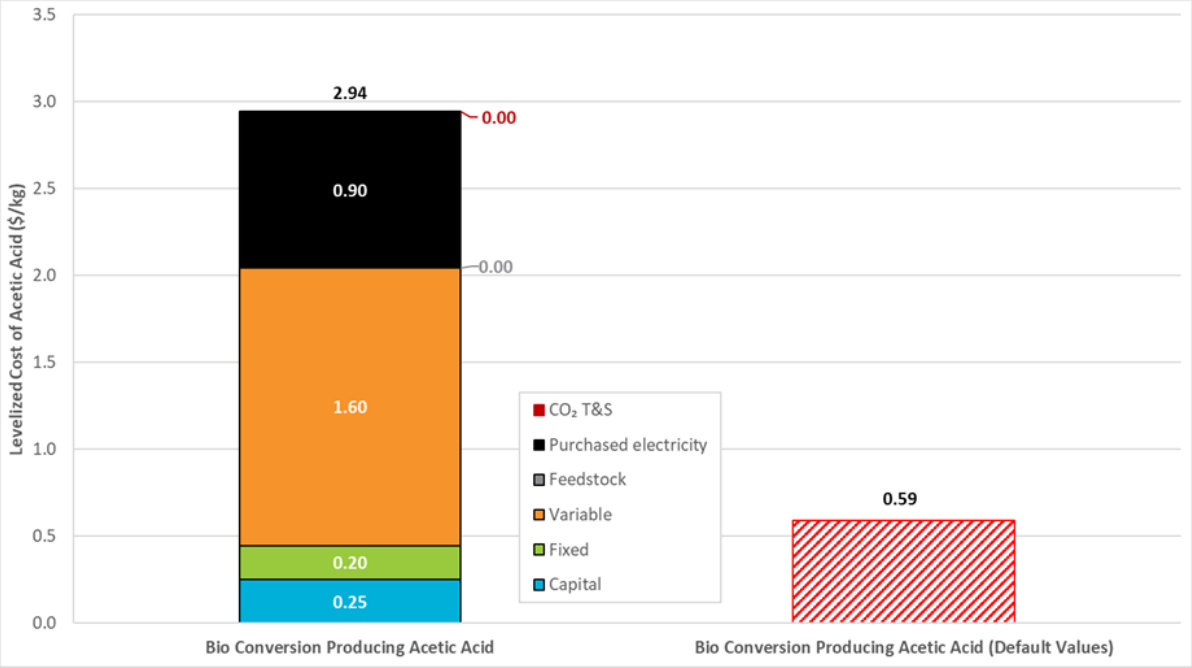
Exhibit 5-11. LCOP versus membrane separator capital costs



6 CONCLUSION

This example TEA evaluated a microbial conversion pathway producing comprising a biological catalyst used to efficiently convert a feedstock composed of 20 percent CO_2 and 80 percent electrolysis-derived H_2 to dilute acetic acid. Membrane separation is included downstream from the bioreactor to filter impurities from the acetic acid product. Performance and costs for the system were evaluated by scaling up the system to a capacity of 36,000 tpy representing typical gas fermentation plants producing ethanol and comparing the resulting LCOP to the market price of acetic acid (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 acetic acid production via microbial conversion is less economically favorable than conventional acetic acid production methods. The microbial conversion process producing acetic acid results in an LCOP 5.0 times greater than the market price of acetic acid. Variable O&M costs, considered separate from the cost of purchased electricity in this analysis, are the largest economic constraint representing 54 percent of the LCOP. The cost of nutrient feed to the microbes in the bioreactor is the largest contributor to variable O&M costs (excluding purchased electricity) accounting for 97 percent of the variable O&M costs.

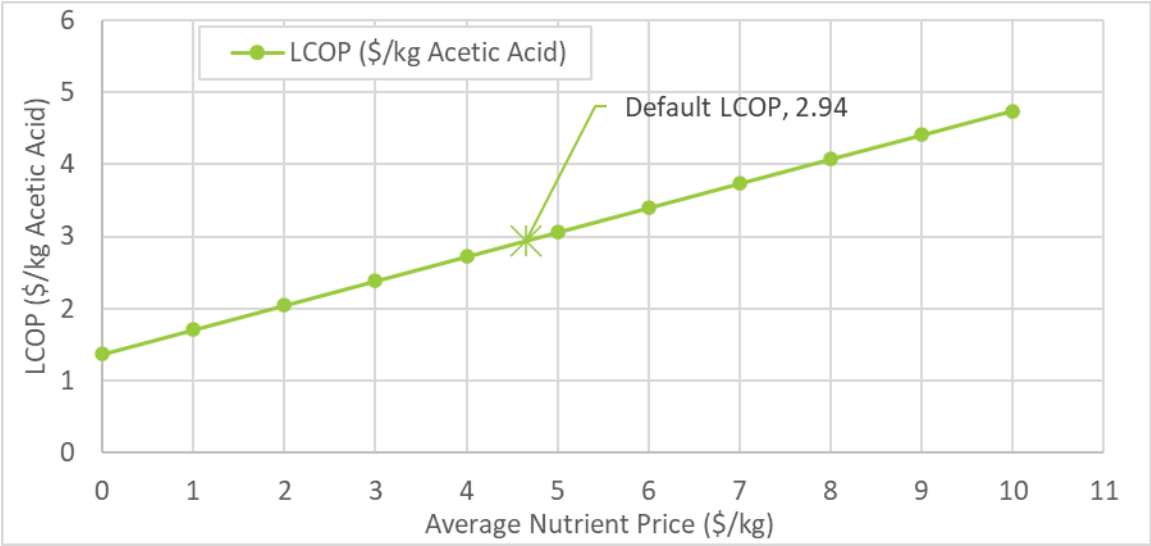
The example TEA shows favorable CO_2 conversion efficiency, potential, and intensity. However, the cost of producing acetic acid via microbial conversion would require that CO_2 producers pay for processing CO_2 emissions into beneficial products.

Sensitivity analyses on impactful assumptions associated with the microbial acetic acid production system, as well as general financial assumptions, were completed for all cases

EXAMPLE

considered. Reducing the average nutrient price was shown to be particularly impactful with a 42 percent reduction of LCOP realized when the average nutrient price falls from $4.66/kg to $1/kg (Exhibit 6-2).

Exhibit 6-2. LCOP versus average nutrient price



EXAMPLE

7 REFERENCES

[1] S. Henry, "CO2 Conversion: Screening Analysis of Biological CO2 Conversion Technology," NETL, Pittsburgh, 2022.

[2] Argus Consulting Services, "Petrochemical Market Study," Argus Media Group, Houston, 2020.

[3] J. Phillips, R. Huhnke and H. Atiyeh, "Syngas Fermentation: A Microbial Conversion Process of Gaseous Substrates to Various Products," *Fermentation,* vol. 3, 2017.

[4] G. Merli, A. Becci, A. Amato and F. Beolchini, "Acetic acid bioproduction: The technological innovation change," *Science of The Total Environment,* vol. 798, 2021.

[5] D. DeSantis, B. James and G. Saur, "Current (2015) Hydrogen Production from Central PEM Electrolysis," NREL, 2019.

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[7] Z. Huang, R. Grim, J. Schaidle and L. Tao, "The economic outlook for converting CO2 and electrons to molecules," *The Royal Society of Chemistry 2021,* vol. 14, no. 7, pp. 3664-3678, 2021.

[8] NETL, "Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance," U.S. Department of Energy, Pittsburgh, PA, 2019.

[9] NETL, "Quality Guidelines for Energy System Studies: Performing a Techno-economic Analysis for CO2 Utilization Technologies," NETL, Pittsburgh, 2020.

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APPENDIX A: STREAM TABLES

Exhibit A-1. Stream table

	1	2	3	4	5	6
V-L Mole Fraction						
H_2	1.0000	0.0000	0.0000	0.0289	0.0000	1.0000
CO_2	0.0000	0.9861	0.0000	0.0000	0.0000	0.0000
H_2O	0.0000	0.0139	1.0000	0.9639	0.9926	0.0000
Acetic Acid	0.0000	0.0000	0.0000	0.0072	0.0074	0.0000
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Molecular Weight	2.016	43.648	18.015	17.857	18.328	2.016
V-L Flowrate (lb_{mole}/hr)	1,094	277	17,959	18,921	18,373	547
V-L Flowrate (lb/hr)	2,206	12,108	323,542	337,855	336,753	1,103
Temperature (°F)	176	86	59	86	86	86
Pressure (psia)	28.9	28.9	14.7	25.5	25.5	25.5
Steam Table Enthalpy (Btu/lb)[A]	492.9	16.1	27.0	51.8	51.0	184.1
AspenPlus® Enthalpy (Btu/lb)[B]	340.0	-3,854.2	-6,839.0	-6,708.8	-6,731.3	31.2
Density (lb/ft^3)	0.009	0.218	62.650	2.526	61.665	0.009

[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

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APPENDIX B: DETAILED COST ESTIMATES

Exhibit B-1. Owner's costs

Description	$/1,000	$/kg Acetic Acid
Pre-Production Costs		
6 Months All Labor	$2,051	$0.06
1-Month Maintenance Materials	$76	$0.00
1-Month Non-Fuel Consumables	$6,788	$0.21
1-Month Waste Disposal	$0	$0.00
25% of 1-Month Fuel Cost at 100% CF	$0	$0.00
2% of TPC	$1,366	$0.04
Total	**$10,283**	**$0.32**
Inventory Capital		
60-day supply of fuel and consumables at 100% CF	$8,576	$0.26
0.5% of TPC (spare parts)	$342	$0.01
Total	**$8,918**	**$0.27**
Other Costs		
Initial Cost for Catalyst and Chemicals	$0	$0.00
Land	$20	$0.00
Other Owner's Costs	$10,247	$0.31
Financing Costs	$1,844	$0.06
TOC	**$99,623**	**$3.053**
TASC Multiplier (ethanol plant, 30 year)	1.047	
TASC	**$104,305**	**$3.20**

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Exhibit B-2. Capital costs

Case:	Microbial Conversion Producing Acetic Acid					Estimate Type:	Conceptual			
Representative Plant Size:	36,000 tpy Acetic Acid					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	$/kg Acetic Acid
3	Feedwater & Miscellaneous BOP Systems										
3.2	Water Makeup & Pretreating	$1,331	$133	$754	$0	$2,218	$444	$0	$532	$3,194	$0.09
3.7	Waste Water Treatment Equipment	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0.00
3.9	Miscellaneous Plant Equipment	$2,135	$280	$1,085	$0	$3,501	$700	$0	$840	$5,041	$0.14
	Subtotal	**$3,466**	**$413**	**$1,839**	**$0**	**$5,719**	**$1,144**	**$0**	**$1,372**	**$8,235**	**$0.23**
4	Bioreactor & Accessories										
4.1	Bioreactor	$14,152	w/equip	w/equip	w/equip	$14,152	$2,830	$0	$3,397	$20,380	$0.62
4.2	Feed Cooler	$25	w/equip	w/equip	w/equip	$25	$5	$0	$6	$36	$0.00
4.3	Feedwater Heater	$139	w/equip	w/equip	w/equip	$139	$28	$0	$33	$200	$0.01
4.4	Feedwater Pump	$10	w/equip	w/equip	w/equip	$10	$2	$0	$2	$14	$0.00
	Subtotal	**$14,327**	**$0**	**$0**	**$0**	**$14,327**	**$2,865**	**$0**	**$3,438**	**$20,631**	**$0.63**
9	Cooling Water System										
9.1	Cooling Towers	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0.00
9.2	Circulating Water Pumps	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0.00
9.3	Circulating Water System Aux.	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0.00
9.4	Circulating Water Piping	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0.00
9.5	Make-up Water System	$172	$0	$220	$0	$392	$78	$0	$94	$564	$0.02
9.6	Component Cooling Water System	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0.00
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0.00
	Subtotal	**$172**	**$0**	**$220**	**$0**	**$392**	**$78**	**$0**	**$94**	**$564**	**$0.02**
12	Instrumentation & Control										
12.1	Control Boards, Panels & Racks	$0	$300	$35	$27	$362	$72	$0	$87	$522	$0.02
12.2	Computer & Accessories	$8,065	$0	$247	$0	$8,312	$1,662	$0	$1,995	$11,969	$0.37
12.3	Instrument Wiring & Tubing	$0	$210	$360	$281	$851	$170	$0	$204	$1,225	$0.04
12.4	Other I&C Equipment	$0	$1,299	$340	$265	$1,904	$381	$0	$457	$2,742	$0.08
	Subtotal	**$8,065**	**$1,809**	**$982**	**$573**	**$11,429**	**$2,286**	**$0**	**$2,743**	**$16,458**	**$0.50**
13	Improvements to Site										
13.1	Site Preparations	$0	$95	$2,020	$0	$2,115	$423	$0	$507	$3,045	$0.09
13.2	Site Improvements	$0	$52	$208	$162	$422	$84	$0	$101	$607	$0.02
13.3	Site Facilities	$294	$0	$308	$0	$602	$120	$0	$144	$866	$0.03
	Subtotal	**$294**	**$147**	**$2,536**	**$162**	**$3,138**	**$628**	**$0**	**$753**	**$4,518**	**$0.14**

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Case:		Microbial Conversion Producing Acetic Acid					Estimate Type:		Conceptual		
Representative Plant Size:		36,000 tpy Acetic Acid					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	$/kg Acetic Acid
14						Buildings & Structures					
14.4	Administration Building	$0	$55	$37	$0	$92	$18	$0	$22	$132	$0.00
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0.00
14.6	Water Treatment Buildings	$0	$122	$112	$0	$234	$47	$0	$56	$337	$0.01
14.7	Machine Shop	$0	$82	$52	$0	$134	$27	$0	$32	$193	$0.01
14.8	Warehouse	$0	$64	$38	$0	$102	$20	$0	$24	$147	$0.00
14.9	Other Buildings & Structures	$0	$259	$148	$115	$522	$104	$0	$125	$751	$0.02
14.10	Waste Treating Building & Str.	$0	$406	$726	$0	$1,132	$226	$0	$272	$1,630	$0.05
	Subtotal	**$0**	**$988**	**$1,112**	**$115**	**$2,216**	**$443**	**$0**	**$532**	**$3,191**	**$0.10**
15						Membrane Separator					
15.1	Membrane Separator	$363	w/ equip	w/ equip	w/ equip	$363	$73	$0	$87	$523	$0.02
	Subtotal	**$363**	**$0**	**$0**	**$0**	**$363**	**$73**	**$0**	**$87**	**$523**	**$0.02**
16						Hydrogen Electrolyzer					
16.1	Stack Capital Cost	$7,388	w/ equip	w/ equip	w/ equip	$7,388	$1,478	$0	$1,773	$10,639	$0.33
16.2	Mechanical BOP	$697	w/ equip	w/ equip	w/ equip	$697	$139	$0	$167	$1,004	$0.03
16.3	Electrical BOP	$1,770	w/ equip	w/ equip	w/ equip	$1,770	$354	$0	$425	$2,549	$0.08
	Subtotal	**$9,855**	**$0**	**$0**	**$0**	**$9,855**	**$1,971**	**$0**	**$2,365**	**$14,192**	**$0.43**
	Total	**$36,542.04**	**$3,357.33**	**$6,689.15**	**$850.33**	**$47,438.85**	**$9,487.77**	**$0.00**	**$11,385.32**	**$68,311.94**	**$2.09**

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

Case:	Microbial Conversion Producing Acetic Acid				Cost Base:	Dec 2018
Representative Plant Size:	36,000 tpy Acetic Acid				Capacity Factor (%):	85
O&M Labor						
Operating Labor				**Operating Labor Requirements per Shift**		
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:		1.0
Operating Labor Burden:		30.00	**% of base**	Operator:		3.3
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:		1.0
				Lab Techs, etc.:		1.0
				Total:		**6.3**
Fixed Operating Costs						
					Annual Cost	
					($)	**($/kg Acetic Acid)**
Annual Operating Labor:					$2,762,159	$0.085
Maintenance Labor:					$519,171	$0.016
Administrative & Support Labor:					$820,333	$0.025
Property Taxes and Insurance:					$1,366,239	$0.042
Total:					**$5,467,901**	**$0.168**
Variable Operating Costs						
					($)	**($/kg Acetic Acid)**
Maintenance Material:					$778,756	$0.02
Consumables						
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**		
Water (/1000 gallons):	0	1,023	$1.90	$0	$602,779	$0.02173
Makeup and Waste Water Treatment Chemicals (ton):	0	1.5	$550	$0	$259,889	$0.00937
Electricity (MWh):	0	1,203	$66.70	$0	$24,899,619	$0.89759
Nutrient Mix (kg):	0	29,534	$4.66	$0	$42,699,630	$1.53925
Subtotal:				**$0**	**$68,461,916**	**$2.46793**
Variable Operating Costs Total:				**$0**	**$69,240,672**	**$2.49179**
Fuel/Feedstock Cost						
CO_2 (ton):	0	144	$0.00	$0	$0	$0.00000
Total:				**$0**	**$0**	**$0.00000**

Exhibit B-4. LCOP results

Component	LCOP, $/kg Acetic Acid
Capital	0.25
Fixed	0.20
Variable	1.60
Feedstock	0.00
Purchased Power	0.90
Total	**2.94**

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APPENDIX C: COMPONENT BALANCES

Exhibit C-1. Water balance

Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)	m^3/min (gpm)
Water Feed	2.45 (647)	–	2.45 (647)	–	2.45 (647)
Water Electrolysis	0.24 (63)	–	0.24 (63)	–	0.24 (63)
Total	**2.69 (710)**	**0.00 (0)**	**1.78 (470)**	**0.00 (0)**	**1.78 (470)**

Exhibit C-2. Carbon balance

Carbon In		Carbon Out	
	kg/hr (lb/hr)		kg/hr (lb/hr)
CO_2 Feed	1,490 (3,286)	Reactor Product	1,490 (3,286)
Total	**1,490 (3,286)**	**Total**	**1,490 (3,286)**

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