NATIONAL ENERGY TECHNOLOGY LABORATORY

TECHNO-ECONOMIC ANALYSIS OF LARGE-SCALE HYDROGEN PRODUCTION FROM SOLID OXIDE ELECTROLYSIS CELL SYSTEMS

May 31, 2024

DOE/NETL-2024/4438

Disclaimer

Alex Noring[1,2]*: Formal Analysis, Investigation, Methodology, Software, Visualization, Writing – Original Draft;* ***Kyle Buchheit***[1,2]*: Data Curation, Investigation, Methodology, Project Administration, Visualization, Writing – Review & Editing;* ***Arun K.S. Iyengar***[1,2]*: Conceptualization, Writing – Review & Editing;* ***Gregory Hackett***[1*]*: Supervision, Review & Editing*

[1]National Energy Technology Laboratory
[2]National Energy Technology Laboratory Support Contractor
*Corresponding contact: Gregory.Hackett@netl.doe.gov, 304.285.5279

Suggested Citation:
A. Noring, K. Buchheit, and A.K.S. Iyengar, "Techno-Economic Analysis of Large-Scale Hydrogen Production from Solid Oxide Electrolysis Cell Systems," National Energy Technology Laboratory, Pittsburgh, May 31, 2024.

This page intentionally left blank.

TABLE OF CONTENTS

LIST OF EXHIBITS

ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius
°F	Degrees Fahrenheit
abs	Absolute
A	Ampere
AC	Alternating current
Ar	Argon
Aspen	Aspen Plus®
atm	Atmosphere
BOP	Balance of plant
Btu	British thermal unit
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	n-Butane
CF	Capacity factor
CH_4	Methane
cm^2	Square centimeter
CO	Carbon monoxide
CO_2	Carbon dioxide
DOE	Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
Eng'g CM H.O.& Fee	Engineering construction management home office and fees
FEB	Fossil Energy Baseline
ft	Foot
ft^3	Cubic foot
FW	Feedwater
gal	Gallon
GJ	Gigajoule
gpm	Gallons per minute
GW_{DC}	Gigawatt, direct current
h, hr	Hour
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
Hg	Mercury
HHV	Higher heating value
HTX, HX	Heat exchanger
HVAC	Heating, ventilation, and air conditioning
I&C	Instrumentation and control
IOU	Investor-owned utility
ISO	International Organization for Standardization
kg	Kilogram
kh	Thousand hour
kJ	Kilojoule
kW, kWe	Kilowatt electric
kW_{AC}, kWe_{AC}	Kilowatt electric, alternating current
kWh	Kilowatt-hour
kWt	Kilowatt thermal
lb	Pound
lb_M	Pound-mass
LCOH	Levelized cost of hydrogen
LHV	Lower heating value
m	Meter
m^3	Cubic meter
mA	Milliamp
min	Minute
MJ	Megajoule
MM	Million
MPa	Megapascal
mV	Millivolt
MW, MWe	Megawatt electric
MW_{AC}	Megawatt electric, alternating current
MWh	Megawatt-hour
N/A	Not applicable/available
N_2	Nitrogen
NETL	National Energy Technology Laboratory
NGFC	Natural gas fuel cell
Nm^3	Normal cubic meter
NOx	Oxides of nitrogen
O&M	Operation and maintenance
O_2	Oxygen
O-H	Overhead
PM	Particulate matter
ppb	Parts per billion
ppm	Parts per million
psia	Pounds per square inch absolute
psig	Pounds per square inch gauge

QGESS	Quality Guidelines for Energy System Studies
R&D	Research and development
SO_2	Sulfur dioxide
SOA	State-of-the-art
SOEC	Solid oxide electrolysis cell
SOFC	Solid oxide fuel cell
Sorbead	Sorbead® Adsorption Technology
T	Trillion
T&S	Transport and storage
TASC	Total as-spent cost
TOC	Total overnight cost
TPC	Total plant cost
TSA	Temperature swing adsorption
U.S.	United States
V	Volt
V-L	Vapor-liquids
vol%	Percent by volume
y, yr	Years

EXECUTIVE SUMMARY

The United States (U.S.) Department of Energy's (DOE) Energy Earthshots Initiative aims to accelerate breakthroughs of more abundant, affordable, and reliable low carbon energy solutions within the next decade. The production cost of clean hydrogen (H_2), an energy carrier with a critical role in achieving net-zero carbon emissions by 2050, can be as high as $5/kg presently [1]. The first Energy Earthshot—Hydrogen Shot—announced in June 2021, seeks to reduce the cost of clean hydrogen (H_2) to $1 per 1 kg in 1 decade.

Of the numerous methods for producing clean H_2, solid oxide electrolysis cell (SOEC) technology offers several potential advantages but requires additional research and development (R&D) for wide-scale commercial deployment. Compared to low temperature electrolyzers (alkaline and proton exchange membrane for example), SOEC can be 20 percent more efficient at converting electrical and thermal energy into chemical energy in the form of H_2 [2]. However, a major challenge to the commercialization of SOEC technology is the reduction of the degradation rates at the required operating temperatures of 700–850°C (1292–1562°F). With limited commercial deployment, SOEC systems have not yet been able to capitalize on the cost reduction mechanisms of "economies of scale" and "learning by doing," and accordingly are presently more expensive than low-temperature electrolysis alternatives.

This report seeks to aid decision makers in prioritizing technological advances along a research pathway to the realization of SOEC systems capable of producing clean H_2 at $1/kg. In particular, the performance and cost of gigawatt-scale SOEC systems is presented. The systems analyzed use electricity, instead of fossil fuels, for all process needs and have no direct CO_2 emissions.

The technology advancements for the SOEC R&D pathway considered in this study are depicted in Exhibit ES-1. The advancements consider anticipated improvements in SOEC electrochemical performance, operating conditions, plant operation and maintenance (O&M), and stack cost reductions. State-of-the-art SOEC performance serves as a basis for the research pathway. Exhibit ES-2 lists the key technology parameters and their state-of-the-art values as determined by literature review.

Exhibit ES-1. SOEC R&D pathway

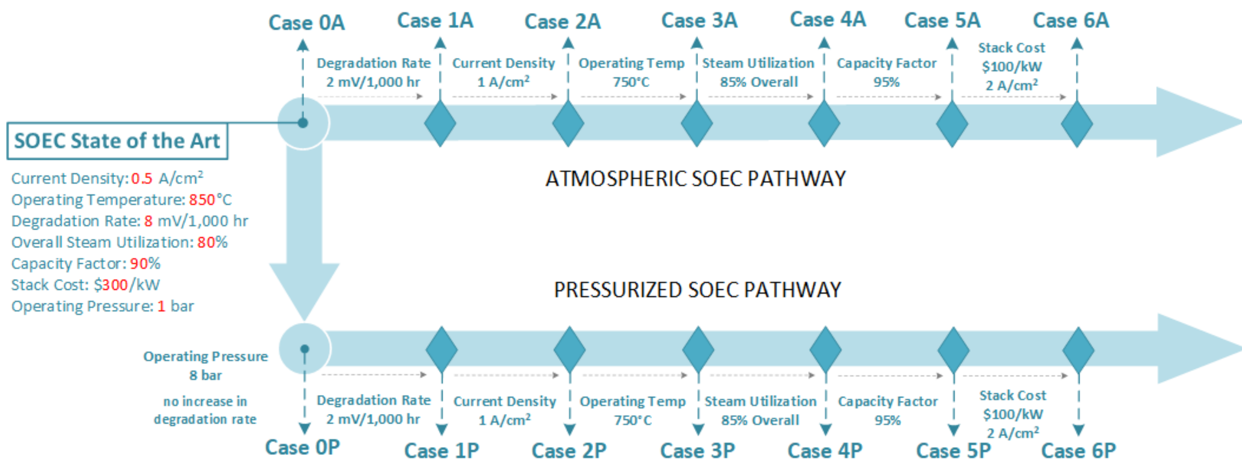


Exhibit ES-2. State-of-the-art values for key SOEC technology parameters

Parameter	Value	Justification
Current Density, A/cm^2	500	Operating condition of 9 out of 16 stacks in the literature review
Operating Temperature, °C	850	Operating temperature of the MultiPHLY (2.6 MW_{AC}) [3] and GrInHy2.0 (720 kW_{AC}) [4] projects
Degradation Rate, mV/1000 h	8	Post-2016 average degradation rate from literature review
Overall Steam Utilization	80%	Several stack tests from the literature review operated at a 70% single pass conversion; recycle can be used to obtain an 80% overall conversion
Capacity Factor	90%	This value was not found in the literature, it is assumed to be the same as the commercial natural gas reforming plants in the H_2 baseline study [5]
Stack Cost, $/kW	300	Baseline stack cost used in EERE SOEC study (adjusted to 2018$) [6]; value used by Idaho National Laboratory in several SOEC studies

Two parallel SOEC configurations—one with the SOEC operating at atmospheric pressure and one based on pressurized operation—are considered as part of the study. Pressurized SOEC operation is expected to be more efficient due to decreased auxiliary loads for the compression of H_2 to pressures required for pipeline transport. The technology advancements along the pathway are applied concomitantly to both configurations.

The specific SOEC pathway cases analyzed in this study are listed in Exhibit ES-3. Case 0 represents the reference case corresponding to the state-of-the-art (SOA). Case 1 represents cell material or manufacturing improvements that decrease the degradation rate to 2 mV/kh. In Case 2, a reduction in area specific resistance results in an increase in the operational current density from the SOA to 1 A/cm^2. Case 3 assumes a switch from electrolyte supported cells to cathode supported cells enabling a reduction in the operating temperature to 750°C (1382°F). Improvements to system control and design lead to an increase in steam utilization to 85 percent in Case 4. Enhanced reliability of balance of plant (BOP) components combined with optimized O&M is reflected by an increase in capacity factor (CF) to 90 percent in Case 5. Case 6 considers further increases in current density to 2 A/cm^2, the upper envelope being touted currently for future SOEC technology, along with a reduction in stack cost to $100/kW.

Exhibit ES-3. SOEC pathway case descriptions

<table>
<tr><th>Case Designation</th><th>Pathway Parameter</th><th>Case Identification</th><th>SOEC Pressure (bar)</th><th>Degradation Rate (mV/kh)</th><th>Current Density (A/cm²)</th><th>Stack Temperature (°C)</th><th>Steam Utilization (%)</th><th>Capacity Factor (%)</th><th>Stack Cost ($/kW)</th></tr>
<tr><td rowspan="2">State-of-the-Art</td><td rowspan="2">Reference</td><td>SOEC-EB-0A</td><td>1</td><td rowspan="2">8</td><td rowspan="4">0.5</td><td rowspan="6">850</td><td rowspan="8">80%</td><td rowspan="10">90</td><td rowspan="12">300</td></tr>
<tr><td>SOEC-EB-0P</td><td>8</td></tr>
<tr><td rowspan="2">Case 1</td><td rowspan="2">2 mV/kh Degradation Rate</td><td>SOEC-EB-1A</td><td>1</td><td rowspan="12">2</td></tr>
<tr><td>SOEC-EB-1P</td><td>8</td></tr>
<tr><td rowspan="2">Case 2</td><td rowspan="2">1 A/cm² Current Density</td><td>SOEC-EB-2A</td><td>1</td><td rowspan="8">1</td></tr>
<tr><td>SOEC-EB-2P</td><td>8</td></tr>
<tr><td rowspan="2">Case 3</td><td rowspan="2">750°C Operating Temperature</td><td>SOEC-EB-3A</td><td>1</td><td rowspan="8">750</td></tr>
<tr><td>SOEC-EB-3P</td><td>8</td></tr>
<tr><td rowspan="2">Case 4</td><td rowspan="2">85% Steam Utilization</td><td>SOEC-EB-4A</td><td>1</td><td rowspan="6">85%</td></tr>
<tr><td>SOEC-EB-4P</td><td>8</td></tr>
<tr><td rowspan="2">Case 5</td><td rowspan="2">95% Capacity Factor</td><td>SOEC-EB-5A</td><td>1</td><td rowspan="4">95</td></tr>
<tr><td>SOEC-EB-5P</td><td>8</td></tr>
<tr><td rowspan="2">Case 6</td><td rowspan="2">$100/kW Stack Cost
2 A/cm² Current Density</td><td>SOEC-EB-6A</td><td>1</td><td rowspan="2">2</td><td rowspan="2">100</td></tr>
<tr><td>SOEC-EB-6P</td><td>8</td></tr>
</table>

The performance results presented in this report were obtained by performing steady-state simulations of the SOEC plant configurations at the design capacity using Aspen Plus® (Aspen) process modeling software. The major plant equipment performance and process limits are based on published reports, information obtained from vendors, and/or best engineering judgment. The SOEC electrochemical performance and energy balance was calculated using an algebraic surrogate model fit to data collected from an open-source SOEC model developed by the Institute for the Design of Advanced Energy Systems. [7] Separate SOEC model parameters were used for each pair of current densities and operating temperatures to ensure that in each case the SOEC was operating near the thermoneutral voltage of 1.28 V. Mass and energy balance data from the Aspen models were used to size major pieces of equipment, which formed the basis for developing the cost estimates presented.

Capital and O&M costs for each of the cases were predominantly estimated using a scaling reference cost, wherever available, from prior National Energy Technology Laboratory (NETL) studies according to the 2019 revision of the Quality Guidelines for Energy System Studies (QGESS) report "Capital Cost Scaling Methodology: Revision 4 Report" [8]. The cost results are reported in 2018 dollars. The cost metric used in this report is the levelized cost of hydrogen (LCOH) reported in real 2018 dollars, which is the revenue that must be received by the producer per kg of H_2 produced to meet the desired return on equity after meeting all debt and tax obligations and operating expenses. Detailed information pertaining to LCOH calculations is available in the 2019 revision of the QGESS report "Cost Estimation Methodology for NETL Assessment of Power Plant Performance" [9]. While a reference electricity price of $60/MWh is assumed, [10] sensitivity of the LCOH to the electricity price was assessed to take into account varying market conditions.

RESULTS ANALYSIS

Exhibit ES-4 shows the performance summary for atmospheric cases and Exhibit ES-5 shows the performance summary for the pressurized cases.

Exhibit ES-4. Performance summary for atmospheric cases

Atmospheric Pathway							
Case Name	0A	1A	2A	3A	4A	5A	6A
Capacity Factor	90%	90%	90%	90%	90%	95%	95%
Current Density (A/cm^2)	0.5	0.5	1	1	1	1	2
Voltage (V)	1.290	1.290	1.292	1.288	1.289	1.289	1.291
Stack Temperature (°C)	850	850	850	750	750	750	750
Steam Utilization	80	80	80	80	85	85	85
Stack Degradation Rate (mV/kh)	8	2	2	2	2	2	2
Hydrogen Production Rate (lb/h)	63,641	63,641	63,557	63,757	63,676	63,676	63,583
Gross Power Output (MWe)	0	0	0	0	0	0	0
Electrolysis Power Requirement (MWe)	1,031	1,031	1,031	1,031	1,031	1,031	1,031
Auxiliary Power Requirement (MWe)	368	368	367	364	347	347	347

Atmospheric Pathway							
Case Name	**0A**	**1A**	**2A**	**3A**	**4A**	**5A**	**6A**
Net Power Output (MWe)	-1,399	-1,399	-1,398	-1,395	-1,378	-1,378	-1,378
LHV Net Plant Efficiency (%)	68.8%	68.8%	68.7%	69.1%	69.8%	69.8%	69.8%
Electric Input per Kilogram H_2 (kWh/kg)	48.5	48.5	48.5	48.2	47.7	47.7	47.8
Raw Water Withdrawal (gpm)	2,028	2,028	2,025	2,032	1,915	1,915	1,912
Process Water Discharge (gpm)	330	330	330	331	297	297	296
Raw Water Consumption (gpm)	1,698	1,698	1,696	1,701	1,618	1,618	1,616
CO_2 Emissions (lb/MMBtu)	None						
SO_2 Emissions (lb/MMBtu)							
NOx Emissions (lb/MMBtu)							
PM Emissions (lb/MMBtu)							
Hg Emissions (lb/TBtu)							

Exhibit ES-5. Performance summary for pressurized cases

Pressurized Pathway							
Case Name	**0P**	**1P**	**2P**	**3P**	**4P**	**5P**	**6P**
Capacity Factor	90%	90%	90%	90%	90%	95%	95%
Current Density (A/cm^2)	0.5	0.5	1	1	1	1	2
Voltage (V)	1.298	1.298	1.302	1.292	1.293	1.293	1.289
Stack Temperature (°C)	850	850	850	750	750	750	750
Steam Utilization	80	80	80	80	85	85	85
Stack Degradation Rate (mV/kh)	8	2	2	2	2	2	2
Hydrogen Production Rate (lb/h)	63,225	63,225	63,030	63,534	63,462	63,462	63,695
Gross Power Output (MWe)	62	62	62	59	60	60	60
Electrolysis Power Requirement (MWe)	1,031	1,031	1,031	1,031	1,031	1,031	1,031
Auxiliary Power Requirement (MWe)	380	380	378	379	363	363	366
Net Power Output (MWe)	-1,349	-1,349	-1,346	-1,350	-1,334	-1,334	-1,337
LHV Net Plant Efficiency (%)	70.8	70.8	70.8	71.1	71.9	71.9	72.0
Electric Input per Kilogram H_2 (kWh/kg)	47.1	47.1	47.1	46.9	46.3	46.3	46.3
Raw Water Withdrawal (gpm)	1,907	1,907	1,901	1,916	1,807	1,807	1,814
Process Water Discharge (gpm)	302	302	301	304	272	272	273
Raw Water Consumption (gpm)	1,604	1,604	1,599	1,612	1,536	1,536	1,541
CO_2 Emissions (lb/MMBtu)	None						
SO_2 Emissions (lb/MMBtu)							
NOx Emissions (lb/MMBtu)							
PM Emissions (lb/MMBtu)							
Hg Emissions (lb/TBtu)							

A graph of net plant efficiency (lower heating value [LHV] basis) is provided in Exhibit ES-6. The atmospheric configuration starts the pathway in Case 0A with an LHV efficiency of 68.8 percent.

By the end of the pathway, the cumulative effects of all technology improvements increase the efficiency by 1 percentage point to 69.8 percent. Efficiency increases (as anticipated) are only seen in Cases 3 and 4 where the operating conditions were changed. The decrease in SOEC operating temperature from 850°C (1562°F) to 750°C (1382°F) in Case 3 reduces the auxiliary load of the electric steam superheaters resulting in a 0.4 percentage point increase in efficiency to the atmospheric system. The increased steam utilization in Case 4 results in reduced auxiliary load from the electric boiler and an efficiency increase of 0.7 percentage points to the atmospheric system. The pressurized SOEC configuration is at least 2 percentage points more efficient than the atmospheric configuration across all cases and exhibits similar trends along the pathway. The efficiency of the pressurized system increases by 1.2 percentage points along the pathway, slightly more than the atmospheric configuration.

Exhibit ES-6. Plant efficiencies for all cases (LHV basis)

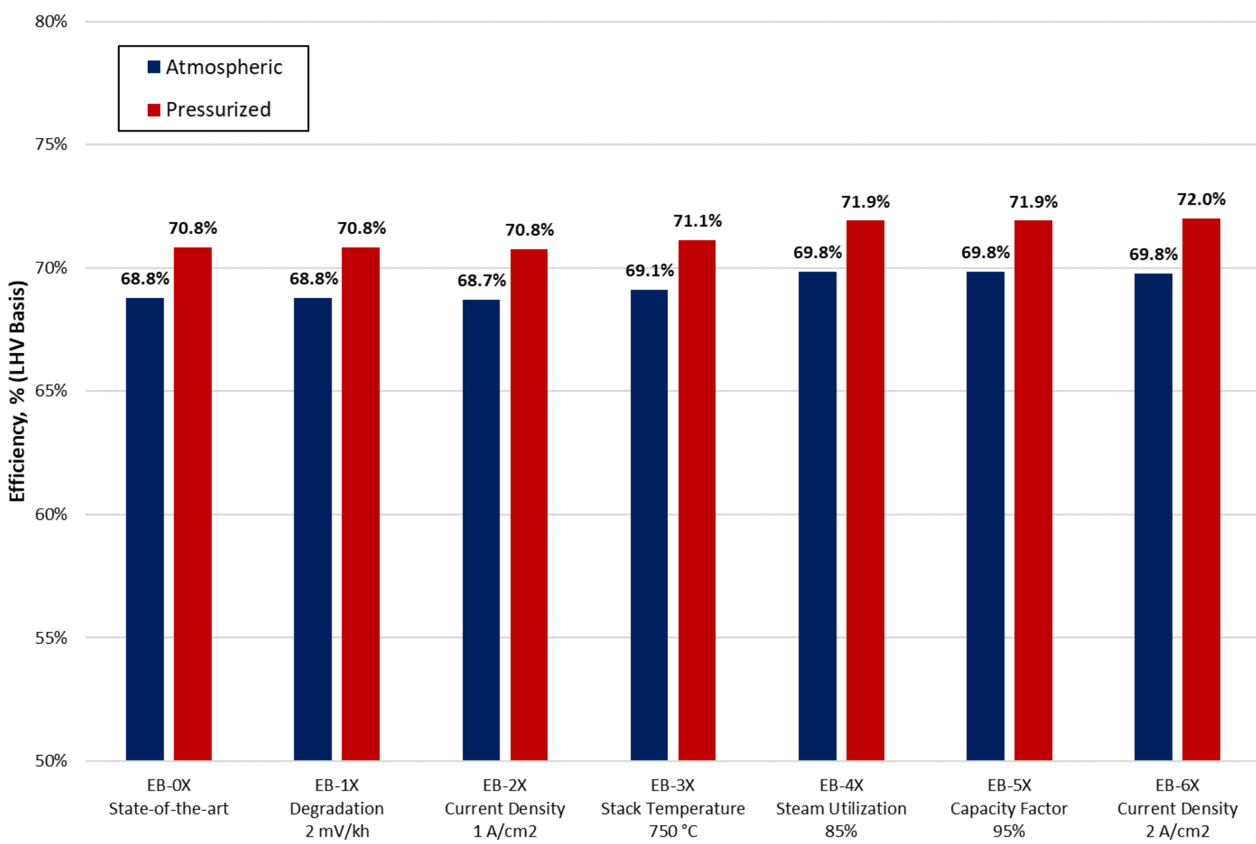


Exhibit ES-7 shows the performance summary for atmospheric cases and Exhibit ES-8 shows the performance summary for the pressurized cases.

Exhibit ES-7. Cost summary for atmospheric cases

Atmospheric Pathway							
Case Name	**0A**	**1A**	**2A**	**3A**	**4A**	**5A**	**6A**
Total Plant Cost (2018$/[kg H_2/day])	1,027	1,027	789	780	765	765	577
Total Overnight Cost (2018$/[kg H_2/day])	1,244	1,244	956	945	927	927	701
Owner's Costs	217	217	168	166	163	163	124
Process Contingency	1	1	1	1	1	1	1
Project Contingency	137	137	106	105	103	103	79
Home Office Expenses	148	148	113	112	110	110	83
Bare Erected Cost	740	740	567	561	550	550	414
Total As-Spent Cost (2018$/[kg H_2/day])	1,331	1,331	1,023	1,011	992	992	750
LCOH ($/kg H_2)	**3.64**	**3.38**	**3.26**	**3.24**	**3.20**	**3.18**	**3.09**
Capital Costs	0.24	0.24	0.18	0.18	0.18	0.17	0.13
Fixed Costs	0.10	0.10	0.08	0.08	0.08	0.08	0.06
Variable Costs	0.40	0.13	0.08	0.08	0.08	0.08	0.04
Electricity Costs	2.91	2.91	2.91	2.89	2.86	2.86	2.87

Exhibit ES-8. Cost summary for pressurized cases

Pressurized Pathway							
Case Name	**0P**	**1P**	**2P**	**3P**	**4P**	**5P**	**6P**
Total Plant Cost (2018$/[kg H_2/day])	1,080	1,080	804	813	798	798	605
Total Overnight Cost (2018$/[kg H_2/day])	1,035	1,035	1,035	1,035	1,035	1,035	1,035
Owner's Costs	228	228	171	173	169	169	130
Process Contingency	1	1	1	1	1	1	1
Project Contingency	144	144	108	109	107	107	82
Home Office Expenses	156	156	116	117	115	115	87
Bare Erected Cost	778	778	579	585	574	574	435
Total As-Spent Cost (2018$/[kg H_2/day])	1,399	1,399	1,043	1,055	1,035	1,035	786
LCOH ($/kg H_2)	**3.58**	**3.31**	**3.17**	**3.17**	**3.13**	**3.11**	**3.01**
Capital Costs	0.25	0.25	0.19	0.19	0.18	0.17	0.13
Fixed Costs	0.11	0.11	0.08	0.09	0.08	0.08	0.06
Variable Costs	0.40	0.13	0.08	0.08	0.08	0.08	0.04
Electricity Costs	2.82	2.82	2.83	2.81	2.78	2.78	2.78

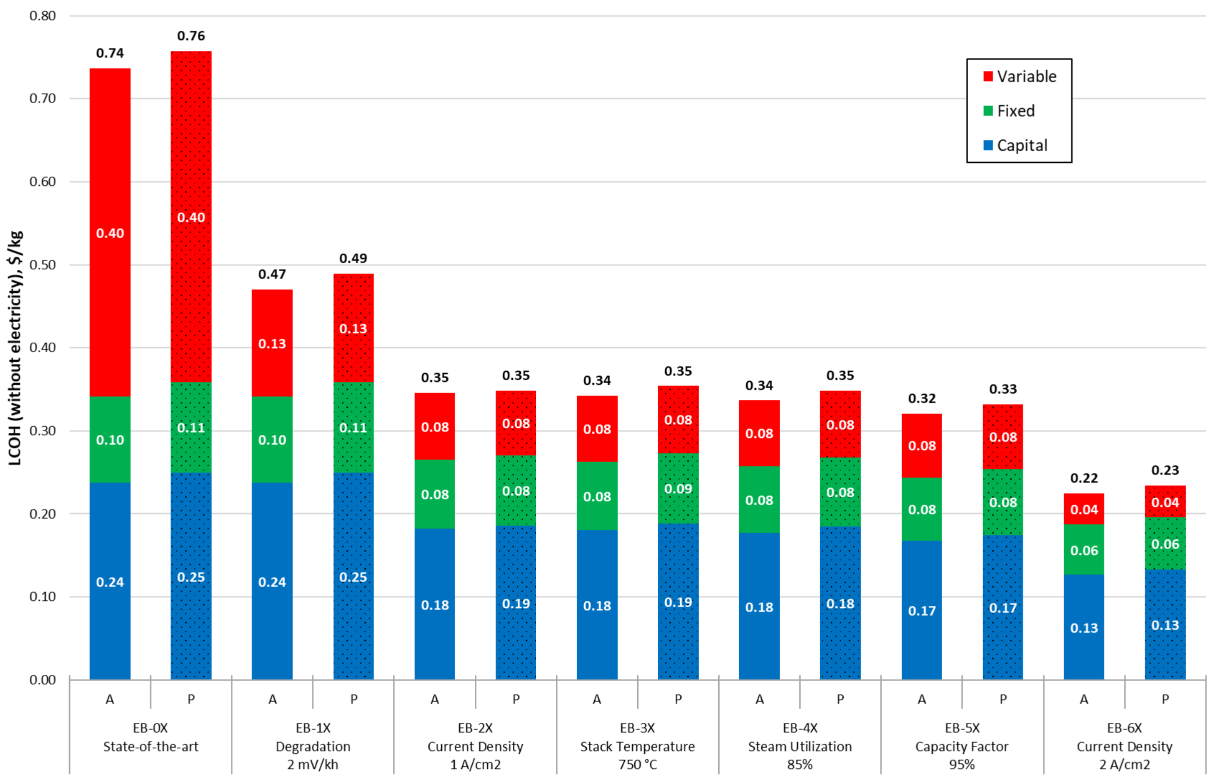
The LCOH breakdown with an electricity price of $60/MWh is presented in Exhibit ES-9. The LCOH for the pressurized cases is $0.06–0.08/kg less than the atmospheric cases. This is primarily due to the increased efficiency of the pressurized configuration and a lower contribution from the auxiliary load electricity cost. There are minor differences in the capital, fixed, and variable cost components of the LCOH between the two configurations. The total

LCOH reduction over both pathways is similar, with the LCOH of atmospheric and pressurized configurations decreasing by $0.55/kg and $0.57/kg, respectively.

Exhibit ES-9. LCOH with electricity for all cases

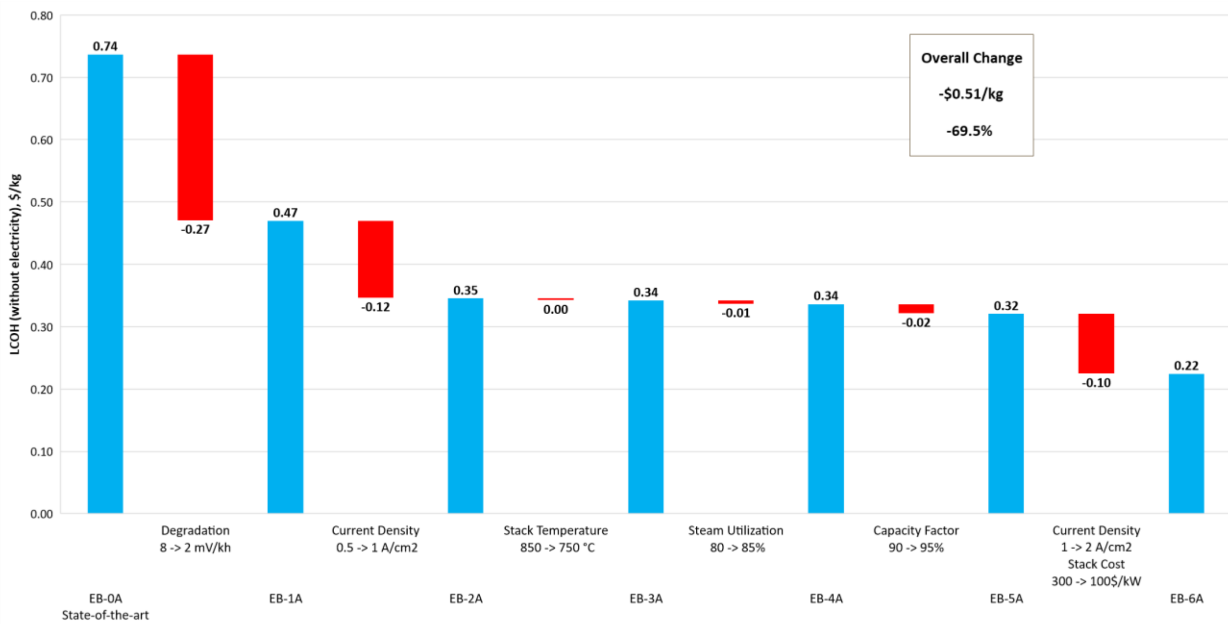
The LCOH breakdown without electricity is presented in Exhibit ES-10. The LCOH for the atmospheric cases is $0.00–0.02/kg less than the pressurized cases. With the efficiency of the cases not accounted for, the higher capital costs of the pressurized configuration result in a larger LCOH. The total LCOH reduction over both pathways is similar, with the LCOH of atmospheric and pressurized configurations decreasing by $0.52/kg and $0.53/kg, respectively.

Exhibit ES-10. LCOH without electricity for all cases



The change in LCOH without electricity along the atmospheric pathway is shown in Exhibit ES-11. The LCOH without electricity decreases by \$0.51/kg H_2, or 70 percent, from Case 0A (\$0.74/kg H_2) to Case 6A (\$0.22/kg H_2). The most significant reductions occur to the variable cost component, which decreases by 90 percent. A major factor in the variable cost reduction is increased stack lifetimes due to the decreased degradation rate in Case 1A. Case 1A (reduction in degradation rate from 8 to 2 mV/kh) displays the largest reduction in LCOH (-\$0.27/kg H_2), contributing about 50 percent of the total pathway reduction. Cases with increases in current density also show significant reductions in the LCOH. Case 2A and 6A contribute LCOH reductions of \$0.12/kg H_2 and \$0.10/kg H_2, respectively. Cases 3A, 4A, and 5A do not contribute significant reductions to the LCOH without electricity. The corresponding figure for the pressurized system can be found in Section 4.4.2; it is not shown here as the values and trends are very similar to the atmospheric system.

Exhibit ES-11. Change in LCOH without electricity over the atmospheric pathway



As shown, electricity prices well below $60/MWh are required to reach the Hydrogen Shot target even if all the technology improvements considered here along the pathway are realized. The electricity prices required to reach the intermediate $2/kg target and ultimate $1/kg target are shown in Exhibit ES-12 and Exhibit ES-13, respectively. At the start of the pathway, both configurations require an electricity price of about $26/MWh to achieve an LCOH of $2/kg. By the end of the pathway, higher electricity prices, $37/MWh to $38/MWh, can be tolerated for a H_2 production cost of $2/kg. The $1/kg target requires even lower electricity prices to achieve ranging from $5/MWh at the start of the pathway to $16/MWh by the end of the pathway for both configurations.

Key takeaways from this study are as follows:

- Reductions in SOEC degradation rate were shown to have the largest impacts on the LCOH sans the electricity price. Increases in current density and reductions in stack cost were also shown to have notable impacts.
- The R&D efforts studied here can lead to only modest improvements in SOEC system performance. Over both the atmospheric and pressurized pathways, the efficiency on an LHV basis increased by 1 percentage point, but these improvements translate to a few cents decrease in the LCOH at an electricity price of $60/MWh.
- Pressurized systems are 2 percentage points more efficient than atmospheric systems largely due to the reduced hydrogen compression load. However, the increased efficiency does not translate to significant LCOH reductions. The large uncertainty in degradation rates at elevated pressures makes it unclear if pressurized systems would have lower LCOHs in practice.

Technology improvements along the R&D pathway have a significant impact on the electricity price needed to reach the Hydrogen Shot production targets. From start to finish, the electricity price (at 95 percent CF) needed to reach the intermediate target of \$2/kg increases from \$26/MWh to \$36/MWh for both pathways. The electricity price needed to reach \$1/kg increases from \$5/MWh to \$16/MWh.

Exhibit ES-12. Electricity price needed for an LCOH of \$2/kg H_2

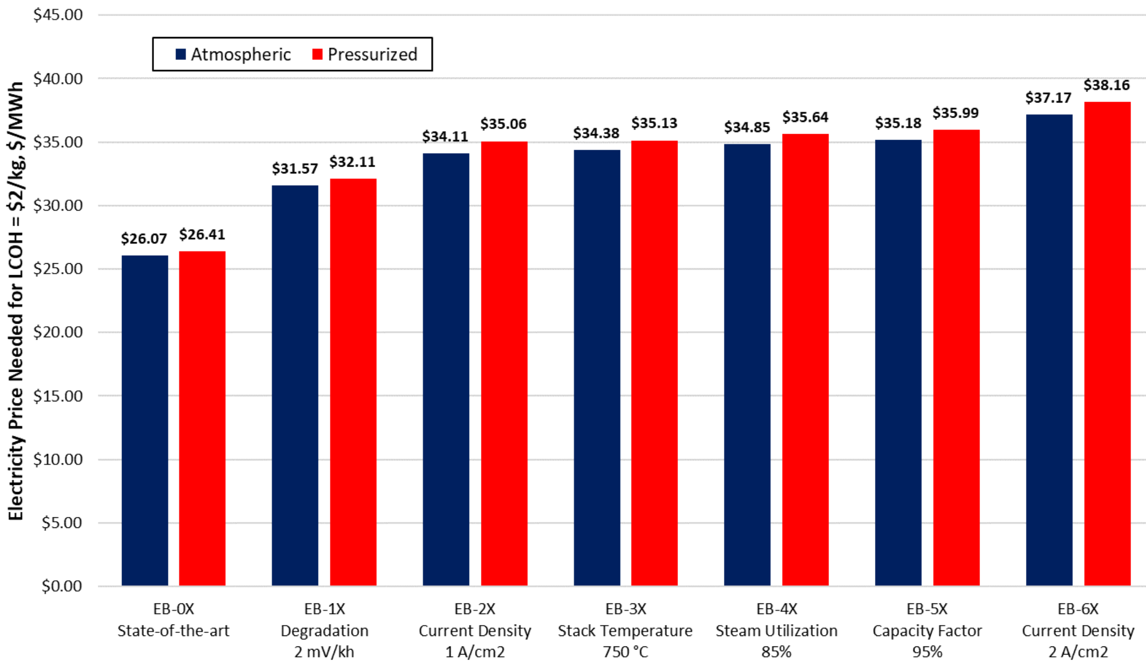
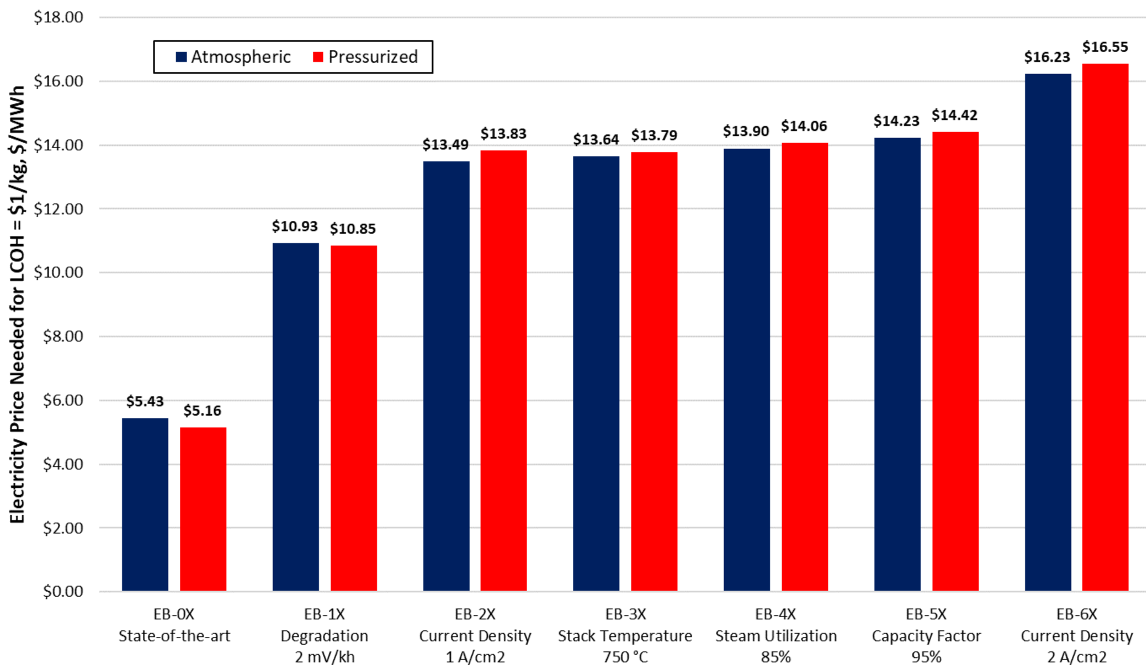


Exhibit ES-13. Electricity price needed for an LCOH of $1/kg H_2



1 INTRODUCTION

The United States (U.S.) Department of Energy's (DOE) Energy Earthshots Initiative aims to accelerate breakthroughs of more abundant, affordable, and reliable low carbon energy solutions within the decade. The production cost of clean hydrogen (H_2), an energy carrier with a potentially critical role in achieving net-zero carbon emissions by 2050, can be as high as $5/kg presently [1]. The first Energy Earthshot—Hydrogen Shot—announced in June 2021, seeks to reduce the cost of clean hydrogen (H_2) to $1 per 1 kg in 1 decade.

Of the numerous methods for producing clean H_2, solid oxide electrolysis cell (SOEC) technology offers several potential advantages but requires additional research and development (R&D) for wide-scale commercial deployment. Compared to low-temperature electrolyzers (alkaline and proton exchange membrane for example), SOEC can be 20 percent more efficient at converting electrical and thermal energy into chemical energy in the form of H_2 [2]. However, a major challenge to the commercialization of SOEC technology is the reduction of the degradation rates at the required operating temperatures of 700–850°C (1292–1562°F). With limited commercial deployment, SOEC systems have not yet been able to capitalize on the cost reduction mechanisms of "economies of scale" and "learning by doing," and accordingly are presently more expensive than low-temperature electrolysis alternatives.

This report seeks to aid decision makers in prioritizing technological advances along a research pathway to the realization of SOEC systems capable of producing clean H_2 at $1/kg. In particular, the performance and cost of gigawatt-scale SOEC systems is presented. The systems analyzed here use electricity, instead of fossil fuels, for all process needs and have no direct CO_2 emissions.

The technology advancements for the SOEC R&D pathway considered in this study are depicted in Exhibit 1-1. The advancements consider anticipated improvements in SOEC electrochemical performance, operating conditions, plant operation and maintenance (O&M), and stack cost reductions. State-of-the-art SOEC performance serves as a basis for the research pathway. Exhibit 1-2 lists the key technology parameters and their state-of-the-art values as determined by literature review.

Exhibit 1-1. The SOEC R&D pathway

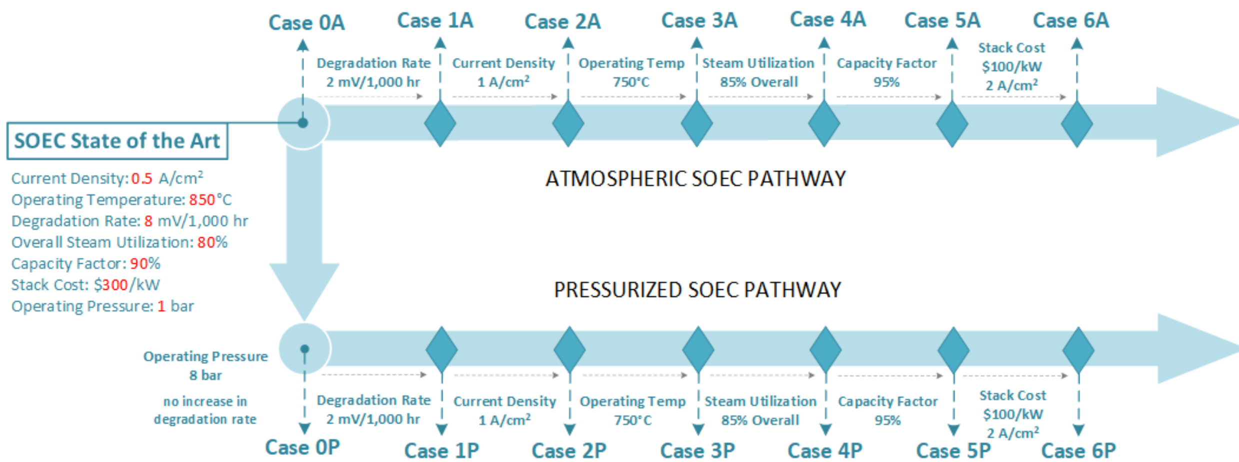


Exhibit 1-2. State-of-the-art values for key SOEC technology parameters and their justifications

Parameter	Value	Justification
Current Density, A/cm^2	500	Operating condition of 9 out of 16 stacks in the literature review
Operating Temperature, °C	850	Operating temperature of the MultiPHLY (2.6 MW_{AC}) [3] and GrInHy2.0 (720 kW_{AC}) [4] projects
Degradation Rate, mV/1000 h	8	Post-2016 average degradation rate from literature review
Overall Steam Utilization	80%	Several stack tests from the literature review operated at a 70% single pass conversion; recycle can be used to obtain an 80% overall conversion
Capacity Factor	90%	This value was not found in the literature, it is assumed to be the same as the commercial natural gas reforming plants in the H_2 baseline study [5]
Stack Cost, $/kW	300	Baseline stack cost used in EERE SOEC study (adjusted to 2018$) [6]; value used by Idaho National Laboratory in several SOEC studies

Two parallel SOEC configurations—one with the SOEC operating at atmospheric pressure and one based on pressurized operation—were considered as part of the study. Pressurized SOEC operation is expected to be more efficient due to decreased auxiliary loads for the compression of H_2 to pressures required for pipeline transport. The technology advancements along the pathway were applied concomitantly to both configurations. Each SOEC case is designated by a numbering system—"SOEC-EB-#X"—where # represents the case number and X represents whether the SOEC is operating under atmospheric (A) or pressurized (P) conditions, respectively.

The specific SOEC pathway cases analyzed in this study are listed in Exhibit 1-3. Case 0 represents the reference case corresponding to the state-of-the-art (SOA). Case 1 represents cell material or manufacturing improvements that decrease the degradation rate to 2 mV/kh. In Case 2, a reduction in area specific resistance results in an increase in the operational current density from the SOA to 1 A/cm^2. Case 3 assumes a switch from electrolyte supported cells to cathode supported cells enabling a reduction in the operating temperature to 750°C (1382°F).

Improvements to system control lead to an increase in steam utilization to 85 percent in Case 4. Enhanced reliability of balance of plant (BOP) components combined with optimized O&M is reflected by an increase in capacity factor (CF) to 90 percent in Case 5. Case 6 considers further increases in current density to 2 A/cm^2, the upper envelope being touted currently for future SOEC technology, along with a reduction in stack cost to $100/kW.

Exhibit 1-3. SOEC pathway case descriptions

<table>
<tr><th>Case Designation</th><th>Pathway Parameter</th><th>Case Identification</th><th>SOEC Pressure (bar)</th><th>Degradation Rate (mV/kh)</th><th>Current Density (A/cm²)</th><th>Stack Temperature (°C)</th><th>Steam Utilization (%)</th><th>Capacity Factor (%)</th><th>Stack Cost ($/kW)</th></tr>
<tr><td rowspan="2">State-of-the-Art</td><td rowspan="2">Reference</td><td>SOEC-EB-0A</td><td>1</td><td rowspan="2">8</td><td rowspan="4">0.5</td><td rowspan="6">850</td><td rowspan="8">80%</td><td rowspan="10">90</td><td rowspan="12">300</td></tr>
<tr><td>SOEC-EB-0P</td><td>8</td></tr>
<tr><td rowspan="2">Case 1</td><td rowspan="2">2 mV/kh Degradation Rate</td><td>SOEC-EB-1A</td><td>1</td><td rowspan="12">2</td></tr>
<tr><td>SOEC-EB-1P</td><td>8</td></tr>
<tr><td rowspan="2">Case 2</td><td rowspan="2">1 A/cm² Current Density</td><td>SOEC-EB-2A</td><td>1</td><td rowspan="8">1</td></tr>
<tr><td>SOEC-EB-2P</td><td>8</td></tr>
<tr><td rowspan="2">Case 3</td><td rowspan="2">750°C Operating Temperature</td><td>SOEC-EB-3A</td><td>1</td><td rowspan="8">750</td></tr>
<tr><td>SOEC-EB-3P</td><td>8</td></tr>
<tr><td rowspan="2">Case 4</td><td rowspan="2">85% Steam Utilization</td><td>SOEC-EB-4A</td><td>1</td><td rowspan="6">85%</td></tr>
<tr><td>SOEC-EB-4P</td><td>8</td></tr>
<tr><td rowspan="2">Case 5</td><td rowspan="2">95% Capacity Factor</td><td>SOEC-EB-5A</td><td>1</td><td rowspan="4">95</td></tr>
<tr><td>SOEC-EB-5P</td><td>8</td></tr>
<tr><td rowspan="2">Case 6</td><td rowspan="2">$100/kW Stack Cost
2 A/cm² Current Density</td><td>SOEC-EB-6A</td><td>1</td><td rowspan="2">2</td><td rowspan="2">100</td></tr>
<tr><td>SOEC-EB-6P</td><td>8</td></tr>
</table>

1.1 Literature Review

As part of this work, a literature review was conducted to identify state-of-the-art (SOA) SOEC performance and to inform the pathway technology advancements. The objectives of the literature review were to

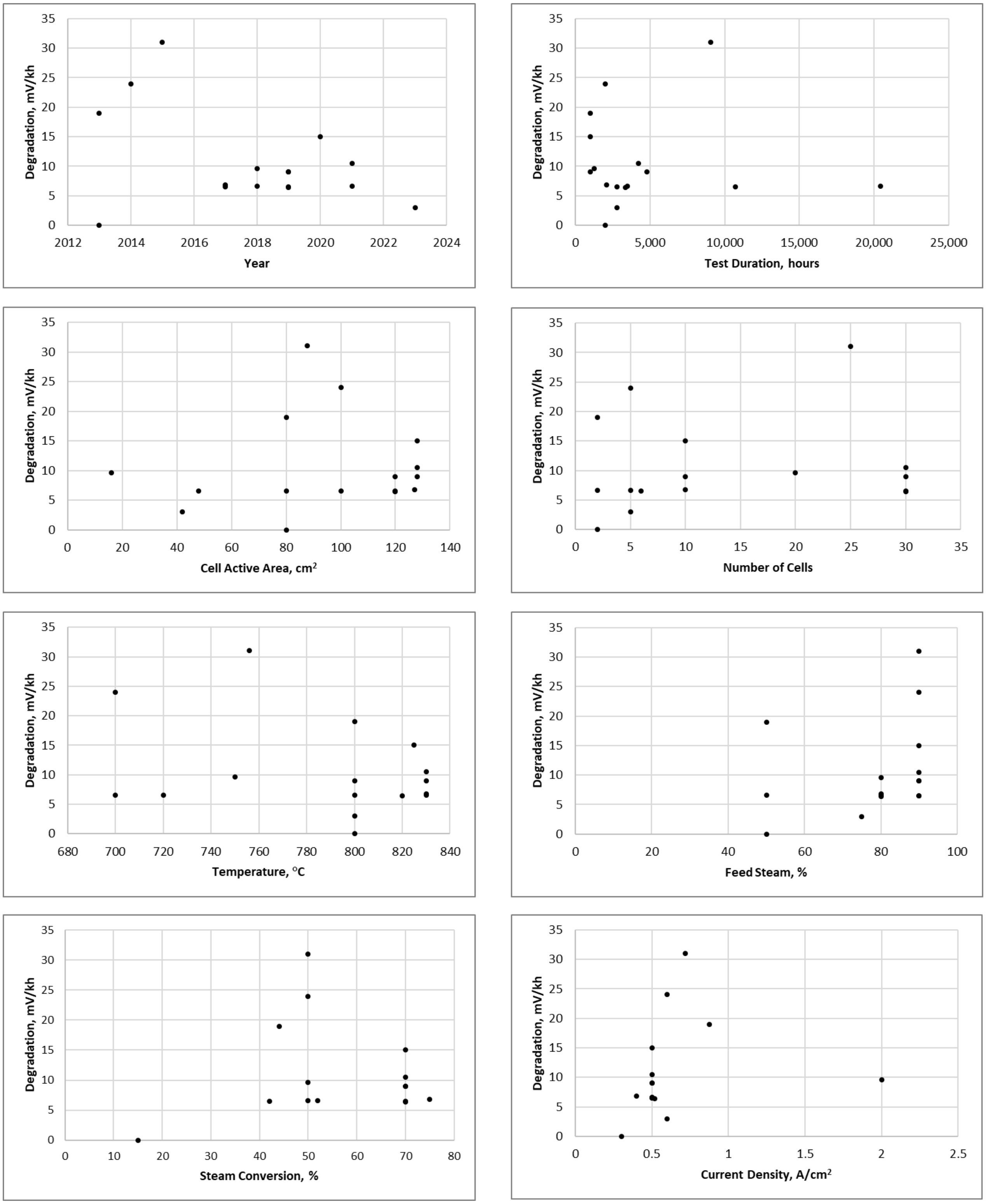
1. Establish the SOA SOEC performance and operating conditions.
2. Determine the state-of-the-art SOEC degradation rate from long-term, bench-scale stack tests and identify any trends between degradation rates and stack design/operating parameters.
3. Determine potential SOEC performance and degradation rates in the long-term.
4. Identify the progress on SOEC scale-up and collect information on pilot-scale design and operating conditions.
5. Compare atmospheric SOEC with pressurized SOEC.

To understand the state-of-the-art, long-term degradation rates of SOEC stacks, the literature review was limited to test durations of at least 1000 hours, stacks with at least two cells, and degradation rates less than 35 mV/kh. The search identified 16 stack tests and the stack design, operating conditions, and degradation rates were recorded and analyzed [11, 12, 13, 14, 15, 16, 17, 18, 19, 20] [21, 22]. Exhibit 1-4 shows scatter plots of the degradation rates against several of the test parameters.

Some useful conclusions from this analysis are as follows:

- Degradation rates appear to be improving over time, with the three highest rates occurring before 2016. The average degradation rate appears to be 8 mV/kh post-2016.
- There is no correlation between the test duration and the observed degradation rate, suggesting that degradation remains stable over long periods.
- There was no correlation between the observed degradation rate and the number of cells or the active cell area.
- Stack tests operated at higher temperatures did not have higher degradation rates. Typically, degradation mechanisms are known to be correlated with temperature and more investigation is required to infer the cause.
- Inlet steam fractions reached as high as 90 percent with no evidence of increased degradation at higher inlet steam fractions.
- The highest steam conversion was 75% and a number of tests operated at 70%. It does not appear that over the operating range of 40–75% increasing the steam conversion increases the degradation.
- Most SOEC were operated nominally at a current density of 0.5 A/cm^2.

Exhibit 1-4. Literature review stack test findings



The two largest SOEC pilot facilities are the Green Industrial Hydrogen (GrInHy2.0) and MULTIPLHY projects both funded by the European Fuel Cell and Hydrogen Joint Undertaking

Programme. The GrInHy2.0 project ran from 2019 to 2022 and supplied almost 100 tons of green H_2 to Salzgitter's steelmaking operations [4]. The system produced 200 Nm^3/h of H_2 at a nominal power input of 720 kW_{AC}. The system consisted of up to eight modules with 24 or 36 SOEC stacks each (30 cells per stack) and was supplied with steam from waste heat of the steel production, enabling an efficiency of 84 percent on a lower heating value (LHV) basis. The system used stacks from the German SOEC manufacturer Sunfire, which operated at 850°C (1562°F). The MULTIPLHY project is a 2.6 MW SOEC system that will be integrated into a renewable products refinery in Rotterdam [3]. Expected to be completed in 2024, the system will produce H_2 at a rate of 60 kg/h, producing over 960 tons of green H_2 during its 16,000-hr operating life. This system is also using Sunfire's SOEC operating at 850°C (1562°F).

Only one source was found studying SOEC performance at different operating pressures [23]. From first principals, elevated pressures should increase the Nernst potential of an SOEC, reducing the efficiency. This trend was observed in the IV curves collected. For electrolyte supported cells, the current-potential (IV) offset was relatively constant across all current densities. However, for the cathode supported cell, the atmospheric IV curve crossed the pressurized IV curve at 0.7 A/cm^2. The authors suggested that pressurized operation reduced the activation and concentration polarizations. The voltage loss of electrolyte supported cells are dominated by ohmic polarization, which is why the same trend was not observed there. The stack operated at 1.4 bar had a degradation rate of 8 mV/kh, while the stack operated at 8 bar had a degradation rate of 31 mV/kh, almost four times higher.

The remainder of this report is organized as follows:

- Section 2 provides the basis for technical and cost evaluations
- Section 3 describes the atmospheric SOEC system and presents the results for the cases along the atmospheric pathway
- Section 4 describes the pressurized SOEC system and presents the results for the cases along the pressurized pathway
- Section 5 provides a discussion of all the pathway results and provides DOE with a basis to measure and prioritize the contribution of its R&D program to SOEC technology
- Section 6 presents the major conclusions from the study

2 DESIGN BASIS

For each of the cases analyzed in this report, an Aspen Plus® (Aspen) model was developed to generate energy and mass balances and plant performance data. Performance data obtained from the models served as the basis for the capital and operating cost estimates. Performance and process limits were primarily based on prior NETL studies and internal vendor quotes, as well as best engineering judgement. Wherever possible, capital and operating costs were scaled from NETL Fossil Energy Baseline (FEB) reports following the capital cost scaling methodology outlined in the NETL Quality Guidelines for Energy System Studies (QGESS) [24]. Ultimately, a levelized cost of hydrogen (LCOH) was calculated for each case and is reported as the revenue requirement figure-of-merit.

The remainder of this section includes the design basis common to all configurations, as well as the environmental targets and cost assumptions used in this study. Discussion of technology-specific design criteria is covered in subsequent sections.

2.1 SOEC PERFORMANCE MODELING

An open-source Python model developed by the Institute for the Design of Advanced Energy Systems was used for determining SOEC electrochemical performance. [7] The model is a two-dimensional, first-principles representation of a planar cell and includes calculations for the cell potential using the Nernst potential, ohmic polarization, and activation polarizations at the fuel and oxygen electrodes.

Model parameters pertaining to the activation and ohmic polarizations were adjusted to achieve a cell voltage of 1.28 V for the specified current density and stack temperature under nominal operating conditions (feed composition of 97 percent steam and 3 percent H_2 with 70 percent steam conversion). Thermoneutral operation is desirable to maintain a constant temperature profile across the cells and to reduce the complexity of thermal management of the stack. Actual operating conditions deviate from the nominal conditions resulting in each case having a slightly different cell voltage. Pressurized and atmospheric cases use the same stack model. In total there are four stack models:

- 0.5 A/cm^2 current density and 850°C (1562°F) stack temperature for Cases 0–1
- 1 A/cm^2 current density and 850°C (1562°F) stack temperature for Case 2
- 1 A/cm^2 current density and 750°C (1382°F) stack temperature for Cases 3–5
- 2 A/cm^2 current density and 750°C (1382°F) stack temperature for Case 6

Each stack model was executed 250 times over a range of current densities, steam utilizations, steam recycle fractions, fuel inlet temperatures, and air inlet temperatures. An algebraic surrogate model of the cell voltage, and outlet stream temperatures was fit for each stack model using the ALAMO software platform. The surrogate models were used to calculate the voltage and energy balance of the SOEC within Aspen.

2.2 Site Characteristic

The site description used in this study is consistent with those described in the FEB [25]. The plants are assumed to be located at a generic site in the midwestern United States with site characteristics and ambient conditions as presented in Exhibit 2-1 and Exhibit 2-2. The ambient conditions are taken to be the same as International Organization for Standardization (ISO) ambient conditions.

Exhibit 2-1. Site characteristics

Parameter	Value
Location	Greenfield, Midwest U.S.
Topography	Level
Size, acres	150
Transportation	Rail or Highway
Water	50% Municipal and 50% Ground Water
Access	Land locked, having access by train and highway
CO_2 Storage	Compressed to 15.3 MPa (2,215 psia), transported 80 kilometers (50 miles) and stored in a saline formation at a depth of 1,239 meters (4,055 feet)

Exhibit 2-2. Site ambient conditions

Parameter	Value
Elevation, m (ft)	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)	11 (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

2.3 Hydrogen Product Specification

The H_2 product specification in this report follows those detailed in the Fossil-Based Hydrogen Production report [5]. All plant configurations in this study produce a H_2 product at the plant gate meeting or exceeding the specification shown in Exhibit 2-3. No site-specific, single end-use is considered. Instead, the study goal was to consider a H_2 product suitable for a wide range of potential energy applications. The maximum impurity concentrations shown in the specification are suitable for ammonia-grade H_2 to avoid catalyst poisoning. The specification also results in a product suitable for the following applications per ISO [26]:

- Type I Grade A – Gaseous H_2; internal combustion engines for transportation; residential/commercial combustion appliances (e.g., boilers, cookers, and similar applications)
- Type I Grade B – Gaseous H_2; industrial fuel for power generation and heat generation except proton-exchange membrane fuel cell applications

Exhibit 2-3. Hydrogen product specification

Characteristic	Specification
H_2 Purity (vol%)	99.90 (min.)
CO_2 (ppm)	A
CO (ppm)	A
H_2S (ppb)	10 (max.)
H_2O (ppm)	A
O_2 (ppm)	A
Pressure (psia)	939.7

[A] The maximum total concentration of all oxygen-containing species is 10 ppm

2.4 Environmental Targets

Emissions of air pollutants (oxides of nitrogen, sulfur dioxide, particulate matter, carbon monoxide, mercury, and carbon dioxide) are assumed to be negligible for every case in this study. SOEC do not generate any direct emissions from the electrolysis process. Steam is generated by an electric boiler, so there are no emissions associated with combustion.

Electricity purchased from non-renewable sources has associated environmental and carbon dioxide (CO_2) emissions, but life-cycle emissions are not considered in this study. There is the possibility of H_2 leakage, but this was not considered in the study.

2.5 Capacity Factor Assumptions

Availability is the percent of time during a specific period that a unit is capable of producing H_2. This report assumes that each new plant would be dispatched any time it is available and would be capable of generating the nameplate capacity when online. Therefore, the CF and availability are equal. The calculations assume that the CF and availability are constant over the life of the plant, but in practice, a plant will have a higher peak availability to counter lower availability in the first several years of operation.

SOEC technology is not yet mature so information on the availability factor cannot be obtained from commercial plants. It was assumed that an SOEC H_2 production facility would have a similar CF to the commercial reforming plants in the Fossil-Based Hydrogen Production report [5]. A baseline CF of 90 percent was chosen with the value increasing to 95 percent with increased R&D.

2.6 Raw Water Withdrawal and Consumption

A water balance was performed for each case on the major water consumers in the process. The total water demand for each subsystem was determined and internal recycle water was applied to offset the water demand. The difference between demand and recycle is raw water withdrawal. Raw water withdrawal is the water removed from the ground or diverted from a municipal source for use in the plant. Raw water consumption is also accounted for as the portion of the raw water withdrawn that is evaporated, transpired, incorporated into products, or otherwise not returned to the water source from which it was withdrawn. Additional details on the calculations and assumptions used in the water balances are available in the FEB [25].

2.7 Cost Estimating Methodology

Capital and production cost estimates follow the economic basis applied in the FEB, which provides factored estimates developed for each plant section for conventional fossil fuel plants [25]. This report scales those costs for comparable plant sections that appear in the SOEC plants according to the NETL QGESS on capital cost scaling [24]. Costs for systems not included in the FEB were taken from estimates used in the Natural Gas Fuel Cell Plant (NGFC) Pathway report [27], Fossil-Based Hydrogen Production report [5], and Direct Air Capture: Sorbent Systems report [10].

A base electricity price of $60/MWh was assumed for all cases. This purchase price represents the average price of electricity from the grid based on output from the National Energy Modeling System in the West North Central region for 2023–2050. [10]

2.7.1 Capital Costs

This report presents capital costs at the total plant cost (TPC), total overnight cost (TOC), and total as-spent cost (TASC) levels, the definitions of which can be found in the FEB [25].

2.7.1.1 Estimate Scope

The estimates represent a complete H_2 production facility on a generic site. The plant boundary limit is defined as the total plant facility within the “fence line” including feedstock receiving and water supply system but terminating at the injection point into the H_2 pipeline network. H_2 pipeline and storage is beyond the estimate scope.

2.7.1.2 Capital Cost Assumptions

Capital cost assumptions are consistent with those detailed in the NGFC Pathways study [27].

2.7.1.3 SOEC Module Costs

The NGFC Pathways study provides cost estimates for solid oxide fuel cell (SOFC) modules [27]. This study assumes no modifications to stack materials or construction are required to operate an SOFC as an SOEC. Thus, SOEC and SOFC module components are assumed to cost the same on a per unit basis. However, SOEC and SOFC operate at different power densities resulting in different costs on a per kW basis. Costs of SOEC module components are shown in Exhibit 2-4 for a nominal stack operating at 0.8 V and 400 mA/cm^2. To provide cost estimates, module costs are adjusted to the stack operating conditions in each case. Except for the $300/kW SOEC stack cost, all module costs are taken from the NGFC Pathway study.

Exhibit 2-4. SOEC module costs

Module Component	SOEC Module Costs[A] (2018$/kWe$_{AC}$)
SOEC Stack	300
Container	9
Insulation	4
Module Assembly	10
Air Distribution	10
Fuel Distribution	10
Module Current Collectors	5
Module Instrumentation and Control	5
Rectifier	68
Total Module	**356**

[A] Module cost for a nominal operating condition of 0.8 V and 400 mA/cm^2

2.7.1.4 Contingency

Both the project contingency and process contingency costs represent costs that are expected to be spent in the development and execution of the project that are not yet fully reflected in the design. It is industry practice to include project contingency in the TPC to cover project uncertainty and the cost of any additional equipment that would result during detailed design. Likewise, the estimates include process contingency to cover the cost of any additional equipment that would be required as a result of continued technology development.

The project and process contingencies applied were taken from the FEB [25] and other NETL reports for the appropriate equipment items. The contingencies applied to the other equipment are listed in Exhibit 2-5. No project contingency has been applied to the SOEC stack unit cost because these contingencies are already being incorporated by vendor estimates for the SOEC stack unit. A 15 percent project contingency has been applied to the ancillary components in the SOEC BOP.

Exhibit 2-5. Project and process contingencies

Equipment Component	Project Contingency	Process Contingency
SOEC Modules	0	0
Air-Electrode Air Blower	15	15
Air-Electrode Heat Exchanger	15	15
Fuel-Electrode Heat Exchanger	15	15
Hydrogen Recycle Gas Blower	15	15

2.7.1.5 Owner's Costs

The owner's costs to be included in the TOC were estimated following the procedures described in the FEB [25]. Detailed explanation of the owner's costs is available in the 2019 revision of the QGESS report "Cost Estimation Methodology for NETL Assessment of Power Plant Performance" [28]. Owner's costs are split into three categories: pre-production costs, inventory capital, and other costs.

2.7.2 Operation and Maintenance Costs

The production costs or operating costs and related maintenance expenses pertain to those charges associated with operating and maintaining the SOEC plants over their expected life. These costs include the following:

- Operating labor
- Maintenance – material and labor
- Administrative and support labor
- Stack degradation
- Consumables
- Fuel

There are two components of O&M costs: fixed O&M, which is independent of H_2 production, and variable O&M, which is proportional to H_2 production. The approach followed in estimating these costs is consistent with that applied in the FEB [25]. Only variations from the methodology described in the NGFC Pathways study will be discussed further [27].

2.7.2.1 Operating Labor

Five operators per shift are assumed in all cases, one less than in the NGFC Pathways study to account for reduced operational complexity.

2.7.2.2 Stack Degradation

The state-of-the-art degradation rate was assumed to be 8 mV/kh (0.63 percent/kh) after a literature review of long-term SOEC stack durability tests. The degradation rate is assumed to decrease to 2 mV/kh (0.16 percent/kh) in Case 1. Throughout this report degradation rates reported in percent/kh assume a starting voltage of 1.28 V. Stack lifetimes are calculated using the average of a linear and first-order degradation rate model. For cases with degradation rates of 8 mV/kh, the stack lifetime is 2.33 years; for cases with degradation rates of 2 mV/kh, the lifetime is 9.34 years.

2.7.3 LCOH

The LCOH is the amount of revenue required per kg of H_2 produced during the plant's operational life to meet all capital and operational costs. The real LCOH can be obtained from the following formula:

$$LCOH = LCC + LOM + LFP$$

Where:

LCOH – the levelized cost of hydrogen, reported in $/kg

LCC – the levelized capital cost

LOM – the levelized operating and maintenance cost

LFP – the levelized fuel price

The method used to determine the capital recovery factor and levelization factors for O&M and fuel costs is found in the QGESS report "Cost Estimation Methodology for NETL Assessments of Power Plant Performance" [28]. No changes were made to the standard global economic assumptions.

3 Atmospheric Pathway

This section discusses the performance and cost results of the SOEC plants along the atmospheric pathway. The pathway consists of seven cases. Starting from state-of-the-art SOEC performance, improvements to the degradation rate, current density, operating temperature, steam utilization, CF, and stack cost are applied sequentially to identify which parameters have the greatest impact on the LCOH. All cases are sized to an electrolysis load of 1 GW_{DC}. For brevity, only the full set of results for the first and last cases along the pathway are presented here. The remainder of the results are available in the Appendix: Additional Case Information. Key results for the intermediate cases are included in a discussion of the entire pathway—found in Section 3.4.

3.1 Atmospheric SOEC Process Description

The configuration of the SOEC system remains constant in all cases along the atmospheric pathway. In each instance, a supply of superheated steam is fed to the SOEC stacks, electrolyzed to H_2, purified, and compressed. All steam and heat is generated in electric boilers and heaters. There is no natural gas combustion and no direct CO_2 emissions from any of the cases analyzed.

3.1.1 SOEC Modules

Saturated steam is generated in an electric boiler at 152°C (305°F) and 70 psia (0.48 MPa). Immediately after the boiler, the steam is throttled to 18.2 psia (0.13 MPa) to avoid a pressure differential with the atmospheric pressured air sweep across the SOEC cells. Electric boilers have a higher blowdown rate than traditional natural gas boilers, with 10 percent blowdown assumed in the Direct Air Capture: Sorbent Systems report [10]. To compensate for this energy loss, a heat exchanger is used to preheat the feedwater using the heat in the blowdown.

In all cases, the steam is superheated and supplied to the fuel-electrode intake of the SOEC module. The temperature of the superheated steam depends on the case and is either 850°C (1562°F) or 750°C (1382°F). The pure steam is mixed with the recycle stream and enters the SOEC stack where it is electrochemically converted to H_2. The overall conversion was set to either 80 or 85 percent, depending on the case, and the steam recycle was fixed at 50 percent. Post-electrolysis, the wet H_2 stream is sent to the H_2 processing unit to be cooled and purified.

Commercially available in-line electric process heaters tend to have a maximum outlet temperature of 649°C (1200°F). These offerings are not suitable for an SOEC system where steam inlet temperatures are closer to 732°C (1350°F). The cost estimate for the electric superheaters in this report is speculative and based on high-temperature heat exchanger cost correlations and the mass of nichrome wire needed.

Air is used as a sweep gas on the air-electrode side of the SOEC to remove the oxygen (O_2) that is produced. The sweep flowrate is adjusted to maintain an outlet O_2 concentration of 35 mole percent. High O_2 concentrations can quickly degrade the interconnect and manifold, especially at high temperatures. Before entering the SOEC, the sweep air is heated to the case-dependent operating temperature of the stacks (750°C [1382°F] or 850°C [1562°F]). The stream is heated using a combination of recuperated heat from the sweep exhaust leaving the SOEC and an electric heater. The SOEC is operated near the thermoneutral voltage, so the full heating requirements cannot be satisfied by heat recuperation alone.

The SOEC cells operate at three different current densities (0.5, 1, and 2 A/cm^2) along the pathway. The different current densities do not have meaningful impacts on the system performance.

3.1.2 Hydrogen Purification and Compression

Before compression, the H_2 stream is cooled to 30°C (86°F) by a series of three heat exchangers: the first partially superheats the electrolysis steam, the second pre-heats the feedwater, and the third removes remaining heat with cooling water. The condensate formed during the cooling process is collected and pumped back to the boiler. At the inlet of the compressor the H_2 steam is about 2 percent water on a molar basis.

The only H_2 contaminate of concern is water. The concentration of O_2 is negligible due to the deaerator and use of O_2 scavenging chemicals in the boiler. The bulk of the water is removed as condensate during cooling. Condensing water in the compressor intercoolers further reduces the concentration of water. A temperature swing adsorption (TSA) drying unit is required to reduce the concentration to the 10-ppm level specified in the design basis.

The TSA dryer is assumed to be using BASF's Sorbead® Adsorption Technology (Sorbead), which is commercially used in green H_2 drying systems. Sorbead properties were obtained from a BASF brochure [29] and are detailed in Exhibit 3-1 along with the operating characteristics of the system. The TSA system consists of two columns packed with Sorbead that alternate between purifying the H_2 stream and regeneration. The on-cycle lasts 12 hours and reduces the concentration of water to 10 ppm. The sorbent is regenerated by the hot air sweep exhaust. In all cases the temperature of the exhaust leaving the air-electrode heat exchanger is above the regeneration temperature of 150°C (302°F). The columns are assumed to include a water-cooled jacket, which is employed during the 8-hour cooling process to return the sorbent back to the operating temperature of 30°C (86°F).

Exhibit 3-1. TSA drying system properties

TSA Drying System	
Sorbead Properties	
Lowest achievable dew point	-76°F
Equilibrium weight capacity	40.0%
Packed bulk density	50 lb/ft^3
Regeneration temperature	302°F
TSA Operation Assumptions	
On-cycle duration	12 hr
Average weight capacity at end of cycle	20%
Operating temperature	86°F
Cooling duration	8 hr
H_2 lost in purge	1%

The H_2 compressor is an integrally geared, multi-stage centrifugal compressor. Interstage cooling to a temperature of 30°C (86°F) is required to control the temperature increase. The high-purity H_2 is compressed to a pipeline-ready pressure of 6.48 MPa (925 psig).

3.2 Case 0A – State-of-the-Art

Case 0A considers a 1 GW_{DC} SOEC system with state-of-the-art performance. The process description is described in Section 3.1. The case specific operating conditions are as follows:

- Current density is 0.5 A/cm^2
- SOEC stack temperature is 850°C (1562°F)
- Overall steam utilization is 80 percent

The plant configuration for Case 0A is illustrated in the block flow diagram in Exhibit 3-2. The associated stream tables containing process data are provided in Exhibit 3-3.

Overall plant performance is summarized in Exhibit 3-4. This case produces H_2 at an energy efficiency of 68.8 percent (LHV basis). Exhibit 3-5 provides a detailed breakdown of the auxiliary power requirements. The electrolysis load accounts for about 74 percent of the total auxiliary load. The electric boiler is the second largest contributor to the auxiliary load at about 18 percent.

Exhibit 3-2. Case 0A block flow diagram

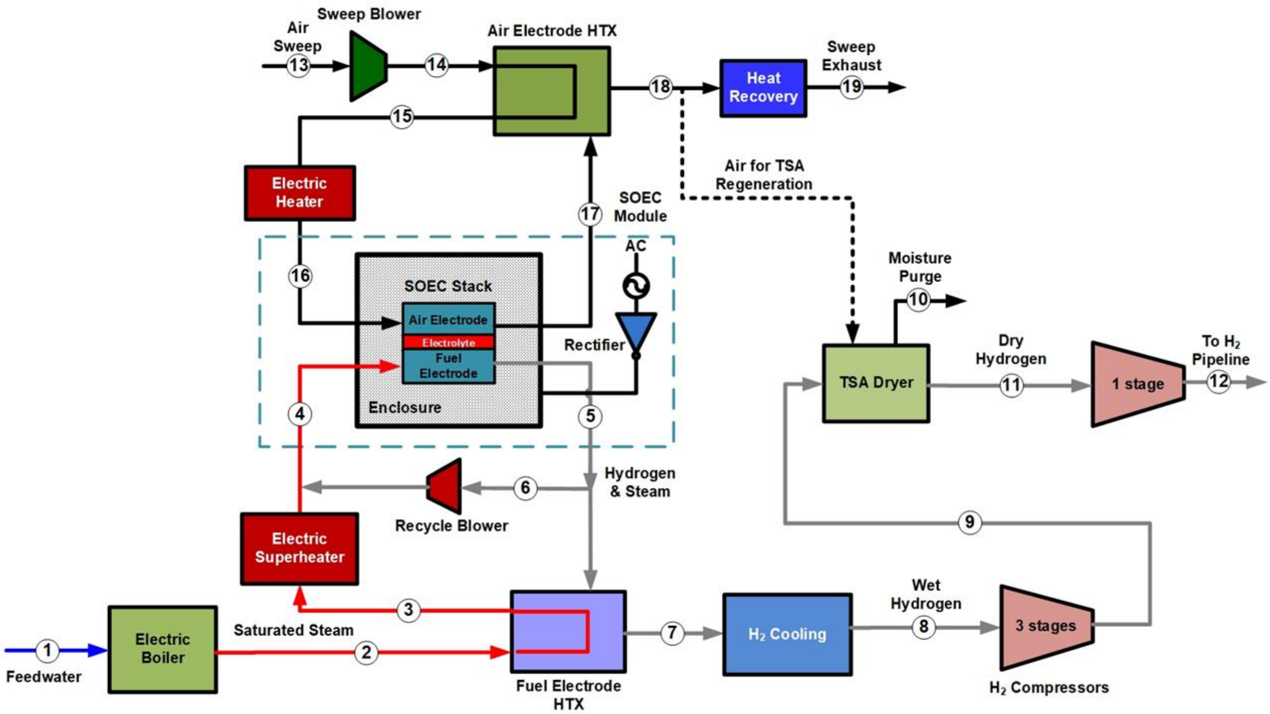


Exhibit 3-3. Case 0A stream table

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	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
C_3H_8	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.4000	0.8000	0.8000	0.8000	0.9655	0.9986
H_2O	1.0000	1.0000	1.0000	0.6000	0.2000	0.2000	0.2000	0.0345	0.0014
N_2	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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,640	18,079	18,079	36,158	36,158	18,079	18,079	14,980	14,483
V-L Flowrate (kg/h)	299,778	325,696	325,696	419,991	188,590	94,295	94,295	38,472	29,521
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	145	720	853	852	852	163	30	30
Pressure (MPa, abs)	0.10	0.13	0.12	0.12	0.12	0.12	0.12	0.10	2.65
Steam Table Enthalpy (kJ/kg)^A	62.80	2,770.89	3,975.64	4,856.00	6,825.39	6,825.39	2,664.16	943.00	461.06
AspenPlus Enthalpy (kJ/kg)^B	-16,017.34	-13,200.46	-11,995.71	-10,031.30	-4,317.62	-4,317.62	-8,478.84	-3,194.04	-87.51
Density (kg/m^3)	1,003.6	0.7	0.3	0.1	0.1	0.1	0.2	0.1	2.1
V-L Molecular Weight	18.015	18.015	18.015	11.616	5.216	5.216	5.216	2.568	2.038
V-L Flowrate (lb_{mol}/h)	36,685	39,857	39,857	79,714	79,714	39,857	39,857	33,026	31,930
V-L Flowrate (lb/h)	660,897	718,037	718,037	925,922	415,770	207,885	207,885	84,816	65,082
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	294	1,329	1,567	1,566	1,566	325	86	86
Pressure (psia)	14.7	18.2	17.4	17.2	17.0	17.0	16.8	14.8	385.0
Steam Table Enthalpy (Btu/lb)^A	27.0	1,191.3	1,709.2	2,087.7	2,934.4	2,934.4	1,145.4	405.4	198.2
AspenPlus Enthalpy (Btu/lb)^B	-6,886.2	-5,675.2	-5,157.2	-4,312.7	-1,856.2	-1,856.2	-3,645.2	-1,373.2	-37.6
Density (lb/ft^3)	62.650	0.041	0.016	0.009	0.004	0.004	0.010	0.006	0.132

^{A}Steam table reference conditions are 32.02°F & 0.089 psia

^{B}AspenPlus thermodynamic reference state is the component's constituent elements in an ideal gas state at 25 °C and 1 atm

Exhibit 3-3. Case 0A stream table (cont'd)

	10	11	12	13	14	15	16	17	18	19
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077
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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,319	14,319	33,032	33,032	33,032	33,032	40,265	40,265	40,265
V-L Flowrate (kg/h)	654	28,867	28,867	953,124	953,124	953,124	953,124	1,184,546	1,184,546	1,184,546
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	31	830	850	854	218	170
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.12	0.11	0.11	0.11	0.11	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	47.31	913.18	936.55	927.92	231.22	182.79
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	-85.41	780.45	803.83	816.66	119.95	71.52
Density (kg/m³)	4.7	2.1	5.0	1.2	1.4	0.4	0.3	0.3	0.8	0.8
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,567	31,567	72,824	72,824	72,824	72,824	88,768	88,768	88,768
V-L Flowrate (lb/h)	1,441	63,641	63,641	2,101,278	2,101,278	2,101,278	2,101,278	2,611,478	2,611,478	2,611,478
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	88	1,526	1,562	1,570	424	338
Pressure (psia)	385.0	383.3	939.7	14.7	17.2	16.4	15.9	15.5	15.3	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	20.3	392.6	402.6	398.9	99.4	78.6
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	-36.7	335.5	345.6	351.1	51.6	30.7
Density (lb/ft³)	0.292	0.129	0.314	0.076	0.084	0.022	0.021	0.021	0.047	0.051

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

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

Exhibit 3-4. Case 0A plant performance summary

Performance Summary	
Total Gross Power, kWe	**0**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	255,190
Hydrogen Compression, kWe	62,524
Balance of Plant, kWe	50,326
Total Auxiliaries, MWe	**368**
Net Power, MWe	**-1,399.0**
Hydrogen Production, kg/h (lb/h)	**28,867 (63,641)**
Energy Efficiency,[A] % HHV (% LHV)	81.3 (68.8)
Electric Input per Kilogram, kWh/kg	48.5
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,137,836 (962,123)
Raw Water Withdrawal, m^3/min (gpm)	7.7 (2,028)
Raw Water Consumption, m^3/min (gpm)	6.4 (1,698)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit 3-5. Case 0A power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Air Electrode Blowers, kWe	4,694
Circulating Water Pumps, kWe	700
Cooling Tower Fans, kWe	360
Electric Boiler, kWe	255,190
Electric Steam Superheater, kWe	27,375
Electric Sweep Heater, kWe	6,188
Feedwater Pumps, kWe	76
Fuel Electrode Recycle Blowers, kWe	762
Ground Water Pumps, kWe	180
Hydrogen Compressor, kWe	62,524
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,700
Total Auxiliaries, MWe	**368**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,399**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

3.2.1 Environmental Performance

Case 0A reports no air emissions of sulfur dioxide (SO_2), oxides of nitrogen (NO_X), particulate matter (PM), mercury (Hg), and carbon monoxide (CO). Electrolysis steam requirements are fully satisfied by the electric boiler without the need for fuel consumption. In this study, only emissions within the plant boundary are considered, any emissions associated with the production of purchased electricity are ignored.

The carbon balance for the plant is shown in Exhibit 3-6. The carbon input to the plant consists of carbon in the air used to sweep the air-electrode. With all the carbon that enters leaving in the air-electrode exhaust, the plant has no net-carbon emissions.

Exhibit 3-6. Case 0A carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (262)	Air-Electrode Sweep Exhaust (CO_2)	119 (262)
Total	**119 (262)**	**Total**	**119 (262)**

Exhibit 3-7 shows the overall water balance for Case 0A.

Exhibit 3-7. Case 0A 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)
Electrolysis Steam	5.0 (1,322)	–	5.0 (1,322)	–	5.0 (1,322)
Deaerator Vent	–	–	–	0.0 (3.4)	0.0 (-3.4)
Boiler Blowdown	–	–	–	0.6 (168)	-0.6 (-168)
Cooling Tower	2.7 (706)	–	2.7 (706)	0.6 (159)	2.1 (547)
Total	**7.7 (2,028)**	**–**	**7.7 (2,028)**	**1.2 (330)**	**6.4 (1,698)**

3.2.2 Energy Balance

An overall plant energy balance for Case 0A is provided in Exhibit 3-8.

Exhibit 3-8. Case 0A overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	29 (27)	–	29 (27)
Auxiliary Power	–	–	5,036 (4,773)	5,036 (4,773)
Total	**0.0 (0.0)**	**58 (55)**	**5,036 (4,773)**	**5,095 (4,829)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,096 (3,882)	13 (12)	–	4,109 (3,895)
Sweep Exhaust	–	217 (205)	–	217 (205)
Motor Losses and Design Allowances	–	7.1 (7.1)	–	7.1 (7.1)
Cooling Tower Load[A]	–	349 (331)	–	349 (331)
Boiler Blowdown	–	7.7 (7.3)	–	7.7 (7.3)
Process Vents[B]	–	0.5 (0.4)	–	0.5 (0.4)
Ambient Losses[C]	–	322 (305)	–	322 (305)
Total	**4,096 (3,882)**	**916 (868)**	**0.0 (0.0)**	**5,012 (4,751)**
Unaccounted Energy[D]	–	–	–	83 (78)

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

3.2.3 Energy and Mass Balance Diagrams

Exhibit 3-9 shows the energy and mass balance for Case 0A.

3.2.4 Cost Estimates

Exhibit 3-10 shows a detailed breakdown of the capital costs; Exhibit 3-11 shows the owner's costs, TOC, and TASC; Exhibit 3-12 shows the initial and annual O&M costs; and Exhibit 3-13 shows the LCOH breakdown.

The estimated TPC of the advanced SOEC is \$1,027/(kg H_2/day) or \$509/kW. Process contingency represents 0.1 percent of the TPC, and project contingency represents 13.4 percent. The LCOH is \$3.64/kg H_2.

Exhibit 3-9. Case 0A energy and mass balance

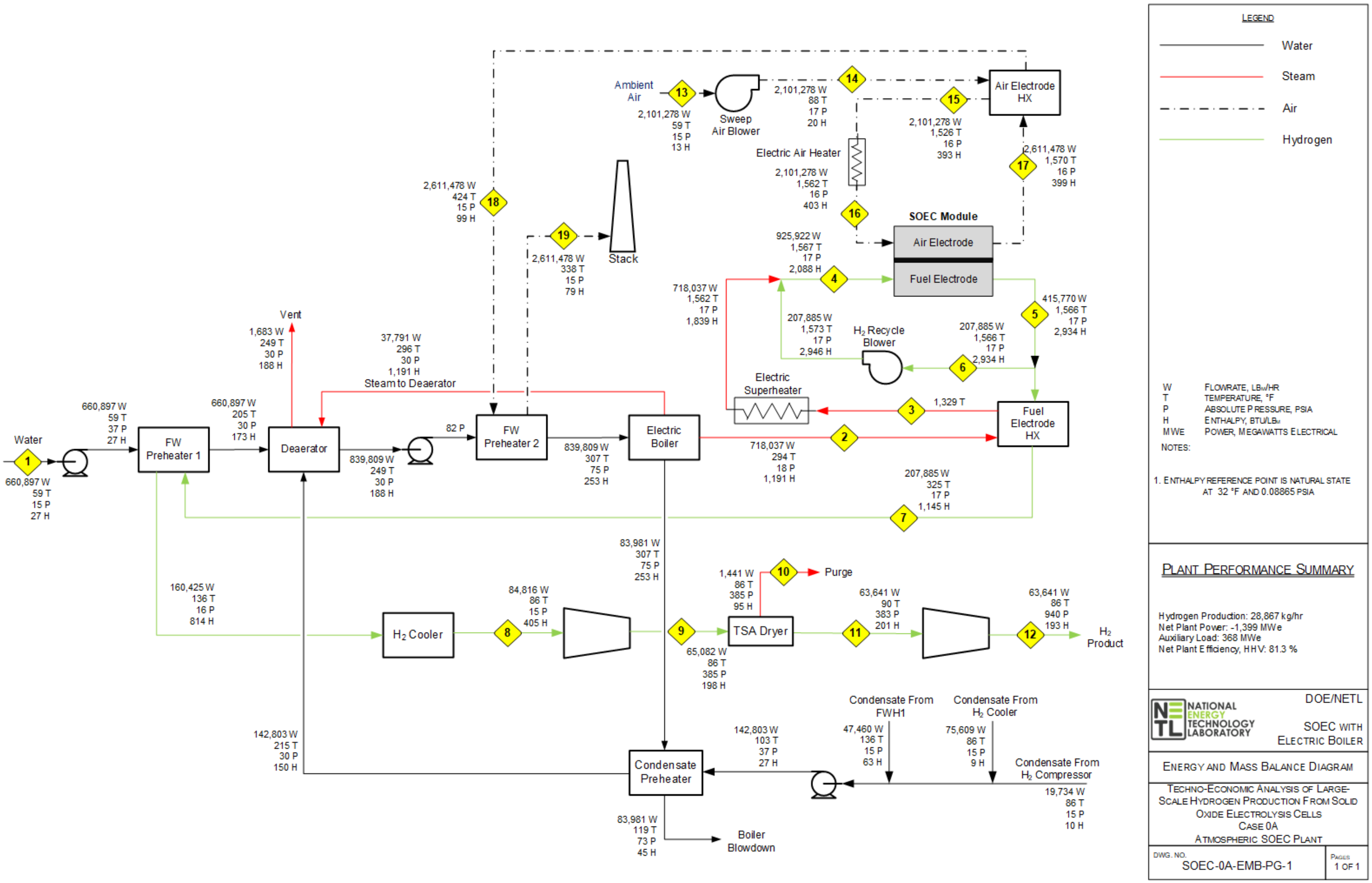


Exhibit 3-10. Case 0A total plant cost details

Item No.	Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies Process	Contingencies Project	Total Plant Cost $/1,000	Total Plant Cost $/[kg H_2/day]	Total Plant Cost $/kW (net)
	Case:	SOEC-EB-0A	State-of-the-Art SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	692,805	Plant Size (MW net):			1,399		Cost Base:		Dec 2018		
1						SOEC Module						
1.1	SOEC Stack	$0	$0	$0	$0	$172,792	$34,558	$0	$31,103	$238,453	$344	$170
1.2	Container	$0	$0	$0	$0	$5,184	$1,037	$0	$933	$7,154	$10	$5
1.3	Insulation	$0	$0	$0	$0	$2,304	$461	$0	$415	$3,179	$5	$2
1.4	Module Assembly	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$11	$6
1.5	Air Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$11	$6
1.6	Fuel Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$11	$6
1.8	Module Current Collectors	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.9	Module I&C	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.10	Rectifier	$0	$0	$0	$0	$39,166	$7,833	$0	$7,050	$54,049	$78	$39
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$242,485**	**$48,497**	**$0**	**$43,647**	**$334,629**	**$483**	**$239**
2						SOEC Balance of Plant						
2.1	Air-Electrode Sweep Blower	$0	$0	$0	$0	$1,141	$228	$0	$205	$1,574	$2	$1
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$24,478	$4,896	$0	$4,406	$33,779	$49	$24
2.3	Hydrogen Recycle Blower	$0	$0	$0	$0	$812	$162	$0	$146	$1,120	$2	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$16,352	$3,270	$0	$2,943	$22,566	$33	$16
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,951	$390	$0	$351	$2,693	$4	$2
2.6	Section and Overall Assembly	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
2.7	Section I&C	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$46,685**	**$9,337**	**$0**	**$8,403**	**$64,426**	**$93**	**$46**
3						Feedwater & Miscellaneous BOP Systems						
3.1	Feedwater System	$0	$0	$0	$0	$4,322	$864	$0	$778	$5,964	$9	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,804	$961	$0	$1,153	$6,918	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,886	$377	$0	$339	$2,602	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,934	$1,987	$0	$2,384	$14,304	$21	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$1,048	$210	$0	$189	$1,446	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,979	$996	$0	$1,195	$7,170	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$26,973**	**$5,395**	**$0**	**$6,038**	**$38,405**	**$55**	**$27**
4						Electric Boiler, Hydrogen Production, and Miscellaneous Systems						
4.1	Feedwater Heaters	$0	$0	$0	$0	$430	$86	$0	$77	$593	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$33,194	$6,639	$0	$5,975	$45,807	$66	$33
4.3	Electric Superheaters	$0	$0	$0	$0	$2,982	$596	$0	$537	$4,115	$6	$3
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$978	$196	$0	$176	$1,349	$2	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$545	$109	$0	$98	$752	$1	$1
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$20,396	$4,079	$0	$3,671	$28,147	$41	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$58,782**	**$11,756**	**$0**	**$10,581**	**$81,119**	**$117**	**$58**

	Case:	SOEC-EB-0A	State-of-the-Art SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	692,805	Plant Size (MW net):			1,399		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 H_2/day]	$/kW (net)
7						Ductwork, & Stack						
7.3	Ductwork	$0	$0	$0	$0	$692	$138	$0	$125	$955	$1	$1
7.4	Stack	$0	$0	$0	$0	$4,627	$925	$0	$833	$6,386	$9	$5
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$590	$118	$0	$142	$850	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,909**	**$1,182**	**$0**	**$1,099**	**$8,190**	**$12**	**$6**
9						Cooling Water System						
9.1	Cooling Towers	$0	$0	$0	$0	$3,773	$755	$0	$679	$5,206	$8	$4
9.2	Circulating Water Pumps	$0	$0	$0	$0	$412	$82	$0	$74	$569	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,637	$927	$0	$835	$6,399	$9	$5
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,889	$378	$0	$340	$2,607	$4	$2
9.5	Make-up Water System	$0	$0	$0	$0	$596	$119	$0	$107	$823	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$610	$122	$0	$146	$879	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$12,176**	**$2,435**	**$0**	**$2,228**	**$16,840**	**$24**	**$12**
11						Accessory Electric Plant						
11.2	Station Service Equipment	$0	$0	$0	$0	$11,778	$2,356	$0	$2,120	$16,254	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$18,176	$3,635	$0	$3,272	$25,082	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,529	$2,906	$0	$2,615	$20,050	$29	$14
11.5	Wire & Cable	$0	$0	$0	$0	$15,575	$3,115	$0	$2,804	$21,494	$31	$15
11.6	Protective Equipment	$0	$0	$0	$0	$1,177	$235	$0	$212	$1,625	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,714	$543	$0	$489	$3,746	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,114	$423	$0	$380	$2,917	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$444	$89	$0	$107	$640	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$66,508**	**$13,302**	**$0**	**$11,998**	**$91,808**	**$133**	**$66**
12						Instrumentation & Control						
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,482	$296	$74	$267	$2,120	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$730	$146	$0	$131	$1,007	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$321	$64	$16	$58	$459	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,434	$2,287	$572	$2,058	$16,351	$24	$12
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,580	$916	$229	$824	$6,550	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,104	$421	$105	$379	$3,008	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,652**	**$4,130**	**$996**	**$3,717**	**$29,496**	**$43**	**$21**
13						Improvements to Site						
13.1	Site Preparation	$0	$0	$0	$0	$17,065	$3,413	$0	$4,096	$24,573	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,731	$1,146	$0	$1,375	$8,253	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,855	$971	$0	$1,165	$6,991	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,651**	**$5,530**	**$0**	**$6,636**	**$39,817**	**$57**	**$28**

	Case:	SOEC-EB-0A	State-of-the-Art SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	692,805	Plant Size (MW net):			1,399		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 H_2/day]	$/kW (net)
14	Buildings & Structures											
14.4	Administration Building	$0	$0	$0	$0	$771	$154	$0	$139	$1,064	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$26	$5	$0	$5	$36	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$468	$94	$0	$84	$645	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,135	$227	$0	$204	$1,567	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$852	$170	$0	$153	$1,176	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$634	$127	$0	$114	$874	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,131	$226	$0	$204	$1,560	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,017**	**$1,003**	**$0**	**$903**	**$6,924**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$512,838**	**$102,568**	**$996**	**$95,252**	**$711,654**	**$1,027**	**$509**

Exhibit 3-11. Case 0A owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$4,750	$7	$3
1 Month Maintenance Materials	$795	$1	$1
1 Month Non-Fuel Consumables	$197	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$14,233	$21	$10
Total	**$19,976**	**$29**	**$14**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$226	$0	$0
0.5% of TPC (spare parts)	$3,558	$5	$3
Total	**$3,784**	**$5**	**$3**
Other Costs			
Initial Cost for Catalyst and Chemicals	$482	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$106,748	$154	$76
Financing Costs	$19,215	$28	$14
Total Overnight Costs (TOC)	**$862,159**	**$1,244**	**$616**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$922,339**	**$1,331**	**$659**

Exhibit 3-12. Case 0A initial and annual O&M costs

Case:	SOEC-EB-0A		State-of-the-Art SOEC		Cost Base:	Dec 2018	
Plant Size (kg H_2/day):	**692,805**	**Plant Size (MW net):**		**1,399**	**Capacity Factor (%):**	**90%**	
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3	$1.567
Maintenance Labor:					$5,408,567	$8	$3.866
Administrative & Support Labor:					$1,900,189	$3	$1.358
Property Taxes and Insurance:					$14,233,070	$21	$10.174
Total:					**$23,734,016**	**$34**	**$16.965**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh)**
Maintenance Material:					$8,590,076	$0.03774	$0.77883
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		2.33	158.28	$68.21	$79,177,245	$0.34790	$7.17871
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,460	$1.90	$0	$911,360	$0.00400	$0.08263
Makeup and Wastewater Treatment Chemicals (ton):	0	4.35	$550	$0	$785,867	$0.00345	$0.07125
Hydrogen Drying Sorbent (lb):	48,237	132.2	$10	$482,368	$434,131	$0.00191	$0.03936
Subtotal:				**$482,368**	**$2,131,359**	**$0.00937**	**$0.19324**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	132.2	$0.02	$0	$825	$0.00000	$0.00007
Subtotal:				**$0**	**$825**	$0.00000	$0.00007
Variable Operating Costs Total:				**$482,368**	**$89,899,506**	**$0.04711**	**$0.97215**
Electricity Cost							
Electricity (MWh):	0	33,575	$60.00	$0	$661,767,325	$2.90776	$60.00000
Total:				**$0**	**$661,767,325**	**$2.90776**	**$60.00000**

Exhibit 3-13. Case 0A LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.24	7%
Fixed	0.10	3%
Variable	0.40	11%
Electricity	2.91	80%
Total	**3.64**	**N/A**

3.3 Case 6A – Advanced Atmospheric SOEC

Case 6A considers a 1 GW_{DC} SOEC system with advanced performance, representing the cumulative performance and cost improvements along the R&D pathway. The process configuration is unchanged from Case 0A and follows the description in Section 3.1. The case specific operating conditions are as follows:

- Current density is 2 A/cm^2
- SOEC stack temperature is 750°C (1382°F)
- Overall steam utilization is 85 percent

The block flow diagram is shown again in Exhibit 3-14 for use with the associated stream tables containing process data provided in Exhibit 3-15.

Overall plant performance is summarized in Exhibit 3-16. Case 6A produces H_2 at an energy efficiency of 69.8 percent (LHV basis). Exhibit 3-17 provides a detailed breakdown of the auxiliary power requirements. Like Case 0A, the electrolysis load accounts for about 75 percent of the total auxiliary load.

Exhibit 3-14. Case 6A block flow diagram

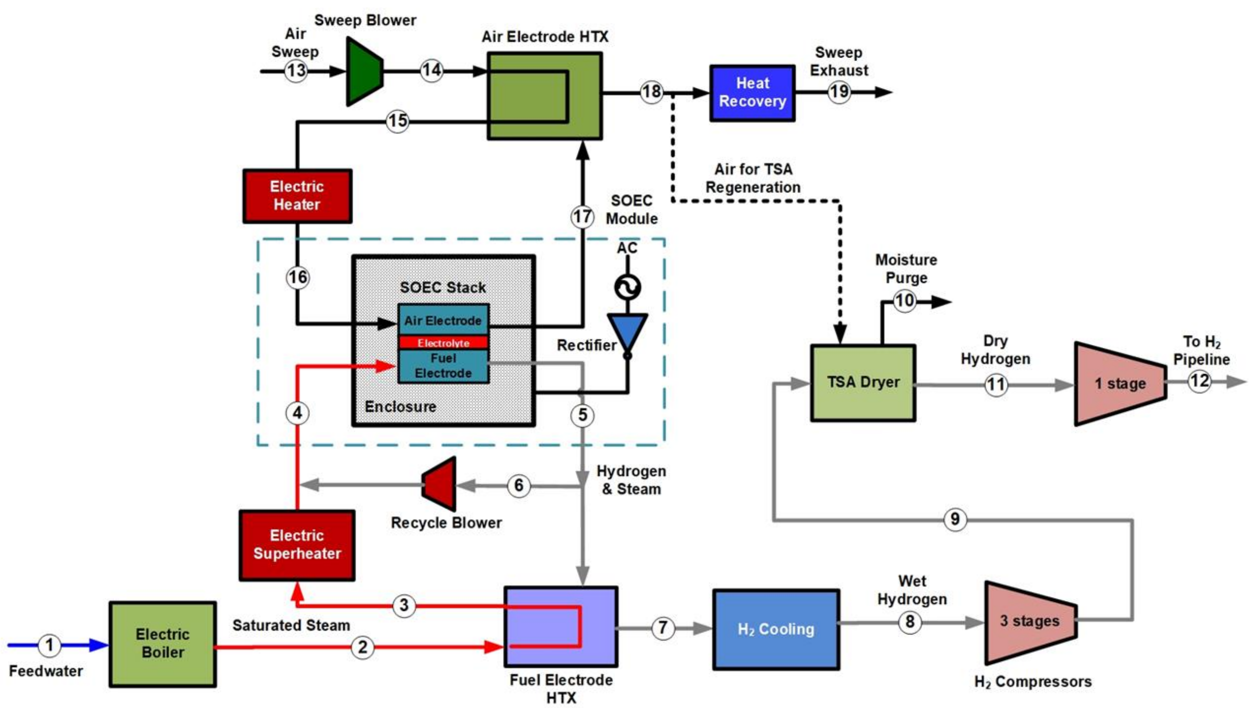


Exhibit 3-15. Case 6A stream table

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	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
C_3H_8	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.4250	0.8500	0.8500	0.8500	0.9655	0.9986
H_2O	1.0000	1.0000	1.0000	0.5750	0.1500	0.1500	0.1500	0.0345	0.0014
N_2	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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,498	17,000	17,000	34,000	34,000	17,000	17,000	14,967	14,470
V-L Flowrate (kg/h)	297,221	306,258	306,258	381,326	150,136	75,068	75,068	38,437	29,494
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	145	637	755	757	757	163	30	30
Pressure (MPa, abs)	0.10	0.13	0.12	0.12	0.12	0.12	0.12	0.10	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,770.89	3,788.61	4,588.08	6,779.77	6,779.77	2,627.72	943.00	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,200.46	-12,182.73	-10,190.40	-3,132.08	-3,132.08	-7,284.14	-3,194.04	-87.51
Density (kg/m^3)	1,003.6	0.7	0.3	0.2	0.1	0.1	0.1	0.1	2.1
V-L Molecular Weight	18.015	18.015	18.015	11.216	4.416	4.416	4.416	2.568	2.038
V-L Flowrate (lb_{mol}/h)	36,373	37,478	37,478	74,957	74,957	37,478	37,478	32,996	31,901
V-L Flowrate (lb/h)	655,261	675,184	675,184	840,680	330,993	165,496	165,496	84,739	65,022
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	294	1,179	1,391	1,395	1,395	325	86	86
Pressure (psia)	14.7	18.2	17.4	17.2	17.0	17.0	16.8	14.8	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,191.3	1,628.8	1,972.5	2,914.8	2,914.8	1,129.7	405.4	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,675.2	-5,237.6	-4,381.1	-1,346.6	-1,346.6	-3,131.6	-1,373.2	-37.6
Density (lb/ft^3)	62.650	0.041	0.018	0.010	0.004	0.004	0.009	0.006	0.132

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

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

Exhibit 3-15. Case 6A stream table (cont'd)

	10	11	12	13	14	15	16	17	18	19
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077
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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,306	14,306	33,002	33,002	33,002	33,002	40,229	40,229	40,229
V-L Flowrate (kg/h)	653	28,841	28,841	952,256	952,255	952,255	952,255	1,183,482	1,183,482	1,183,482
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	31	730	750	761	204	158
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.12	0.11	0.11	0.11	0.11	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	47.31	797.36	820.37	820.40	216.90	170.99
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	-85.41	664.64	687.65	709.14	105.63	59.72
Density (kg/m³)	4.7	2.1	5.0	1.2	1.4	0.4	0.4	0.4	0.8	0.8
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,538	31,538	72,758	72,757	72,757	72,757	88,689	88,689	88,689
V-L Flowrate (lb/h)	1,440	63,583	63,583	2,099,365	2,099,362	2,099,362	2,099,362	2,609,132	2,609,132	2,609,132
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	88	1,346	1,382	1,401	399	317
Pressure (psia)	385.0	383.3	939.7	14.7	17.2	16.4	15.9	15.5	15.3	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	20.3	342.8	352.7	352.7	93.2	73.5
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	-36.7	285.7	295.6	304.9	45.4	25.7
Density (lb/ft³)	0.292	0.129	0.314	0.076	0.084	0.024	0.023	0.023	0.049	0.052

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

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

Exhibit 3-16. Case 6A plant performance summary

Performance Summary	
Total Gross Power, kWe	**0**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	239,960
Hydrogen Compression, kWe	62,467
Balance of Plant, kWe	44,173
Total Auxiliaries, MWe	**347**
Net Power, MWe	**-1,378**
Hydrogen Production, kg/h (lb/h)	**28,841 (63,583)**
Energy Efficiency[A], % HHV (% LHV)	82.5 (69.8)
Electric Input per Kilogram, kWh/kg	47.8
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,136,799 (961,246)
Raw Water Withdrawal, m^3/min (gpm)	7.2 (1,912)
Raw Water Consumption, m^3/min (gpm)	6.1 (1,616)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit 3-17. Case 6A power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Air Electrode Blowers, kWe	4,690
Circulating Water Pumps, kWe	600
Cooling Tower Fans, kWe	310
Electric Boiler, kWe	239,960
Electric Steam Superheater, kWe	21,718
Electric Sweep Heater, kWe	6,088
Feedwater Pumps, kWe	72
Fuel Electrode Recycle Blowers, kWe	656
Ground Water Pumps, kWe	170
Hydrogen Compressor, kWe	62,467
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,580
Total Auxiliaries, MWe	**347**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,378**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

3.3.1 Environmental Performance

Case 6A reports no air emissions of SO_2, NOx, PM, Hg, or CO. The carbon balance for the plant is shown in Exhibit 3-18. The carbon input to the plant consists of carbon in the air used to sweep the air-electrode. With all the carbon that enters leaving in the air-electrode exhaust, the plant has no net-carbon emissions.

Exhibit 3-18. Case 6A carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (262)	Air-Electrode Sweep Exhaust (CO_2)	119 (262)
Total	**119 (262)**	**Total**	**119 (262)**

Exhibit 3-19 shows the overall water balance for the plant.

Exhibit 3-19. Case 6A 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)
Electrolysis Steam	5.0 (1,311)	–	5.0 (1,311)	–	5.0 (1,311)
Deaerator Vent	–	–	–	0.0 (3.2)	0.0 (-3.2)
Boiler Blowdown	–	–	–	0.6 (158)	-0.6 (-158)
Cooling Tower	2.3 (601)	–	2.3 (601)	0.5 (135)	1.8 (466)
Total	**7.2 (1,912)**	**–**	**7.2 (1,912)**	**1.1 (296)**	**6.1 (1,616)**

3.3.2 Energy Balance

The overall energy balance for Case 6A is provided in Exhibit 3-20.

Exhibit 3-20. Case 6A overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	27 (26)	–	27 (26)
Auxiliary Power	–	–	4,959 (4,700)	4,959 (4,700)
Total	**0.0 (0.0)**	**57 (54)**	**4,959 (4,700)**	**5,016 (4,754)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,092 (3,879)	13 (12)	–	4,105 (3,891)
Sweep Exhaust	–	202 (192)	–	202 (192)
Motor Losses and Design Allowances	–	7.1 (7.1)	–	7.1 (7.1)
Cooling Tower Load[A]	–	297 (282)	–	297 (282)
Boiler Blowdown	–	11 (10)	–	11 (10)
Process Vents[B]	–	0.4 (0.4)	–	0.4 (0.4)
Ambient Losses[C]	–	311 (295)	–	311 (295)
Total	**4,092 (3,879)**	**842 (798)**	**0.0 (0.0)**	**4,934 (4,677)**
Unaccounted Energy[D]	–	–	–	81 (77)

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

3.3.3 Energy and Mass Balance Diagrams

Exhibit 3-21 shows the energy and mass balance for Case 6A.

3.3.4 Cost Estimates

Exhibit 3-22 shows a detailed breakdown of the capital costs; Exhibit 3-23 shows the owner's costs, TOC, and TASC; Exhibit 3-24 shows the initial and annual O&M costs; and Exhibit 3-25 shows the LCOH breakdown.

The estimated TPC of the advanced SOEC is $577/[kg H_2/day] or $290/kW. Process contingency represents 0.2 percent of the TPC, and project contingency represents 13.6 percent. The LCOH is $3.09/kg H_2.

Exhibit 3-21. Case 6A energy and mass balance

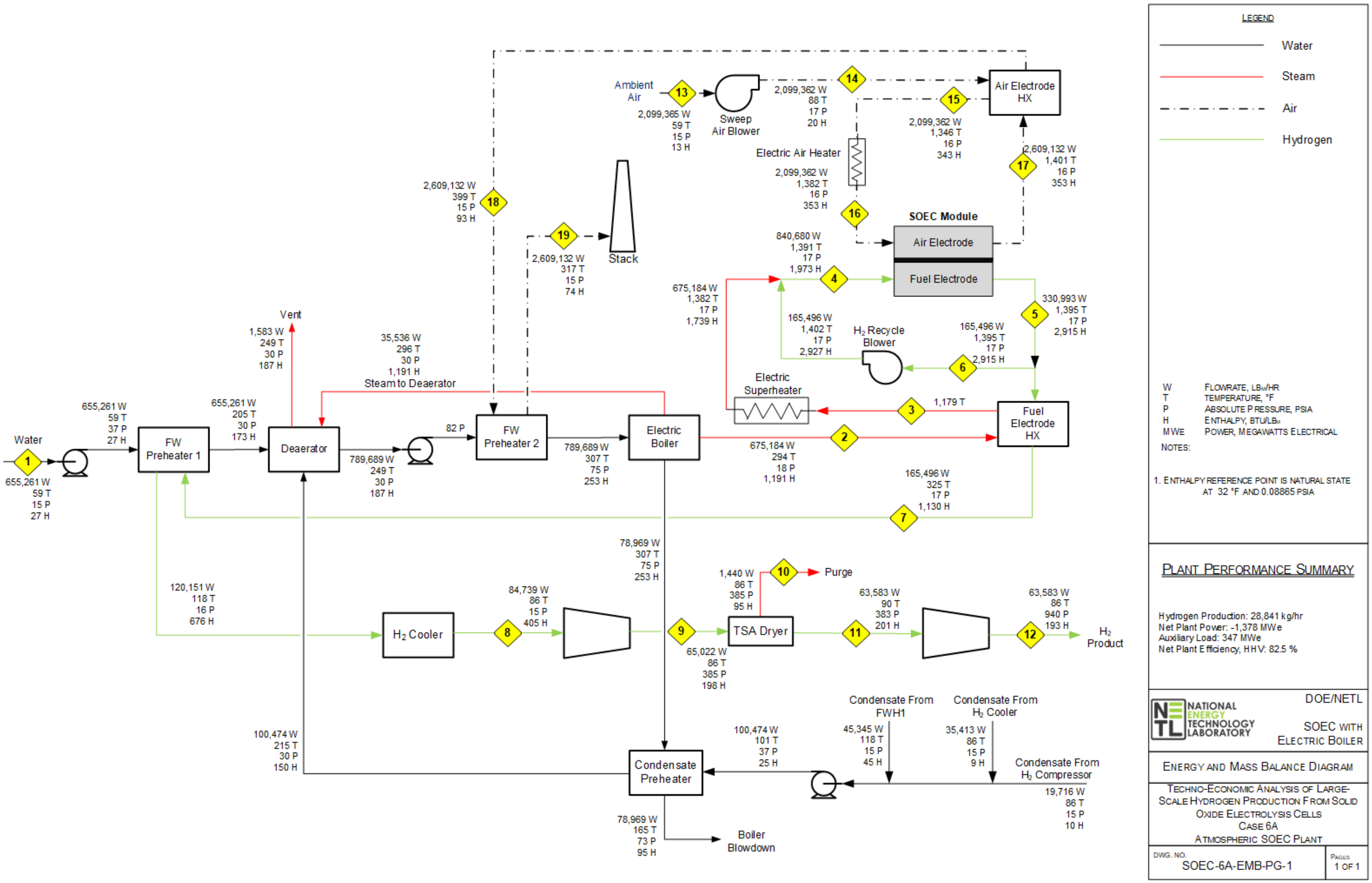


Exhibit 3-22. Case 6A total plant cost details

	Case:	SOEC-EB-6A	Advanced SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	692,174		Plant Size (MW net):		1,378			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 H_2/day]	$/kW (net)
1						SOEC Module						
1.1	SOEC Stack	$0	$0	$0	$0	$14,864	$2,973	$0	$2,675	$20,512	$30	$15
1.2	Container	$0	$0	$0	$0	$1,338	$268	$0	$241	$1,846	$3	$1
1.3	Insulation	$0	$0	$0	$0	$595	$119	$0	$107	$820	$1	$1
1.4	Module Assembly	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.5	Air Distribution	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.6	Fuel Distribution	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.8	Module Current Collectors	$0	$0	$0	$0	$743	$149	$0	$134	$1,026	$1	$1
1.9	Module I&C	$0	$0	$0	$0	$743	$149	$0	$134	$1,026	$1	$1
1.10	Rectifier	$0	$0	$0	$0	$10,107	$2,021	$0	$1,819	$13,948	$20	$10
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$32,849**	**$6,570**	**$0**	**$5,913**	**$45,332**	**$65**	**$33**
2						SOEC Balance of Plant						
2.1	Air-Electrode Sweep Blower	$0	$0	$0	$0	$811	$162	$0	$146	$1,119	$2	$1
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$20,480	$4,096	$0	$3,686	$28,262	$41	$21
2.3	Hydrogen Recycle Blower	$0	$0	$0	$0	$473	$95	$0	$85	$653	$1	$0
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$13,831	$2,766	$0	$2,490	$19,087	$28	$14
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$855	$171	$0	$154	$1,180	$2	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$428	$86	$0	$77	$590	$1	$0
2.7	Section I&C	$0	$0	$0	$0	$428	$86	$0	$77	$590	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$37,306**	**$7,461**	**$0**	**$6,715**	**$51,482**	**$74**	**$37**
3						Feedwater & Miscellaneous BOP Systems						
3.1	Feedwater System	$0	$0	$0	$0	$4,142	$828	$0	$746	$5,716	$8	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,602	$920	$0	$1,104	$6,627	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,785	$357	$0	$321	$2,463	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,476	$1,895	$0	$2,274	$13,646	$20	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$992	$198	$0	$178	$1,368	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,612	$922	$0	$1,107	$6,641	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$25,609**	**$5,122**	**$0**	**$5,731**	**$36,462**	**$53**	**$26**
4						Electric Boiler, Hydrogen Production, and Miscellaneous Systems						
4.1	Feedwater Heaters	$0	$0	$0	$0	$484	$97	$0	$87	$668	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$31,599	$6,320	$0	$5,688	$43,607	$63	$32
4.3	Electric Superheaters	$0	$0	$0	$0	$1,679	$336	$0	$302	$2,317	$3	$2
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$653	$131	$0	$117	$900	$1	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$301	$60	$0	$54	$416	$1	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$20,383	$4,077	$0	$3,669	$28,129	$41	$20

Item No.	Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies Process	Contingencies Project	Total Plant Cost $/1,000	Total Plant Cost $/[kg H_2/day]	Total Plant Cost $/kW (net)
	Case:	SOEC-EB-6A	Advanced SOEC				Estimate Type:			Conceptual		
	Plant Size (kg H_2/day):	692,174	Plant Size (MW net):			1,378	Cost Base:			Dec 2018		
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$55,357**	**$11,071**	**$0**	**$9,964**	**$76,393**	**$110**	**$55**
7	**Ductwork, & Stack**											
7.3	Ductwork	$0	$0	$0	$0	$679	$136	$0	$122	$937	$1	$1
7.4	Stack	$0	$0	$0	$0	$4,539	$908	$0	$817	$6,263	$9	$5
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$579	$116	$0	$139	$833	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,796**	**$1,159**	**$0**	**$1,078**	**$8,033**	**$12**	**$6**
9	**Cooling Water System**											
9.1	Cooling Towers	$0	$0	$0	$0	$3,355	$671	$0	$604	$4,630	$7	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$367	$73	$0	$66	$507	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,286	$857	$0	$772	$5,915	$9	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,716	$343	$0	$309	$2,368	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$583	$117	$0	$105	$804	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$235	$47	$0	$42	$324	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$554	$111	$0	$133	$798	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$11,096**	**$2,219**	**$0**	**$2,030**	**$15,345**	**$22**	**$11**
11	**Accessory Electric Plant**											
11.2	Station Service Equipment	$0	$0	$0	$0	$11,662	$2,332	$0	$2,099	$16,094	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$17,997	$3,599	$0	$3,239	$24,836	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,386	$2,877	$0	$2,590	$19,853	$29	$14
11.5	Wire & Cable	$0	$0	$0	$0	$15,422	$3,084	$0	$2,776	$21,283	$31	$15
11.6	Protective Equipment	$0	$0	$0	$0	$1,166	$233	$0	$210	$1,609	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,688	$538	$0	$484	$3,709	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,093	$419	$0	$377	$2,888	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$440	$88	$0	$106	$634	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$65,854**	**$13,171**	**$0**	**$11,880**	**$90,905**	**$131**	**$66**
12	**Instrumentation & Control**											
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,468	$294	$73	$264	$2,099	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$724	$145	$0	$130	$1,000	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$318	$64	$16	$57	$455	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,325	$2,265	$566	$2,039	$16,195	$23	$12
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,537	$907	$227	$817	$6,487	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,084	$417	$104	$375	$2,980	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,456**	**$4,091**	**$987**	**$3,682**	**$29,216**	**$42**	**$21**

	Case:	SOEC-EB-6A	Advanced SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	692,174	Plant Size (MW net):			1,378		Cost Base:		Dec 2018		
Item No.	Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies Process	Contingencies Project	Total Plant Cost $/1,000	Total Plant Cost $/[kg H_2/day]	Total Plant Cost $/kW (net)
13	Improvements to Site											
13.1	Site Preparation	$0	$0	$0	$0	$16,944	$3,389	$0	$4,067	$24,399	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,690	$1,138	$0	$1,366	$8,194	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,821	$964	$0	$1,157	$6,942	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,455**	**$5,491**	**$0**	**$6,589**	**$39,535**	**$57**	**$29**
14	Buildings & Structures											
14.4	Administration Building	$0	$0	$0	$0	$767	$153	$0	$138	$1,058	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$23	$5	$0	$4	$32	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$450	$90	$0	$81	$621	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,129	$226	$0	$203	$1,558	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$848	$170	$0	$153	$1,170	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$631	$126	$0	$114	$871	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,090	$218	$0	$196	$1,504	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,938**	**$988**	**$0**	**$889**	**$6,814**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$286,716**	**$57,343**	**$987**	**$54,472**	**$399,518**	**$577**	**$290**

Exhibit 3-23. Case 6A owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,268	$5	$2
1 Month Maintenance Materials	$447	$1	$0
1 Month Non-Fuel Consumables	$188	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$7,990	$12	$6
Total	**$11,893**	**$17**	**$9**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$218	$0	$0
0.5% of TPC (spare parts)	$1,998	$3	$1
Total	**$2,215**	**$3**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$482	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$59,928	$87	$44
Financing Costs	$10,787	$16	$8
Total Overnight Costs (TOC)	**$485,122**	**$701**	**$352**
TASC Multiplier (IOU, 35 year)		1.070	
Total As-Spent Cost (TASC)	**$518,985**	**$750**	**$377**

Exhibit 3-24. Case 6A initial and annual O&M costs

Case:	**SOEC-EB-6A**		**Advanced SOEC**		**Cost Base:**		**Dec 2018**
Plant Size (kg H_2/day):	**692,174**	**Plant Size (MW net):**		**1,378**	**Capacity Factor (%):**		**95%**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.167	$1.591
Maintenance Labor:					$3,036,334	$4.387	$2.204
Administrative & Support Labor:					$1,307,131	$1.888	$0.949
Property Taxes and Insurance:					$7,990,352	$11.544	$5.800
Total:					**$14,526,007**	**$20.986**	**$10.545**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh-net)**
Maintenance Material:					$5,090,324	$0.02121	$0.44403
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	14.75	$1.49	$1,785,251	$0.00744	$0.15573
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,377	$1.90	$0	$906,946	$0.00378	$0.07911
Makeup and Wastewater Treatment Chemicals (ton):	0	4.10	$550	$0	$782,061	$0.00326	$0.06822
Hydrogen Drying Sorbent (lb):	48,193	132.0	$10	$481,928	$457,832	$0.00191	$0.03994
Subtotal:				**$481,928**	**$2,146,839**	**$0.00894**	**$0.18727**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	132.0	$0.02	$0	$870	$0.00000	$0.00008
Subtotal:				$0	$870	$0.00000	$0.00008
Variable Operating Costs Total:				**$481,928**	**$9,023,285**	**$0.03016**	**$0.63138**
Electricity Cost							
Electricity (MWh):	0	33,061	$60.00	$0	$687,831,730	$2.86583	$60.00000
Total:				**$0**	**$687,831,730**	**$2.86583**	**$60.00000**

Exhibit 3-25. Case 6A LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.13	4%
Fixed	0.06	2%
Variable	0.04	1%
Electricity	2.87	93%
Total	**3.09**	**N/A**

3.4 Atmospheric Pathway Results

The performance and cost results of all seven cases in the atmospheric pathway are summarized in Exhibit 3-26. The following section discusses the improvements to SOEC performance and cost along the pathway.

Exhibit 3-26. Performance and cost summary for all atmospheric cases

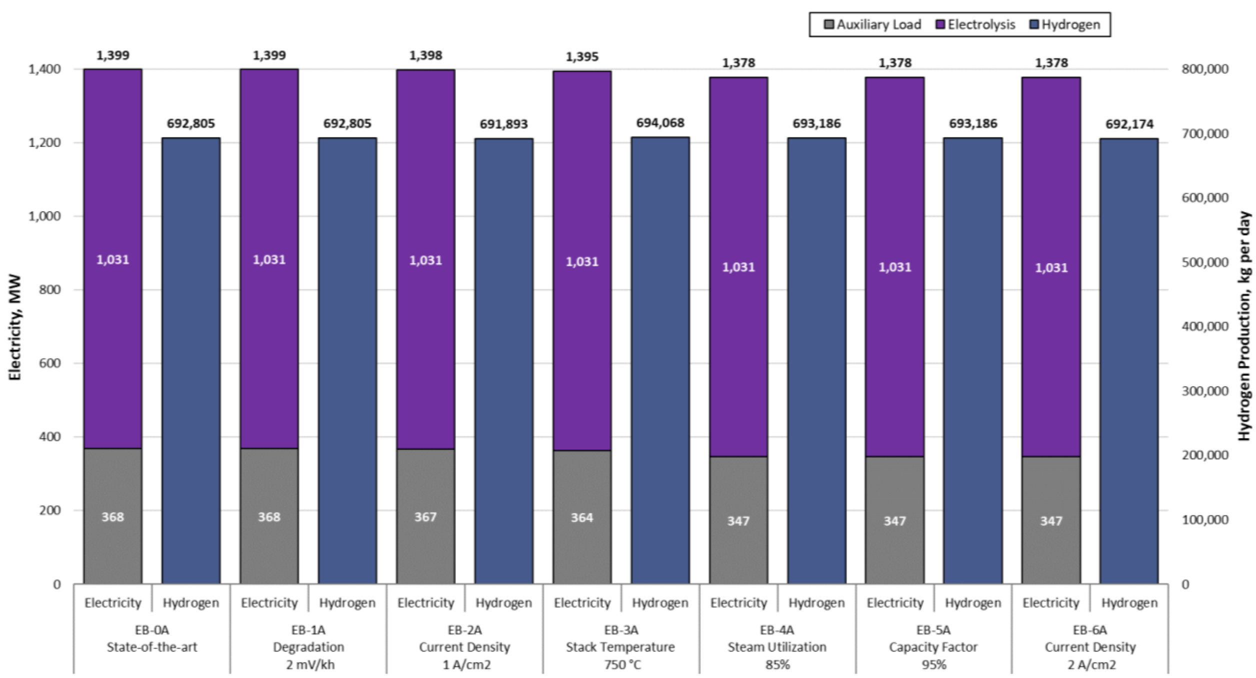
Atmospheric Pathway							
Case Name	0A	1A	2A	3A	4A	5A	6A
PERFORMANCE							
Capacity Factor	90%	90%	90%	90%	90%	95%	95%
Current Density (A/cm^2)	0.5	0.5	1	1	1	1	2
Voltage (V)	1.290	1.290	1.292	1.288	1.289	1.289	1.291
Stack Temperature (°C)	850	850	850	750	750	750	750
Steam Utilization	80	80	80	80	85	85	85
Stack Degradation Rate (mV/kh)	8	2	2	2	2	2	2
Hydrogen Production Rate (lb/h)	63,641	63,641	63,557	63,757	63,676	63,676	63,583
Gross Power Output (MWe)	0	0	0	0	0	0	0
Electrolysis Power Requirement (MWe)	1,031	1,031	1,031	1,031	1,031	1,031	1,031
Auxiliary Power Requirement (MWe)	368	368	367	364	347	347	347
Net Power Output (MWe)	-1,399	-1,399	-1,398	-1,395	-1,378	-1,378	-1,378
LHV Net Plant Efficiency (%)	68.8%	68.8%	68.7%	69.1%	69.8%	69.8%	69.8%
Electric Input per Kilogram H_2 (kWh/kg)	48.5	48.5	48.5	48.2	47.7	47.7	47.8
Raw Water Withdrawal (gpm)	2,028	2,028	2,025	2,032	1,915	1,915	1,912
Process Water Discharge (gpm)	330	330	330	331	297	297	296
Raw Water Consumption (gpm)	1,698	1,698	1,696	1,701	1,618	1,618	1,616
CO_2 Emissions (lb/MMBtu)	None						
SO_2 Emissions (lb/MMBtu)							
NOx Emissions (lb/MMBtu)							
PM Emissions (lb/MMBtu)							
Hg Emissions (lb/TBtu)							
COST							
Total Plant Cost (2018$/[kg H_2/day])	1,027	1,027	789	780	765	765	577
Total Overnight Cost (2018$/[kg H_2/day])	1,244	1,244	956	945	927	927	701
Owner's Costs	217	217	168	166	163	163	124
Process Contingency	1	1	1	1	1	1	1
Project Contingency	137	137	106	105	103	103	79
Home Office Expenses	148	148	113	112	110	110	83
Bare Erected Cost	740	740	567	561	550	550	414

Atmospheric Pathway							
Case Name	**0A**	**1A**	**2A**	**3A**	**4A**	**5A**	**6A**
Total As-Spent Cost (2018$/[kg H_2/day])	1,331	1,331	1,023	1,011	992	992	750
LCOH ($/kg H_2)	3.64	3.38	3.26	3.24	3.20	3.18	3.09
Capital Costs	0.24	0.24	0.18	0.18	0.18	0.17	0.13
Fixed Costs	0.10	0.10	0.08	0.08	0.08	0.08	0.06
Variable Costs	0.40	0.13	0.08	0.08	0.08	0.08	0.04
Electricity Costs	2.91	2.91	2.91	2.89	2.86	2.86	2.87

3.4.1 Performance and Environmental Results Summary

A graph of the electricity consumed, and H_2 produced by the atmospheric cases is shown in Exhibit 3-27. Each case was sized to an electrical input of 1 GW_{DC}. A rectifier efficiency of 97 percent yields the constant electrolysis load of 1,031 MW seen in the exhibit. For every case, the electrolysis load makes up about 74 percent of the total electric load. The remainder consists of the BOP auxiliary load, which decreases slightly as the pathway progresses. From start to finish, the BOP auxiliary load decreases by only 21 MW, equating to about 1.5 percent of the total electrical load of any case.

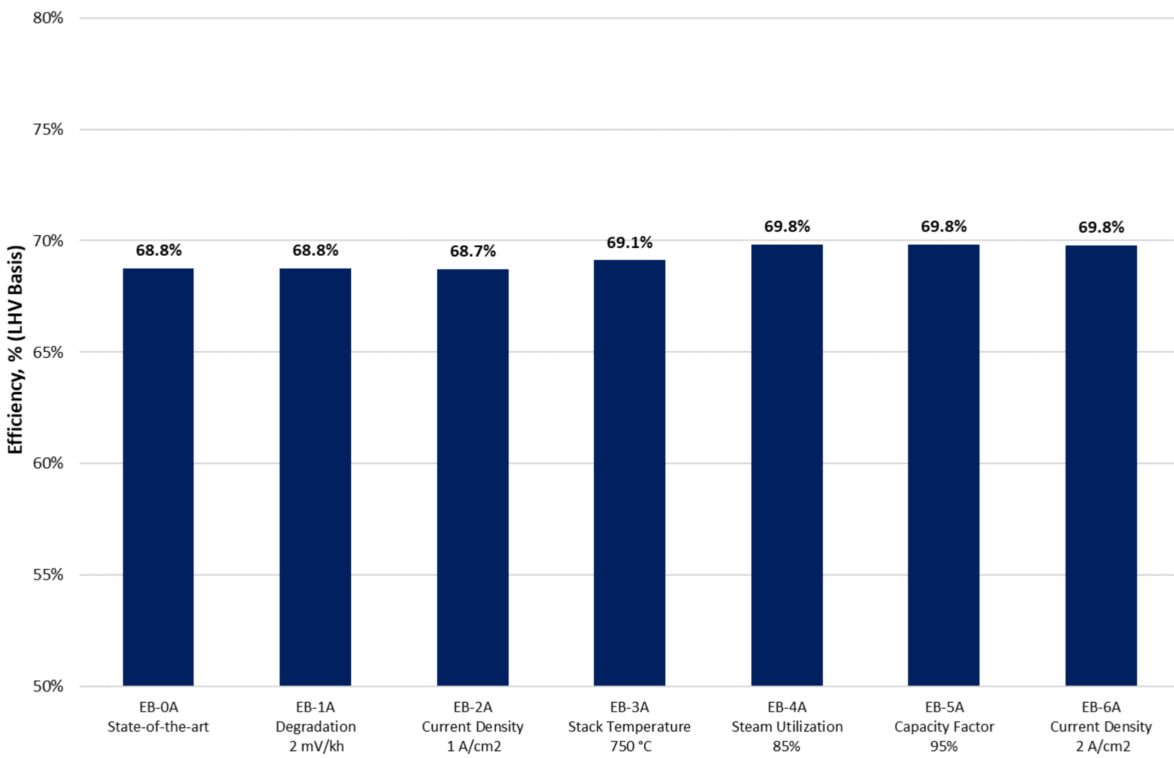
Exhibit 3-27. Electric load and hydrogen production for all atmospheric cases



The amount of H_2 produced is similar in all cases and averages around 693,000 kg per day. The slight variation in production (less than 1 percent) is due to small differences in the operating voltages of each case, producing different amounts of H_2 for a fixed power input.

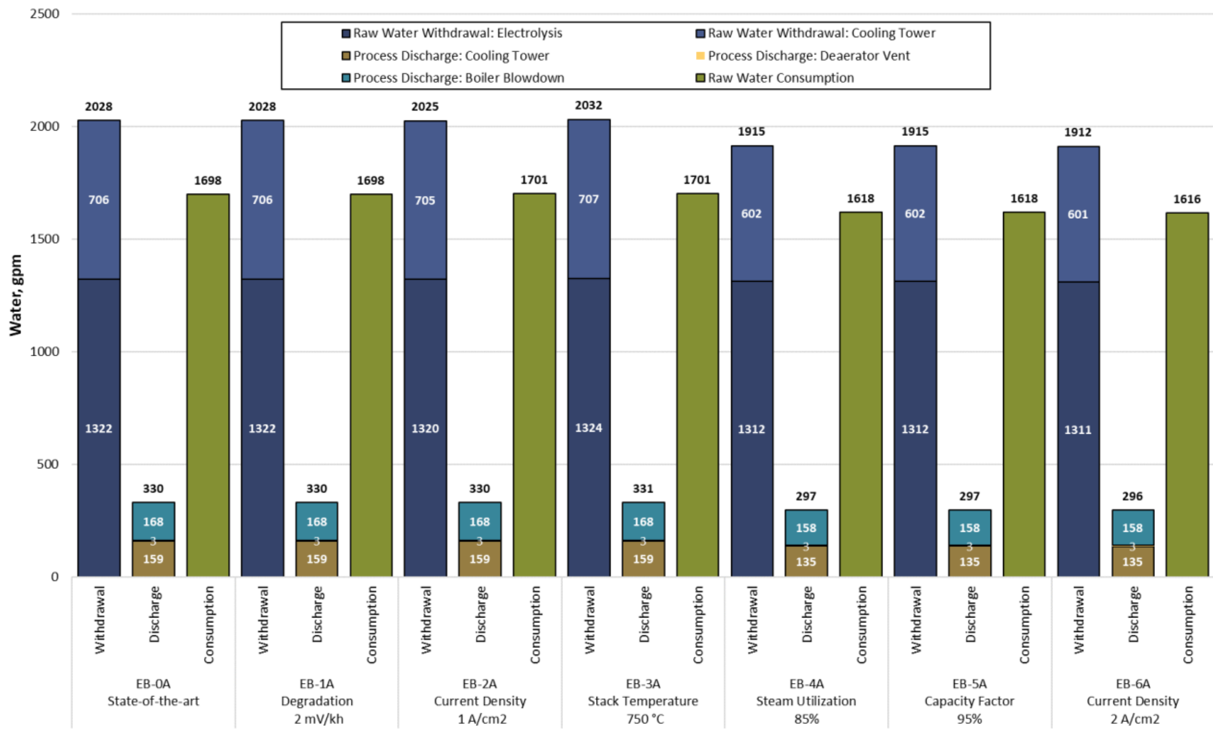
The progression in net plant efficiency (LHV basis) along the atmospheric pathway is shown in Exhibit 3-28. At the start of the pathway, Case 0A has an LHV efficiency of 68.8 percent. By the end of the pathway, the cumulative effects of all technology improvements increase the efficiency by 1 percentage point to 69.8 percent. The only cases that see efficiency increases along the pathway are Cases 3A and 4A. The decrease in SOEC operating temperature from 850°C (1562°F) to 750°C (1382°F) in Case 3A reduces the auxiliary load of the electric steam superheaters resulting in a 0.4 percentage point increase in efficiency. The increased steam utilization in Case 4A results in reduced auxiliary load from the electric boiler and an efficiency increase of 0.7 percentage points.

Exhibit 3-28. Net plant efficiency (LHV basis) for all atmospheric cases



Finally, water use for the atmospheric cases is shown in Exhibit 3-29. Case 0A has a raw water withdrawal of 2,028 gpm. About 65 percent of the water demand is for electrolysis steam and the remaining 35 percent is used for evaporative cooling. The process water discharge is 330 gpm resulting in a net water consumption of 1,698 gpm. Case 4A is the only pathway step with a significant reduction in water use. Water consumption decreases by 5 percent to 1,618 gpm: driven by a reduction in the cooling tower duty. There are no further significant changes in water use between Case 4A and the end of the pathway.

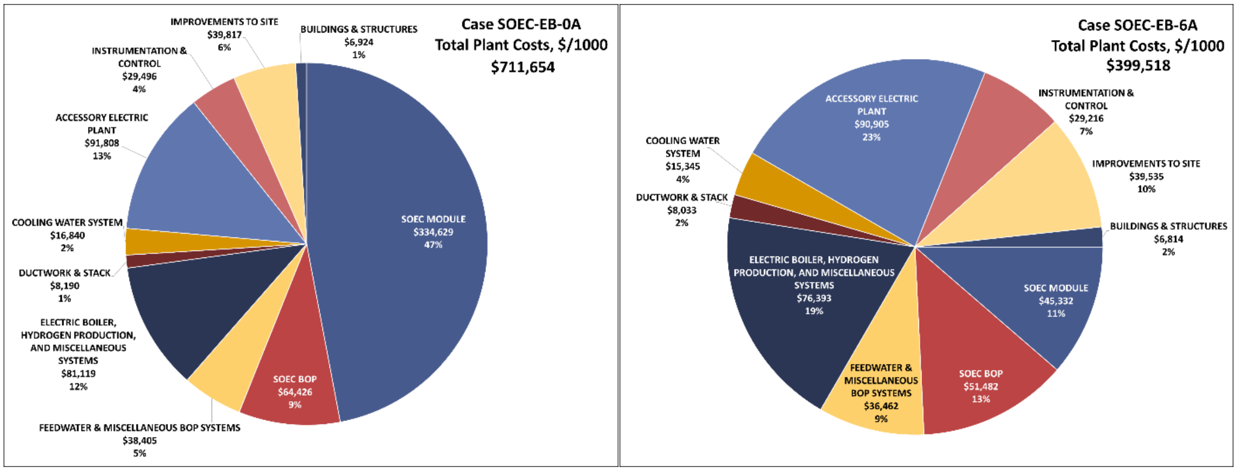
Exhibit 3-29. Water use for all atmospheric cases



3.4.2 Cost Results Summary

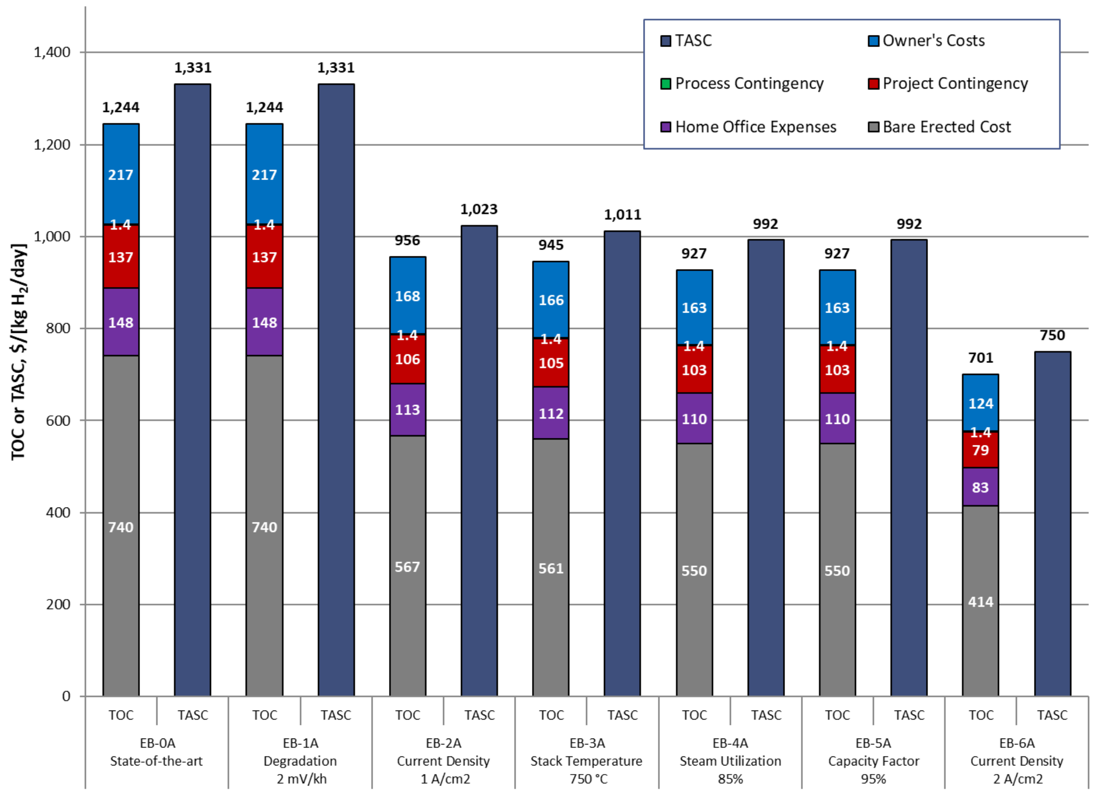
A TPC breakdown for Cases 0A and 6A is shown in Exhibit 3-30. At the start of the atmospheric pathway the TPC is $712 million (MM). By the final step in the pathway, the TPC has decreased 56 percent to $400 MM. Over 90 percent of the reduction in TPC can be attributed to the SOEC module account, which decreases from $335 MM to $45 MM. The effective SOEC stack cost decreases dramatically over the pathway due to a quadrupling of the current density (i.e., fewer stacks are required to produce the same amount of H_2) and a decrease in the nominal stack cost. The 1) SOEC BOP; 2) electric boiler, hydrogen production, and miscellaneous systems; and 3) feedwater and miscellaneous systems accounts also contribute to the decrease in TPC.

Exhibit 3-30. Total plant cost breakdown for Cases 0A and 6A



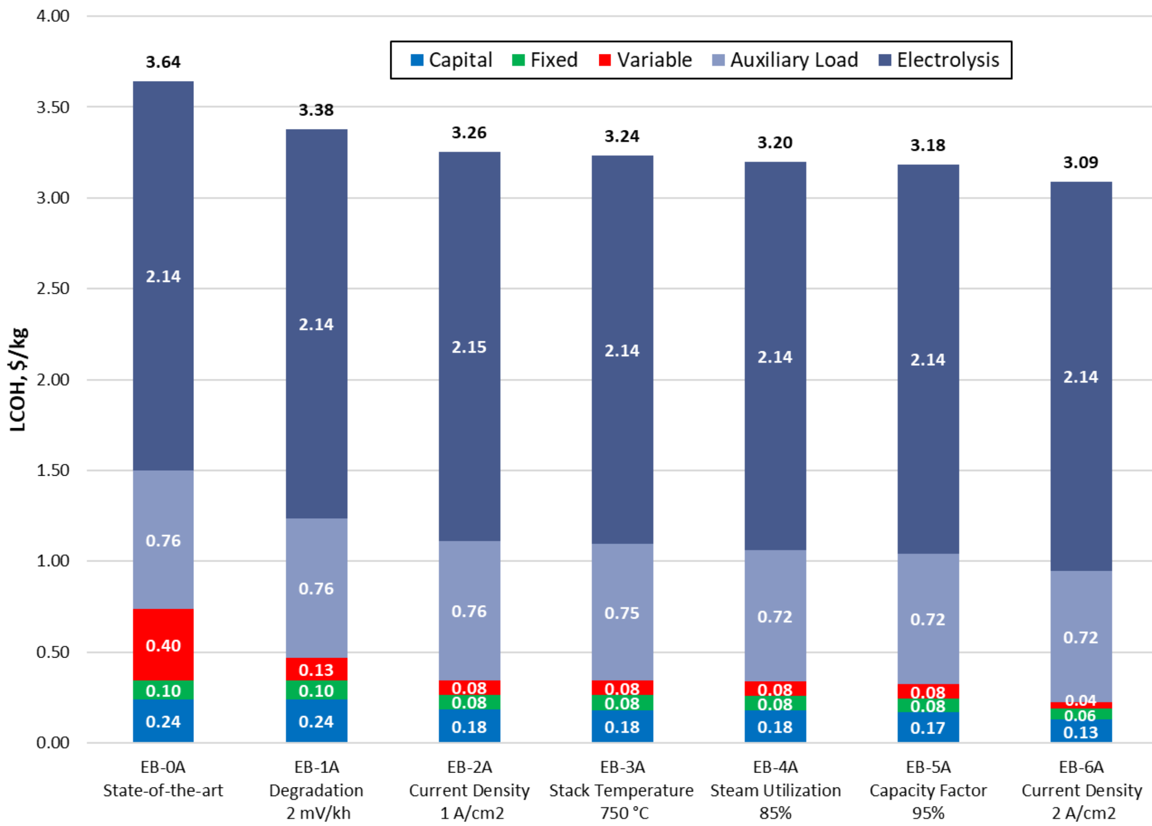
The components of TOC and the overall TASC of the atmospheric cases are shown in Exhibit 3-31. The atmospheric pathway starts with a TOC of $616/kW and TASC of $659/kW. The largest component of the TOC is the bare erected cost, which accounts for 60 percent of the TOC in Case 0A. The next largest contributor is the owner’s costs, accounting for 18 percent. The process contingency is negligible in all atmospheric cases. By the end of the pathway, both the TOC and TASC have decreased by 43 percent to $352/kW and $377/kW, respectively. The only significant reductions in capital costs are seen in Cases 2A (23 percent reduction) and 6A (24 percent reduction).

Exhibit 3-31. Plant capital cost for all atmospheric cases



The LCOH considering an electricity price of \$60/MWh is shown in Exhibit 3-32 for the atmospheric pathway. The state-of-the-art SOEC has an LCOH of \$3.64/kg H_2. By the end of the pathway, the LCOH decreases by 15 percent to \$3.09/kg H_2. The LCOH of every case is dominated by the electricity component. Electricity makes up 80 and 93 percent of the total LCOH in Cases 0A and 6A, respectively. About 75 percent of the electricity is used for electrolysis and 25 percent for the auxiliary load. The electricity component of the LCOH only decreases by \$0.04/kg H_2 over the course of the pathway. The efficiency improvements observed along the pathway do not translate into large reductions in LCOH. The LCOH from SOEC systems is largely dependent on the price of electricity, which researchers have little control over.

Exhibit 3-32. LCOH with $60/MWh electricity for all atmospheric cases



To better understand the influence R&D can have on the economics of SOEC systems, the LCOH without the electricity component is shown in Exhibit 3-33. The change in LCOH without electricity along the atmospheric pathway is shown in Exhibit 3-34. The LCOH without electricity decreases by $0.51/kg H_2, or 70 percent, from Case 0A ($0.74/kg H_2) to Case 6A ($0.22/kg H_2). The most significant reductions occur to the variable cost component, which decreases by 90 percent. A major factor in the variable cost reduction is increased stack lifetimes due to the decreased degradation rate in Case 1A. Case 1A (reduction in degradation rate from 8 to 2 mV/kh) displays the largest reduction in LCOH (-$0.27/kg H_2), contributing about 50 percent of the total pathway reduction. Cases with increases in current density also show significant reductions in the LCOH. Case 2A and 6A contribute LCOH reductions of $0.12/kg H_2 and $0.10/kg H_2, respectively. Cases 3A, 4A, and 5A do not contribute significant reductions to the LCOH without electricity.

Exhibit 3-33. LCOH without electricity for all atmospheric cases

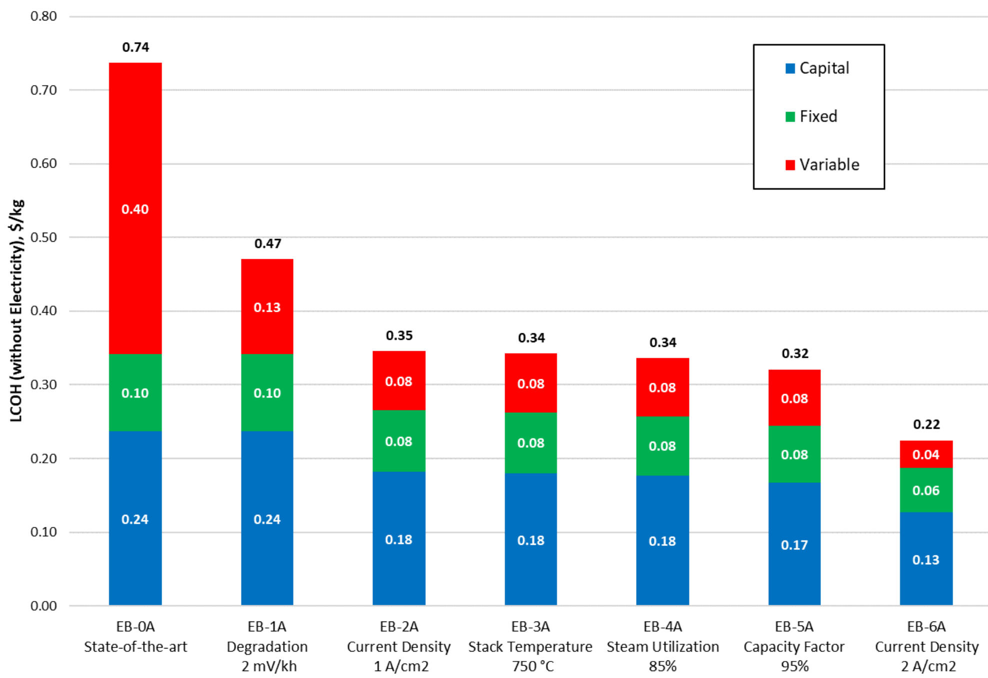
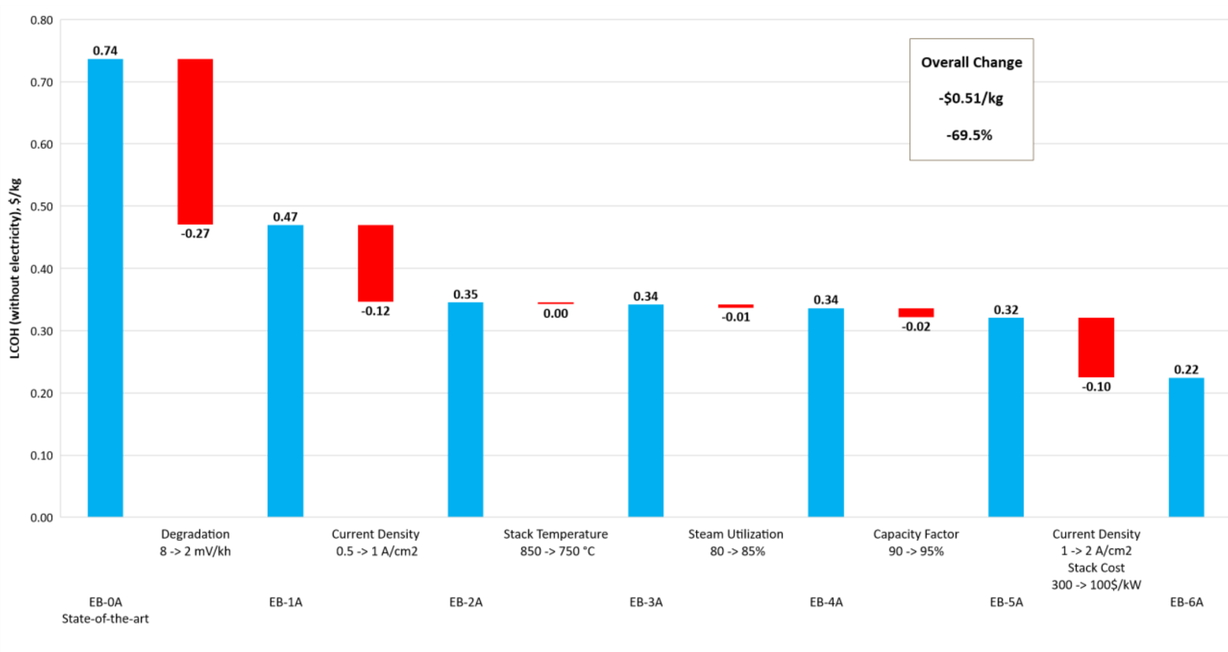


Exhibit 3-34. Change in LCOH without electricity over the atmospheric pathway



4 PRESSURIZED PATHWAY

This section discusses the performance and cost results of the SOEC plants along the pressurized pathway. The pathway consists of seven cases. Starting from state-of-the-art SOEC performance, improvements to the degradation rate, current density, operating temperature, steam utilization, CF, and stack cost are applied sequentially to identify which parameters have the greatest impact on the LCOH. All cases are sized to an electrolysis load of 1 GW_{DC}. For brevity, only the full set of results for the first and last cases along the pathway are presented here. The remainder of the results are available in the Appendix: Additional Case Information. Key results for the intermediate cases are included in a discussion of the entire pathway—found in Section 4.4.

4.1 PRESSURIZED SOEC PROCESS DESCRIPTION

The configuration of the pressurized SOEC system remains constant in all cases along the pressurized pathway and is based on the atmospheric system configuration described in Section 3.1. In the pressurized pathway, the SOEC stacks are operated at 8 bar to take advantage of the fact that pressurizing a liquid (boiler feedwater) is more efficient than pressurizing a gas (H_2 product). Pressurized operation requires the following BOP changes from the atmospheric system:

- SOEC stacks must be contained within pressure vessels and BOP components such as heat exchangers, electric heaters, and boilers must be designed to accommodate the increased operating pressures.
- To maintain constant pressure across the cells the sweep air must also be pressurized to 8 bar. This requires additional capital expenses in the form of an air compressor over the air blower required in the atmospheric cases. A turbine is included at the end of the sweep stream to recover some of the energy required for compression.
- A jet pump is required for the H_2 recycle due to the design challenges of housing a blower within the hot SOEC pressure vessel. The electric boiler produces saturated steam at 170 psia (1.14 MPa) to provide a high-pressure motive for the jet pump that is 50 psia higher than the pressure of the entrained recycle stream.

4.2 CASE 0P – STATE-OF-THE-ART

Case 0P considers a 1 GW_{DC} pressurized SOEC system with state-of-the-art performance. The process description is described in Section 634.1. The case specific operating conditions are as follows:

- Current density is 0.5 A/cm^2
- SOEC stack temperature is 850°C (1562°F)
- Overall steam utilization is 80 percent

The plant configuration for Case 0P is illustrated in the block flow diagram in Exhibit 4-1. The associated stream tables containing process data are provided in Exhibit 4-2.

Overall plant performance is summarized in Exhibit 4-3. This case produces H_2 at an energy efficiency of 70.8 percent (LHV basis). Exhibit 4-4 provides a detailed breakdown of the auxiliary power requirements. The electrolysis load accounts for about 73 percent of the total auxiliary load. The electric boiler is the second largest contributor to the auxiliary load at about 17 percent.

Exhibit 4-1. Case 0P block flow diagram

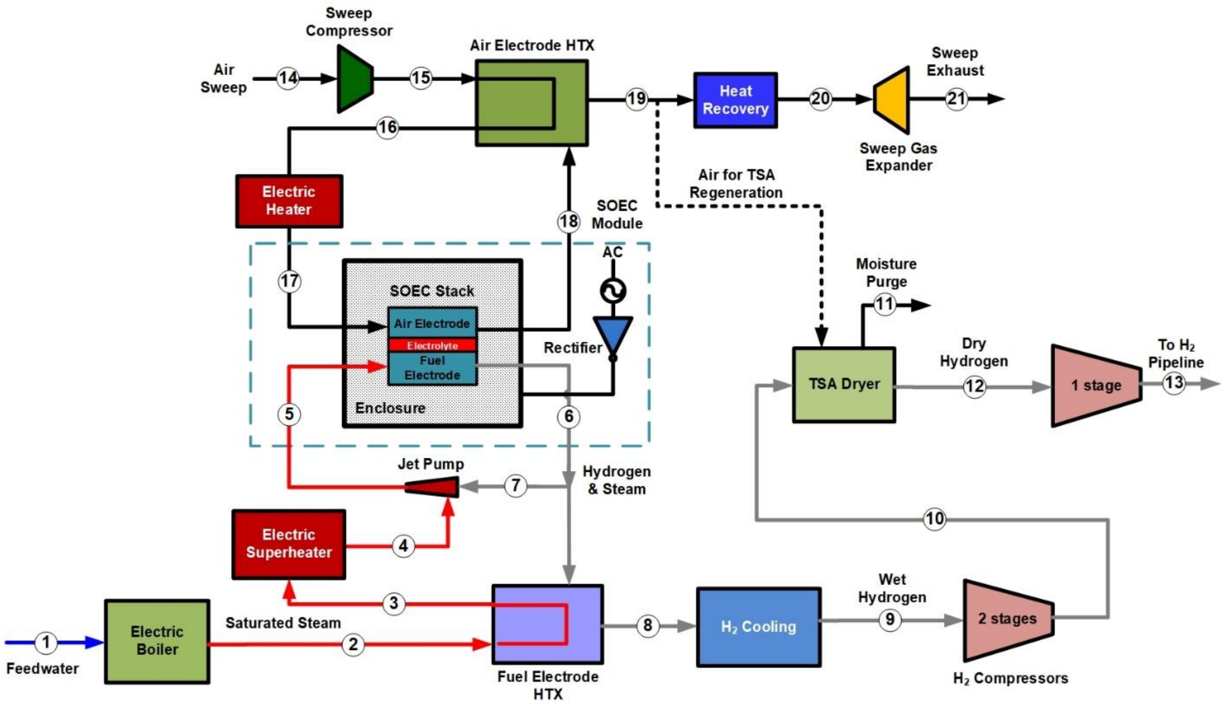


Exhibit 4-2. Case 0P stream table

	1	2	3	4	5	6	7	8	9	10
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.4000	0.8000	0.8000	0.8000	0.9954	0.9986
H_2O	1.0000	1.0000	1.0000	1.0000	0.6000	0.2000	0.2000	0.2000	0.0046	0.0014
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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,510	17,961	17,961	17,961	35,922	35,922	17,961	17,961	14,435	14,389
V-L Flowrate (kg/h)	297,424	323,575	323,575	323,575	417,253	187,359	93,678	93,679	30,152	29,328
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	187	730	845	851	861	861	193	30	30
Pressure (MPa, abs)	0.10	1.17	1.16	1.14	0.80	0.80	0.80	0.80	0.78	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,820.32	3,990.49	4,260.52	4,848.98	6,881.55	6,881.56	2,839.71	512.84	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,151.02	-11,980.85	-11,710.82	-10,038.35	-4,261.44	-4,261.43	-8,303.28	-457.12	-87.51
Density (kg/m^3)	1,003.6	5.9	2.5	2.2	1.0	0.4	0.4	1.1	0.6	2.1
V-L Molecular Weight	18.015	18.015	18.015	18.015	11.616	5.216	5.216	5.216	2.089	2.038
V-L Flowrate (lb_{mol}/h)	36,397	39,598	39,598	39,598	79,194	79,194	39,596	39,597	31,823	31,722
V-L Flowrate (lb/h)	655,707	713,360	713,360	713,360	919,885	413,056	206,525	206,528	66,473	64,657
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	369	1,346	1,553	1,564	1,581	1,581	380	86	86
Pressure (psia)	14.7	170.0	168.0	166.0	116.0	115.8	115.8	115.6	113.6	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,212.5	1,715.6	1,831.7	2,084.7	2,958.5	2,958.5	1,220.9	220.5	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,653.9	-5,150.8	-5,034.7	-4,315.7	-1,832.1	-1,832.1	-3,569.8	-196.5	-37.6
Density (lb/ft^3)	62.650	0.366	0.157	0.139	0.062	0.028	0.028	0.067	0.040	0.132

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

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

Exhibit 4-2. Case 0P stream table (cont'd)

	11	12	13	14	15	16	17	18	19	20	21
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077	0.0077
CH_4	0.0000	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	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	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	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	164	14,225	14,225	32,817	32,819	32,819	32,819	40,006	40,006	40,006	40,006
V-L Flowrate (kg/h)	649	28,679	28,679	946,917	946,973	946,973	946,973	1,176,933	1,176,933	1,176,933	1,176,933
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	160	830	850	861	328	271	80
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.81	0.80	0.80	0.80	0.80	0.79	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	177.60	913.61	936.99	936.77	344.57	285.23	92.61
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	44.88	780.89	804.27	825.50	233.30	173.96	-18.66
Density (kg/m^3)	4.7	2.1	5.0	1.2	6.5	2.5	2.5	2.5	4.7	5.2	1.0
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	361	31,361	31,361	72,350	72,354	72,354	72,354	88,198	88,198	88,198	88,198
V-L Flowrate (lb/h)	1,432	63,225	63,225	2,087,595	2,087,717	2,087,717	2,087,717	2,594,694	2,594,694	2,594,694	2,594,694
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	320	1,526	1,562	1,583	622	519	177
Pressure (psia)	385.0	383.3	939.7	14.7	117.3	116.5	116.0	115.8	115.6	115.1	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	76.4	392.8	402.8	402.7	148.1	122.6	39.8
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	19.3	335.7	345.8	354.9	100.3	74.8	-8.0
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.404	0.157	0.154	0.155	0.292	0.322	0.063

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

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

Exhibit 4-3. Case 0P plant performance summary

Performance Summary	
Total Gross Power, kWe	**62**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	239,238
Hydrogen Compression, kWe	30,022
Balance of Plant, kWe	111,199
Total Auxiliaries, MWe	**380**
Net Power, MWe	**-1,349**
Hydrogen Production, kg/h (lb/h)	**28,679 (63,225)**
Energy Efficiency,[A] % HHV (% LHV)	83.8 (70.8)
Electric Input per Kilogram, kWh/kg	47.1
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,130,411 (955,844)
Raw Water Withdrawal, m^3/min (gpm)	7.2 (1,907)
Raw Water Consumption, m^3/min (gpm)	6.1 (1,604)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit 4-4. Case 0P power summary

Power Summary	
Sweep Gas Expander, MWe	62
Total Gross Power, MWe	**62**
Auxiliary Load Summary	
Air Electrode Compressors, kWe	69,765
Circulating Water Pumps, kWe	590
Cooling Tower Fans, kWe	300
Electric Boiler, kWe	239,238
Electric Steam Superheater, kWe	24,271
Electric Sweep Heater, kWe	6,151
Feedwater Pumps, kWe	173
Fuel Electrode Recycle Blowers, kWe	0
Ground Water Pumps, kWe	170
Hydrogen Compressor, kWe	30,022
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,490
Total Auxiliaries, MWe	**380**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,349**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

4.2.1 Environmental Performance

Case 0P reports no air emissions of SO_2, NOx, PM, Hg, CO. Electrolysis steam requirements are fully satisfied by the electric boiler without the need for fuel consumption. In this study, only emissions within the plant boundary are considered, any emissions associated with the production of purchased electricity are ignored.

The carbon balance for the plant is shown in Exhibit 4-5. The carbon input to the plant consists of carbon in the air used to sweep the air-electrode. With all the carbon that enters leaving in the air-electrode exhaust, the plant has no net-carbon emissions.

Exhibit 4-5. Case 0P carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	118 (261)	Air-Electrode Sweep Exhaust (CO_2)	118 (261)
Total	**118 (261)**	**Total**	**118 (261)**

Exhibit 4-6 shows the overall water balance for Case 0P.

Exhibit 4-6. Case 0P 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)
Electrolysis Steam	5.0 (1,311)	–	5.0 (1,311)	–	5.0 (1,311)
Deaerator Vent	–	–	–	0.0 (3.3)	0.0 (-3.3)
Boiler Blowdown	–	–	–	0.6 (165)	-0.6 (-165)
Cooling Tower	2.3 (595)	–	2.3 (595)	0.5 (134)	1.7 (461)
Total	**7.2 (1,907)**	**–**	**7.2 (1,907)**	**1.1 (302)**	**6.1 (1,604)**

4.2.2 Energy Balance

An overall plant energy balance for Case 0P is provided in Exhibit 4-7.

Exhibit 4-7. Case 0P overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	29 (28)	–	29 (28)
Raw Water Makeup	–	27 (26)	–	27 (26)
Auxiliary Power	–	–	4,858 (4,604)	4,858 (4,604)
Total	**0.0 (0.0)**	**57 (54)**	**4,858 (4,604)**	**4,914 (4,658)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,069 (3,857)	13 (12)	–	4,082 (3,869)
Sweep Exhaust	–	109 (103)	–	109 (103)
Motor Losses and Design Allowances	–	13 (13)	–	13 (13)
Cooling Tower Load[A]	–	294 (279)	–	294 (279)
Boiler Blowdown	–	13 (12)	–	13 (12)
Process Vents[B]	–	0.6 (0.5)	–	0.6 (0.5)
Ambient Losses[C]	–	318 (301)	–	318 (301)
Total	**4,069 (3,857)**	**761 (722)**	**0.0 (0.0)**	**4,830 (4,579)**
Unaccounted Energy[D]	–	–	–	84 (79)

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

4.2.3 Energy and Mass Balance Diagrams

Exhibit 4-8 shows the energy and mass balance for Case 0P.

4.2.4 Cost Estimates

Exhibit 4-9 shows a detailed breakdown of the capital costs; Exhibit 4-10 shows the owner's costs, TOC, and TASC; Exhibit 4-11 shows the initial and annual O&M costs; and Exhibit 4-12 shows the LCOH breakdown.

The estimated TPC of the state-of-the-art pressurized SOEC is $1,080/[kg H_2/day] or $551/kW. Process contingency represents 0.2 percent of the TPC, and project contingency represents 15 percent. The LCOH is $3.58/kg H_2.

Exhibit 4-8. Case 0P energy and mass balance

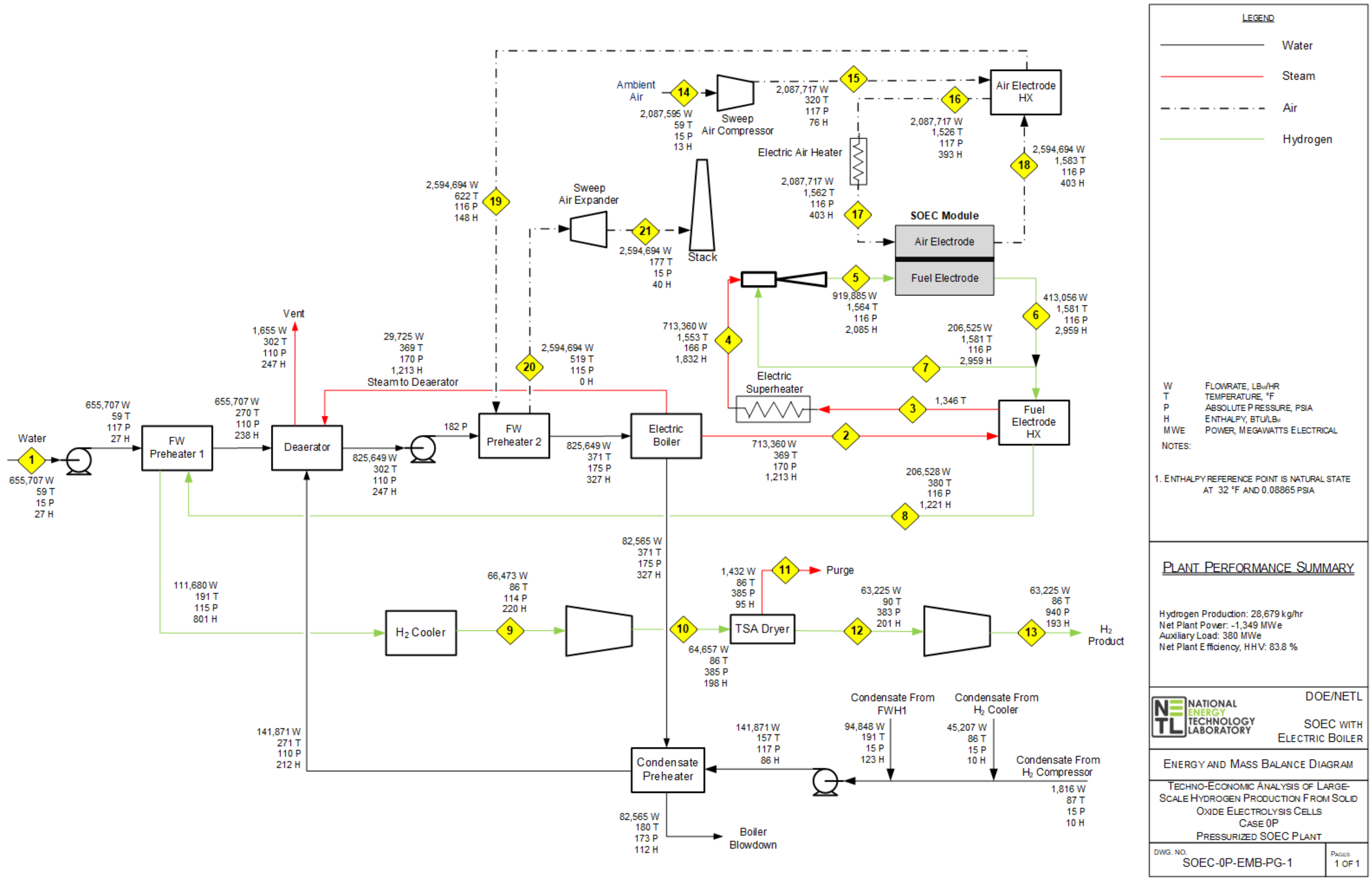


Exhibit 4-9. Case 0P total plant cost details

Case:		SOEC-EB-0P	State-of-the-Art Pressurized SOEC					Estimate Type:		Conceptual		
Plant Size (kg H_2/day):		688,284	Plant Size (MW net):			1,349		Cost Base:		Dec 2018		
Item No.	Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies Process	Contingencies Project	Total Plant Cost $/1,000	$/[kg H_2/day]	$/kW (net)
1		SOEC Module										
1.1	SOEC Stack	$0	$0	$0	$0	$172,792	$34,558	$0	$31,103	$238,453	$346	$177
1.2	Container	$0	$0	$0	$0	$24,597	$4,919	$0	$4,427	$33,943	$49	$25
1.3	Insulation	$0	$0	$0	$0	$2,304	$461	$0	$415	$3,179	$5	$2
1.4	Module Assembly	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.5	Air Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.6	Fuel Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.8	Module Current Collectors	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.9	Module I&C	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.10	Rectifier	$0	$0	$0	$0	$39,166	$7,833	$0	$7,050	$54,049	$79	$40
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$261,898**	**$52,380**	**$0**	**$47,142**	**$361,419**	**$525**	**$268**
2		SOEC Balance of Plant										
2.1	Air-Electrode Sweep Compressor	$0	$0	$0	$0	$7,735	$1,547	$0	$1,392	$10,674	$16	$8
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$20,605	$4,121	$0	$3,709	$28,435	$41	$21
2.3	Hydrogen Recycle Jet Pump	$0	$0	$0	$0	$809	$162	$0	$146	$1,117	$2	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$22,498	$4,500	$0	$4,050	$31,047	$45	$23
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,951	$390	$0	$351	$2,693	$4	$2
2.6	Section and Overall Assembly	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
2.7	Section I&C	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
2.8	Sweep Gas Expander	$0	$0	$0	$0	$6,577	$1,315	$0	$1,184	$9,076	$13	$7
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$62,127**	**$12,425**	**$0**	**$11,183**	**$85,735**	**$125**	**$64**
3		Feedwater & Miscellaneous BOP Systems										
3.1	Feedwater System	$0	$0	$0	$0	$4,272	$854	$0	$769	$5,895	$9	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,592	$918	$0	$1,102	$6,613	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,857	$371	$0	$334	$2,563	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,455	$1,891	$0	$2,269	$13,615	$20	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$1,032	$206	$0	$186	$1,424	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,677	$935	$0	$1,123	$6,735	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$25,885**	**$5,177**	**$0**	**$5,783**	**$36,845**	**$54**	**$27**
4		Electric Boiler, Hydrogen Production, and Miscellaneous Systems										
4.1	Feedwater Heaters	$0	$0	$0	$0	$391	$78	$0	$70	$540	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$32,745	$6,549	$0	$5,894	$45,188	$66	$33
4.3	Electric Superheaters	$0	$0	$0	$0	$2,709	$542	$0	$488	$3,738	$5	$3
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$984	$197	$0	$177	$1,358	$2	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$264	$53	$0	$48	$365	$1	$0

	Case:	SOEC-EB-0P	State-of-the-Art Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	688,284	Plant Size (MW net):			1,349		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 H_2/day]	$/kW (net)
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$257	$51	$0	$46	$354	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$15,227	$3,045	$0	$2,741	$21,013	$31	$16
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$52,577**	**$10,515**	**$0**	**$9,464**	**$72,557**	**$105**	**$54**
	7	**Ductwork, & Stack**										
7.3	Ductwork	$0	$0	$0	$0	$588	$118	$0	$106	$811	$1	$1
7.4	Stack	$0	$0	$0	$0	$3,931	$786	$0	$707	$5,424	$8	$4
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$501	$100	$0	$120	$722	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,019**	**$1,004**	**$0**	**$934**	**$6,957**	**$10**	**$5**
	9	**Cooling Water System**										
9.1	Cooling Towers	$0	$0	$0	$0	$3,330	$666	$0	$599	$4,595	$7	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$365	$73	$0	$66	$503	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,264	$853	$0	$768	$5,885	$9	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,705	$341	$0	$307	$2,353	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$582	$116	$0	$105	$803	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$233	$47	$0	$42	$322	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$551	$110	$0	$132	$793	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$11,029**	**$2,206**	**$0**	**$2,018**	**$15,253**	**$22**	**$11**
	11	**Accessory Electric Plant**										
11.2	Station Service Equipment	$0	$0	$0	$0	$11,509	$2,302	$0	$2,072	$15,883	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$17,760	$3,552	$0	$3,197	$24,509	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,197	$2,839	$0	$2,555	$19,592	$28	$15
11.5	Wire & Cable	$0	$0	$0	$0	$15,220	$3,044	$0	$2,740	$21,003	$31	$16
11.6	Protective Equipment	$0	$0	$0	$0	$1,150	$230	$0	$207	$1,588	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,652	$530	$0	$477	$3,660	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,065	$413	$0	$372	$2,850	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$434	$87	$0	$104	$625	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$64,989**	**$12,998**	**$0**	**$11,724**	**$89,711**	**$130**	**$66**
	12	**Instrumentation & Control**										
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,448	$290	$72	$261	$2,071	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$716	$143	$0	$129	$989	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$314	$63	$16	$57	$449	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,173	$2,235	$559	$2,011	$15,977	$23	$12
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,475	$895	$224	$806	$6,400	$9	$5

	Case:	SOEC-EB-0P	State-of-the-Art Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	688,284	Plant Size (MW net):			1,349		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 H_2/day]	$/kW (net)
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,056	$411	$103	$370	$2,940	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,182**	**$4,036**	**$973**	**$3,633**	**$28,825**	**$42**	**$21**
	13					**Improvements to Site**						
13.1	Site Preparation	$0	$0	$0	$0	$16,783	$3,357	$0	$4,028	$24,168	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,637	$1,127	$0	$1,353	$8,117	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,775	$955	$0	$1,146	$6,876	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,195**	**$5,439**	**$0**	**$6,527**	**$39,161**	**$57**	**$29**
	14					**Buildings & Structures**						
14.4	Administration Building	$0	$0	$0	$0	$761	$152	$0	$137	$1,051	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$23	$5	$0	$4	$31	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$449	$90	$0	$81	$620	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,121	$224	$0	$202	$1,547	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$842	$168	$0	$152	$1,162	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$628	$126	$0	$113	$866	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,097	$219	$0	$198	$1,514	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,921**	**$984**	**$0**	**$886**	**$6,791**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$535,824**	**$107,165**	**$973**	**$99,293**	**$743,254**	**$1,080**	**$551**

Exhibit 4-10. Case 0P owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$4,901	$7	$4
1 Month Maintenance Materials	$831	$1	$1
1 Month Non-Fuel Consumables	$188	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$14,865	$22	$11
Total	**$20,784**	**$30**	**$15**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$217	$0	$0
0.5% of TPC (spare parts)	$3,716	$5	$3
Total	**$3,933**	**$6**	**$3**
Other Costs			
Initial Cost for Catalyst and Chemicals	$479	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$111,488	$162	$83
Financing Costs	$20,068	$29	$15
Total Overnight Costs (TOC)	**$900,306**	**$1,308**	**$667**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$963,150**	**$1,399**	**$714**

Exhibit 4-11. Case 0P initial and annual O&M costs

Case:	**SOEC-EB-0P**		**State-of-the-Art Pressurized SOEC**		**Cost Base:**	**Dec 2018**	
Plant Size (kg H_2/day):	**688,284**	**Plant Size (MW net):**		**1,349**	**Capacity Factor (%):**	**90%**	
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.185	$1.625
Maintenance Labor:					$5,648,732	$8.207	$4.186
Administrative & Support Labor:					$1,960,230	$2.848	$1.453
Property Taxes and Insurance:					$14,865,083	$21.597	$11.016
Total:					**$24,666,235**	**$35.837**	**$18.280**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh-net)**
Maintenance Material:					$8,971,515	$0.03968	$0.84332
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		2.33	157.25	$67.76	$79,177,245	$0.35018	$7.44264
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,373	$1.90	$0	$856,802	$0.00379	$0.08054
Makeup and Wastewater Treatment Chemicals (ton):	0	4.09	$550	$0	$738,822	$0.00327	$0.06945
Hydrogen Drying Sorbent (lb):	47,922	131.3	$10	$479,220	$431,298	$0.00191	$0.04054
Subtotal:				**$479,220**	**$2,026,923**	**$0.00896**	**$0.19053**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	131.3	$0.02	$0	$819	$0.00000	$0.00008
Subtotal:				**$0**	**$819**	**$0.00000**	**$0.00008**
Variable Operating Costs Total:				**$479,220**	**$90,176,502**	**$0.04865**	**$1.03393**
Electricity Cost							
Electricity (MWh):	0	32,385	$60.00	$0	$638,299,443	$2.82307	$60.00000
Total:				**$0**	**$638,299,443**	**$2.82307**	**$60.00000**

Exhibit 4-12. Case 0P LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.25	7%
Fixed	0.11	3%
Variable	0.40	11%
Electricity	2.82	79%
Total	**3.58**	**N/A**

4.3 Case 6P – Advanced Pressurized SOEC

Case 6P considers a 1 GW_{DC} pressurized SOEC system with advanced performance, representing the cumulative performance and cost improvements along the R&D pathway. The process configuration is unchanged from Case 0P and follows the description in Section 4.1. The case specific operating conditions are as follows:

- Current density is 2 A/cm^2
- SOEC stack temperature is 750°C (1382°F)
- Overall steam utilization is 85 percent

The block flow diagram is shown again in Exhibit 4-13 for use with the associated stream tables containing process data provided in Exhibit 4-14.

Overall plant performance is summarized in Exhibit 4-15. Case 6P produces H_2 at an energy efficiency of 72.0 percent (LHV basis). Exhibit 4-16 provides a detailed breakdown of the auxiliary power requirements. Similar to Case 0P, the electrolysis load accounts for about 74 percent of the total auxiliary load.

Exhibit 4-13. Case 6P block flow diagram

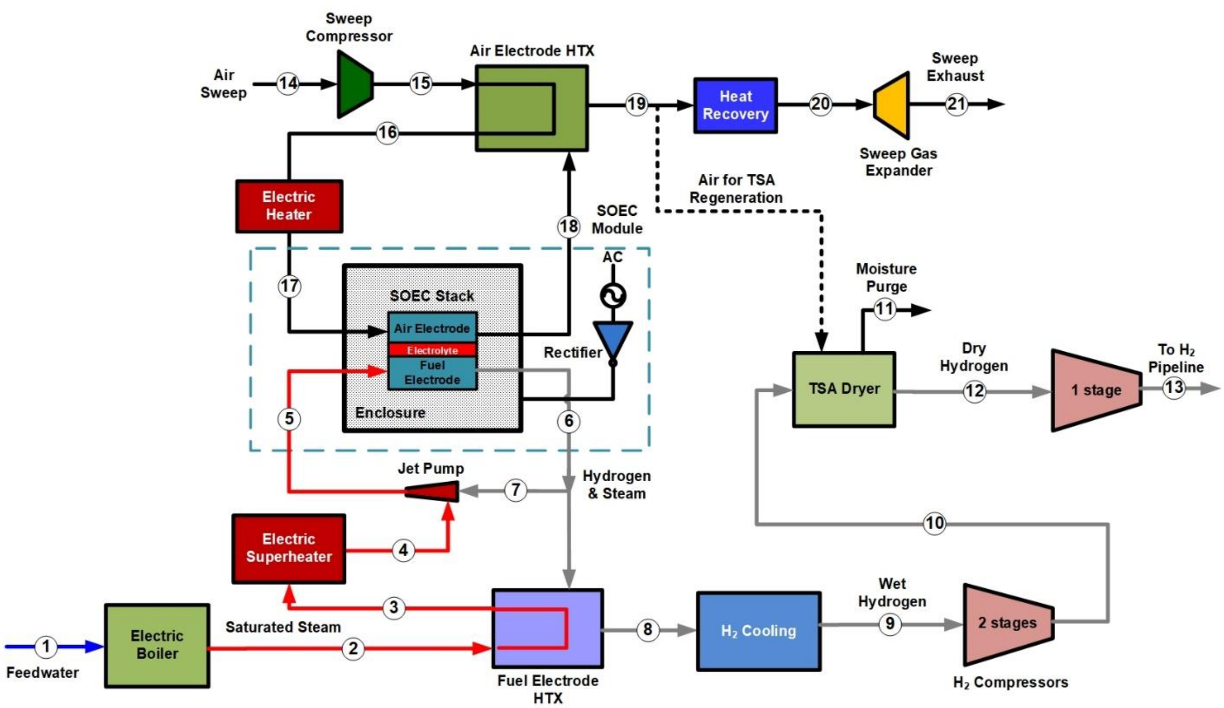


Exhibit 4-14. Case 6P stream table

	1	2	3	4	5	6	7	8	9	10
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.4250	0.8500	0.8500	0.8500	0.9954	0.9986
H_2O	1.0000	1.0000	1.0000	1.0000	0.5750	0.1500	0.1500	0.1500	0.0046	0.0014
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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,506	17,030	17,030	17,030	34,060	34,060	17,030	17,030	14,542	14,496
V-L Flowrate (kg/h)	297,366	306,800	306,800	306,800	382,001	150,402	75,201	75,201	30,376	29,546
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	187	638	749	750	754	754	193	30	30
Pressure (MPa, abs)	0.10	1.17	1.16	1.14	0.80	0.80	0.80	0.80	0.78	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,820.32	3,781.19	4,034.43	4,570.00	6,754.95	6,754.95	2,834.87	512.84	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,151.02	-12,190.16	-11,936.91	-10,208.48	-3,156.89	-3,156.89	-7,076.98	-457.12	-87.51
Density (kg/m^3)	1,003.6	5.9	2.8	2.4	1.1	0.4	0.4	0.9	0.6	2.1
V-L Molecular Weight	18.015	18.015	18.015	18.015	11.216	4.416	4.416	4.416	2.089	2.038
V-L Flowrate (lb_{mol}/h)	36,390	37,545	37,545	37,545	75,089	75,089	37,545	37,545	32,059	31,958
V-L Flowrate (lb/h)	655,580	676,378	676,378	676,378	842,168	331,579	165,789	165,789	66,967	65,137
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	369	1,181	1,380	1,382	1,388	1,388	380	86	86
Pressure (psia)	14.7	170.0	168.0	166.0	116.0	115.8	115.8	115.6	113.6	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,212.5	1,625.6	1,734.5	1,964.7	2,904.1	2,904.1	1,218.8	220.5	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,653.9	-5,240.8	-5,131.9	-4,388.9	-1,357.2	-1,357.2	-3,042.6	-196.5	-37.6
Density (lb/ft^3)	62.650	0.366	0.173	0.152	0.066	0.026	0.026	0.057	0.040	0.132

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

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

Exhibit 4-14. Case 6P stream table (cont'd)

	11	12	13	14	15	16	17	18	19	20	21
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077	0.0077
CH_4	0.0000	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	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	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	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,331	14,331	33,061	33,061	33,061	33,061	40,298	40,298	40,298	40,298
V-L Flowrate (kg/h)	654	28,892	28,892	953,941	953,941	953,941	953,941	1,185,520	1,185,520	1,185,520	1,185,520
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	160	730	750	754	298	246	64
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.81	0.80	0.80	0.80	0.80	0.79	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	177.60	797.73	820.76	812.65	313.65	259.58	75.98
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	44.88	665.01	688.04	701.38	202.38	148.32	-35.29
Density (kg/m^3)	4.7	2.1	5.0	1.2	6.5	2.8	2.7	2.7	4.9	5.4	1.1
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,594	31,594	72,886	72,886	72,886	72,886	88,841	88,841	88,841	88,841
V-L Flowrate (lb/h)	1,442	63,695	63,695	2,103,079	2,103,080	2,103,080	2,103,080	2,613,623	2,613,623	2,613,623	2,613,623
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	320	1,346	1,382	1,389	568	475	147
Pressure (psia)	385.0	383.3	939.7	14.7	117.3	116.5	116.0	115.8	115.6	115.1	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	76.4	343.0	352.9	349.4	134.8	111.6	32.7
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	19.3	285.9	295.8	301.5	87.0	63.8	-15.2
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.404	0.173	0.169	0.171	0.308	0.337	0.066

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

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

Exhibit 4-15. Case 6P plant performance summary

Performance Summary	
Total Gross Power, kWe	**60**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	226,744
Hydrogen Compression, kWe	30,245
Balance of Plant, kWe	108,760
Total Auxiliaries, MWe	**366**
Net Power, MWe	**-1,337**
Hydrogen Production, kg/h (lb/h)	**28,892 (63,695)**
Energy Efficiency,[A] % HHV (% LHV)	85.2 (72.0)
Electric Input per Kilogram, kWh/kg	46.3
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,138,813 (962,949)
Raw Water Withdrawal, m^3/min (gpm)	6.9 (1,814)
Raw Water Consumption, m^3/min (gpm)	5.8 (1,541)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit 4-16. Case 6P power summary

Power Summary	
Sweep Gas Expander, MWe	60
Total Gross Power, MWe	**60**
Auxiliary Load Summary	
Air Electrode Compressors, kWe	70,282
Circulating Water Pumps, kWe	500
Cooling Tower Fans, kWe	260
Electric Boiler, kWe	226,744
Electric Steam Superheater, kWe	21,582
Electric Sweep Heater, kWe	6,102
Feedwater Pumps, kWe	163
Fuel Electrode Recycle Blowers, kWe	0
Ground Water Pumps, kWe	160
Hydrogen Compressor, kWe	30,245
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,420
Total Auxiliaries, MWe	**366**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,337**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

4.3.1 Environmental Performance

Case 6P reports no air emissions of SO_2, NO_X, PM, Hg, CO. Electrolysis steam requirements are fully satisfied by the electric boiler without the need for fuel consumption. In this study, only emissions within the plant boundary are considered, any emissions associated with the production of purchased electricity are ignored.

The carbon balance for the plant is shown in Exhibit 4-17. The carbon input to the plant consists of carbon in the air used to sweep the air-electrode. With all the carbon that enters leaving in the air-electrode exhaust, the plant has no net-carbon emissions.

Exhibit 4-17. Case 6P carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (263)	Air-Electrode Sweep Exhaust (CO_2)	119 (263)
Total	**119 (263)**	**Total**	**119 (263)**

Exhibit 4-18 shows the overall water balance for Case 6P.

Exhibit 4-18. Case 6P 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)
Electrolysis Steam	5.0 (1,311)	–	5.0 (1,311)	–	5.0 (1,311)
Deaerator Vent	–	–	–	0.0 (3.1)	0.0 (-3.1)
Boiler Blowdown	–	–	–	0.6 (157)	-0.6 (-157)
Cooling Tower	1.9 (503)	–	1.9 (503)	0.4 (113)	1.5 (390)
Total	**6.9 (1,814)**	**–**	**6.9 (1,814)**	**1.0 (273)**	**5.8 (1,541)**

4.3.2 Energy Balance

An overall plant energy balance for Case 6P is provided in Exhibit 4-19.

Exhibit 4-19. Case 6P overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	26 (24)	–	26 (24)
Auxiliary Power	–	–	4,814 (4,562)	4,814 (4,562)
Total	**0.0 (0.0)**	**55 (53)**	**4,814 (4,562)**	**4,869 (4,615)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,100 (3,886)	13 (12)	–	4,113 (3,898)
Sweep Exhaust	–	90 (85)	–	90 (85)
Motor Losses and Design Allowances	–	13 (13)	–	13 (13)
Cooling Tower Load[A]	–	249 (236)	–	249 (236)
Boiler Blowdown	–	12 (12)	–	12 (12)
Process Vents[B]	–	0.5 (0.5)	–	0.5 (0.5)
Ambient Losses[C]	–	308 (292)	–	308 (292)
Total	**4,100 (3,886)**	**686 (651)**	**0.0 (0.0)**	**4,786 (4,537)**
Unaccounted Energy[D]	–	–	–	83 (78)

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

4.3.3 Energy and Mass Balance Diagrams

Exhibit 4-20 shows the energy and mass balance for Case 6P.

4.3.4 Cost Estimates

Exhibit 4-21 shows a detailed breakdown of the capital costs; Exhibit 4-22 shows the owner's costs, TOC, and TASC; Exhibit 4-23 shows the initial and annual O&M costs; and Exhibit 4-24 shows the LCOH breakdown.

The estimated TPC of the state-of-the-art pressurized SOEC is $605/[kg H_2/day] or $314/kW. Process contingency represents 0.3 percent of the TPC, and project contingency represents 16 percent. The LCOH is $3.01/kg H_2.

Exhibit 4-20. Case 6P energy and mass balance

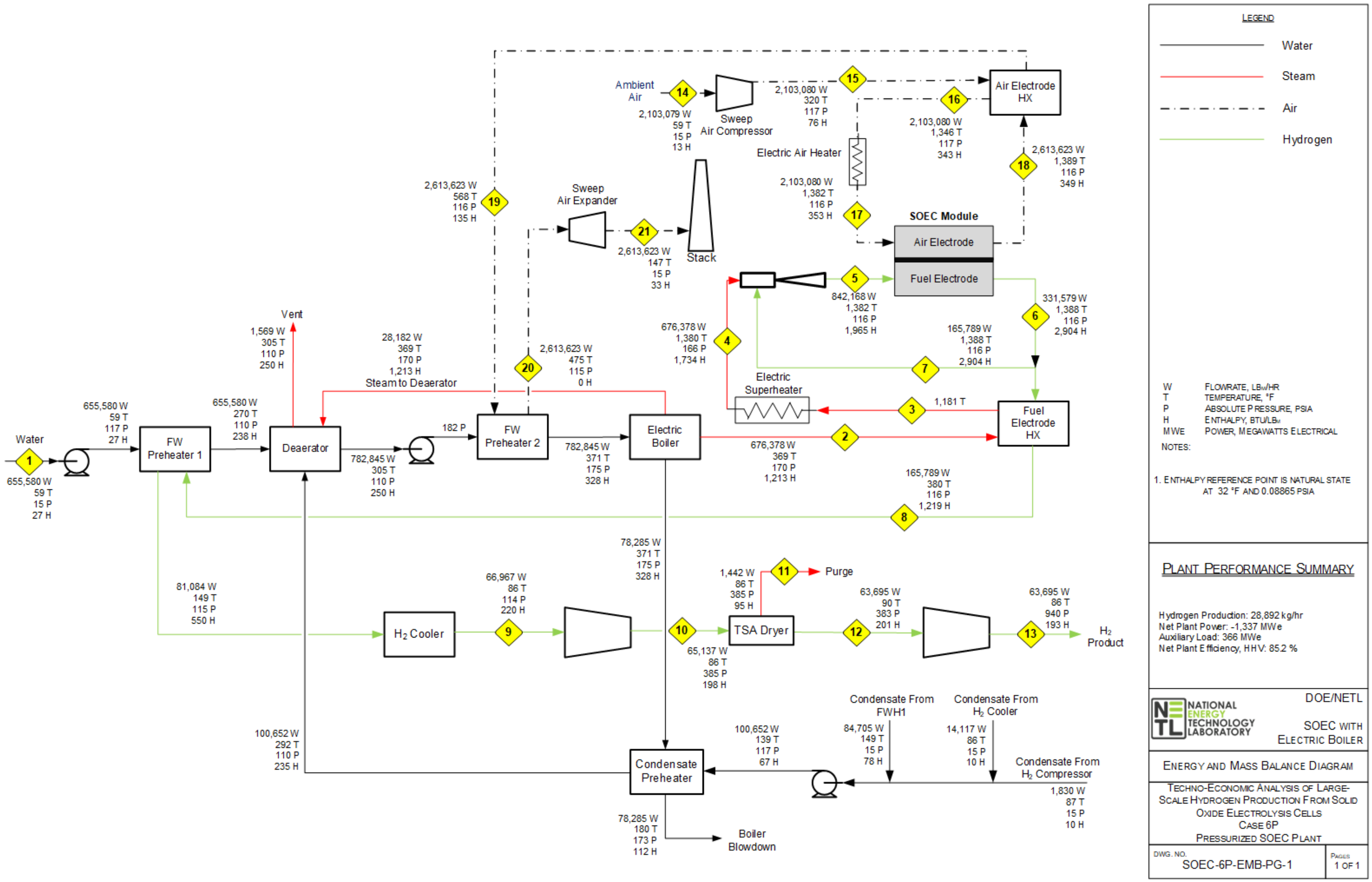


Exhibit 4-21. Case 6P total plant cost details

	Case:	SOEC-EB-6P	Advanced Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	693,400	Plant Size (MW net):			1,337			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 H_2/day]	$/kW (net)
1						SOEC Module						
1.1	SOEC Stack	$0	$0	$0	$0	$172,792	$34,558	$0	$31,103	$238,453	$346	$177
1.2	Container	$0	$0	$0	$0	$24,597	$4,919	$0	$4,427	$33,943	$49	$25
1.3	Insulation	$0	$0	$0	$0	$2,304	$461	$0	$415	$3,179	$5	$2
1.4	Module Assembly	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.5	Air Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.6	Fuel Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.8	Module Current Collectors	$0	$0	$0	$0	$743	$149	$0	$134	$1,026	$1	$1
1.9	Module I&C	$0	$0	$0	$0	$743	$149	$0	$134	$1,026	$1	$1
1.10	Rectifier	$0	$0	$0	$0	$10,107	$2,021	$0	$1,819	$13,948	$20	$10
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$37,859**	**$7,572**	**$0**	**$6,815**	**$52,245**	**$75**	**$39**
2						SOEC Balance of Plant						
2.1	Air-Electrode Sweep Compressor	$0	$0	$0	$0	$7,775	$1,555	$0	$1,399	$10,729	$15	$8
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$21,943	$4,389	$0	$3,950	$30,281	$44	$23
2.3	Hydrogen Recycle Jet Pump	$0	$0	$0	$0	$474	$95	$0	$85	$655	$1	$0
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$19,169	$3,834	$0	$3,450	$26,453	$38	$20
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$855	$171	$0	$154	$1,180	$2	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$428	$86	$0	$77	$590	$1	$0
2.7	Section I&C	$0	$0	$0	$0	$428	$86	$0	$77	$590	$1	$0
2.8	Sweep Gas Expander	$0	$0	$0	$0	$6,392	$1,278	$0	$1,151	$8,822	$13	$7
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$57,463**	**$11,493**	**$0**	**$10,343**	**$79,300**	**$114**	**$59**
3						Feedwater & Miscellaneous BOP Systems						
3.1	Feedwater System	$0	$0	$0	$0	$4,118	$824	$0	$741	$5,682	$8	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,429	$886	$0	$1,063	$6,377	$9	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,771	$354	$0	$319	$2,444	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,086	$1,817	$0	$2,181	$13,084	$19	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$984	$197	$0	$177	$1,358	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,349	$870	$0	$1,044	$6,262	$9	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$24,736**	**$4,947**	**$0**	**$5,524**	**$35,208**	**$51**	**$26**
4						Electric Boiler, Hydrogen Production, and Miscellaneous Systems						
4.1	Feedwater Heaters	$0	$0	$0	$0	$464	$93	$0	$84	$641	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$31,380	$6,276	$0	$5,648	$43,304	$62	$32
4.3	Electric Superheaters	$0	$0	$0	$0	$1,697	$339	$0	$306	$2,342	$3	$2
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$662	$132	$0	$119	$913	$1	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$140	$28	$0	$25	$193	$0	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$47	$357	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$15,306	$3,061	$0	$2,755	$21,123	$30	$16

	Case:	SOEC-EB-6P	Advanced Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	693,400	Plant Size (MW net):			1,337		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 H_2/day]	\$/kW (net)
	Subtotal	**\$0**	**\$0**	**\$0**	**\$0**	**\$49,908**	**\$9,982**	**\$0**	**\$8,983**	**\$68,873**	**\$99**	**\$52**
7						Ductwork, & Stack						
7.3	Ductwork	\$0	\$0	\$0	\$0	\$571	\$114	\$0	\$103	\$788	\$1	\$1
7.4	Stack	\$0	\$0	\$0	\$0	\$3,819	\$764	\$0	\$687	\$5,270	\$8	\$4
7.5	Ductwork & Stack Foundations	\$0	\$0	\$0	\$0	\$487	\$97	\$0	\$117	\$701	\$1	\$1
	Subtotal	**\$0**	**\$0**	**\$0**	**\$0**	**\$4,877**	**\$975**	**\$0**	**\$907**	**\$6,759**	**\$10**	**\$5**
9						Cooling Water System						
9.1	Cooling Towers	\$0	\$0	\$0	\$0	\$2,945	\$589	\$0	\$530	\$4,064	\$6	\$3
9.2	Circulating Water Pumps	\$0	\$0	\$0	\$0	\$323	\$65	\$0	\$58	\$446	\$1	\$0
9.3	Circulating Water System Auxiliaries	\$0	\$0	\$0	\$0	\$3,927	\$785	\$0	\$707	\$5,419	\$8	\$4
9.4	Circulating Water Piping	\$0	\$0	\$0	\$0	\$1,541	\$308	\$0	\$277	\$2,127	\$3	\$2
9.5	Make-up Water System	\$0	\$0	\$0	\$0	\$570	\$114	\$0	\$103	\$787	\$1	\$1
9.6	Component Cooling Water System	\$0	\$0	\$0	\$0	\$211	\$42	\$0	\$38	\$291	\$0	\$0
9.7	Circulating Water System Foundations	\$0	\$0	\$0	\$0	\$498	\$100	\$0	\$119	\$717	\$1	\$1
	Subtotal	**\$0**	**\$0**	**\$0**	**\$0**	**\$10,014**	**\$2,003**	**\$0**	**\$1,832**	**\$13,850**	**\$20**	**\$10**
11						Accessory Electric Plant						
11.2	Station Service Equipment	\$0	\$0	\$0	\$0	\$11,442	\$2,288	\$0	\$2,060	\$15,790	\$23	\$12
11.3	Switchgear & Motor Control	\$0	\$0	\$0	\$0	\$17,657	\$3,531	\$0	\$3,178	\$24,367	\$35	\$18
11.4	Conduit & Cable Tray	\$0	\$0	\$0	\$0	\$14,115	\$2,823	\$0	\$2,541	\$19,478	\$28	\$15
11.5	Wire & Cable	\$0	\$0	\$0	\$0	\$15,131	\$3,026	\$0	\$2,724	\$20,881	\$30	\$16
11.6	Protective Equipment	\$0	\$0	\$0	\$0	\$1,144	\$229	\$0	\$206	\$1,578	\$2	\$1
11.7	Standby Equipment	\$0	\$0	\$0	\$0	\$2,637	\$527	\$0	\$475	\$3,639	\$5	\$3
11.8	Main Power Transformers	\$0	\$0	\$0	\$0	\$2,053	\$411	\$0	\$370	\$2,834	\$4	\$2
11.9	Electrical Foundations	\$0	\$0	\$0	\$0	\$432	\$86	\$0	\$104	\$622	\$1	\$0
	Subtotal	**\$0**	**\$0**	**\$0**	**\$0**	**\$64,611**	**\$12,922**	**\$0**	**\$11,656**	**\$89,189**	**\$129**	**\$67**
12						Instrumentation & Control						
12.4	Other Major Component Control Equipment	\$0	\$0	\$0	\$0	\$1,439	\$288	\$72	\$259	\$2,058	\$3	\$2
12.5	Signal Processing Equipment	\$0	\$0	\$0	\$0	\$713	\$143	\$0	\$128	\$984	\$1	\$1
12.6	Control Boards, Panels & Racks	\$0	\$0	\$0	\$0	\$312	\$62	\$16	\$56	\$446	\$1	\$0
12.7	Distributed Control System Equipment	\$0	\$0	\$0	\$0	\$11,103	\$2,221	\$555	\$1,999	\$15,877	\$23	\$12
12.8	Instrument Wiring & Tubing	\$0	\$0	\$0	\$0	\$4,447	\$889	\$222	\$801	\$6,360	\$9	\$5
12.9	Other Instrumentation & Controls Equipment	\$0	\$0	\$0	\$0	\$2,043	\$409	\$102	\$368	\$2,921	\$4	\$2
	Subtotal	**\$0**	**\$0**	**\$0**	**\$0**	**\$20,057**	**\$4,011**	**\$967**	**\$3,610**	**\$28,646**	**\$41**	**\$21**

	Case:	SOEC-EB-6P	Advanced Pressurized SOEC				Estimate Type:			Conceptual		
	Plant Size (kg H_2/day):	693,400	Plant Size (MW net):			1,337	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 H_2/day]	\$/kW (net)
	13	Improvements to Site										
13.1	Site Preparation	\$0	\$0	\$0	\$0	\$16,713	\$3,343	\$0	\$4,011	\$24,067	\$35	\$18
13.2	Site Improvements	\$0	\$0	\$0	\$0	\$5,613	\$1,123	\$0	\$1,347	\$8,083	\$12	\$6
13.3	Site Facilities	\$0	\$0	\$0	\$0	\$4,755	\$951	\$0	\$1,141	\$6,847	\$10	\$5
	Subtotal	**\$0**	**\$0**	**\$0**	**\$0**	**\$27,082**	**\$5,416**	**\$0**	**\$6,500**	**\$38,997**	**\$56**	**\$29**
	14	Buildings & Structures										
14.4	Administration Building	\$0	\$0	\$0	\$0	\$759	\$152	\$0	\$137	\$1,047	\$2	\$1
14.5	Circulation Water Pumphouse	\$0	\$0	\$0	\$0	\$20	\$4	\$0	\$4	\$27	\$0	\$0
14.6	Water Treatment Buildings	\$0	\$0	\$0	\$0	\$435	\$87	\$0	\$78	\$600	\$1	\$0
14.7	Machine Shop	\$0	\$0	\$0	\$0	\$1,117	\$223	\$0	\$201	\$1,541	\$2	\$1
14.8	Warehouse	\$0	\$0	\$0	\$0	\$839	\$168	\$0	\$151	\$1,158	\$2	\$1
14.9	Other Buildings & Structures	\$0	\$0	\$0	\$0	\$626	\$125	\$0	\$113	\$865	\$1	\$1
14.10	Waste Treating Building & Structures	\$0	\$0	\$0	\$0	\$1,060	\$212	\$0	\$191	\$1,462	\$2	\$1
	Subtotal	**\$0**	**\$0**	**\$0**	**\$0**	**\$4,856**	**\$971**	**\$0**	**\$874**	**\$6,701**	**\$10**	**\$5**
	Total	**\$0**	**\$0**	**\$0**	**\$0**	**\$301,463**	**\$60,293**	**\$967**	**\$57,045**	**\$419,768**	**\$605**	**\$314**

Exhibit 4-22. Case 6P owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,364	$5	$3
1 Month Maintenance Materials	$469	$1	$0
1 Month Non-Fuel Consumables	$181	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$8,395	$12	$6
Total	**$12,409**	**$18**	**$9**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$211	$0	$0
0.5% of TPC (spare parts)	$2,099	$3	$2
Total	**$2,309**	**$3**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$483	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$62,965	$91	$47
Financing Costs	$11,334	$16	$8
Total Overnight Costs (TOC)	**$509,568**	**$735**	**$381**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$545,137**	**$786**	**$408**

Exhibit 4-23. Case 6P initial and annual O&M costs

Case:	**SOEC-EB-6P**		**Advanced Pressurized SOEC**		**Cost Base:**		**Dec 2018**
Plant Size (kg H_2/day):	**693,400**	**Plant Size (MW net):**		**1,337**	**Capacity Factor (%):**		**95%**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.162	$1.639
Maintenance Labor:					$3,190,236	$4.601	$2.386
Administrative & Support Labor:					$1,345,606	$1.941	$1.006
Property Taxes and Insurance:					$8,395,358	$12.108	$6.279
Total:					**$15,123,390**	**$21.810**	**$11.310**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh-net)**
Maintenance Material:					$5,348,337	$0.02224	$0.48064
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	14.77	$1.49	$1,785,251	$0.00743	$0.16044
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,306	$1.90	$0	$860,534	$0.00358	$0.07733
Makeup and Wastewater Treatment Chemicals (ton):	0	3.89	$550	$0	$742,039	$0.00309	$0.06668
Hydrogen Drying Sorbent (lb):	48,278	132.3	$10	$482,782	$458,643	$0.00191	$0.04122
Subtotal:				**$482,782**	**$2,061,216**	**$0.00857**	**$0.18524**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	132.3	$0.02	$0	$871	$0.00000	$0.00008
Subtotal:				**$0**	**$871**	**$0.00000**	**$0.00008**
Variable Operating Costs Total:				**$482,782**	**$9,195,676**	**$0.03082**	**$0.66595**
Electricity Cost							
Electricity (MWh):	0	32,091	$60.00	$0	$667,652,688	$2.77684	$60.00000
Total:				**$0**	**$667,652,688**	**$2.77684**	**$60.00000**

Exhibit 4-24. Case 6P LCOH breakdown

Component	**LCOH, $/kg H_2**	**Percentage**
Capital	0.13	4%
Fixed	0.06	2%
Variable	0.04	1%
Electricity	2.78	92%
Total	**3.01**	**N/A**

4.4 Pressurized Pathway Results

The performance and cost results of all seven cases in the pressurized pathway are summarized in Exhibit 4-25. The following section discusses the improvements to SOEC performance and cost along the pathway.

Exhibit 4-25. Performance and cost summary for all pressurized cases

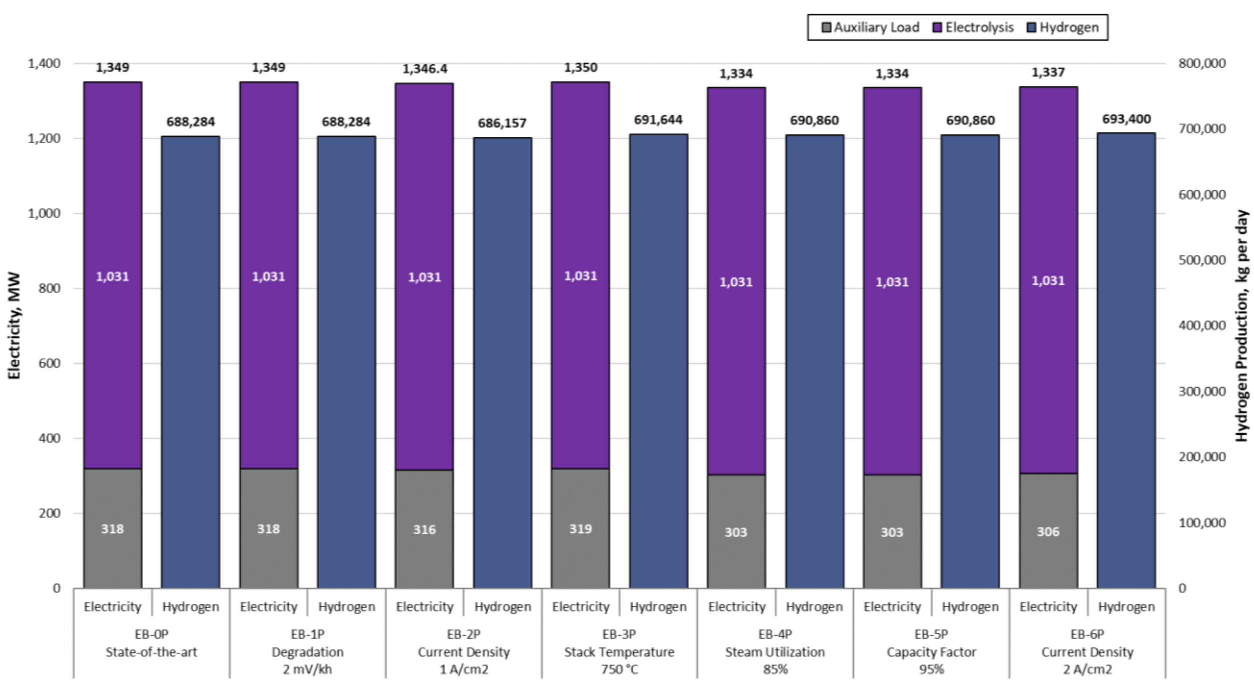
Pressurized Pathway							
Case Name	0P	1P	2P	3P	4P	5P	6P
PERFORMANCE							
Capacity Factor	90%	90%	90%	90%	90%	95%	95%
Current Density (A/cm^2)	0.5	0.5	1	1	1	1	2
Voltage (V)	1.298	1.298	1.302	1.292	1.293	1.293	1.289
Stack Temperature (°C)	850	850	850	750	750	750	750
Steam Utilization	80	80	80	80	85	85	85
Stack Degradation Rate (mV/kh)	8	2	2	2	2	2	2
Hydrogen Production Rate (lb/h)	63,225	63,225	63,030	63,534	63,462	63,462	63,695
Gross Power Output (MWe)	62	62	62	59	60	60	60
Electrolysis Power Requirement (MWe)	1,031	1,031	1,031	1,031	1,031	1,031	1,031
Auxiliary Power Requirement (MWe)	380	380	378	379	363	363	366
Net Power Output (MWe)	-1,349	-1,349	-1,346	-1,350	-1,334	-1,334	-1,337
LHV Net Plant Efficiency (%)	70.8	70.8	70.8	71.1	71.9	71.9	72.0
Electric Input per Kilogram H_2 (kWh/kg)	47.1	47.1	47.1	46.9	46.3	46.3	46.3
Raw Water Withdrawal (gpm)	1,907	1,907	1,901	1,916	1,807	1,807	1,814
Process Water Discharge (gpm)	302	302	301	304	272	272	273
Raw Water Consumption (gpm)	1,604	1,604	1,599	1,612	1,536	1,536	1,541
CO_2 Emissions (lb/MMBtu)	None						
SO_2 Emissions (lb/MMBtu)							
NOx Emissions (lb/MMBtu)							
PM Emissions (lb/MMBtu)							
Hg Emissions (lb/TBtu)							
COST							
Total Plant Cost (2018$/[kg H_2/day])	1,080	1,080	804	813	798	798	605
Total Overnight Cost (2018$/[kg H_2/day])	1,035	1,035	1,035	1,035	1,035	1,035	1,035
Owner's Costs	228	228	171	173	169	169	130
Process Contingency	1	1	1	1	1	1	1
Project Contingency	144	144	108	109	107	107	82
Home Office Expenses	156	156	116	117	115	115	87
Bare Erected Cost	778	778	579	585	574	574	435

Pressurized Pathway							
Case Name	**0P**	**1P**	**2P**	**3P**	**4P**	**5P**	**6P**
Total As-Spent Cost (2018$/[kg H_2/day])	1,399	1,399	1,043	1,055	1,035	1,035	786
LCOH ($/kg H_2)	3.58	3.31	3.17	3.17	3.13	3.11	3.01
Capital Costs	0.25	0.25	0.19	0.19	0.18	0.17	0.13
Fixed Costs	0.11	0.11	0.08	0.09	0.08	0.08	0.06
Variable Costs	0.40	0.13	0.08	0.08	0.08	0.08	0.04
Electricity Costs	2.82	2.82	2.83	2.81	2.78	2.78	2.78

4.4.1 Performance and Environmental Results Summary

A graph of the net electricity consumed and H_2 produced by the pressurized cases is shown in Exhibit 4-26. Each case was sized to an electrical input of 1 GW_{DC}. A rectifier efficiency of 97 percent yields the constant electrolysis load of 1,031 MW seen in the exhibit. For every case, the electrolysis load makes up 76–77 percent of the net electric load. The remainder consists of the net BOP auxiliary load, which decreases by 12 MW over the pathway, less than 1 percent of the net electricity of Case 0P.

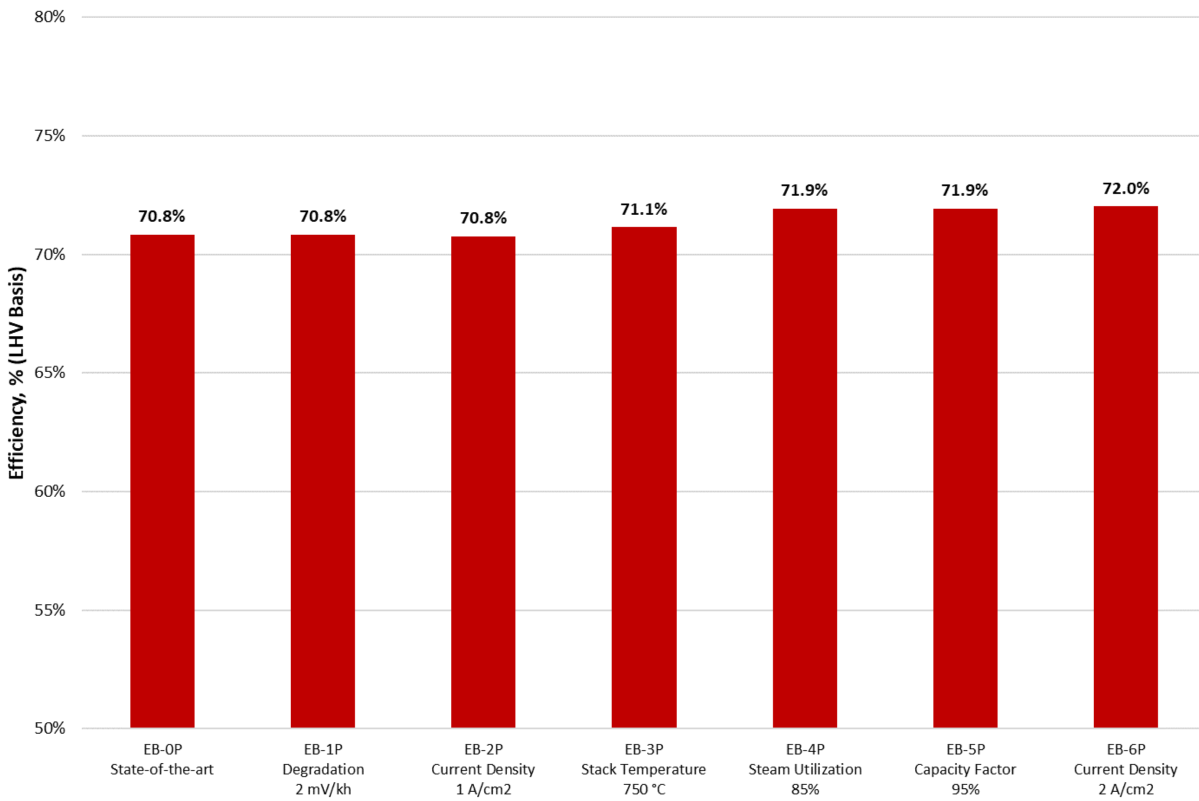
Exhibit 4-26. Electric load and hydrogen production for all pressurized cases



The amount of H_2 produced is similar in all cases and averages around 690,000 kg per day. The slight (about 1 percent) variation in production is due to small differences in the operating voltages of each case, producing different amounts of H_2 for a fixed power input.

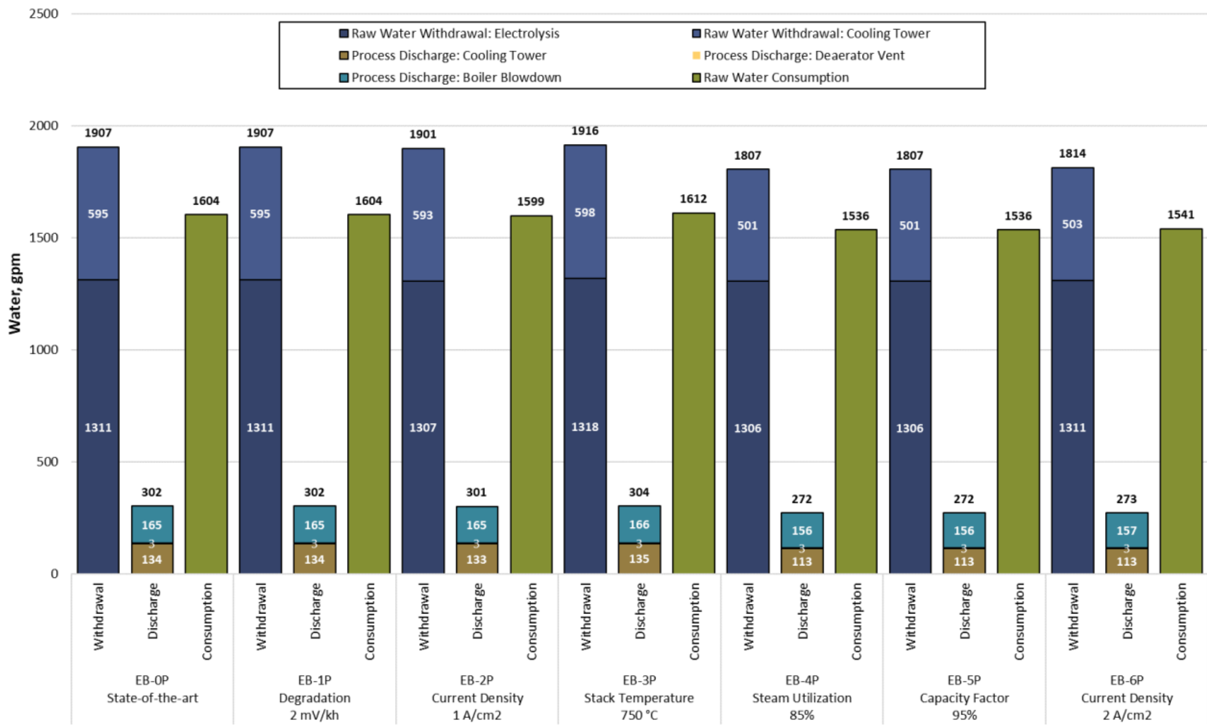
The progression in net plant efficiency (LHV basis) along the pressurized pathway is shown in Exhibit 4-27. At the start of the pathway, Case 0P has an LHV efficiency of 70.8 percent. By the end of the pathway, the cumulative effects of all technology improvements increase the efficiency by 1.2 percentage points to 72 percent. The only cases that see efficiency increases along the pathway are Cases 3P and 4P. The decrease in SOEC operating temperature from 850°C (1562°F) to 750°C (1382°F) in Case 3P reduces the auxiliary load of the electric steam superheaters resulting in a 0.3 percentage point increase in efficiency. The increased steam utilization in Case 4P results in reduced auxiliary load from the electric boiler and an efficiency increase of 0.8 percentage points.

Exhibit 4-27. Net plant efficiency (LHV basis) for all pressurized cases



Finally, water use for the pressurized cases is shown in Exhibit 4-28. Case 0P has a raw water withdrawal of 1,907 gpm. About 69 percent of the water demand is for electrolysis steam and the remaining 31 percent is used for evaporative cooling. The process water discharge is 302 gpm resulting in a net water consumption of 1,604 gpm. Case 4P is the only pathway step with a significant reduction in water use. Water consumption decreases by 5 percent to 1,536 gpm: driven by a reduction in the cooling tower duty. There are no further significant changes in water use between case 4P and the end of the pathway.

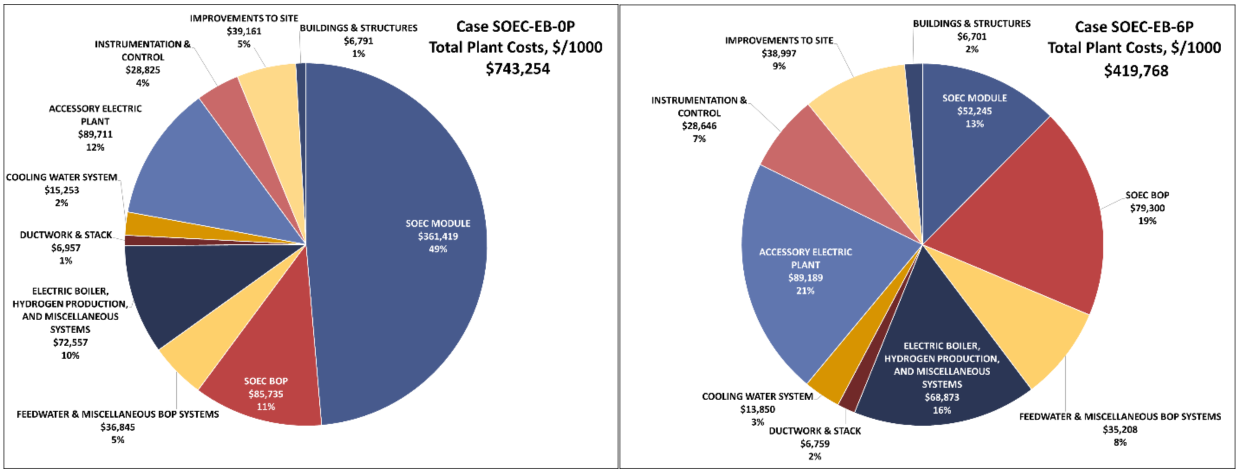
Exhibit 4-28. Water use for all pressurized cases



4.4.2 Cost Results Summary

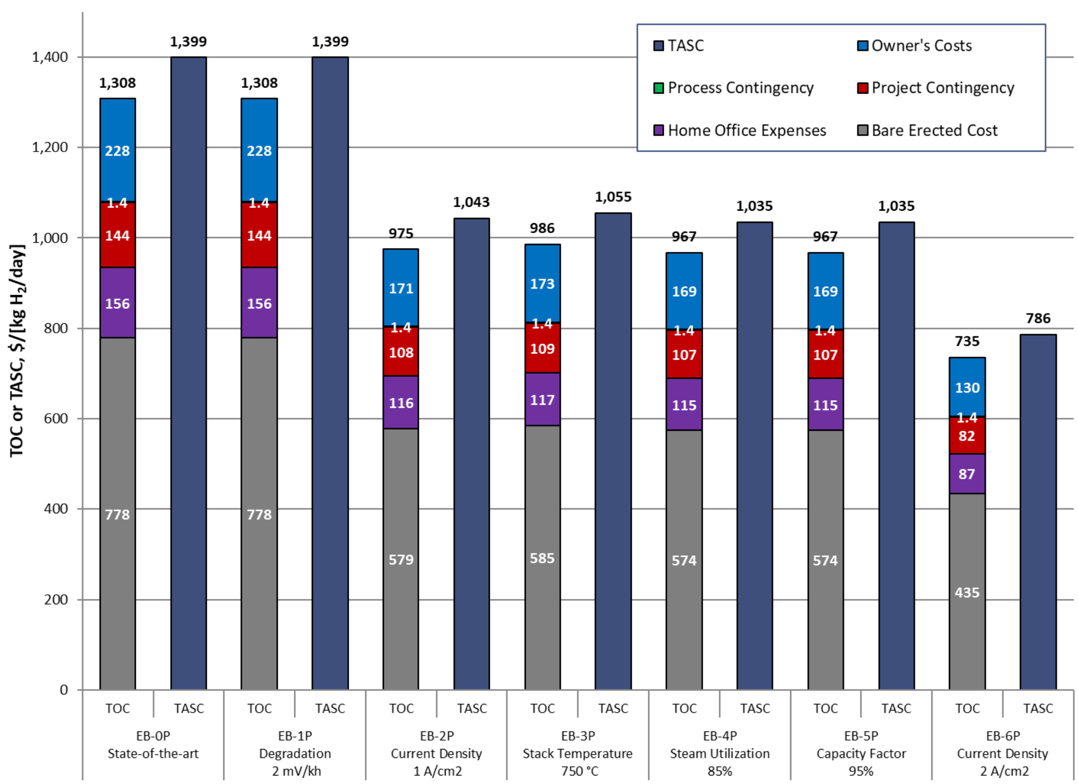
A TPC breakdown for Cases 0P and 6P is shown in Exhibit 4-29. At the start of the pressurized pathway, the TPC is $743 MM. By the final step in the pathway, the TPC has decreased 44 percent to $420 MM. Over 90 percent of the reduction in TPC can be attributed to the SOEC module account, which decreases from $361 MM to $52 MM. The effective SOEC stack cost decreases dramatically over the pathway due to a quadrupling of the current density (i.e., fewer stacks are required to produce the same amount of H_2) and a decrease in the nominal stack cost. The 1) SOEC BOP; 2) electric boiler, hydrogen production, and miscellaneous systems; and 3) feedwater and miscellaneous systems accounts also contribute to the decrease in TPC.

Exhibit 4-29. Total plant cost breakdown for Cases 0P and 6P



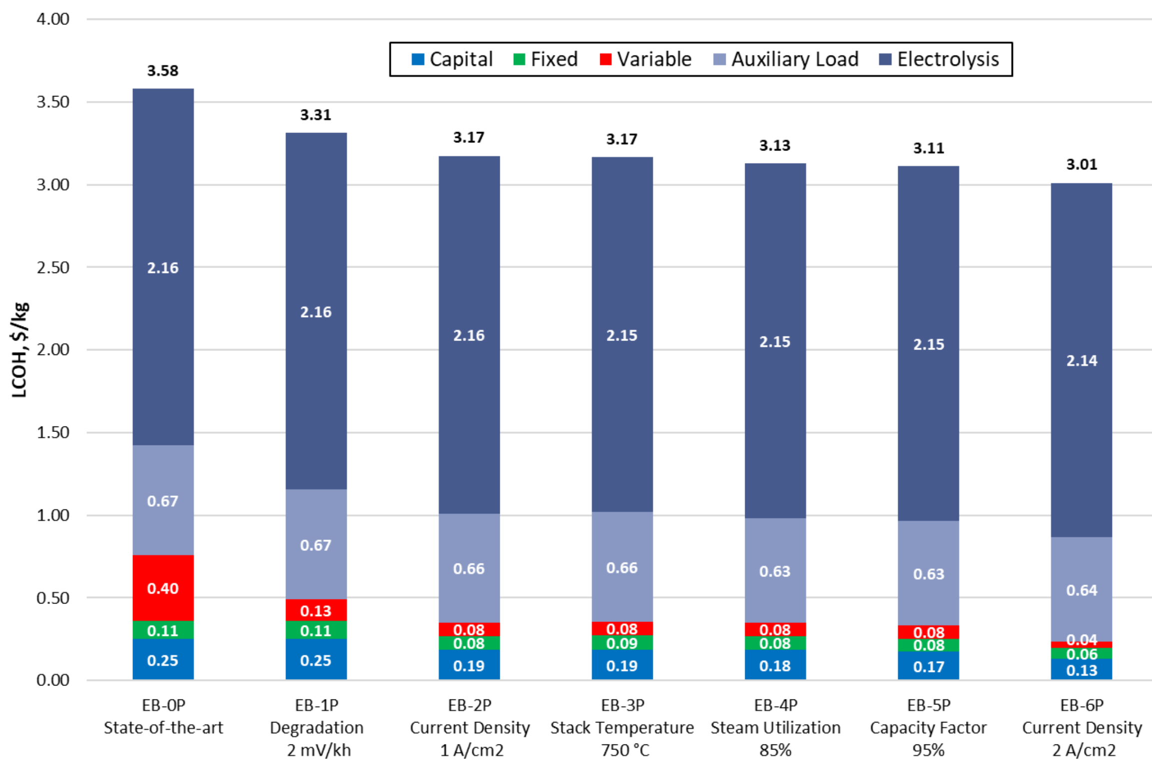
The components of TOC and the overall TASC of the atmospheric cases are shown in Exhibit 4-30. The atmospheric pathway starts with a TOC of $667/kW and TASC of $714/kW. The largest component of the TOC is the bare erected cost, which accounts for 60 percent of the TOC in Case 0P. The next largest contributor is the owner's costs, accounting for 17 percent. The process contingency is negligible in all pressurized cases. By the end of the pathway, both the TOC and TASC have decreased by 43 percent to $381/kW and $408/kW, respectively. The only significant reductions in capital costs are seen in Cases 2P (25 percent reduction) and 6P (24 percent reduction).

Exhibit 4-30. Plant capital cost for all pressurized cases



The LCOH considering an electricity price of \$60/MWh is shown in Exhibit 4-31 for the pressurized pathway. The state-of-the-art pressurized SOEC has an LCOH of \$3.58/kg H_2. By the end of the pathway, the LCOH decreases by 16 percent to \$3.01/kg H_2. The LCOH of every case is dominated by the electricity component. Electricity makes up 79 and 92 percent of the total LCOH in Cases 0P and 6P, respectively. About 76 percent of the electricity is used for electrolysis and 24 percent for the auxiliary load. The electricity component of the LCOH only decreases by \$/0.05kg H_2 over the course of the pathway. The efficiency improvements observed along the pathway do not translate into large reductions in LCOH. The LCOH from SOEC systems is largely dependent on the price of electricity, which researchers have little control over.

Exhibit 4-31. LCOH with \$60/MWh electricity for all pressurized cases



To better understand the influence R&D can have on the economics of SOEC systems, the LCOH without the electricity component is shown in Exhibit 4-32. The change in LCOH without electricity along the pressurized pathway is shown in Exhibit 4-33. The LCOH without electricity decreases by \$0.52/kg H_2, or 69 percent, from Case 0P (\$0.76/kg H_2) to Case 6P (\$0.23/kg H_2). The most significant reductions occur to the variable cost component, which decreases by 90 percent. A major factor in the variable cost reduction is increased stack lifetimes due to the decreased degradation rate in Case 1P. Case 1P (reduction in degradation rate from 8 to 2 mV/kh) displays the largest reduction in LCOH (-\$0.27/kg H_2), contributing about 50 percent of the total pathway reduction. Cases with increases in current density also show significant reductions in the LCOH. Case 2P and 6P contribute LCOH reductions of \$0.14/kg H_2 and \$0.14/kg H_2, respectively. Cases 3P, 4P, and 5P do not contribute significant reductions to the LCOH without electricity.

Exhibit 4-32. LCOH without electricity for all pressurized cases

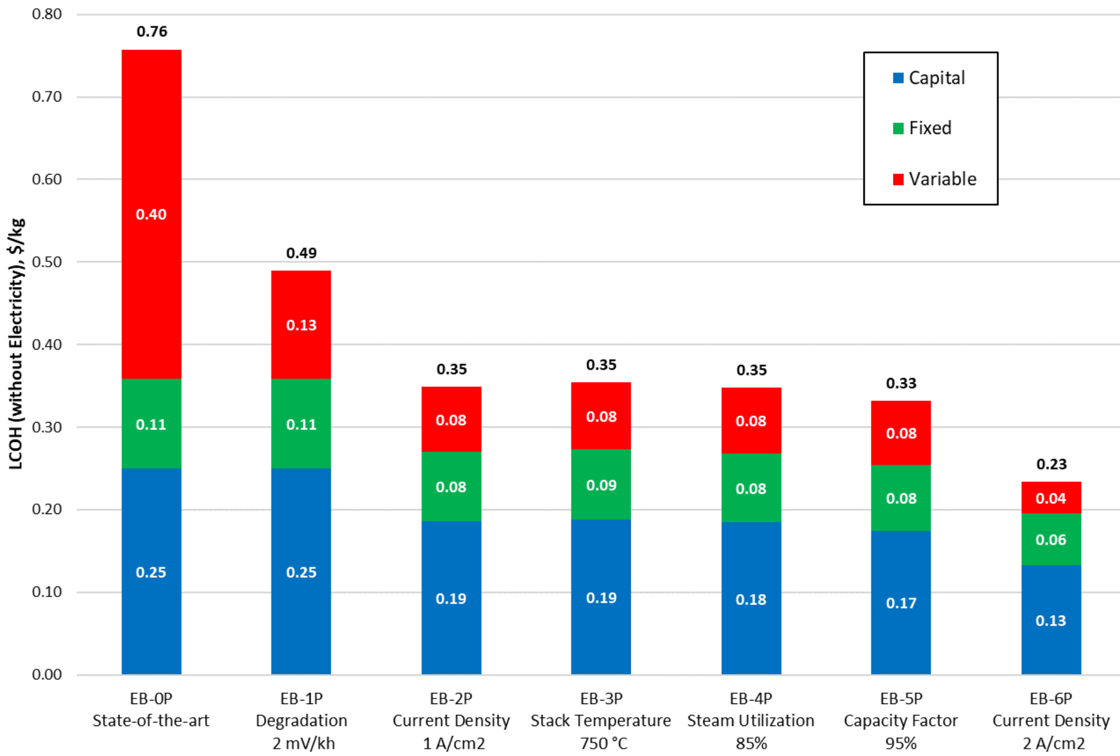
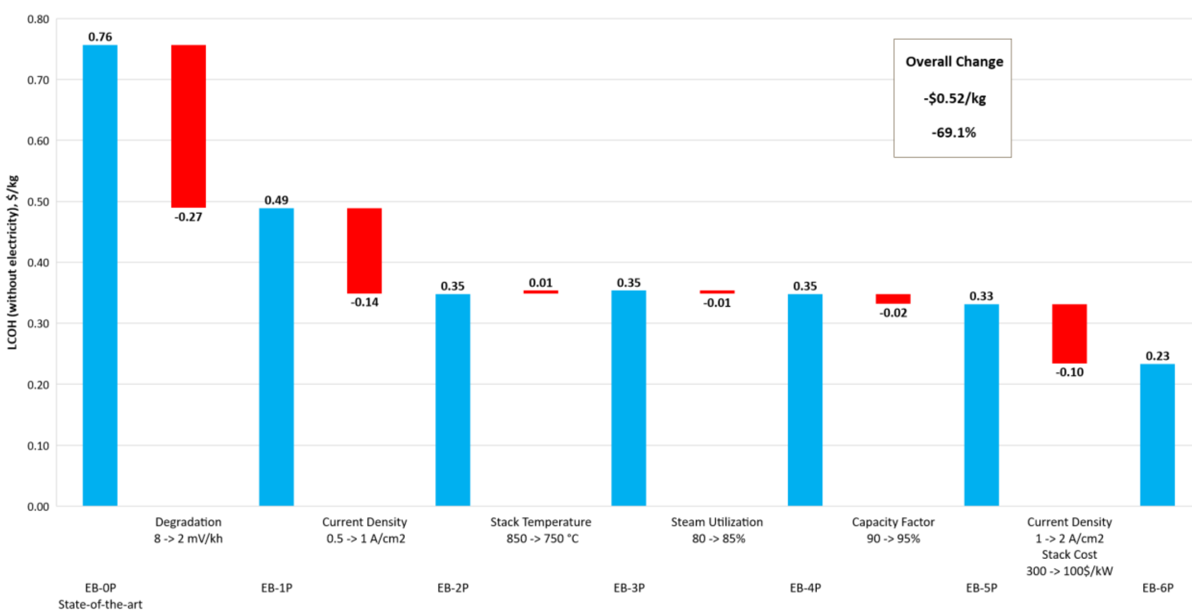


Exhibit 4-33. Change in LCOH without electricity over the pressurized pathway



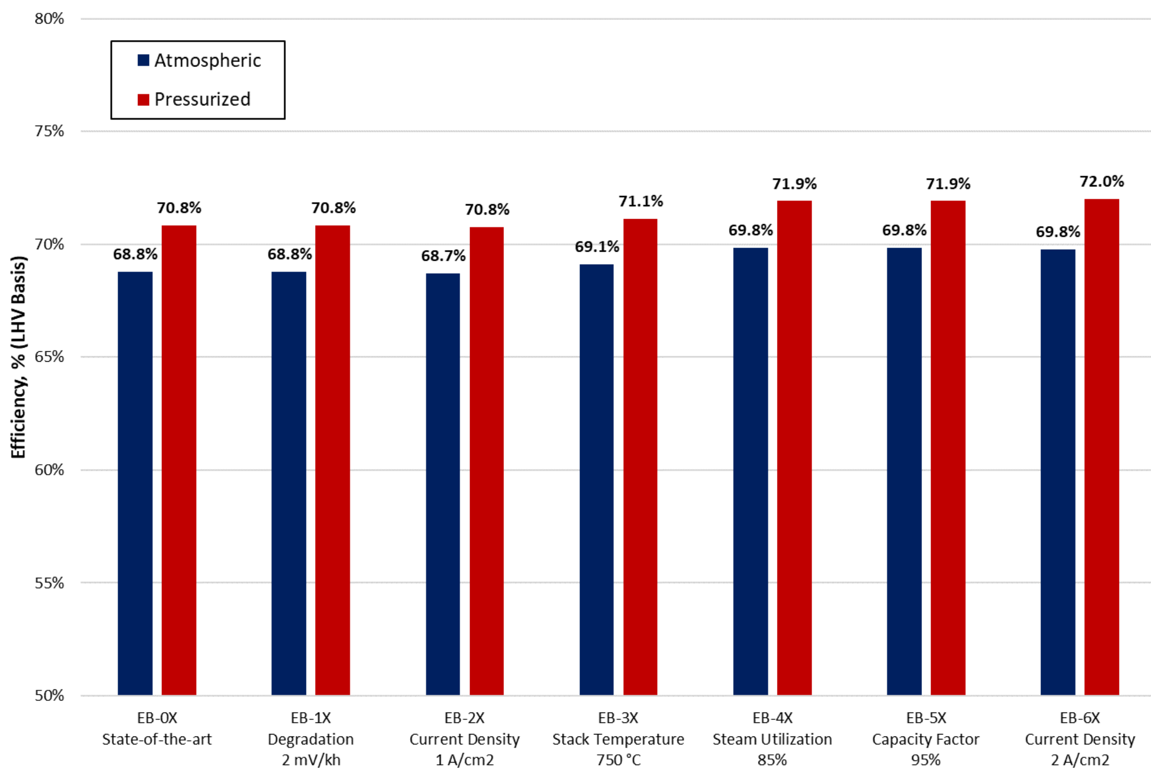
5 Results Analysis

Summaries of the individual pathways were provided in Section 3 and Section 4. This section provides the results of both pathways for direct comparison.

5.1 Performance

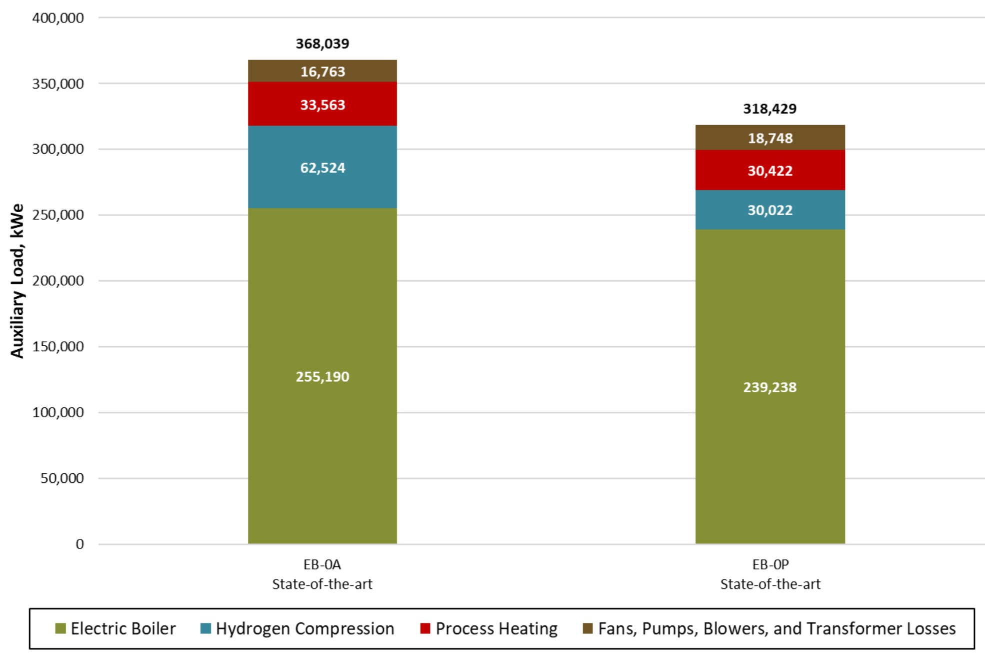
A graph of net plant efficiency (LHV basis) is provided in Exhibit 5-1. The pressurized SOEC configuration is at least 2 percentage points more efficient than the atmospheric configuration across all cases. Both configurations exhibit similar trends along the pathway. The efficiency of the atmospheric and pressurized systems increases by 1 and 1.2 percentage points, respectively. Both systems only see efficiency improvements in Cases 3 and 4.

Exhibit 5-1. Plant efficiencies for all cases (LHV basis)



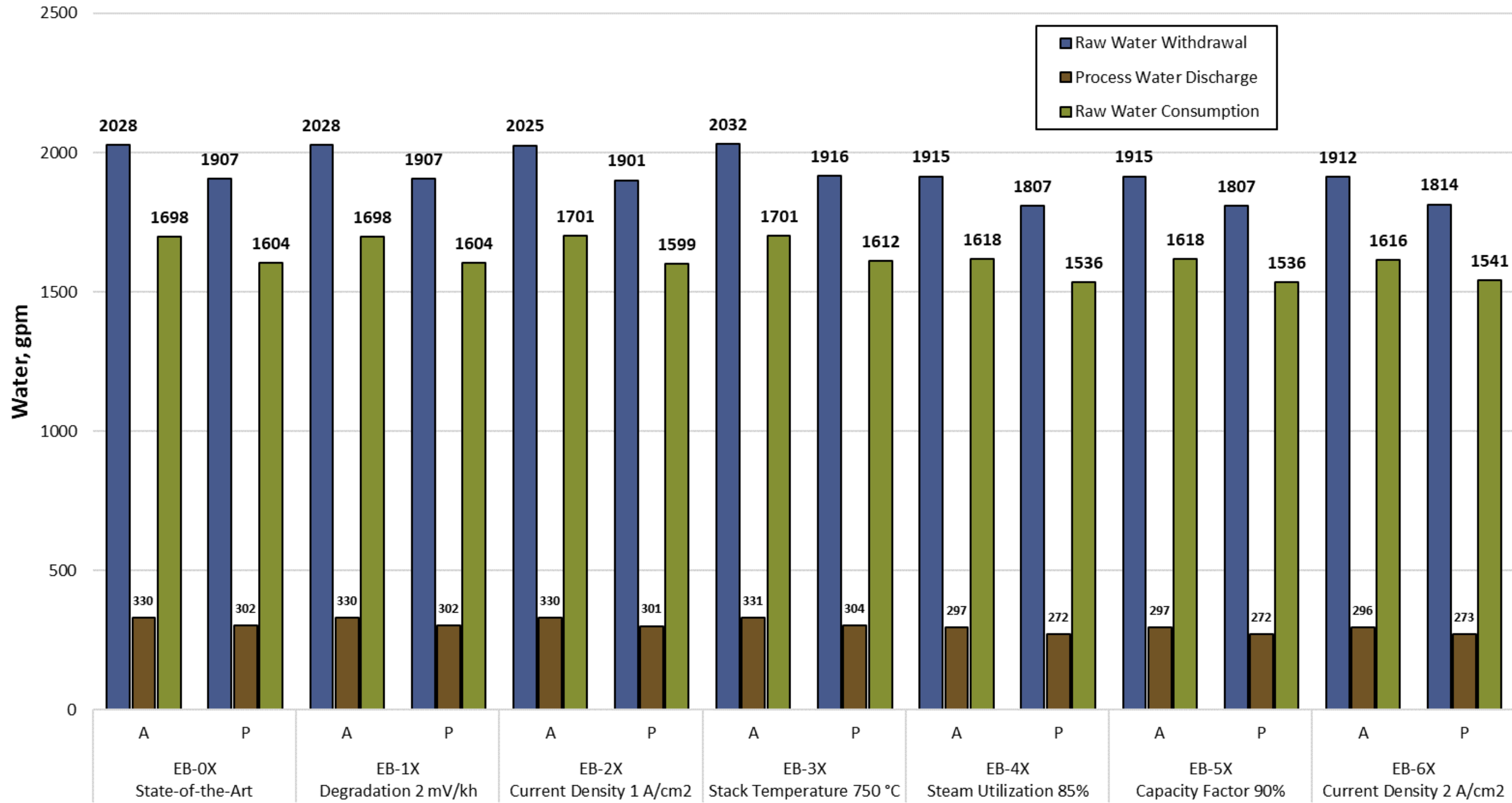
A breakdown of the auxiliary load for state-of-the-art Cases 0A and 0P is presented in Exhibit 5-2. The auxiliary load for the pressurized system is about 50 MW or 13 percent less than the atmospheric system. The largest source of this difference can be attributed to a 32 MW reduction in the H_2 compression load of the pressurized case. There are also reductions to the electric boiler and process heating loads due to more efficient heat recovery to the pressurized boiler feedwater.

Exhibit 5-2. Auxiliary load breakdown for state-of-the-art cases



The raw water withdrawal, process discharge, and raw water consumption are presented for all cases in Exhibit 5-3. The raw water withdrawal of the pressurized configuration is 98–121 gpm (about 6 percent) lower than the atmospheric configuration. The raw water consumption of the pressurized configuration is 75–94 gpm (about 6 percent) lower than the atmospheric configuration. The pressurized configuration has lower water requirements due to a lower cooling duty stemming from the higher efficiency.

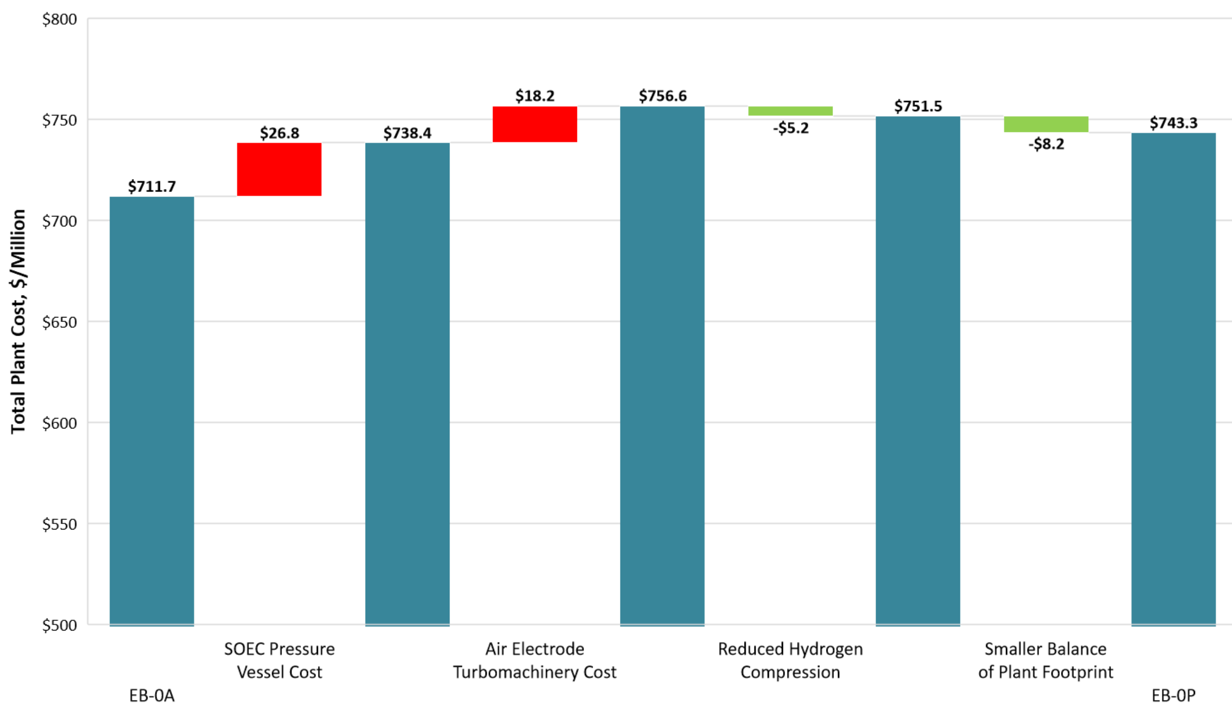
Exhibit 5-3. Water use for all cases



5.2 Cost Results

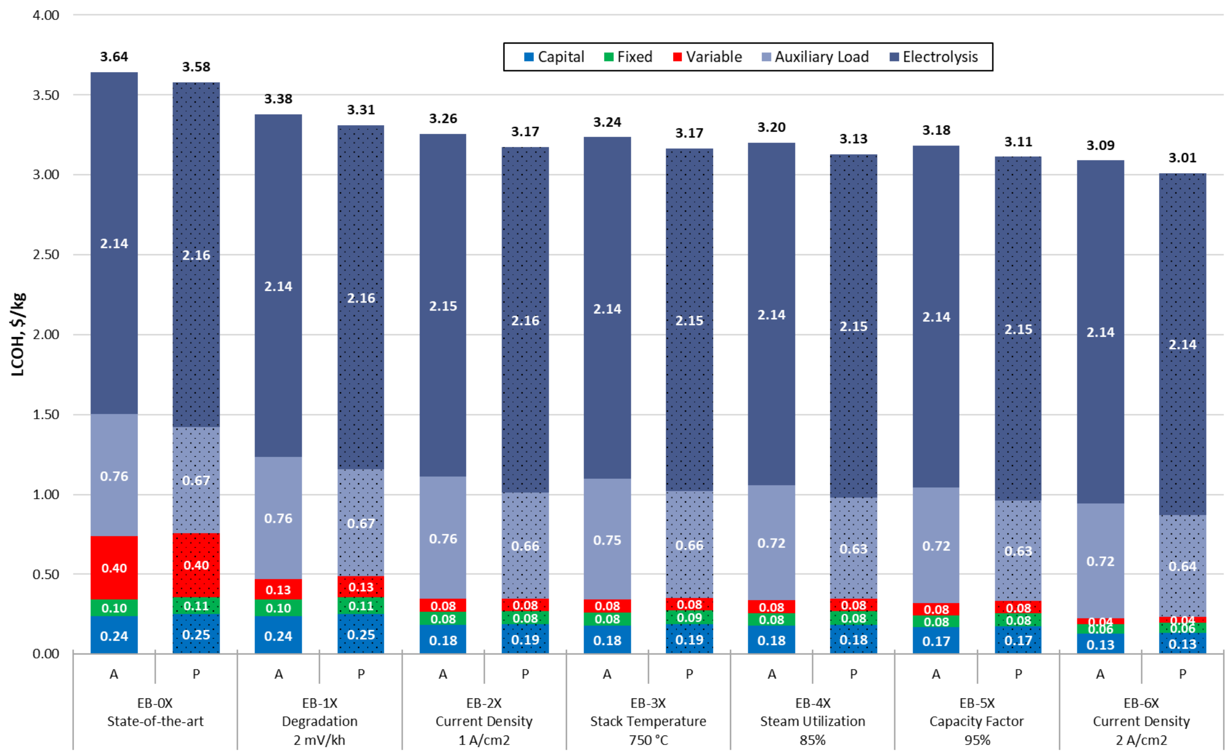
A waterfall plot showing the differences in TPC between Cases 0A and 0P is shown in Exhibit 5-4. The TPC of the pressurized system in Case 0 is 4 percent or $31.6 MM larger than the atmospheric system. The additional requirement of SOEC pressure vessels in the pressurized configuration is the largest source of the increase in TPC, adding $26.8 MM. The TPC of the sweep compressor and expander is $18.2 MM larger than the cost of the sweep blower in the atmospheric configuration. On the other hand, there are changes to the pressurized configuration that reduce the TPC. H_2 compression requires one fewer stage in the pressurized configuration, reducing the TPC by $5.2 MM. A higher system efficiency and a lower cooling duty result in a smaller BOP footprint, reducing the TPC by $8.2 MM.

Exhibit 5-4. Comparison of the total plant costs of Cases 0A and 0P



The LCOH breakdown with an electricity price of $60/MWh is presented in Exhibit 5-5. The LCOH for the pressurized cases is $0.06–0.08/kg less than the atmospheric cases. This is almost entirely due to the increased efficiency of the pressurized configuration and a lower contribution from the auxiliary load electricity cost. There are only minor differences in the capital, fixed, and variable cost components of the LCOH between the two configurations. The total LCOH reduction over both pathways is similar, with the LCOH of atmospheric and pressurized configurations decreasing by $0.55–0.57/kg, respectively.

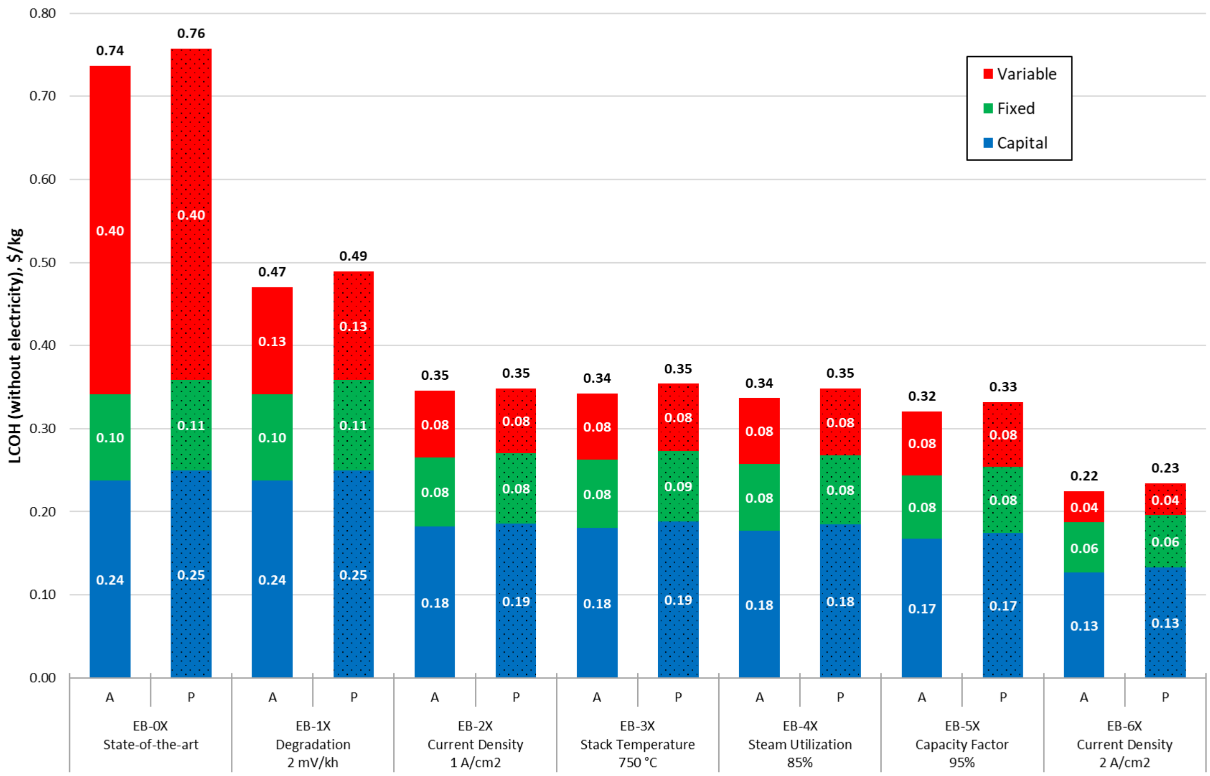
Exhibit 5-5. LCOH with electricity for all cases



The LCOH breakdown without electricity is presented in Exhibit 5-6. The LCOH for the atmospheric cases is \$0.00–0.02/kg less than the pressurized cases. With the efficiency of the cases not accounted for, the higher capital costs of the pressurized configuration result in a larger LCOH. The total LCOH reduction over both pathways is similar, with the LCOH of atmospheric and pressurized configurations decreasing by \$0.52/kg and \$0.53/kg, respectively.

In practice, the slight cost advantage of pressurized SOEC relative to atmospheric SOEC have to be weighed against the additional complexities and uncertainties generally associated with a pressurized SOEC system that are not valorized here.

Exhibit 5-6. LCOH without electricity for all cases



5.3 Sensitivity Analysis

A sensitivity of the LCOH to the stack degradation rate (for the first and last cases in the pathway) is shown in Exhibit 5-7. The degradation rate was varied from 0 to 16 mV/kh. The baseline degradation rates were 8 mV/kh and 2 mV/kh for Cases 0 and 6, respectively. The plot shows that changes in degradation rate do not favor one configuration over the other, and that cases at the start of the pathway are more sensitive to changes in degradation rate than cases at the end of the pathway. For Cases 0A and 0P, a 1 mV/kh decrease in the degradation rate decreases the LCOH by $0.04/kg. For Cases 6A and 6P, a 1 mV/kh decrease in the degradation rate decreases the LCOH by less than $0.01/kg. The cost and technology improvements along the pathway, especially the increased operating current density and the low SOEC cost, render the LCOH only slightly sensitive to the degradation rate. However, in practice, higher degradation rates result in more frequent replacements and can significantly impose larger downtimes and lower effective capacity factors, an aspect that has not been taken into account in current calculations. Further, the frequent replacements also carry additional thermal cycling risks that can prevent re-use of other module components. Accordingly, low degradation rates, say 2 mv/kh, associated with 9.3 years between stack replacements, is preferable while being consistent with conventional equipment degradation rates.

Exhibit 5-7. LCOH sensitivity to stack degradation rate

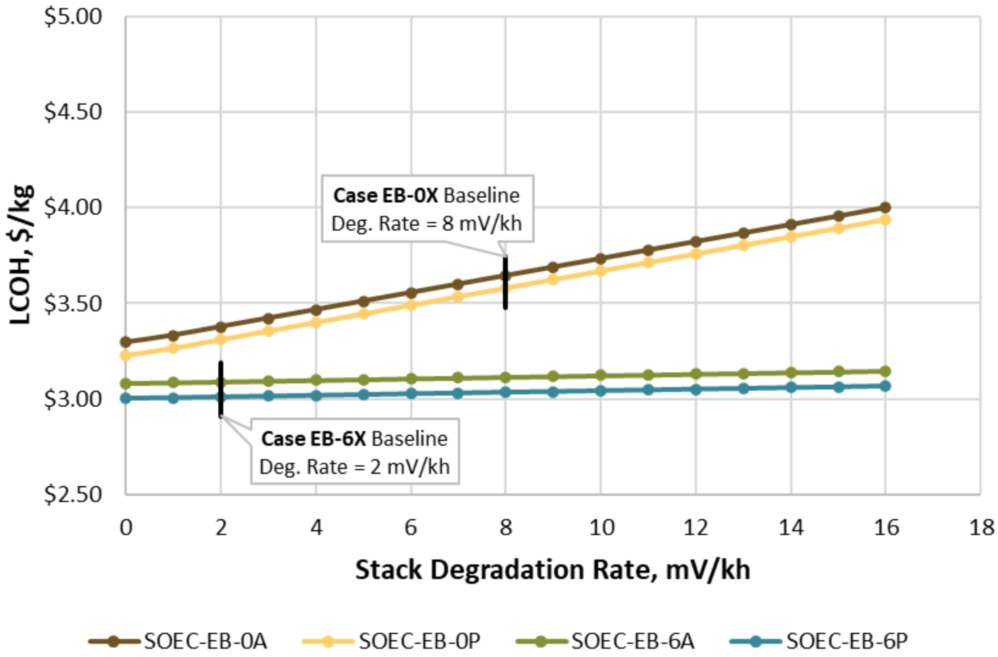


Exhibit 5-8 shows the LCOH sensitivity to the nominal stack cost (for the first and last cases in the pathway) over a range of prices of $50–500/kW. The stack cost assumed in the study were $300/kW and $100/kW for Cases 0 and 6, respectively. The plot shows that changes in stack costs do not favor one configuration over the other. Cases at the start of the pathway are more sensitive to changes in stack cost than cases at the end of the pathway. This is due to the earlier cases operating at lower current densities and requiring more stacks than cases at the end of the pathway. For Cases 0A and 0P, a $50/kW decrease in the stack cost decreases the LCOH by $0.08/kg. For Cases 6A and 6P, the same decrease in stack cost only decreases the LCOH by $0.01/kg. If all the technology improvements along the pathway are realized, reducing the stack cost below $100/kW will not move the needle toward achieving an LCOH of $1/kg H_2.

Exhibit 5-8. LCOH sensitivity to nominal stack cost

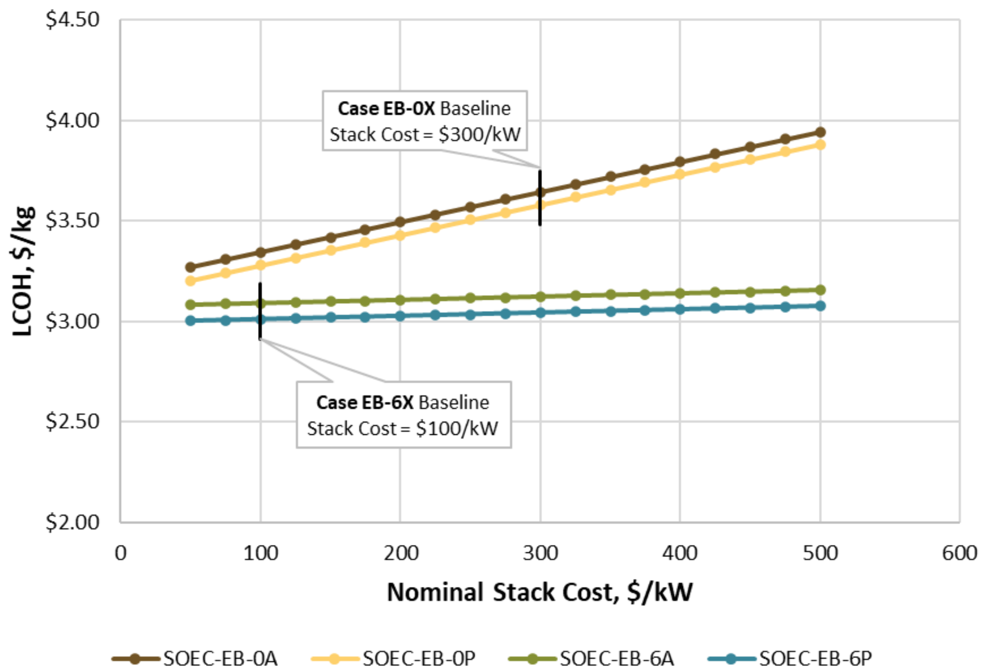


Exhibit 5-9 shows the LCOH sensitivity to the percentage of the electric boiler's heat duty that can be supplied with free waste heat from an existing industrial process. The waste heat is assumed to be above 153°C (307°F) in the atmospheric configuration and 188°C (371°F) in the pressurized configuration. This sensitivity only includes the reduction in electricity costs and does not consider the capital costs of eliminating the electric boilers. The percentage of waste heat is varied 0–100 percent with the baseline study assuming no free waste heat. This graph highlights that the LCOH can be reduced by around $0.50/kg in all cases if the heat duty of the electric boiler can be fully replaced with waste heat. It is important to note that this effect would be diminished at lower electricity prices.

Exhibit 5-9. LCOH sensitivity to the availability of free waste heat

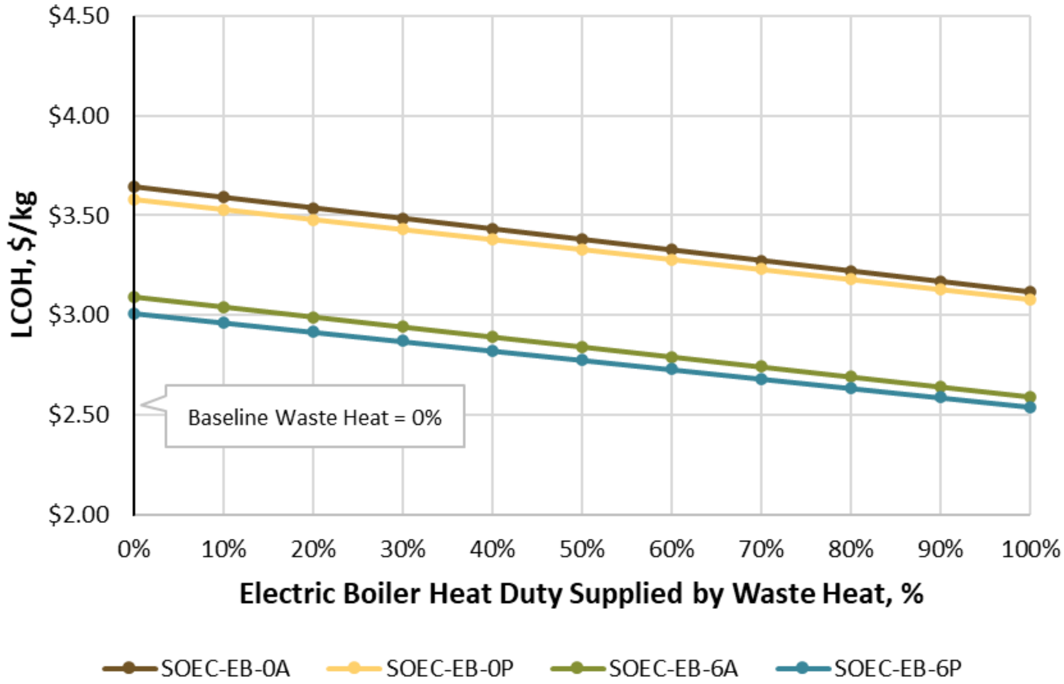
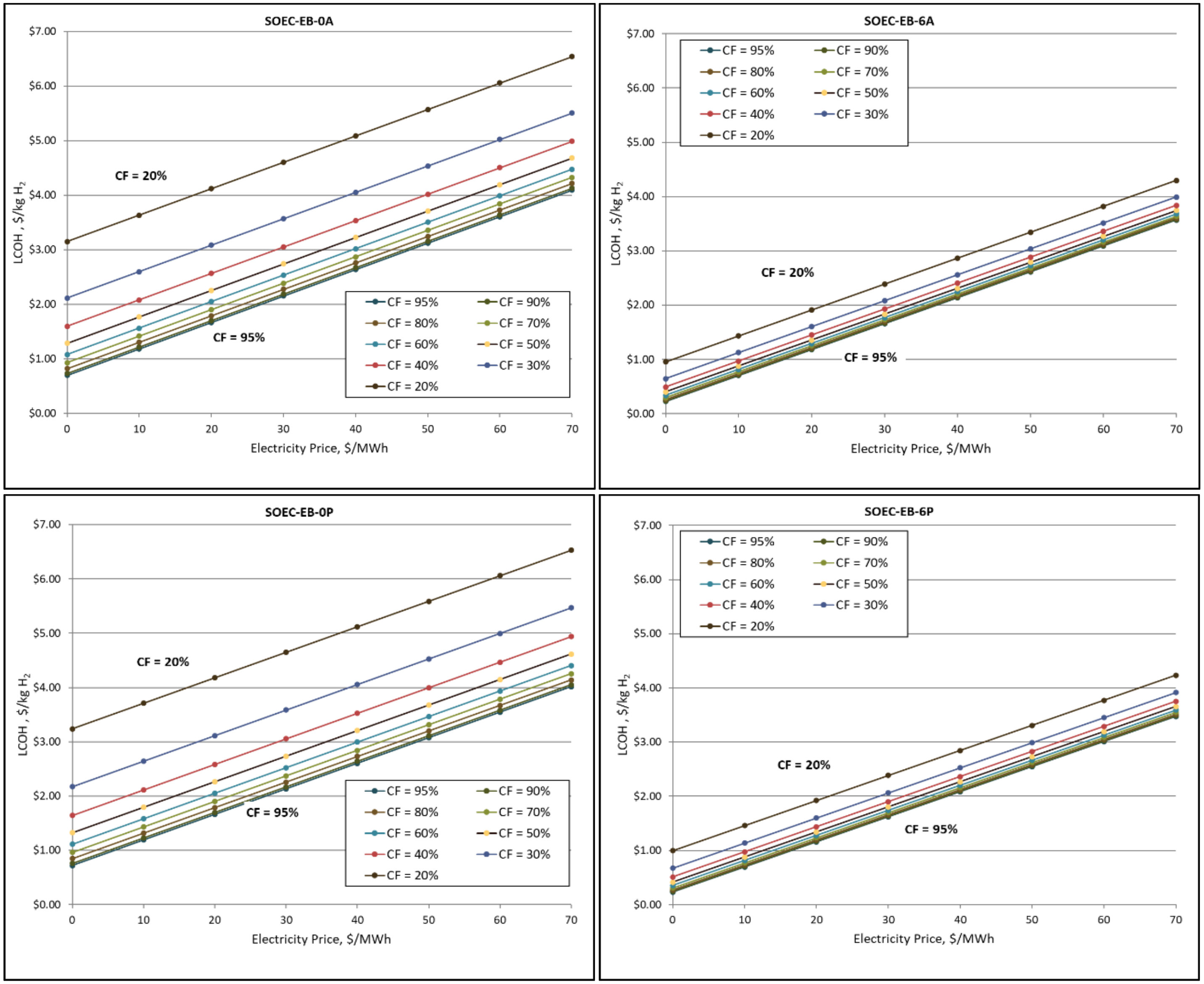


Exhibit 5-10 shows the LCOH sensitivity to the grid electricity price over a range of prices of \$10–70/MWh. The reference price point used in this study is \$60/MWh and the CF is 90 or 95 depending on the case. Separate graphs are shown for Cases 0A, 0P, 6A, and 6P. The LCOH is very sensitive to changes in grid electricity price and its availability. A \$1/MWh decrease in the electricity prices decreases the LCOH of all cases by about \$0.05/kg. Systems become less sensitive to the CF toward the end of the pathway as capital costs decrease. The LCOH of cases 0A and 0P decrease by \$2.45/kg and \$2.52/kg, respectively, as the CF is increased from 20 to 95 percent (for all electricity prices). In comparison, the LCOH of Cases 6A and 6P decrease by \$0.73/kg and \$0.76/kg as the CF is increased the same amount. Movement along the R&D pathways enables new combinations of electricity prices and CF for achieving the Hydrogen Shot targets. In Case 0A, the highest electricity price that can achieve an LCOH of \$1/kg is around \$6/MWh at a CF of 95 percent. The lowest CF that can achieve the target is around 70 percent with freely available electricity. In Case 6A, the highest electricity price that can achieve an LCOH of \$1/kg is around \$16/MWh at a CF of 95 percent. The lowest CF that can achieve the target has significantly decreased to around 20 percent with freely available electricity.

Exhibit 5-10. LCOH sensitivity to electricity price and CF

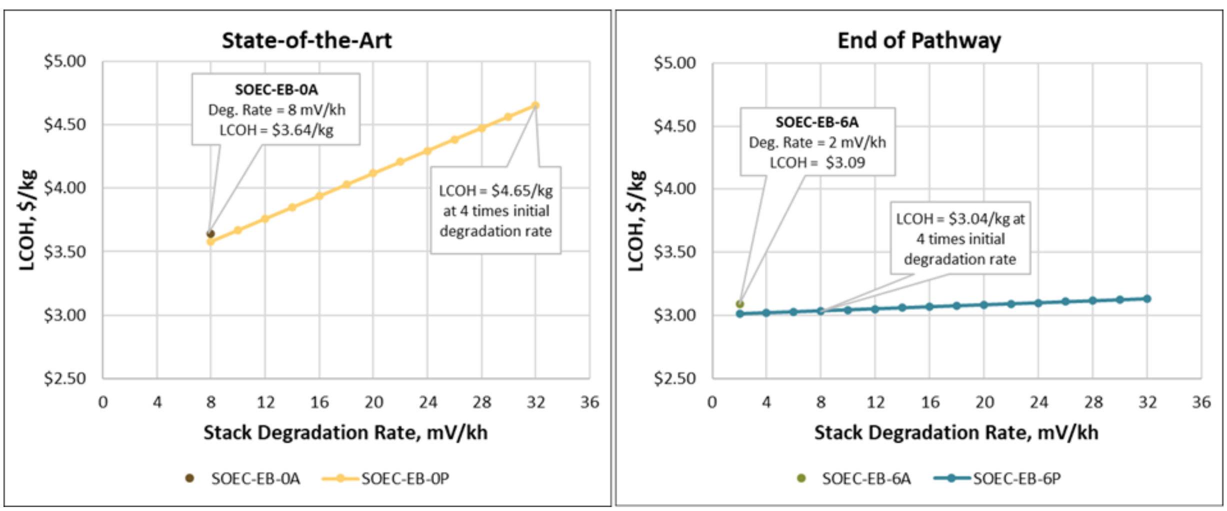


5.4 Other Analyses

5.4.1 Elevated Degradation Rates for Pressurized SOEC

SOEC stacks operated at 8 bar have been shown to degrade up to 4 times faster than stacks operated at atmospheric pressure. In the main analysis, it is assumed that the atmospheric and pressurized configurations have the same degradation rate. Here, the effect of increased degradation rates for the pressurized SOEC is examined. The sensitivity analysis presented in Exhibit 5-11 shows the effect on the LCOH of increasing the pressurized SOEC degradation rate by up to 4 times above the baseline rate. At the start of the pathway (Case 0P) the LCOH is highly sensitive to the degradation rate. Only a modest increase in the degradation rate to 10 mV/kh is required for the pressurized configuration's LCOH to exceed the atmospheric configuration's LCOH. A 4-fold increase in the degradation rate to 32 mV/kh increases the LCOH to $4.65/kg, exceeding the atmospheric configuration's LCOH by $1.01/kg. By the end of the pathway, the LCOH of the pressurized system is significantly less sensitive to the degradation rate. A 4-fold increase in the degradation rate to 8 mV/kh increases the LCOH to $3.04/kg, still less than the atmospheric system's LCOH of $3.09/kg.

Exhibit 5-11. LCOH sensitivity to pressurized SOEC degradation rate



5.4.2 Electricity Prices Required for Hydrogen Shot Targets

As shown in figures above, electricity prices below $60/MWh are required to reach the Hydrogen Shot targets even if all the technology improvements along the pathway are realized. The electricity prices required to reach the intermediate $2/kg target and ultimate $1/kg target are shown in Exhibit 5-12 and Exhibit 5-13, respectively. At the start of the pathway, both configurations require an electricity price of about $26/MWh to achieve an LCOH of $2/kg. By the end of the pathway, the electricity price required has increased to $37/MWh for the atmospheric system and $38/MWh for the pressurized system. The $1/kg target requires even lower electricity prices to achieve. Both configurations require a $5/MWh electricity price at the start of the pathway. The required price increases to $16/MWh by the end of the pathway for both configurations.

Exhibit 5-12. Electricity price needed for an LCOH of $2/kg H_2

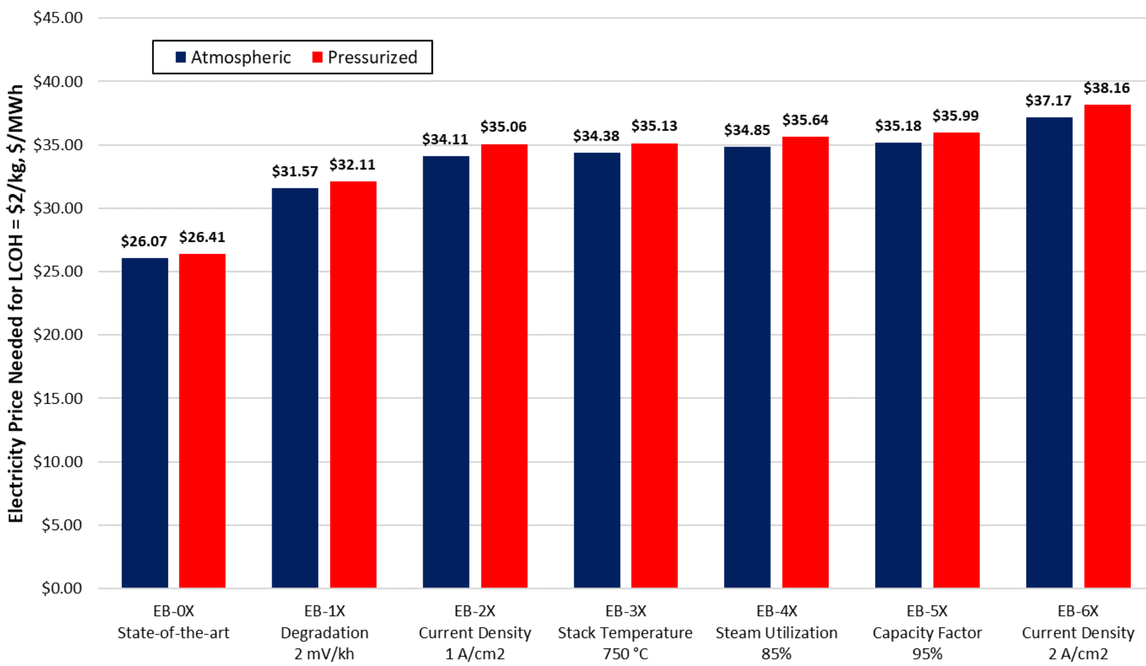
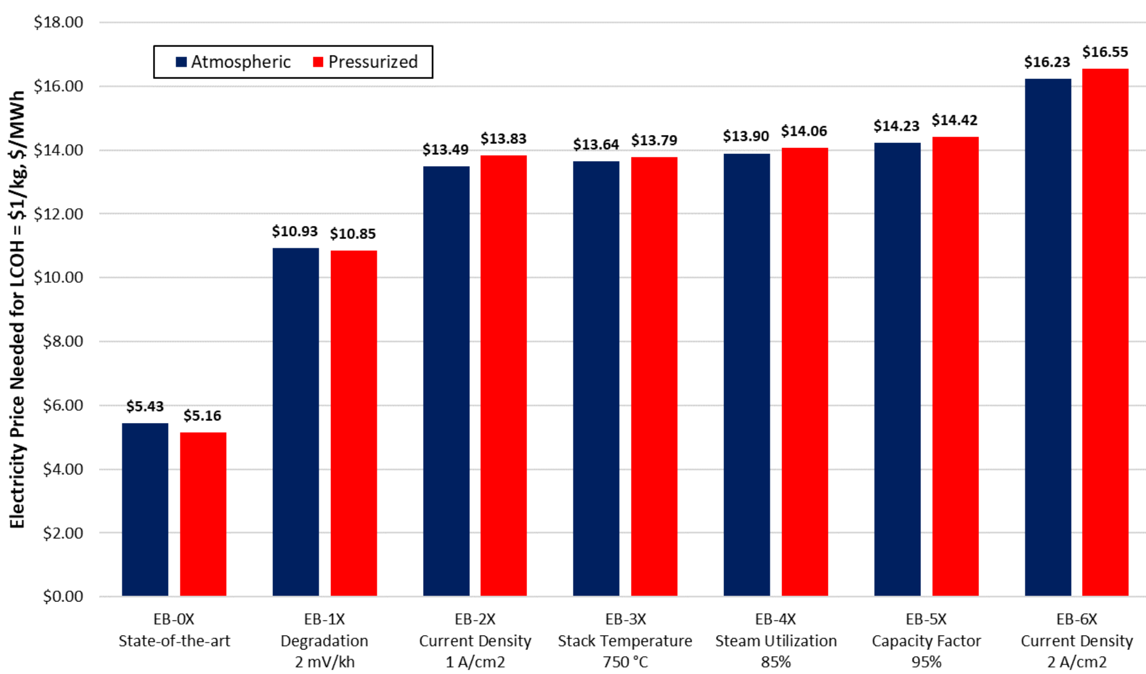


Exhibit 5-13. Electricity price needed for an LCOH of $1/kg H_2



6 CONCLUSIONS

The R&D efforts identified here can lead to modest improvements in SOEC system performance. Over both the atmospheric and pressurized pathways, the efficiency on an LHV basis increased by 1 percentage point. Lower operating temperatures and increased steam utilization can lead to slight efficiency improvements, but these improvements translate to a few cents decrease in the LCOH at an electricity price of $60/MWh. Pressurized systems are 2 percentage points more efficient than atmospheric systems largely due to the reduced hydrogen compression load. However, the increased efficiency does not translate to significant LCOH reductions. Due to increases in capital cost, this only translates to a $0.06–0.08 reduction in LCOH with further diminishing returns as electricity gets less expensive. The slight cost advantage of pressurized SOEC relative to atmospheric SOEC must be weighed against the additional complexities and uncertainties generally associated with a pressurized SOEC system that are not valorized here. Further, the large uncertainty in degradation rates at elevated pressures makes it unclear if pressurized systems would have lower LCOHs in practice. Literature suggests that SOEC could degrade four times faster when operated at 8 bar compared to 1 bar. At the start of the pathway a four times degradation rate would make a pressurized SOEC significantly more expensive than an atmospheric one. At the end of the pathway a pressurized SOEC with a four times degradation rate remains cheaper than an atmospheric SOEC due to the large reduction in stack costs.

At an electricity price of $60/MWh, the LCOH reduction along the pathway was ≈$0.55/kg or 15 percent relative to the reference case. However, the LCOH reduction (without considering the electricity price) over both pathways was about $0.50/kg or 70 percent with respect to the reference case. Reductions in SOEC degradation rate and increases in current density were shown to have the largest impacts on the LCOH sans the electricity price. Decreasing the degradation rate from 8 to 2 mV/kh contributed over 50 percent of the total LCOH reduction (without electricity) and increasing the current density from 0.5 to 1.0 mA/cm^2 contributed about 25 percent of the total LCOH reduction (without electricity).

Technology improvements along the R&D pathway have a significant impact on the electricity price needed to reach the Hydrogen Shot production targets. From start to finish, the electricity price (at 95 percent CF) needed to reach the intermediate target of $2/kg increases from $26/MWh to $36/MWh for both pathways. The electricity price needed to reach $1/kg increases from $5/MWh to $16/MWh.

The study has revealed a few promising avenues for achieving the Hydrogen Shot target of $1/kg hydrogen produced. The significant capital cost reductions along the pathway reduce the penalty for operating at low CF. This may enable SOEC systems to economically take advantage of cheap electricity from variable renewable sources while idling when electricity prices are high. More advanced configurations could operate reversibly, producing power when electricity prices are high to subsidize their H_2 production. Additionally, completely replacing the auxiliary load of the electric boiler with free waste heat decreases the LCOH by $0.50/kg at an electricity price of $60/MWh. This effect is less pronounced at lower electricity prices (e.g., at $30/MWh, the LCOH reduction would be closer to $0.25/kg). Opportunities for industrial heat integration should be analyzed in future studies.

7 REFERENCES

[1] DOE Hydrogen and Fuel Cell Technologies Office, "DOE Hydrogen Shot," [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[2] S. S. Kumar and H. Lim, "An overview of water electrolysis technologies for green hydrogen production," *Energy Reports,* vol. 8, pp. 13793-13813, 2022.

[3] MULTIPLHY Project, "MultiPLHY Flyer A5," [Online]. Available: https://multiplhy-project.eu/Documents/(Flyer)_Multiplhy_A5.pdf.

[4] SalzgitterAG, "Project GrInHy2.0," [Online]. Available: https://salcos.salzgitter-ag.com/en/grinhy-20.html.

[5] NETL, "Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies," U.S. Department of Energy, Pittsburgh, PA, 2021.

[6] D. Peterson and E. Miller, "Hydrogen Production Cost from Solid Oxide Electrolysis," DOE Hydrogen and Fuel Cells Program Record, 2016.

[7] IDAES, "SOEC Simple Design Model," [Online]. Available: https://idaes-pse.readthedocs.io/en/stable/reference_guides/model_libraries/power_generation/unit_models/soec_design.html. [Accessed 29 March 2024].

[8] NETL, "Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology: Revision 4 Report," U.S. Department of Energy, Pittsburgh, PA, 2019.

[9] 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.

[10] NETL, "Direct Air Capture Studies: Sorbent System," U.S. Department of Energy, Pittsburgh, PA, 2022.

[11] V. N. Nguyen, Q. Fang, U. Packbier and L. Blum, "Long-term tests of a Jülich planar short stack with reversible solid oxide cells in both fuel cell and electrolysis modes," *International Journal of Hydrogen Energy,* vol. 38, no. 11, pp. 4281-4290, 2013.

[12] Q. Fu, J. Schefold, A. Brisse and J. Nielsen, "Durability Testing of a High-Temperature Steam Electrolyzer Stack at 700 °C," *Fuel Cells,* vol. 14, no. 3, pp. 395-402, 2014.

[13] G. Corre and A. Brisse, "9000 Hours Operation of a 25 Solid Oxide Cells Stack in Steam Electrolysis Mode," *ECS Transactions,* vol. 68, 2015.

[14] G. Rinaldi, S. Diethelm, E. Oveisi, P. Burdet, J. Van Herle, D. Montinaro, Q. Fu and A. Brisse, "Post-test Analysis on a Solid Oxide Cell Stack Operated for 10,700 Hours in Steam Electrolysis Mode," *Fuel Cells,* vol. 17, no. 4, pp. 541-549, 2017.

[15] S. Megel, C. Dosch, S. Rothe, C. Folgner, N. Trofimenko, A. Rost, M. Kusnezoff, E. Reichelt, M. Jahn and A. Michaelis, "Co-Electrolysis with CFY-Stacks," *ECS Transactions,* vol. 78, 2017.

[16] Q. Fang, C. E. Frey, N. H. Menzler and L. Blum, "Electrochemical Performance and Preliminary Post-Mortem Analysis of a Solid Oxide Cell Stack with 20,000 h of Operation," *Journal of The Electrochemical Society,* vol. 165, 2018.

[17] E. Tang, T. Wood, C. Brown, M. Casteel, M. Pastula, M. Richards and R. Petri, "Solid Oxide Based Electrolysis and Stack Technology with Ultra-High Electrolysis Current Density (>3A/cm2) and Efficiency," United States, 2018.

[18] M. Lang, S. Raab, M. S. Lemcke, C. Bohn and M. Pysik, "Long Term Behavior of Solid Oxide Electrolyser Stacks," *ECS Transactions,* vol. 91, 2019.

[19] C. Geipel, K. Hauptmeier, K. Herbrig, F. Mittmann, M. Münch, M. Pötschke, L. Reichel, T. Strohbach, T. Seidel and A. Surrey, "Stack Development and Industrial Scale-Up," *ECS Transactions,* vol. 91, 2019.

[20] M. Riedel, M. Heddrich and K. Friedrich, "Analysis of pressurized operation of 10 layer solid oxide electrolysis stacks," *International Journal of Hydrogen Energy,* vol. 44, no. 10, pp. 4570-4581, 2019.

[21] A. Léon, A. Micero, B. Ludwig and A. Brisse, "Effect of scaling-up on the performance and degradation of long-term operated electrolyte supported solid oxide cell, stack and module in electrolysis mode," *Journal of Power Sources,* vol. 510, 2021.

[22] S. N. Sampathkumar, P. Aubin, K. Couturier, X. Sun, B. R. Sudireddy, S. Diethelm, M. Pérez-Fortes and J. Van Herle, "Degradation study of a reversible solid oxide cell (rSOC) short stack using distribution of relaxation times (DRT) analysis," *International Journal of Hydrogen Energy,* vol. 47, no. 18, pp. 10175-10193, 2022.

[23] M. Riedel, M. Heddrich, A. Ansar, Q. Fang, L. Blum and K. Friedrich, "Pressurized operation of solid oxide electrolysis stacks: An experimental comparison of the performance of 10-layer stacks with fuel electrode and electrolyte supported cell concepts," *Journal of Power Sources,* vol. 475, 2020.

[24] NETL, "Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology," U.S. Department of Energy, Pittsburgh, PA, Revision 4 2019.

[25] NETL, "Cost and Performance for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity," U.S. Department of Energy, Pittsburgh, PA, Revision 4, June 2019.

[26] International Organization for Standardization, "ISO 14687:2019 Hydrogen fuel quality - Product specification," 2019.

[27] NETL, "Techno-Economic Analysis of Natural Gas Fuel Cell Plant Configurations," U.S. Department of Energy, Pittsburgh, PA, April 8, 2015.

[28] 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.

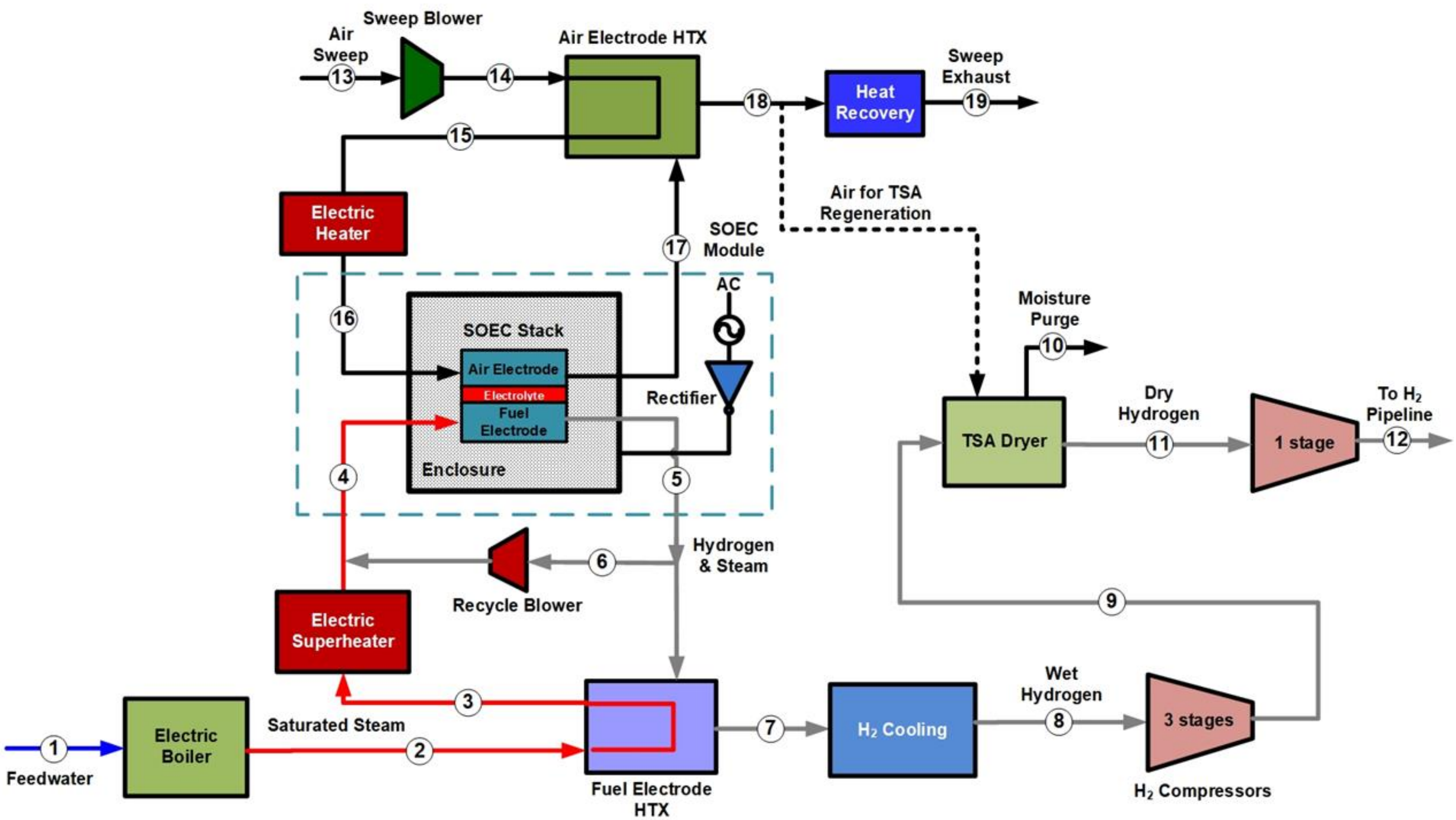
[29] BASF, "Adsorbent Solutions for Compressed Air Drying," January 2021. [Online]. [Accessed December 2022].

Appendix: Additional Case Information

Detailed stream table data, energy and mass balance diagrams, and other performance and cost information for each case and step along the pathway are presented here.

Atmospheric Cases

Exhibit A-1. BFD for all atmospheric cases



CASE 0A

Exhibit A-2. Case 0A stream table

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	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
C_3H_8	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.4000	0.8000	0.8000	0.8000	0.9655	0.9986
H_2O	1.0000	1.0000	1.0000	0.6000	0.2000	0.2000	0.2000	0.0345	0.0014
N_2	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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,640	18,079	18,079	36,158	36,158	18,079	18,079	14,980	14,483
V-L Flowrate (kg/h)	299,778	325,696	325,696	419,991	188,590	94,295	94,295	38,472	29,521
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	145	720	853	852	852	163	30	30
Pressure (MPa, abs)	0.10	0.13	0.12	0.12	0.12	0.12	0.12	0.10	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,770.89	3,975.64	4,856.00	6,825.39	6,825.39	2,664.16	943.00	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,200.46	-11,995.71	-10,031.30	-4,317.62	-4,317.62	-8,478.84	-3,194.04	-87.51
Density (kg/m^3)	1,003.6	0.7	0.3	0.1	0.1	0.1	0.2	0.1	2.1
V-L Molecular Weight	18.015	18.015	18.015	11.616	5.216	5.216	5.216	2.568	2.038
V-L Flowrate (lb_{mol}/h)	36,685	39,857	39,857	79,714	79,714	39,857	39,857	33,026	31,930
V-L Flowrate (lb/h)	660,897	718,037	718,037	925,922	415,770	207,885	207,885	84,816	65,082
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	294	1,329	1,567	1,566	1,566	325	86	86
Pressure (psia)	14.7	18.2	17.4	17.2	17.0	17.0	16.8	14.8	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,191.3	1,709.2	2,087.7	2,934.4	2,934.4	1,145.4	405.4	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,675.2	-5,157.2	-4,312.7	-1,856.2	-1,856.2	-3,645.2	-1,373.2	-37.6
Density (lb/ft^3)	62.650	0.041	0.016	0.009	0.004	0.004	0.010	0.006	0.132

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

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

Exhibit A-2. Case 0A stream table (cont'd)

	10	11	12	13	14	15	16	17	18	19
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077
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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,319	14,319	33,032	33,032	33,032	33,032	40,265	40,265	40,265
V-L Flowrate (kg/h)	654	28,867	28,867	953,124	953,124	953,124	953,124	1,184,546	1,184,546	1,184,546
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	31	830	850	854	218	170
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.12	0.11	0.11	0.11	0.11	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	47.31	913.18	936.55	927.92	231.22	182.79
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	-85.41	780.45	803.83	816.66	119.95	71.52
Density (kg/m³)	4.7	2.1	5.0	1.2	1.4	0.4	0.3	0.3	0.8	0.8
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,567	31,567	72,824	72,824	72,824	72,824	88,768	88,768	88,768
V-L Flowrate (lb/h)	1,441	63,641	63,641	2,101,278	2,101,278	2,101,278	2,101,278	2,611,478	2,611,478	2,611,478
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	88	1,526	1,562	1,570	424	338
Pressure (psia)	385.0	383.3	939.7	14.7	17.2	16.4	15.9	15.5	15.3	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	20.3	392.6	402.6	398.9	99.4	78.6
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	-36.7	335.5	345.6	351.1	51.6	30.7
Density (lb/ft³)	0.292	0.129	0.314	0.076	0.084	0.022	0.021	0.021	0.047	0.051

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

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

Exhibit A-3. Case 0A plant performance summary

Performance Summary	
Total Gross Power, kWe	**0**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	255,190
Hydrogen Compression, kWe	62,524
Balance of Plant, kWe	50,326
Total Auxiliaries, MWe	**368**
Net Power, MWe	**-1,399.0**
Hydrogen Production, kg/h (lb/h)	**28,867 (63,641)**
Energy Efficiency,[A] % HHV (% LHV)	81.3 (68.8)
Electric Input per Kilogram, kWh/kg	48.5
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,137,836 (962,123)
Raw Water Withdrawal, m^3/min (gpm)	7.7 (2,028)
Raw Water Consumption, m^3/min (gpm)	6.4 (1,698)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-4. Case 0A power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Air Electrode Blowers, kWe	4,694
Circulating Water Pumps, kWe	700
Cooling Tower Fans, kWe	360
Electric Boiler, kWe	255,190
Electric Steam Superheater, kWe	27,375
Electric Sweep Heater, kWe	6,188
Feedwater Pumps, kWe	76
Fuel Electrode Recycle Blowers, kWe	762
Ground Water Pumps, kWe	180
Hydrogen Compressor, kWe	62,524
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,700
Total Auxiliaries, MWe	**368**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,399**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-5. Case 0A carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (262)	Air-Electrode Sweep Exhaust (CO_2)	119 (262)
Total	**119 (262)**	**Total**	**119 (262)**

Exhibit A-6. Case 0A 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)
Electrolysis Steam	5.0 (1,322)	–	5.0 (1,322)	–	5.0 (1,322)
Deaerator Vent	–	–	–	0.0 (3.4)	0.0 (-3.4)
Boiler Blowdown	–	–	–	0.6 (168)	-0.6 (-168)
Cooling Tower	2.7 (706)	–	2.7 (706)	0.6 (159)	2.1 (547)
Total	**7.7 (2,028)**	**–**	**7.7 (2,028)**	**1.2 (330)**	**6.4 (1,698)**

Exhibit A-7. Case 0A overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	29 (27)	–	29 (27)
Auxiliary Power	–	–	5,036 (4,773)	5,036 (4,773)
Total	**0.0 (0.0)**	**58 (55)**	**5,036 (4,773)**	**5,095 (4,829)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,096 (3,882)	13 (12)	–	4,109 (3,895)
Sweep Exhaust	–	217 (205)	–	217 (205)
Motor Losses and Design Allowances	–	7.1 (7.1)	–	7.1 (7.1)
Cooling Tower Load[A]	–	349 (331)	–	349 (331)
Boiler Blowdown	–	7.7 (7.3)	–	7.7 (7.3)
Process Vents[B]	–	0.5 (0.4)	–	0.5 (0.4)
Ambient Losses[C]	–	322 (305)	–	322 (305)
Total	**4,096 (3,882)**	**916 (868)**	**0.0 (0.0)**	**5,012 (4,751)**
Unaccounted Energy[D]	–	–	–	83 (78)

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-8. Case 0A energy and mass balance diagram

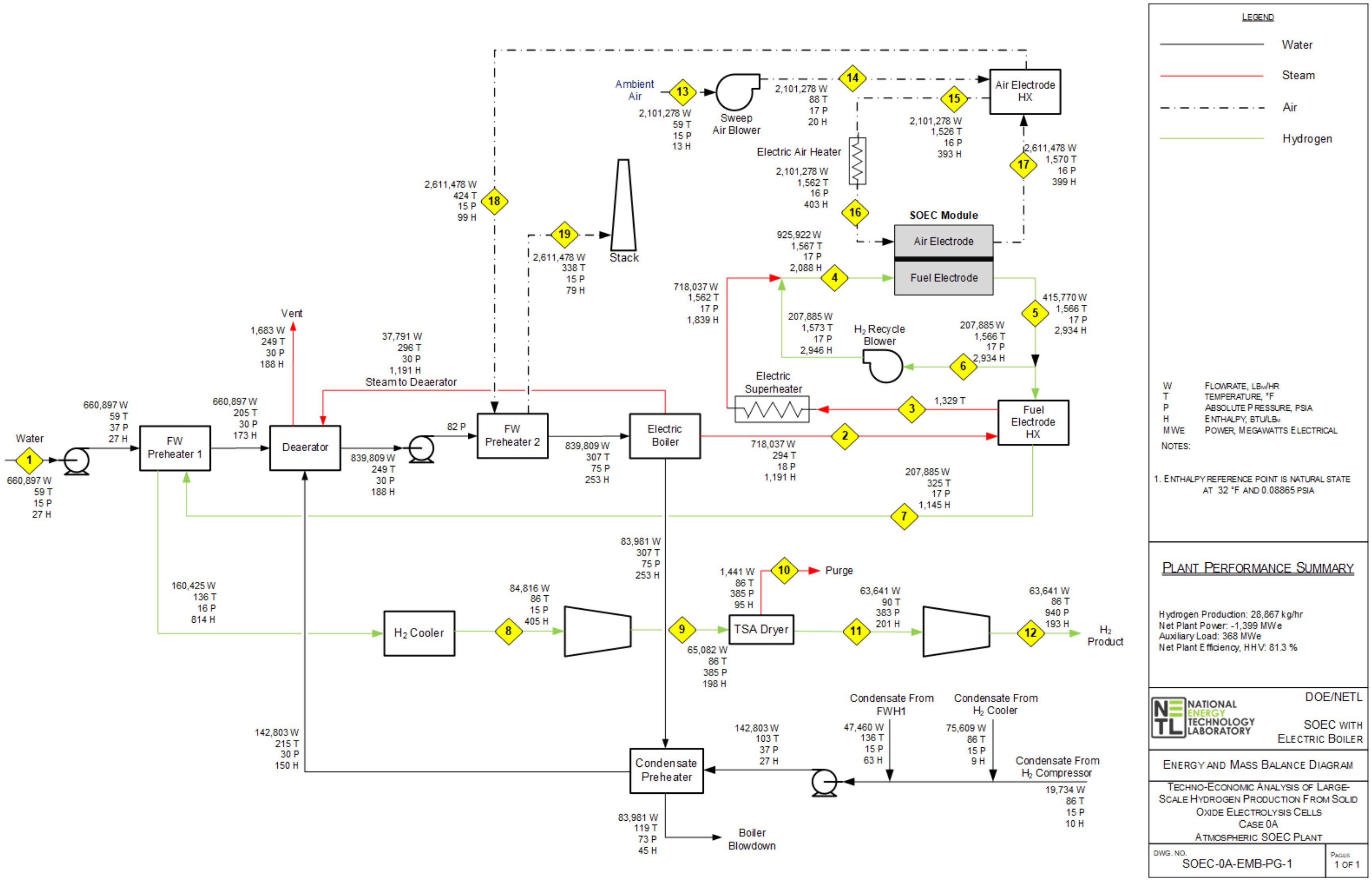


Exhibit A-9. Case 0A total plant cost details

	Case:	SOEC-EB-0A	State-of-the-Art SOEC				Estimate Type:			Conceptual		
	Plant Size (kg H_2/day):	692,805	Plant Size (MW net):			1,399	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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$172,792	$34,558	$0	$31,103	$238,453	$344	$170
1.2	Container	$0	$0	$0	$0	$5,184	$1,037	$0	$933	$7,154	$10	$5
1.3	Insulation	$0	$0	$0	$0	$2,304	$461	$0	$415	$3,179	$5	$2
1.4	Module Assembly	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$11	$6
1.5	Air Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$11	$6
1.6	Fuel Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$11	$6
1.8	Module Current Collectors	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.9	Module I&C	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.10	Rectifier	$0	$0	$0	$0	$39,166	$7,833	$0	$7,050	$54,049	$78	$39
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$242,485**	**$48,497**	**$0**	**$43,647**	**$334,629**	**$483**	**$239**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Blower	$0	$0	$0	$0	$1,141	$228	$0	$205	$1,574	$2	$1
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$24,478	$4,896	$0	$4,406	$33,779	$49	$24
2.3	Hydrogen Recycle Blower	$0	$0	$0	$0	$812	$162	$0	$146	$1,120	$2	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$16,352	$3,270	$0	$2,943	$22,566	$33	$16
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,951	$390	$0	$351	$2,693	$4	$2
2.6	Section and Overall Assembly	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
2.7	Section I&C	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$46,685**	**$9,337**	**$0**	**$8,403**	**$64,426**	**$93**	**$46**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,322	$864	$0	$778	$5,964	$9	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,804	$961	$0	$1,153	$6,918	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,886	$377	$0	$339	$2,602	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,934	$1,987	$0	$2,384	$14,304	$21	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$1,048	$210	$0	$189	$1,446	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,979	$996	$0	$1,195	$7,170	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$26,973**	**$5,395**	**$0**	**$6,038**	**$38,405**	**$55**	**$27**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$430	$86	$0	$77	$593	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$33,194	$6,639	$0	$5,975	$45,807	$66	$33
4.3	Electric Superheaters	$0	$0	$0	$0	$2,982	$596	$0	$537	$4,115	$6	$3
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$978	$196	$0	$176	$1,349	$2	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$545	$109	$0	$98	$752	$1	$1

	Case:	SOEC-EB-0A	State-of-the-Art SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	692,805	Plant Size (MW net):			1,399			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 H_2/day]	$/kW (net)
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$20,396	$4,079	$0	$3,671	$28,147	$41	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$58,782**	**$11,756**	**$0**	**$10,581**	**$81,119**	**$117**	**$58**
	7					**Ductwork, & Stack**						
7.3	Ductwork	$0	$0	$0	$0	$692	$138	$0	$125	$955	$1	$1
7.4	Stack	$0	$0	$0	$0	$4,627	$925	$0	$833	$6,386	$9	$5
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$590	$118	$0	$142	$850	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,909**	**$1,182**	**$0**	**$1,099**	**$8,190**	**$12**	**$6**
	9					**Cooling Water System**						
9.1	Cooling Towers	$0	$0	$0	$0	$3,773	$755	$0	$679	$5,206	$8	$4
9.2	Circulating Water Pumps	$0	$0	$0	$0	$412	$82	$0	$74	$569	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,637	$927	$0	$835	$6,399	$9	$5
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,889	$378	$0	$340	$2,607	$4	$2
9.5	Make-up Water System	$0	$0	$0	$0	$596	$119	$0	$107	$823	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$610	$122	$0	$146	$879	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$12,176**	**$2,435**	**$0**	**$2,228**	**$16,840**	**$24**	**$12**
	11					**Accessory Electric Plant**						
11.2	Station Service Equipment	$0	$0	$0	$0	$11,778	$2,356	$0	$2,120	$16,254	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$18,176	$3,635	$0	$3,272	$25,082	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,529	$2,906	$0	$2,615	$20,050	$29	$14
11.5	Wire & Cable	$0	$0	$0	$0	$15,575	$3,115	$0	$2,804	$21,494	$31	$15
11.6	Protective Equipment	$0	$0	$0	$0	$1,177	$235	$0	$212	$1,625	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,714	$543	$0	$489	$3,746	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,114	$423	$0	$380	$2,917	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$444	$89	$0	$107	$640	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$66,508**	**$13,302**	**$0**	**$11,998**	**$91,808**	**$133**	**$66**
	12					**Instrumentation & Control**						
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,482	$296	$74	$267	$2,120	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$730	$146	$0	$131	$1,007	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$321	$64	$16	$58	$459	$1	$0

	Case:	SOEC-EB-0A	State-of-the-Art SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	692,805	Plant Size (MW net):			1,399		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 H_2/day]	$/kW (net)
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,434	$2,287	$572	$2,058	$16,351	$24	$12
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,580	$916	$229	$824	$6,550	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,104	$421	$105	$379	$3,008	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,652**	**$4,130**	**$996**	**$3,717**	**$29,496**	**$43**	**$21**
	13					**Improvements to Site**						
13.1	Site Preparation	$0	$0	$0	$0	$17,065	$3,413	$0	$4,096	$24,573	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,731	$1,146	$0	$1,375	$8,253	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,855	$971	$0	$1,165	$6,991	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,651**	**$5,530**	**$0**	**$6,636**	**$39,817**	**$57**	**$28**
	14					**Buildings & Structures**						
14.4	Administration Building	$0	$0	$0	$0	$771	$154	$0	$139	$1,064	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$26	$5	$0	$5	$36	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$468	$94	$0	$84	$645	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,135	$227	$0	$204	$1,567	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$852	$170	$0	$153	$1,176	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$634	$127	$0	$114	$874	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,131	$226	$0	$204	$1,560	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,017**	**$1,003**	**$0**	**$903**	**$6,924**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$512,838**	**$102,568**	**$996**	**$95,252**	**$711,654**	**$1,027**	**$509**

Exhibit A-10. Case 0A owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$4,750	$7	$3
1 Month Maintenance Materials	$795	$1	$1
1 Month Non-Fuel Consumables	$197	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$14,233	$21	$10
Total	**$19,976**	**$29**	**$14**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$226	$0	$0
0.5% of TPC (spare parts)	$3,558	$5	$3
Total	**$3,784**	**$5**	**$3**
Other Costs			
Initial Cost for Catalyst and Chemicals	$482	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$106,748	$154	$76
Financing Costs	$19,215	$28	$14
Total Overnight Costs (TOC)	**$862,159**	**$1,244**	**$616**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$922,339**	**$1,331**	**$659**

Exhibit A-11. Case 0A initial and annual O&M costs

Case:	SOEC-EB-0A		State-of-the-Art SOEC		Cost Base:		Dec 2018
Plant Size (kg H_2/day):	**692,805**	**Plant Size (MW net):**		**1,399**	**Capacity Factor (%):**		**90%**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3	$1.567
Maintenance Labor:					$5,408,567	$8	$3.866
Administrative & Support Labor:					$1,900,189	$3	$1.358
Property Taxes and Insurance:					$14,233,070	$21	$10.174
Total:					**$23,734,016**	**$34**	**$16.965**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh)**
Maintenance Material:					$8,590,076	$0.03774	$0.77883
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		2.33	158.28	$68.21	$79,177,245	$0.34790	$7.17871
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,460	$1.90	$0	$911,360	$0.00400	$0.08263
Makeup and Wastewater Treatment Chemicals (ton):	0	4.35	$550	$0	$785,867	$0.00345	$0.07125
Hydrogen Drying Sorbent (lb):	48,237	132.2	$10	$482,368	$434,131	$0.00191	$0.03936
Subtotal:				**$482,368**	**$2,131,359**	**$0.00937**	**$0.19324**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	132.2	$0.02	$0	$825	$0.00000	$0.00007
Subtotal:				**$0**	**$825**	$0.00000	$0.00007
Variable Operating Costs Total:				**$482,368**	**$89,899,506**	**$0.04711**	**$0.97215**
Electricity Cost							
Electricity (MWh):	0	33,575	$60.00	$0	$661,767,325	$2.90776	$60.00000
Total:				**$0**	**$661,767,325**	**$2.90776**	**$60.00000**

Exhibit A-12. Case 0A LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.24	7%
Fixed	0.10	3%
Variable	0.40	11%
Electricity	2.91	80%
Total	**3.64**	**N/A**

Case 1A

Exhibit A-13. Case 1A stream table

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	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
C_3H_8	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.4000	0.8000	0.8000	0.8000	0.9655	0.9986
H_2O	1.0000	1.0000	1.0000	0.6000	0.2000	0.2000	0.2000	0.0345	0.0014
N_2	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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,640	18,079	18,079	36,158	36,158	18,079	18,079	14,980	14,483
V-L Flowrate (kg/h)	299,778	325,696	325,696	419,991	188,590	94,295	94,295	38,472	29,521
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	145	720	853	852	852	163	30	30
Pressure (MPa, abs)	0.10	0.13	0.12	0.12	0.12	0.12	0.12	0.10	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,770.89	3,975.64	4,856.00	6,825.39	6,825.39	2,664.16	943.00	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,200.46	-11,995.71	-10,031.30	-4,317.62	-4,317.62	-8,478.84	-3,194.04	-87.51
Density (kg/m³)	1,003.6	0.7	0.3	0.1	0.1	0.1	0.2	0.1	2.1
V-L Molecular Weight	18.015	18.015	18.015	11.616	5.216	5.216	5.216	2.568	2.038
V-L Flowrate (lb_{mol}/h)	36,685	39,857	39,857	79,714	79,714	39,857	39,857	33,026	31,930
V-L Flowrate (lb/h)	660,897	718,037	718,037	925,922	415,770	207,885	207,885	84,816	65,082
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	294	1,329	1,567	1,566	1,566	325	86	86
Pressure (psia)	14.7	18.2	17.4	17.2	17.0	17.0	16.8	14.8	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,191.3	1,709.2	2,087.7	2,934.4	2,934.4	1,145.4	405.4	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,675.2	-5,157.2	-4,312.7	-1,856.2	-1,856.2	-3,645.2	-1,373.2	-37.6
Density (lb/ft³)	62.650	0.041	0.016	0.009	0.004	0.004	0.010	0.006	0.132

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

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

Exhibit A-13. Case 1A stream table (cont'd)

	10	11	12	13	14	15	16	17	18	19
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077
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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,319	14,319	33,032	33,032	33,032	33,032	40,265	40,265	40,265
V-L Flowrate (kg/h)	654	28,867	28,867	953,124	953,124	953,124	953,124	1,184,546	1,184,546	1,184,546
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	31	830	850	854	218	170
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.12	0.11	0.11	0.11	0.11	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	47.31	913.18	936.55	927.92	231.22	182.79
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	-85.41	780.45	803.83	816.66	119.95	71.52
Density (kg/m³)	4.7	2.1	5.0	1.2	1.4	0.4	0.3	0.3	0.8	0.8
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,567	31,567	72,824	72,824	72,824	72,824	88,768	88,768	88,768
V-L Flowrate (lb/h)	1,441	63,641	63,641	2,101,278	2,101,278	2,101,278	2,101,278	2,611,478	2,611,478	2,611,478
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	88	1,526	1,562	1,570	424	338
Pressure (psia)	385.0	383.3	939.7	14.7	17.2	16.4	15.9	15.5	15.3	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	20.3	392.6	402.6	398.9	99.4	78.6
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	-36.7	335.5	345.6	351.1	51.6	30.7
Density (lb/ft³)	0.292	0.129	0.314	0.076	0.084	0.022	0.021	0.021	0.047	0.051

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

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

Exhibit A-14. Case 1A plant performance summary

Performance Summary	
Total Gross Power, kWe	**0**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	255,190
Hydrogen Compression, kWe	62,524
Balance of Plant, kWe	50,326
Total Auxiliaries, MWe	**368**
Net Power, MWe	**-1,399.0**
Hydrogen Production, kg/h (lb/h)	**28,867 (63,641)**
Energy Efficiency,[A] % HHV (% LHV)	81.3 (68.8)
Electric Input per Kilogram, kWh/kg	48.5
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,137,836 (962,123)
Raw Water Withdrawal, m^3/min (gpm)	7.7 (2,028)
Raw Water Consumption, m^3/min (gpm)	6.4 (1,698)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-15. Case 1A power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Air Electrode Blowers, kWe	4,694
Circulating Water Pumps, kWe	700
Cooling Tower Fans, kWe	360
Electric Boiler, kWe	255,190
Electric Steam Superheater, kWe	27,375
Electric Sweep Heater, kWe	6,188
Feedwater Pumps, kWe	76
Fuel Electrode Recycle Blowers, kWe	762
Ground Water Pumps, kWe	180
Hydrogen Compressor, kWe	62,524
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,700
Total Auxiliaries, MWe	**368**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,399**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-16. Case 1A carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (262)	Air-Electrode Sweep Exhaust (CO_2)	119 (262)
Total	**119 (262)**	**Total**	**119 (262)**

Exhibit A-17. Case 1A 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)
Electrolysis Steam	5.0 (1,322)	–	5.0 (1,322)	–	5.0 (1,322)
Deaerator Vent	–	–	–	0.0 (3.4)	0.0 (-3.4)
Boiler Blowdown	–	–	–	0.6 (168)	-0.6 (-168)
Cooling Tower	2.7 (706)	–	2.7 (706)	0.6 (159)	2.1 (547)
Total	**7.7 (2,028)**	**–**	**7.7 (2,028)**	**1.2 (330)**	**6.4 (1,698)**

Exhibit A-18. Case 1A overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	29 (27)	–	29 (27)
Auxiliary Power	–	–	5,036 (4,773)	5,036 (4,773)
Total	**0.0 (0.0)**	**58 (55)**	**5,036 (4,773)**	**5,095 (4,829)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,096 (3,882)	13 (12)	–	4,109 (3,895)
Sweep Exhaust	–	217 (205)	–	217 (205)
Motor Losses and Design Allowances	–	7.1 (7.1)	–	7.1 (7.1)
Cooling Tower Load[A]	–	349 (331)	–	349 (331)
Boiler Blowdown	–	7.7 (7.3)	–	7.7 (7.3)
Process Vents[B]	–	0.5 (0.4)	–	0.5 (0.4)
Ambient Losses[C]	–	322 (305)	–	322 (305)
Total	**4,096 (3,882)**	**916 (868)**	**0.0 (0.0)**	**5,012 (4,751)**
Unaccounted Energy[D]	–	–	–	83 (78)

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-19. Case 1A energy and mass balance diagram (identical to Case 0A)

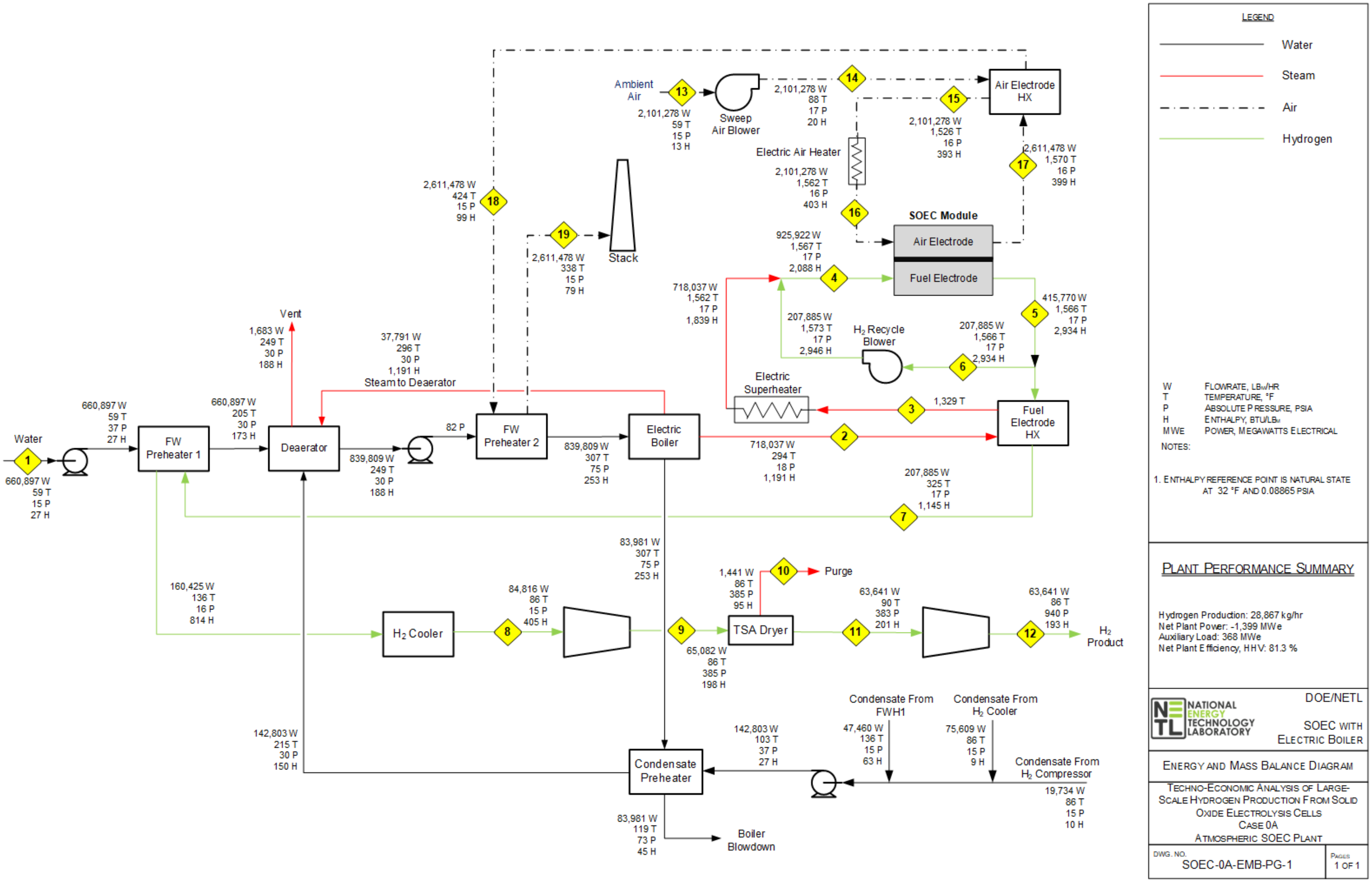


Exhibit A-20. Case 1A total plant cost details

	Case:	SOEC-EB-1A	Pathway Step 1 SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	692,805	Plant Size (MW net):			1,399			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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$172,792	$34,558	$0	$31,103	$238,453	$344	$170
1.2	Container	$0	$0	$0	$0	$5,184	$1,037	$0	$933	$7,154	$10	$5
1.3	Insulation	$0	$0	$0	$0	$2,304	$461	$0	$415	$3,179	$5	$2
1.4	Module Assembly	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$11	$6
1.5	Air Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$11	$6
1.6	Fuel Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$11	$6
1.8	Module Current Collectors	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.9	Module I&C	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.10	Rectifier	$0	$0	$0	$0	$39,166	$7,833	$0	$7,050	$54,049	$78	$39
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$242,485**	**$48,497**	**$0**	**$43,647**	**$334,629**	**$483**	**$239**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Blower	$0	$0	$0	$0	$1,141	$228	$0	$205	$1,574	$2	$1
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$24,478	$4,896	$0	$4,406	$33,779	$49	$24
2.3	Hydrogen Recycle Blower	$0	$0	$0	$0	$812	$162	$0	$146	$1,120	$2	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$16,352	$3,270	$0	$2,943	$22,566	$33	$16
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,951	$390	$0	$351	$2,693	$4	$2
2.6	Section and Overall Assembly	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
2.7	Section I&C	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$46,685**	**$9,337**	**$0**	**$8,403**	**$64,426**	**$93**	**$46**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,322	$864	$0	$778	$5,964	$9	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,804	$961	$0	$1,153	$6,918	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,886	$377	$0	$339	$2,602	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,934	$1,987	$0	$2,384	$14,304	$21	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$1,048	$210	$0	$189	$1,446	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,979	$996	$0	$1,195	$7,170	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$26,973**	**$5,395**	**$0**	**$6,038**	**$38,405**	**$55**	**$27**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$430	$86	$0	$77	$593	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$33,194	$6,639	$0	$5,975	$45,807	$66	$33
4.3	Electric Superheaters	$0	$0	$0	$0	$2,982	$596	$0	$537	$4,115	$6	$3
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$978	$196	$0	$176	$1,349	$2	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$545	$109	$0	$98	$752	$1	$1

	Case:	SOEC-EB-1A	Pathway Step 1 SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	692,805		Plant Size (MW net):		1,399		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 H_2/day]	$/kW (net)
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$20,396	$4,079	$0	$3,671	$28,147	$41	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$58,782**	**$11,756**	**$0**	**$10,581**	**$81,119**	**$117**	**$58**
7						Ductwork, & Stack						
7.3	Ductwork	$0	$0	$0	$0	$692	$138	$0	$125	$955	$1	$1
7.4	Stack	$0	$0	$0	$0	$4,627	$925	$0	$833	$6,386	$9	$5
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$590	$118	$0	$142	$850	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,909**	**$1,182**	**$0**	**$1,099**	**$8,190**	**$12**	**$6**
9						Cooling Water System						
9.1	Cooling Towers	$0	$0	$0	$0	$3,773	$755	$0	$679	$5,206	$8	$4
9.2	Circulating Water Pumps	$0	$0	$0	$0	$412	$82	$0	$74	$569	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,637	$927	$0	$835	$6,399	$9	$5
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,889	$378	$0	$340	$2,607	$4	$2
9.5	Make-up Water System	$0	$0	$0	$0	$596	$119	$0	$107	$823	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$610	$122	$0	$146	$879	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$12,176**	**$2,435**	**$0**	**$2,228**	**$16,840**	**$24**	**$12**
11						Accessory Electric Plant						
11.2	Station Service Equipment	$0	$0	$0	$0	$11,778	$2,356	$0	$2,120	$16,254	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$18,176	$3,635	$0	$3,272	$25,082	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,529	$2,906	$0	$2,615	$20,050	$29	$14
11.5	Wire & Cable	$0	$0	$0	$0	$15,575	$3,115	$0	$2,804	$21,494	$31	$15
11.6	Protective Equipment	$0	$0	$0	$0	$1,177	$235	$0	$212	$1,625	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,714	$543	$0	$489	$3,746	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,114	$423	$0	$380	$2,917	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$444	$89	$0	$107	$640	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$66,508**	**$13,302**	**$0**	**$11,998**	**$91,808**	**$133**	**$66**
12						Instrumentation & Control						
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,482	$296	$74	$267	$2,120	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$730	$146	$0	$131	$1,007	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$321	$64	$16	$58	$459	$1	$0

	Case:	SOEC-EB-1A	Pathway Step 1 SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	692,805	Plant Size (MW net):			1,399		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 H_2/day]	$/kW (net)
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,434	$2,287	$572	$2,058	$16,351	$24	$12
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,580	$916	$229	$824	$6,550	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,104	$421	$105	$379	$3,008	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,652**	**$4,130**	**$996**	**$3,717**	**$29,496**	**$43**	**$21**
13	**Improvements to Site**											
13.1	Site Preparation	$0	$0	$0	$0	$17,065	$3,413	$0	$4,096	$24,573	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,731	$1,146	$0	$1,375	$8,253	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,855	$971	$0	$1,165	$6,991	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,651**	**$5,530**	**$0**	**$6,636**	**$39,817**	**$57**	**$28**
14	**Buildings & Structures**											
14.4	Administration Building	$0	$0	$0	$0	$771	$154	$0	$139	$1,064	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$26	$5	$0	$5	$36	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$468	$94	$0	$84	$645	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,135	$227	$0	$204	$1,567	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$852	$170	$0	$153	$1,176	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$634	$127	$0	$114	$874	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,131	$226	$0	$204	$1,560	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,017**	**$1,003**	**$0**	**$903**	**$6,924**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$512,838**	**$102,568**	**$996**	**$95,252**	**$711,654**	**$1,027**	**$509**

Exhibit A-21. Case 1A owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$4,750	$7	$3
1 Month Maintenance Materials	$795	$1	$1
1 Month Non-Fuel Consumables	$197	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$14,233	$21	$10
Total	**$19,976**	**$29**	**$14**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$226	$0	$0
0.5% of TPC (spare parts)	$3,558	$5	$3
Total	**$3,784**	**$5**	**$3**
Other Costs			
Initial Cost for Catalyst and Chemicals	$482	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$106,748	$154	$76
Financing Costs	$19,215	$28	$14
Total Overnight Costs (TOC)	**$862,159**	**$1,244**	**$616**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$922,339**	**$1,331**	**$659**

Exhibit A-22. Case 1A initial and annual O&M costs

Case:	SOEC-EB-0A		State-of-the-Art SOEC		Cost Base:	Dec 2018	
Plant Size (kg H_2/day):	**692,805**	**Plant Size (MW net):**		**1,399**	**Capacity Factor (%):**		**90%**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.16	$1.57
Maintenance Labor:					$5,408,567	$7.81	$3.87
Administrative & Support Labor:					$1,900,189	$2.74	$1.36
Property Taxes and Insurance:					$14,233,070	$20.54	$10.17
Total:					**$23,734,016**	**$34.26**	**$16.97**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh)**
Maintenance Material:					$8,590,076	$0.04	$0.78
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	158.28	$15.98	$18,544,484	$0.08	$1.68
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,460	$1.90	$0	$911,360	$0.00400	$0.08263
Makeup and Wastewater Treatment Chemicals (ton):	0	4.35	$550	$0	$785,867	$0.00345	$0.07125
Hydrogen Drying Sorbent (lb):	48,237	132.2	$10	$482,368	$434,131	$0.00191	$0.03936
Subtotal:				**$482,368**	**$29,266,744**	**$0.05**	**$0.97**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	132.2	$0.02	$0	$825	$0.00000	$0.00007
Subtotal:				**$0**	**$825**	$0.00000	$0.00007
Variable Operating Costs Total:				**$482,368**	**$89,899,506**	**$0.04711**	**$0.97215**
Electricity Cost							
Electricity (MWh):	0	33,575	$60.00	$0	$661,767,325	$2.90776	$60.00000
Total:				**$0**	**$661,767,325**	**$2.90776**	**$60.00000**

Exhibit A-23. Case 1A LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.24	7%
Fixed	0.10	3%
Variable	0.13	4%
Electricity	2.91	86%
Total	**3.38**	**N/A**

CASE 2A

Exhibit A-24. Case 2A stream table

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	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
C_3H_8	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.4000	0.8000	0.8000	0.8000	0.9655	0.9986
H_2O	1.0000	1.0000	1.0000	0.6000	0.2000	0.2000	0.2000	0.0345	0.0014
N_2	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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,618	18,055	18,055	36,110	36,110	18,055	18,055	14,960	14,464
V-L Flowrate (kg/h)	299,384	325,269	325,269	419,440	188,342	94,171	94,171	38,421	29,482
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	145	722	854	854	854	163	30	30
Pressure (MPa, abs)	0.10	0.13	0.12	0.12	0.12	0.12	0.12	0.10	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,770.89	3,979.35	4,858.89	6,838.22	6,838.22	2,664.16	943.00	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,200.46	-11,991.99	-10,028.42	-4,304.79	-4,304.79	-8,478.84	-3,194.04	-87.51
Density (kg/m^3)	1,003.6	0.7	0.3	0.1	0.1	0.1	0.2	0.1	2.1
V-L Molecular Weight	18.015	18.015	18.015	11.616	5.216	5.216	5.216	2.568	2.038
V-L Flowrate (lb_{mol}/h)	36,637	39,805	39,805	79,609	79,609	39,805	39,805	32,982	31,888
V-L Flowrate (lb/h)	660,029	717,095	717,095	924,707	415,224	207,611	207,611	84,704	64,996
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	294	1,331	1,568	1,569	1,569	325	86	86
Pressure (psia)	14.7	18.2	17.4	17.2	17.0	17.0	16.8	14.8	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,191.3	1,710.8	2,088.9	2,939.9	2,939.9	1,145.4	405.4	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,675.2	-5,155.6	-4,311.4	-1,850.7	-1,850.7	-3,645.2	-1,373.2	-37.6
Density (lb/ft^3)	62.650	0.041	0.016	0.009	0.004	0.004	0.010	0.006	0.132

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

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

Exhibit A-24. Case 2A stream table (cont'd)

	10	11	12	13	14	15	16	17	18	19
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077
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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,300	14,300	32,989	32,992	32,992	32,992	40,211	40,211	40,211
V-L Flowrate (kg/h)	653	28,829	28,829	951,874	951,946	951,946	951,946	1,182,967	1,182,967	1,182,967
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	31	830	850	857	221	173
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.12	0.11	0.11	0.11	0.11	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	47.31	913.18	936.55	930.89	234.12	185.69
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	-85.41	780.45	803.83	819.63	122.86	74.43
Density (kg/m^3)	4.7	2.1	5.0	1.2	1.4	0.4	0.3	0.3	0.8	0.8
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,526	31,526	72,728	72,734	72,734	72,734	88,650	88,650	88,650
V-L Flowrate (lb/h)	1,439	63,557	63,557	2,098,524	2,098,683	2,098,683	2,098,683	2,607,997	2,607,997	2,607,997
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	88	1,526	1,562	1,574	429	343
Pressure (psia)	385.0	383.3	939.7	14.7	17.2	16.4	15.9	15.5	15.3	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	20.3	392.6	402.6	400.2	100.7	79.8
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	-36.7	335.5	345.6	352.4	52.8	32.0
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.084	0.022	0.021	0.021	0.047	0.050

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

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

Exhibit A-25. Case 2A plant performance summary

Performance Summary	
Total Gross Power, kWe	**0**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	254,855
Hydrogen Compression, kWe	62,442
Balance of Plant, kWe	49,931
Total Auxiliaries, MWe	**367**
Net Power, MWe	**-1,398.2**
Hydrogen Production, kg/h (lb/h)	**28,829 (63,557)**
Energy Efficiency,[A] % HHV (% LHV)	81.3 (68.7)
Electric Input per Kilogram, kWh/kg	48.5
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,136,337 (960,856)
Raw Water Withdrawal, m^3/min (gpm)	7.7 (2,025)
Raw Water Consumption, m^3/min (gpm)	6.4 (1,696)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-26. Case 2A power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Air Electrode Blowers, kWe	4,688
Circulating Water Pumps, kWe	700
Cooling Tower Fans, kWe	360
Electric Boiler, kWe	254,855
Electric Steam Superheater, kWe	27,003
Electric Sweep Heater, kWe	6,181
Feedwater Pumps, kWe	76
Fuel Electrode Recycle Blowers, kWe	763
Ground Water Pumps, kWe	180
Hydrogen Compressor, kWe	62,442
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,690
Total Auxiliaries, MWe	**367**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,398**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-27. Case 2A carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (262)	Air-Electrode Sweep Exhaust (CO_2)	119 (262)
Total	**119 (262)**	**Total**	**119 (262)**

Exhibit A-28. Case 2A 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)
Electrolysis Steam	5.0 (1,320)	–	5.0 (1,320)	–	5.0 (1,320)
Deaerator Vent	–	–	–	0.0 (3.4)	0.0 (-3.4)
Boiler Blowdown	–	–	–	0.6 (168)	-0.6 (-168)
Cooling Tower	2.7 (705)	–	2.7 (705)	0.6 (159)	2.1 (547)
Total	**7.7 (2,025)**	**–**	**7.7 (2,025)**	**1.2 (330)**	**6.4 (1,696)**

Exhibit A-29. Case 2A overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	29 (27)	–	29 (27)
Auxiliary Power	–	–	5,033 (4,771)	5,033 (4,771)
Total	**0.0 (0.0)**	**58 (55)**	**5,033 (4,771)**	**5,092 (4,826)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,091 (3,877)	13 (12)	–	4,104 (3,890)
Sweep Exhaust	–	220 (208)	–	220 (208)
Motor Losses and Design Allowances	–	7.1 (7.1)	–	7.1 (7.1)
Cooling Tower Load[A]	–	349 (330)	–	349 (330)
Boiler Blowdown	–	7.7 (7.3)	–	7.7 (7.3)
Process Vents[B]	–	0.5 (0.4)	–	0.5 (0.4)
Ambient Losses[C]	–	322 (305)	–	322 (305)
Total	**–**	**918 (871)**	**0.0 (0.0)**	**5,009 (4,748)**
Unaccounted Energy[D]	**–**	*83 (78)*	–	*83 (78)*

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-30. Case 2A energy and mass balance diagram

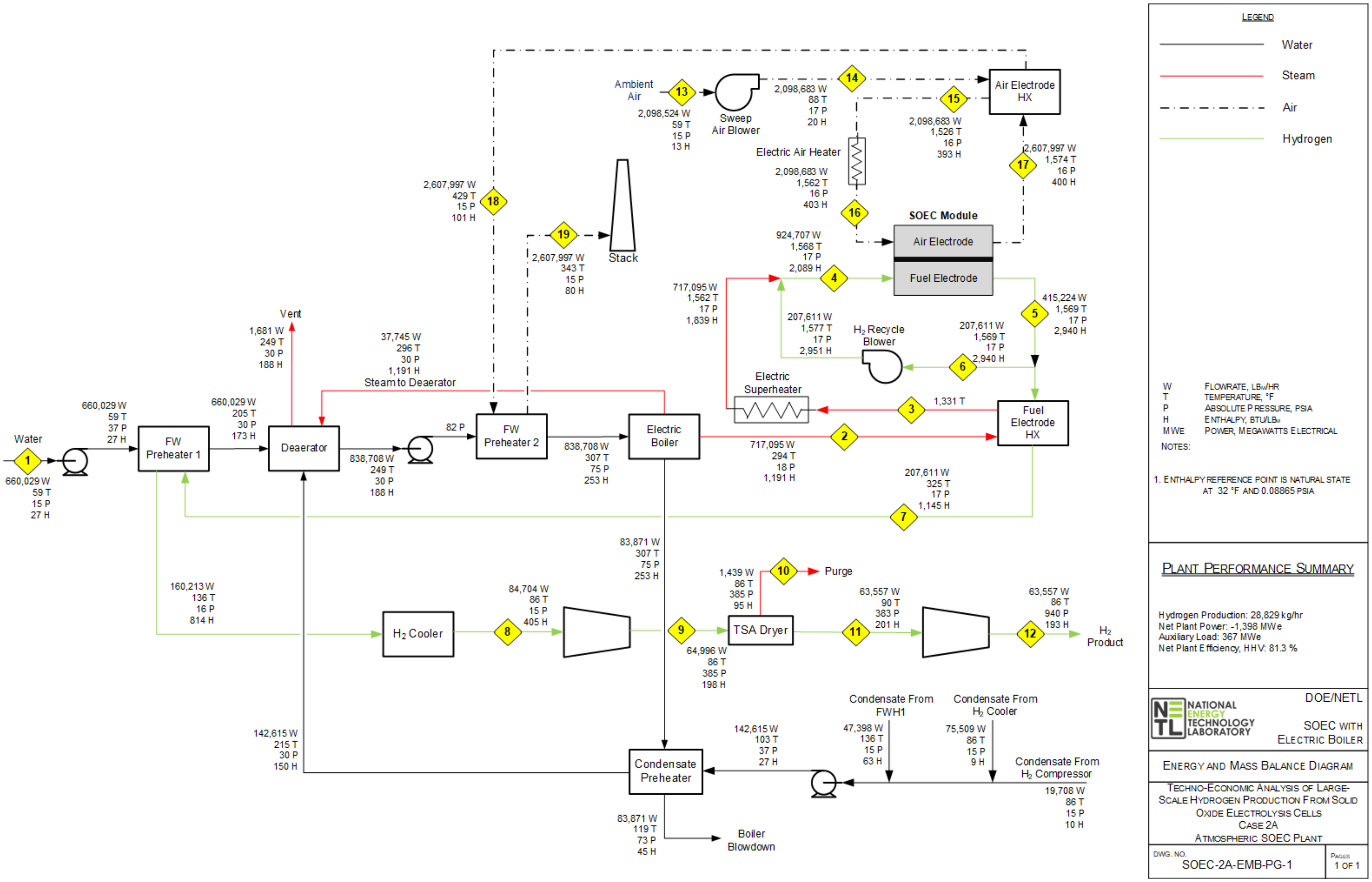


Exhibit A-31. Case 2A total plant cost details

	Case:	SOEC-EB-2A	Pathway Step 2 SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	691,893	Plant Size (MW net):			1,398			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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$89,183	$17,837	$0	$16,053	$123,073	$178	$88
1.2	Container	$0	$0	$0	$0	$2,675	$535	$0	$482	$3,692	$5	$3
1.3	Insulation	$0	$0	$0	$0	$1,189	$238	$0	$214	$1,641	$2	$1
1.4	Module Assembly	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.5	Air Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.6	Fuel Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.8	Module Current Collectors	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.9	Module I&C	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.10	Rectifier	$0	$0	$0	$0	$20,215	$4,043	$0	$3,639	$27,896	$40	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$125,153**	**$25,031**	**$0**	**$22,528**	**$172,712**	**$250**	**$124**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Blower	$0	$0	$0	$0	$925	$185	$0	$166	$1,276	$2	$1
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$23,383	$4,677	$0	$4,209	$32,269	$47	$23
2.3	Hydrogen Recycle Blower	$0	$0	$0	$0	$611	$122	$0	$110	$843	$1	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$16,349	$3,270	$0	$2,943	$22,561	$33	$16
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,288	$258	$0	$232	$1,778	$3	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
2.7	Section I&C	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$43,844**	**$8,769**	**$0**	**$7,892**	**$60,504**	**$87**	**$43**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,318	$864	$0	$777	$5,959	$9	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,799	$960	$0	$1,152	$6,911	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,883	$377	$0	$339	$2,599	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,923	$1,985	$0	$2,382	$14,289	$21	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$1,047	$209	$0	$188	$1,445	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,975	$995	$0	$1,194	$7,164	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$26,945**	**$5,389**	**$0**	**$6,032**	**$38,367**	**$55**	**$27**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$421	$84	$0	$76	$581	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$33,159	$6,632	$0	$5,969	$45,759	$66	$33
4.3	Electric Superheaters	$0	$0	$0	$0	$2,951	$590	$0	$531	$4,073	$6	$3
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$977	$195	$0	$176	$1,348	$2	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$544	$109	$0	$98	$751	$1	$1

	Case:	SOEC-EB-2A	Pathway Step 2 SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	691,893	Plant Size (MW net):			1,398		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 H_2/day]	$/kW (net)
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$20,377	$4,075	$0	$3,668	$28,121	$41	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$58,687**	**$11,737**	**$0**	**$10,564**	**$80,988**	**$117**	**$58**
7	Ductwork, & Stack											
7.3	Ductwork	$0	$0	$0	$0	$694	$139	$0	$125	$958	$1	$1
7.4	Stack	$0	$0	$0	$0	$4,644	$929	$0	$836	$6,409	$9	$5
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$592	$118	$0	$142	$853	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,930**	**$1,186**	**$0**	**$1,103**	**$8,220**	**$12**	**$6**
9	Cooling Water System											
9.1	Cooling Towers	$0	$0	$0	$0	$3,769	$754	$0	$678	$5,201	$8	$4
9.2	Circulating Water Pumps	$0	$0	$0	$0	$412	$82	$0	$74	$569	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,634	$927	$0	$834	$6,395	$9	$5
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,888	$378	$0	$340	$2,605	$4	$2
9.5	Make-up Water System	$0	$0	$0	$0	$596	$119	$0	$107	$823	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$610	$122	$0	$146	$878	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$12,167**	**$2,433**	**$0**	**$2,227**	**$16,827**	**$24**	**$12**
11	Accessory Electric Plant											
11.2	Station Service Equipment	$0	$0	$0	$0	$11,774	$2,355	$0	$2,119	$16,248	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$18,169	$3,634	$0	$3,270	$25,073	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,524	$2,905	$0	$2,614	$20,043	$29	$14
11.5	Wire & Cable	$0	$0	$0	$0	$15,570	$3,114	$0	$2,803	$21,486	$31	$15
11.6	Protective Equipment	$0	$0	$0	$0	$1,177	$235	$0	$212	$1,624	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,713	$543	$0	$488	$3,744	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,113	$423	$0	$380	$2,916	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$444	$89	$0	$107	$640	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$66,483**	**$13,297**	**$0**	**$11,994**	**$91,774**	**$133**	**$66**
12	Instrumentation & Control											
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,482	$296	$74	$267	$2,119	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$730	$146	$0	$131	$1,007	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$321	$64	$16	$58	$459	$1	$0

	Case:	SOEC-EB-2A	Pathway Step 2 SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	691,893	Plant Size (MW net):			1,398		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 H_2/day]	$/kW (net)
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,430	$2,286	$572	$2,057	$16,346	$24	$12
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,579	$916	$229	$824	$6,547	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,103	$421	$105	$379	$3,007	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,645**	**$4,129**	**$996**	**$3,716**	**$29,486**	**$43**	**$21**
	13					**Improvements to Site**						
13.1	Site Preparation	$0	$0	$0	$0	$17,060	$3,412	$0	$4,094	$24,566	$36	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,729	$1,146	$0	$1,375	$8,250	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,854	$971	$0	$1,165	$6,990	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,643**	**$5,529**	**$0**	**$6,634**	**$39,806**	**$58**	**$28**
	14					**Buildings & Structures**						
14.4	Administration Building	$0	$0	$0	$0	$771	$154	$0	$139	$1,064	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$26	$5	$0	$5	$36	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$467	$93	$0	$84	$645	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,135	$227	$0	$204	$1,566	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$852	$170	$0	$153	$1,176	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$633	$127	$0	$114	$874	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,130	$226	$0	$203	$1,560	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,016**	**$1,003**	**$0**	**$903**	**$6,921**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$392,514**	**$78,503**	**$996**	**$73,592**	**$545,604**	**$789**	**$390**

Exhibit A-32. Case 2A owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,962	$6	$3
1 Month Maintenance Materials	$610	$1	$0
1 Month Non-Fuel Consumables	$197	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$10,912	$16	$8
Total	**$15,681**	**$23**	**$11**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$226	$0	$0
0.5% of TPC (spare parts)	$2,728	$4	$2
Total	**$2,954**	**$4**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$482	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$81,841	$118	$59
Financing Costs	$14,731	$21	$11
Total Overnight Costs (TOC)	**$661,592**	**$956**	**$473**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$707,772**	**$1,023**	**$506**

Exhibit A-33. Case 2A initial and annual O&M costs

Case:	**SOEC-EB-2A**		**Pathway Step 2 SOEC**		**Cost Base:**		**Dec 2018**
Plant Size (kg H_2/day):	**691,893**	**Plant Size (MW net):**		**1,398**	**Capacity Factor (%):**		**90%**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.17	$1.57
Maintenance Labor:					$4,146,588	$5.99	$2.97
Administrative & Support Labor:					$1,584,694	$2.29	$1.13
Property Taxes and Insurance:					$10,912,074	$15.77	$7.80
Total:					**$18,835,546**	**$27.22**	**$13.47**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh)**
Maintenance Material:					$6,585,757	$0.03	$0.60
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	79.04	$7.98	$9,571,347	$0.04	$0.87
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,458	$1.90	$0	$910,162	$0.004	$0.083
Makeup and Wastewater Treatment Chemicals (ton):	0	4.34	$550	$0	$784,834	$0.003	$0.071
Hydrogen Drying Sorbent (lb):	48173	131.98	$10	$481,733	$433,559	$0.002	$0.039
Subtotal:				**$481,733**	**$2,128,555**	**$0.009**	**$0.193**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	131.98	$0.02	$0	$824	$0.00	$0.00
Subtotal:				**$0**	**$824**	$0.00	**$0.00**
Variable Operating Costs Total:				**$481,733**	**$18,286,483**	**$0.04**	**$0.79**
Electricity Cost							
Electricity (MWh):	0	33,556	$60.00	$0	$661,383,636	$2.91	$60.00
Total:				**$0**	**$661,383,636**	**$2.91**	**$60.00**

Exhibit A-34. Case 2A LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.18	6%
Fixed	0.08	3%
Variable	0.08	2%
Electricity	2.91	89%
Total	**3.26**	**N/A**

Case 3A

Exhibit A-35. Case 3A stream table

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	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
C_3H_8	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.4000	0.8000	0.8000	0.8000	0.9655	0.9986
H_2O	1.0000	1.0000	1.0000	0.6000	0.2000	0.2000	0.2000	0.0345	0.0014
N_2	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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,670	18,111	18,111	36,223	36,223	18,112	18,112	15,008	14,510
V-L Flowrate (kg/h)	300,315	326,281	326,281	420,748	188,931	94,467	94,467	38,542	29,574
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	145	640	753	753	753	163	30	30
Pressure (MPa, abs)	0.10	0.13	0.12	0.12	0.12	0.12	0.12	0.10	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,770.89	3,795.22	4,533.85	6,202.15	6,202.15	2,664.16	943.00	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,200.46	-12,176.13	-10,353.43	-4,940.86	-4,940.86	-8,478.84	-3,194.04	-87.51
Density (kg/m³)	1,003.6	0.7	0.3	0.2	0.1	0.1	0.2	0.1	2.1
V-L Molecular Weight	18.015	18.015	18.015	11.615	5.216	5.216	5.216	2.568	2.038
V-L Flowrate (lb_{mol}/h)	36,751	39,929	39,929	79,858	79,858	39,930	39,930	33,086	31,989
V-L Flowrate (lb/h)	662,081	719,326	719,326	927,590	416,522	208,264	208,264	84,971	65,200
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	294	1,185	1,387	1,388	1,388	325	86	86
Pressure (psia)	14.7	18.2	17.4	17.2	17.0	17.0	16.8	14.8	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,191.3	1,631.6	1,949.2	2,666.4	2,666.4	1,145.4	405.4	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,675.2	-5,234.8	-4,451.2	-2,124.2	-2,124.2	-3,645.2	-1,373.2	-37.6
Density (lb/ft³)	62.650	0.041	0.018	0.010	0.004	0.004	0.010	0.006	0.132

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

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

Exhibit A-35. Case 3A stream table (cont'd)

	10	11	12	13	14	15	16	17	18	19
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077
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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,345	14,345	33,092	33,091	33,091	33,091	40,335	40,335	40,335
V-L Flowrate (kg/h)	655	28,920	28,920	954,835	954,825	954,825	954,825	1,186,606	1,186,606	1,186,606
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	31	730	750	755	197	150
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.12	0.11	0.11	0.11	0.11	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	47.31	797.36	820.37	814.00	210.46	162.03
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	-85.41	664.64	687.65	702.74	99.19	50.76
Density (kg/m^3)	4.7	2.1	5.0	1.2	1.4	0.4	0.4	0.4	0.8	0.8
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	364	31,625	31,625	72,955	72,954	72,954	72,954	88,923	88,923	88,923
V-L Flowrate (lb/h)	1,444	63,757	63,757	2,105,052	2,105,029	2,105,029	2,105,029	2,616,018	2,616,018	2,616,018
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	88	1,346	1,382	1,391	387	301
Pressure (psia)	385.0	383.3	939.7	14.7	17.2	16.4	15.9	15.5	15.3	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	20.3	342.8	352.7	350.0	90.5	69.7
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	-36.7	285.7	295.6	302.1	42.6	21.8
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.084	0.024	0.023	0.023	0.050	0.053

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

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

Exhibit A-36. Case 3A plant performance summary

Performance Summary	
Total Gross Power, kWe	**0**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	255,648
Hydrogen Compression, kWe	62,638
Balance of Plant, kWe	45,289
Total Auxiliaries, MWe	**364**
Net Power, MWe	**-1,394.5**
Hydrogen Production, kg/h (lb/h)	**28,829 (63,557)**
Energy Efficiency,[A] % HHV (% LHV)	81.7 (69.1)
Electric Input per Kilogram, kWh/kg	48.2
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,139,910 (963,877)
Raw Water Withdrawal, m^3/min (gpm)	7.7 (2,032)
Raw Water Consumption, m^3/min (gpm)	6.4 (1,701)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-37. Case 3A power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Air Electrode Blowers, kWe	4,703
Circulating Water Pumps, kWe	700
Cooling Tower Fans, kWe	360
Electric Boiler, kWe	255,648
Electric Steam Superheater, kWe	22,539
Electric Sweep Heater, kWe	6,104
Feedwater Pumps, kWe	76
Fuel Electrode Recycle Blowers, kWe	697
Ground Water Pumps, kWe	180
Hydrogen Compressor, kWe	62,638
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,640
Total Auxiliaries, MWe	**364**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,395**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-38. Case 3A carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (263)	Air-Electrode Sweep Exhaust (CO_2)	119 (263)
Total	**119 (263)**	**Total**	**119 (263)**

Exhibit A-39. Case 3A 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)
Electrolysis Steam	5.0 (1,324)	–	5.0 (1,324)	–	5.0 (1,324)
Deaerator Vent	–	–	–	0.0 (3.4)	0.0 (-3.4)
Boiler Blowdown	–	–	–	0.6 (168)	-0.6 (-168)
Cooling Tower	2.7 (707)	–	2.7 (707)	0.6 (159)	2.1 (548)
Total	**7.7 (2,032)**	**–**	**7.7 (2,032)**	**1.3 (331)**	**6.4 (1,701)**

Exhibit A-40. Case 3A overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	29 (27)	–	29 (27)
Auxiliary Power	–	–	5,020 (4,758)	5,020 (4,758)
Total	**0.0 (0.0)**	**59 (56)**	**5,020 (4,758)**	**5,079 (4,814)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,104 (3,890)	13 (12)	–	4,117 (3,902)
Sweep Exhaust	–	192 (182)	–	192 (182)
Motor Losses and Design Allowances	–	7.1 (7.1)	–	7.1 (7.1)
Cooling Tower Load[A]	–	350 (331)	–	350 (331)
Boiler Blowdown	–	7.7 (7.3)	–	7.7 (7.3)
Process Vents[B]	–	0.5 (0.4)	–	0.5 (0.4)
Ambient Losses[C]	–	322 (305)	–	322 (305)
Total	**–**	**892 (846)**	**0.0 (0.0)**	**4,996 (4,736)**
Unaccounted Energy[D]	–	*83 (78)*	–	*83 (78)*

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-41. Case 3A energy and mass balance diagram

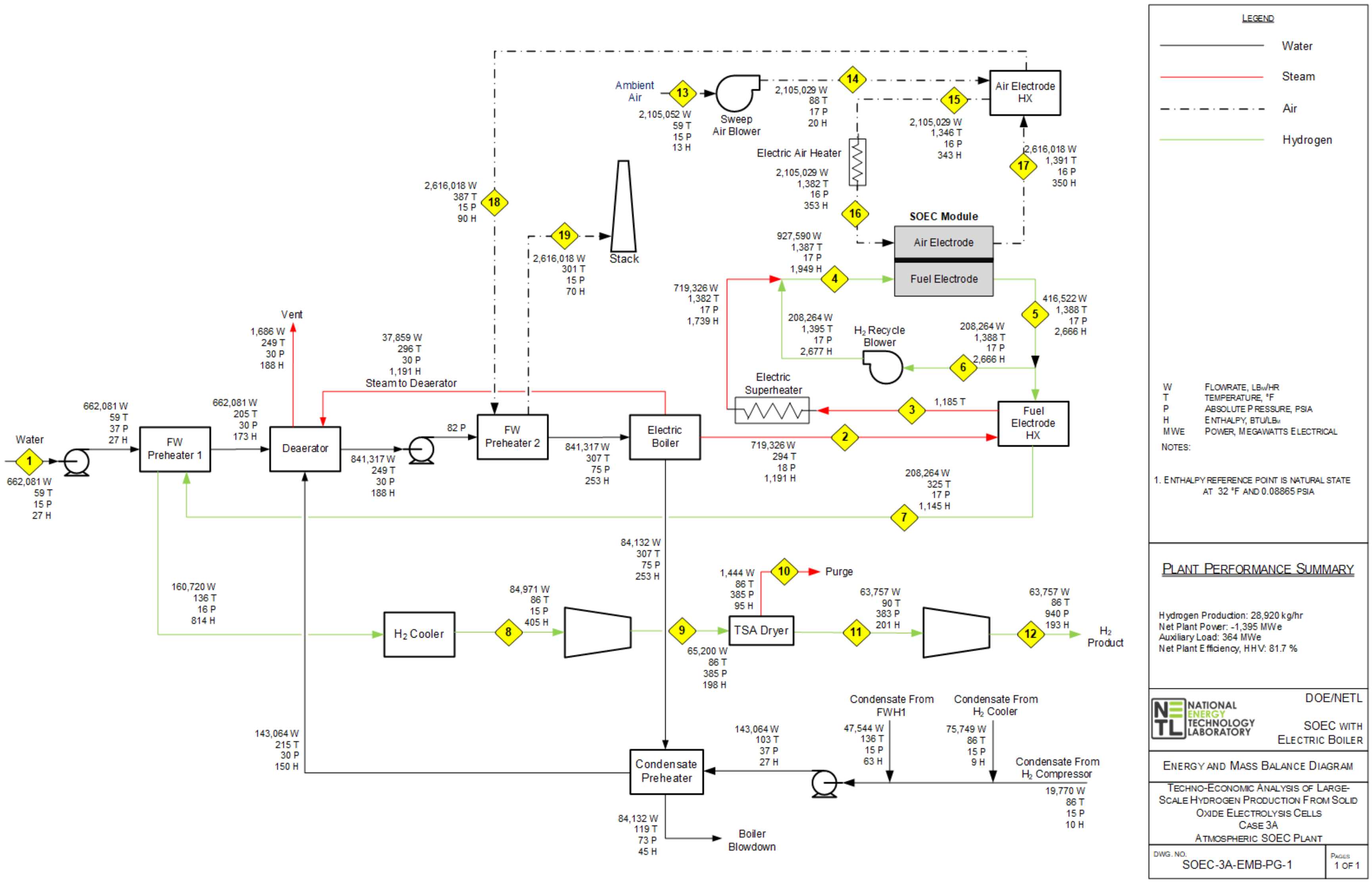


Exhibit A-42. Case 3A total plant cost details

	Case:	SOEC-EB-3A	Pathway Step 3 SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	694,068	Plant Size (MW net):			1,395			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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$89,183	$17,837	$0	$16,053	$123,073	$177	$88
1.2	Container	$0	$0	$0	$0	$2,675	$535	$0	$482	$3,692	$5	$3
1.3	Insulation	$0	$0	$0	$0	$1,189	$238	$0	$214	$1,641	$2	$1
1.4	Module Assembly	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.5	Air Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.6	Fuel Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.8	Module Current Collectors	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.9	Module I&C	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.10	Rectifier	$0	$0	$0	$0	$20,215	$4,043	$0	$3,639	$27,896	$40	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$125,153**	**$25,031**	**$0**	**$22,528**	**$172,712**	**$249**	**$124**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Blower	$0	$0	$0	$0	$927	$185	$0	$167	$1,279	$2	$1
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$22,598	$4,520	$0	$4,068	$31,185	$45	$22
2.3	Hydrogen Recycle Blower	$0	$0	$0	$0	$612	$122	$0	$110	$845	$1	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$15,423	$3,085	$0	$2,776	$21,284	$31	$15
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,288	$258	$0	$232	$1,778	$3	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
2.7	Section I&C	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$42,137**	**$8,427**	**$0**	**$7,585**	**$58,149**	**$84**	**$42**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,327	$865	$0	$779	$5,972	$9	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,810	$962	$0	$1,154	$6,927	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,889	$378	$0	$340	$2,606	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,948	$1,990	$0	$2,387	$14,325	$21	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$1,050	$210	$0	$189	$1,449	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,986	$997	$0	$1,197	$7,180	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,010**	**$5,402**	**$0**	**$6,046**	**$38,458**	**$55**	**$28**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$539	$108	$0	$97	$744	$1	$1
4.2	Electric Boiler	$0	$0	$0	$0	$33,241	$6,648	$0	$5,983	$45,873	$66	$33
4.3	Electric Superheaters	$0	$0	$0	$0	$1,744	$349	$0	$314	$2,407	$3	$2
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$654	$131	$0	$118	$902	$1	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$546	$109	$0	$98	$754	$1	$1

	Case:	SOEC-EB-3A	Pathway Step 3 SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	694,068	Plant Size (MW net):			1,395		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 H_2/day]	$/kW (net)
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$259	$52	$0	$47	$357	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$20,422	$4,084	$0	$3,676	$28,183	$41	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$57,405**	**$11,481**	**$0**	**$10,333**	**$79,219**	**$114**	**$57**
	7					**Ductwork, & Stack**						
7.3	Ductwork	$0	$0	$0	$0	$670	$134	$0	$121	$925	$1	$1
7.4	Stack	$0	$0	$0	$0	$4,481	$896	$0	$807	$6,184	$9	$4
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$571	$114	$0	$137	$823	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,723**	**$1,145**	**$0**	**$1,064**	**$7,932**	**$11**	**$6**
	9					**Cooling Water System**						
9.1	Cooling Towers	$0	$0	$0	$0	$3,778	$756	$0	$680	$5,213	$8	$4
9.2	Circulating Water Pumps	$0	$0	$0	$0	$413	$83	$0	$74	$570	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,641	$928	$0	$835	$6,405	$9	$5
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,891	$378	$0	$340	$2,610	$4	$2
9.5	Make-up Water System	$0	$0	$0	$0	$597	$119	$0	$107	$824	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$259	$52	$0	$47	$357	$1	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$611	$122	$0	$147	$880	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$12,189**	**$2,438**	**$0**	**$2,231**	**$16,858**	**$24**	**$12**
	11					**Accessory Electric Plant**						
11.2	Station Service Equipment	$0	$0	$0	$0	$11,754	$2,351	$0	$2,116	$16,221	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$18,139	$3,628	$0	$3,265	$25,031	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,499	$2,900	$0	$2,610	$20,009	$29	$14
11.5	Wire & Cable	$0	$0	$0	$0	$15,544	$3,109	$0	$2,798	$21,450	$31	$15
11.6	Protective Equipment	$0	$0	$0	$0	$1,175	$235	$0	$211	$1,621	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,709	$542	$0	$488	$3,738	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,109	$422	$0	$380	$2,911	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$443	$89	$0	$106	$639	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$66,372**	**$13,274**	**$0**	**$11,974**	**$91,620**	**$132**	**$66**
	12					**Instrumentation & Control**						
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,479	$296	$74	$266	$2,115	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$729	$146	$0	$131	$1,006	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$321	$64	$16	$58	$458	$1	$0

Case:		SOEC-EB-3A	Pathway Step 3 SOEC					Estimate Type:			Conceptual		
Plant Size (kg H_2/day):		694,068	Plant Size (MW net):			1,395		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 H_2/day]	$/kW (net)
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,412	$2,282	$571	$2,054	$16,319	$24	$12
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,571	$914	$229	$823	$6,537	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,100	$420	$105	$378	$3,003	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,612**	**$4,122**	**$994**	**$3,710**	**$29,439**	**$42**	**$21**
13						**Improvements to Site**						
13.1	Site Preparation	$0	$0	$0	$0	$17,040	$3,408	$0	$4,089	$24,537	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,723	$1,145	$0	$1,373	$8,240	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,848	$970	$0	$1,164	$6,981	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,610**	**$5,522**	**$0**	**$6,626**	**$39,758**	**$57**	**$29**
14						**Buildings & Structures**						
14.4	Administration Building	$0	$0	$0	$0	$770	$154	$0	$139	$1,063	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$26	$5	$0	$5	$36	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$468	$94	$0	$84	$646	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,134	$227	$0	$204	$1,565	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$852	$170	$0	$153	$1,175	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$633	$127	$0	$114	$874	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,131	$226	$0	$204	$1,561	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,015**	**$1,003**	**$0**	**$903**	**$6,920**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$389,227**	**$77,845**	**$994**	**$73,000**	**$541,066**	**$780**	**$388**

Exhibit A-43. Case 3A owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,940	$6	$3
1 Month Maintenance Materials	$605	$1	$0
1 Month Non-Fuel Consumables	$198	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$10,821	$16	$8
Total	**$15,564**	**$22**	**$11**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$226	$0	$0
0.5% of TPC (spare parts)	$2,705	$4	$2
Total	**$2,932**	**$4**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$483	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$81,160	$117	$58
Financing Costs	$14,609	$21	$10
Total Overnight Costs (TOC)	**$656,113**	**$945**	**$470**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$701,911**	**$1,011**	**$503**

Exhibit A-44. Case 3A initial and annual O&M costs

Case:	SOEC-EB-3A		Pathway Step 3 SOEC		Cost Base:		Dec 2018
Plant Size (kg H_2/day):	**694,068**	**Plant Size (MW net):**		**1,395**	**Capacity Factor (%):**		**90%**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.16	$1.57
Maintenance Labor:					$4,112,098	$5.92	$2.95
Administrative & Support Labor:					$1,576,072	$2.27	$1.13
Property Taxes and Insurance:					$10,821,312	$15.59	$7.76
Total:					**$18,701,672**	**$26.95**	**$13.41**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh)**
Maintenance Material:					$6,530,980	$0.03	$0.59
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	79.28	$8.00	$9,571,347	$0.04	$0.87
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,463	$1.90	$0	$913,006	$0.004	$0.083
Makeup and Wastewater Treatment Chemicals (ton):	0	4.36	$550	$0	$787,286	$0.003	$0.072
Hydrogen Drying Sorbent (lb):	48325	132.40	$10	$483,248	$434,923	$0.002	$0.040
Subtotal:				**$483,248**	**$2,135,215**	**$0.009**	**$0.194**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	132.40	$0.02	$0	$826	$0.00	$0.00
Subtotal:				**$0**	**$826**	$0.00	**$0.00**
Variable Operating Costs Total:				**$483,248**	**$18,238,368**	**$0.04**	**$0.79**
Electricity Cost							
Electricity (MWh):	0	33,468	$60.00	$0	$659,656,786	$2.89	$60.00
Total:				**$0**	**$659,656,786**	**$2.89**	**$60.00**

Exhibit A-45. Case 3A LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.18	6%
Fixed	0.08	3%
Variable	0.08	2%
Electricity	2.89	89%
Total	**3.24**	**N/A**

CASE 4A

Exhibit A-46. Case 4A stream table

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	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
C_3H_8	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.4250	0.8500	0.8500	0.8500	0.9655	0.9986
H_2O	1.0000	1.0000	1.0000	0.5750	0.1500	0.1500	0.1500	0.0345	0.0014
N_2	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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,522	17,025	17,025	34,050	34,050	17,025	17,025	14,988	14,491
V-L Flowrate (kg/h)	297,656	306,706	306,706	381,884	150,356	75,178	75,178	38,493	29,537
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	145	636	754	755	755	163	30	30
Pressure (MPa, abs)	0.10	0.13	0.12	0.12	0.12	0.12	0.12	0.10	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,770.89	3,784.42	4,584.70	6,762.67	6,762.67	2,627.72	943.00	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,200.46	-12,186.93	-10,193.78	-3,149.19	-3,149.19	-7,284.14	-3,194.04	-87.51
Density (kg/m³)	1,003.6	0.7	0.3	0.2	0.1	0.1	0.1	0.1	2.1
V-L Molecular Weight	18.015	18.015	18.015	11.216	4.416	4.416	4.416	2.568	2.038
V-L Flowrate (lb_{mol}/h)	36,426	37,533	37,533	75,066	75,066	37,533	37,533	33,044	31,948
V-L Flowrate (lb/h)	656,220	676,171	676,171	841,910	331,477	165,739	165,739	84,863	65,117
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	294	1,176	1,389	1,391	1,391	325	86	86
Pressure (psia)	14.7	18.2	17.4	17.2	17.0	17.0	16.8	14.8	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,191.3	1,627.0	1,971.1	2,907.4	2,907.4	1,129.7	405.4	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,675.2	-5,239.4	-4,382.5	-1,353.9	-1,353.9	-3,131.6	-1,373.2	-37.6
Density (lb/ft³)	62.650	0.041	0.018	0.010	0.004	0.004	0.009	0.006	0.132

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

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

Exhibit A-46. Case 4A stream table (cont'd)

	10	11	12	13	14	15	16	17	18	19
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077
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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,326	14,326	33,051	33,051	33,051	33,051	40,287	40,287	40,287
V-L Flowrate (kg/h)	654	28,883	28,883	953,649	953,647	953,647	953,647	1,185,211	1,185,211	1,185,211
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	31	730	750	758	200	155
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.12	0.11	0.11	0.11	0.11	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	47.31	797.36	820.37	817.04	213.53	167.62
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	-85.41	664.64	687.65	705.77	102.27	56.36
Density (kg/m^3)	4.7	2.1	5.0	1.2	1.4	0.4	0.4	0.4	0.8	0.8
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,584	31,584	72,864	72,864	72,864	72,864	88,818	88,818	88,818
V-L Flowrate (lb/h)	1,442	63,676	63,676	2,102,436	2,102,433	2,102,433	2,102,433	2,612,944	2,612,944	2,612,944
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	88	1,346	1,382	1,396	393	311
Pressure (psia)	385.0	383.3	939.7	14.7	17.2	16.4	15.9	15.5	15.3	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	20.3	342.8	352.7	351.3	91.8	72.1
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	-36.7	285.7	295.6	303.4	44.0	24.2
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.084	0.024	0.023	0.023	0.049	0.052

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

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

Exhibit A-47. Case 4A plant performance summary

Performance Summary	
Total Gross Power, kWe	**0**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	240,311
Hydrogen Compression, kWe	62,558
Balance of Plant, kWe	44,578
Total Auxiliaries, MWe	**347**
Net Power, MWe	**-1,378.4**
Hydrogen Production, kg/h (lb/h)	**28,883 (63,676)**
Energy Efficiency,[A] % HHV (% LHV)	82.6 (69.8)
Electric Input per Kilogram, kWh/kg	47.7
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,138,462 (962,652)
Raw Water Withdrawal, m^3/min (gpm)	7.2 (1,915)
Raw Water Consumption, m^3/min (gpm)	6.1 (1,618)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-48. Case 4A power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Air Electrode Blowers, kWe	4,697
Circulating Water Pumps, kWe	600
Cooling Tower Fans, kWe	310
Electric Boiler, kWe	240,311
Electric Steam Superheater, kWe	22,107
Electric Sweep Heater, kWe	6,097
Feedwater Pumps, kWe	72
Fuel Electrode Recycle Blowers, kWe	656
Ground Water Pumps, kWe	170
Hydrogen Compressor, kWe	62,558
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,580
Total Auxiliaries, MWe	347
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,378**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-49. Case 4A carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (263)	Air-Electrode Sweep Exhaust (CO_2)	119 (263)
Total	**119 (263)**	**Total**	**119 (263)**

Exhibit A-50. Case 4A 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)
Electrolysis Steam	5.0 (1,312)	–	5.0 (1,312)	–	5.0 (1,312)
Deaerator Vent	–	–	–	0.0 (3.2)	0.0 (-3.2)
Boiler Blowdown	–	–	–	0.6 (158)	-0.6 (-158)
Cooling Tower	2.3 (602)	–	2.3 (602)	0.5 (135)	1.8 (467)
Total	**7.2 (1,915)**	**–**	**7.2 (1,915)**	**1.1 (297)**	**6.1 (1,618)**

Exhibit A-51. Case 4A overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	27 (26)	–	27 (26)
Auxiliary Power	–	–	4,962 (4,703)	4,962 (4,703)
Total	**0.0 (0.0)**	**57 (54)**	**4,962 (4,703)**	**5,019 (4,757)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,098 (3,885)	13 (12)	–	4,111 (3,897)
Sweep Exhaust	–	199 (188)	–	199 (188)
Motor Losses and Design Allowances	–	7.1 (7.1)	–	7.1 (7.1)
Cooling Tower Load[A]	–	298 (282)	–	298 (282)
Boiler Blowdown	–	11 (10)	–	11 (10)
Process Vents[B]	–	0.4 (0.4)	–	0.4 (0.4)
Ambient Losses[C]	–	311 (295)	–	311 (295)
Total	**–**	**839 (796)**	**0.0 (0.0)**	**4,937 (4,680)**
Unaccounted Energy[D]	**–**	*82 (77)*	–	*82 (77)*

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-52. Case 4A energy and mass balance diagram

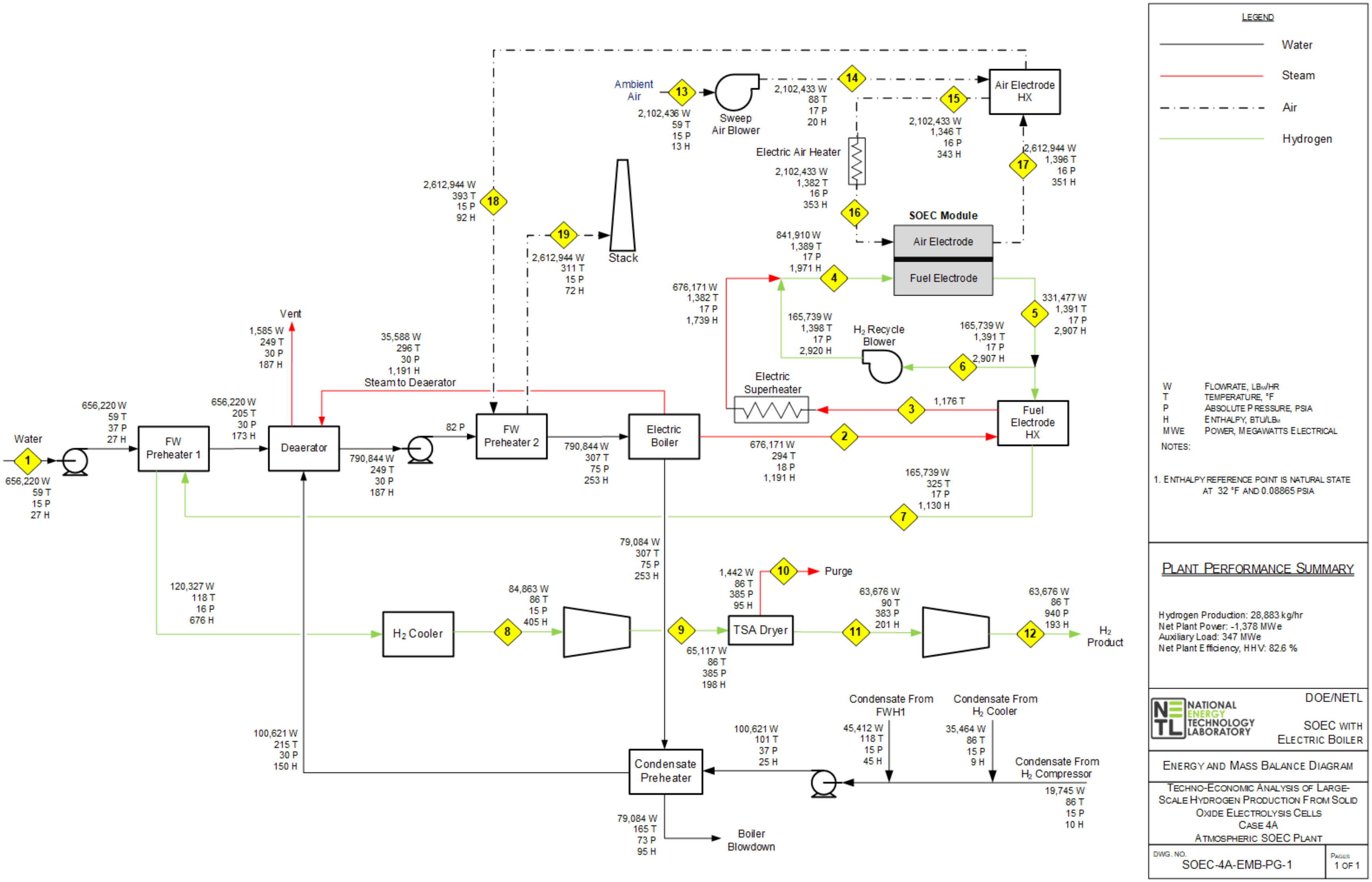


Exhibit A-53. Case 4A total plant cost details

	Case:	SOEC-EB-4A	Pathway Step 4 SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	693,186	Plant Size (MW net):			1,378		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 H_2/day]	$/kW (net)
1						SOEC Module						
1.1	SOEC Stack	$0	$0	$0	$0	$89,183	$17,837	$0	$16,053	$123,073	$177	$89
1.2	Container	$0	$0	$0	$0	$2,675	$535	$0	$482	$3,692	$5	$3
1.3	Insulation	$0	$0	$0	$0	$1,189	$238	$0	$214	$1,641	$2	$1
1.4	Module Assembly	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.5	Air Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.6	Fuel Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.8	Module Current Collectors	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.9	Module I&C	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.10	Rectifier	$0	$0	$0	$0	$20,215	$4,043	$0	$3,639	$27,896	$40	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$125,153**	**$25,031**	**$0**	**$22,528**	**$172,712**	**$249**	**$125**
2						SOEC Balance of Plant						
2.1	Air-Electrode Sweep Blower	$0	$0	$0	$0	$926	$185	$0	$167	$1,278	$2	$1
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$21,530	$4,306	$0	$3,875	$29,712	$43	$22
2.3	Hydrogen Recycle Blower	$0	$0	$0	$0	$589	$118	$0	$106	$812	$1	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$13,831	$2,766	$0	$2,490	$19,086	$28	$14
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,288	$258	$0	$232	$1,778	$3	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
2.7	Section I&C	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$39,452**	**$7,890**	**$0**	**$7,101**	**$54,444**	**$79**	**$39**
3						Feedwater & Miscellaneous BOP Systems						
3.1	Feedwater System	$0	$0	$0	$0	$4,147	$829	$0	$746	$5,722	$8	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,607	$921	$0	$1,106	$6,634	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,787	$357	$0	$322	$2,467	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,487	$1,897	$0	$2,277	$13,662	$20	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$993	$199	$0	$179	$1,370	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,617	$923	$0	$1,108	$6,648	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$25,637**	**$5,127**	**$0**	**$5,737**	**$36,502**	**$53**	**$26**
4						Electric Boiler, Hydrogen Production, and Miscellaneous Systems						
4.1	Feedwater Heaters	$0	$0	$0	$0	$504	$101	$0	$91	$695	$1	$1
4.2	Electric Boiler	$0	$0	$0	$0	$31,636	$6,327	$0	$5,694	$43,658	$63	$32
4.3	Electric Superheaters	$0	$0	$0	$0	$1,703	$341	$0	$306	$2,349	$3	$2
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$653	$131	$0	$118	$901	$1	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$302	$60	$0	$54	$416	$1	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$47	$357	$1	$0

	Case:	SOEC-EB-4A	Pathway Step 4 SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	693,186	Plant Size (MW net):			1,378			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 H_2/day]	$/kW (net)
4.7	Hydrogen Compressor	$0	$0	$0	$0	$20,404	$4,081	$0	$3,673	$28,157	$41	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$55,460**	**$11,092**	**$0**	**$9,983**	**$76,534**	**$110**	**$56**
7	**Ductwork, & Stack**											
7.3	Ductwork	$0	$0	$0	$0	$676	$135	$0	$122	$932	$1	$1
7.4	Stack	$0	$0	$0	$0	$4,519	$904	$0	$813	$6,236	$9	$5
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$576	$115	$0	$138	$830	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,771**	**$1,154**	**$0**	**$1,073**	**$7,998**	**$12**	**$6**
9	**Cooling Water System**											
9.1	Cooling Towers	$0	$0	$0	$0	$3,359	$672	$0	$605	$4,635	$7	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$368	$74	$0	$66	$508	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,289	$858	$0	$772	$5,919	$9	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,717	$343	$0	$309	$2,370	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$583	$117	$0	$105	$804	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$235	$47	$0	$42	$324	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$555	$111	$0	$133	$799	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$11,105**	**$2,221**	**$0**	**$2,032**	**$15,359**	**$22**	**$11**
11	**Accessory Electric Plant**											
11.2	Station Service Equipment	$0	$0	$0	$0	$11,667	$2,333	$0	$2,100	$16,100	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$18,004	$3,601	$0	$3,241	$24,846	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,392	$2,878	$0	$2,591	$19,861	$29	$14
11.5	Wire & Cable	$0	$0	$0	$0	$15,428	$3,086	$0	$2,777	$21,291	$31	$15
11.6	Protective Equipment	$0	$0	$0	$0	$1,166	$233	$0	$210	$1,609	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,689	$538	$0	$484	$3,710	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,094	$419	$0	$377	$2,889	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$440	$88	$0	$106	$634	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$65,880**	**$13,176**	**$0**	**$11,885**	**$90,941**	**$131**	**$66**
12	**Instrumentation & Control**											
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,469	$294	$73	$264	$2,100	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$725	$145	$0	$130	$1,000	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$318	$64	$16	$57	$455	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,330	$2,266	$566	$2,039	$16,201	$23	$12
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,538	$908	$227	$817	$6,490	$9	$5

	Case:	SOEC-EB-4A	Pathway Step 4 SOEC				Estimate Type:			Conceptual		
	Plant Size (kg H_2/day):	693,186	Plant Size (MW net):			1,378	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 H_2/day]	$/kW (net)
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,085	$417	$104	$375	$2,981	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,464**	**$4,093**	**$987**	**$3,683**	**$29,227**	**$42**	**$21**
13	**Improvements to Site**											
13.1	Site Preparation	$0	$0	$0	$0	$16,949	$3,390	$0	$4,068	$24,406	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,692	$1,138	$0	$1,366	$8,196	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,822	$964	$0	$1,157	$6,944	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,463**	**$5,493**	**$0**	**$6,591**	**$39,546**	**$57**	**$29**
14	**Buildings & Structures**											
14.4	Administration Building	$0	$0	$0	$0	$767	$153	$0	$138	$1,059	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$23	$5	$0	$4	$32	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$450	$90	$0	$81	$621	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,129	$226	$0	$203	$1,558	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$848	$170	$0	$153	$1,171	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$631	$126	$0	$114	$871	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,090	$218	$0	$196	$1,505	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,940**	**$988**	**$0**	**$889**	**$6,817**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$381,325**	**$76,265**	**$987**	**$71,503**	**$530,080**	**$765**	**$385**

Exhibit A-54. Case 4A owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,888	$6	$3
1 Month Maintenance Materials	$592	$1	$0
1 Month Non-Fuel Consumables	$189	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$10,602	$15	$8
Total	**$15,271**	**$22**	**$11**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$218	$0	$0
0.5% of TPC (spare parts)	$2,650	$4	$2
Total	**$2,868**	**$4**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$483	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$79,512	$115	$58
Financing Costs	$14,312	$21	$10
Total Overnight Costs (TOC)	**$642,826**	**$927**	**$466**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$687,696**	**$992**	**$499**

Exhibit A-55. Case 4A initial and annual O&M costs

Case:	SOEC-EB-4A		Pathway Step 4 SOEC		Cost Base:		Dec 2018
Plant Size (kg H_2/day):	**693,186**	**Plant Size (MW net):**		**1,378**	**Capacity Factor (%):**		**90%**
			Operating & Maintenance 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:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
			Fixed Operating Costs				
						Annual Cost	
					(\$)	**(\$/[kg H_2/day])**	**(\$/kW-net)**
Annual Operating Labor:					\$2,192,190	\$3.16	\$1.59
Maintenance Labor:					\$4,028,609	\$5.81	\$2.92
Administrative & Support Labor:					\$1,555,200	\$2.24	\$1.13
Property Taxes and Insurance:					\$10,601,602	\$15.29	\$7.69
Total:					**\$18,377,601**	**\$26.51**	**\$13.33**
			Variable Operating Costs				
					(\$)	**(\$/kg H_2)**	**(\$/MWh)**
Maintenance Material:					\$6,398,379	\$0.03	\$0.59
			Stack Replacement				
	Life (yr)		**\$/kW_{AC}**	**\$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	79.18	\$7.99	\$9,571,347	\$0.04	\$0.88
			Consumables				
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,379	\$1.90	\$0	\$860,469	\$0.004	\$0.079
Makeup and Wastewater Treatment Chemicals (ton):	0	4.11	\$550	\$0	\$741,984	\$0.003	\$0.068
Hydrogen Drying Sorbent (lb):	48263	132.23	\$10	\$482,633	\$434,370	\$0.002	\$0.040
Subtotal:				**\$482,633**	**\$2,036,823**	**\$0.009**	**\$0.187**
			Waste Disposal				
Hydrogen Drying Sorbent (lb):	0	132.23	\$0.02	\$0	\$825	\$0.00	\$0.00
Subtotal:				**\$0**	**\$825**	\$0.00	**\$0.00**
Variable Operating Costs Total:				**\$482,633**	**\$18,007,373**	**\$0.04**	**\$0.78**
			Electricity Cost				
Electricity (MWh):	0	33,081	\$60.00	\$0	\$652,030,287	\$2.86	\$60.00
Total:				**\$0**	**\$652,030,287**	**\$2.86**	**\$60.00**

Exhibit A-56. Case 4A LCOH breakdown

Component	LCOH, \$/kg H_2	Percentage
Capital	0.18	6%
Fixed	0.08	3%
Variable	0.08	2%
Electricity	2.86	89%
Total	**3.20**	**N/A**

Case 5A

Exhibit A-57. Case 5A stream table

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	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
C_3H_8	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.4250	0.8500	0.8500	0.8500	0.9655	0.9986
H_2O	1.0000	1.0000	1.0000	0.5750	0.1500	0.1500	0.1500	0.0345	0.0014
N_2	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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,522	17,025	17,025	34,050	34,050	17,025	17,025	14,988	14,491
V-L Flowrate (kg/h)	297,656	306,706	306,706	381,884	150,356	75,178	75,178	38,493	29,537
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	145	636	754	755	755	163	30	30
Pressure (MPa, abs)	0.10	0.13	0.12	0.12	0.12	0.12	0.12	0.10	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,770.89	3,784.42	4,584.70	6,762.67	6,762.67	2,627.72	943.00	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,200.46	-12,186.93	-10,193.78	-3,149.19	-3,149.19	-7,284.14	-3,194.04	-87.51
Density (kg/m³)	1,003.6	0.7	0.3	0.2	0.1	0.1	0.1	0.1	2.1
V-L Molecular Weight	18.015	18.015	18.015	11.216	4.416	4.416	4.416	2.568	2.038
V-L Flowrate (lb_{mol}/h)	36,426	37,533	37,533	75,066	75,066	37,533	37,533	33,044	31,948
V-L Flowrate (lb/h)	656,220	676,171	676,171	841,910	331,477	165,739	165,739	84,863	65,117
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	294	1,176	1,389	1,391	1,391	325	86	86
Pressure (psia)	14.7	18.2	17.4	17.2	17.0	17.0	16.8	14.8	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,191.3	1,627.0	1,971.1	2,907.4	2,907.4	1,129.7	405.4	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,675.2	-5,239.4	-4,382.5	-1,353.9	-1,353.9	-3,131.6	-1,373.2	-37.6
Density (lb/ft³)	62.650	0.041	0.018	0.010	0.004	0.004	0.009	0.006	0.132

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

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

Exhibit A-57. Case 5A stream table (cont'd)

	10	11	12	13	14	15	16	17	18	19
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077
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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,326	14,326	33,051	33,051	33,051	33,051	40,287	40,287	40,287
V-L Flowrate (kg/h)	654	28,883	28,883	953,649	953,647	953,647	953,647	1,185,211	1,185,211	1,185,211
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	31	730	750	758	200	155
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.12	0.11	0.11	0.11	0.11	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	47.31	797.36	820.37	817.04	213.53	167.62
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	-85.41	664.64	687.65	705.77	102.27	56.36
Density (kg/m³)	4.7	2.1	5.0	1.2	1.4	0.4	0.4	0.4	0.8	0.8
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,584	31,584	72,864	72,864	72,864	72,864	88,818	88,818	88,818
V-L Flowrate (lb/h)	1,442	63,676	63,676	2,102,436	2,102,433	2,102,433	2,102,433	2,612,944	2,612,944	2,612,944
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	88	1,346	1,382	1,396	393	311
Pressure (psia)	385.0	383.3	939.7	14.7	17.2	16.4	15.9	15.5	15.3	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	20.3	342.8	352.7	351.3	91.8	72.1
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	-36.7	285.7	295.6	303.4	44.0	24.2
Density (lb/ft³)	0.292	0.129	0.314	0.076	0.084	0.024	0.023	0.023	0.049	0.052

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

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

Exhibit A-58. Case 5A plant performance summary

Performance Summary	
Total Gross Power, kWe	**0**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	240,311
Hydrogen Compression, kWe	62,558
Balance of Plant, kWe	44,578
Total Auxiliaries, MWe	**347**
Net Power, MWe	**-1,378.4**
Hydrogen Production, kg/h (lb/h)	**28,883 (63,676)**
Energy Efficiency,[A] % HHV (% LHV)	82.6 (69.8)
Electric Input per Kilogram, kWh/kg	47.7
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,138,462 (962,652)
Raw Water Withdrawal, m^3/min (gpm)	7.2 (1,915)
Raw Water Consumption, m^3/min (gpm)	6.1 (1,618)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-59. Case 5A power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Air Electrode Blowers, kWe	4,697
Circulating Water Pumps, kWe	600
Cooling Tower Fans, kWe	310
Electric Boiler, kWe	240,311
Electric Steam Superheater, kWe	22,107
Electric Sweep Heater, kWe	6,097
Feedwater Pumps, kWe	72
Fuel Electrode Recycle Blowers, kWe	656
Ground Water Pumps, kWe	170
Hydrogen Compressor, kWe	62,558
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,580
Total Auxiliaries, MWe	347
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,378**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-60. Case 5A carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (263)	Air-Electrode Sweep Exhaust (CO_2)	119 (263)
Total	**119 (263)**	**Total**	**119 (263)**

Exhibit A-61. Case 5A 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)
Electrolysis Steam	5.0 (1,312)	–	5.0 (1,312)	–	5.0 (1,312)
Deaerator Vent	–	–	–	0.0 (3.2)	0.0 (-3.2)
Boiler Blowdown	–	–	–	0.6 (158)	-0.6 (-158)
Cooling Tower	2.3 (602)	–	2.3 (602)	0.5 (135)	1.8 (467)
Total	**7.2 (1,915)**	**–**	**7.2 (1,915)**	**1.1 (297)**	**6.1 (1,618)**

Exhibit A-62. Case 5A overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	27 (26)	–	27 (26)
Auxiliary Power	–	–	4,962 (4,703)	4,962 (4,703)
Total	**0.0 (0.0)**	**57 (54)**	**4,962 (4,703)**	**5,019 (4,757)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,098 (3,885)	13 (12)	–	4,111 (3,897)
Sweep Exhaust	–	199 (188)	–	199 (188)
Motor Losses and Design Allowances	–	7.1 (7.1)	–	7.1 (7.1)
Cooling Tower Load[A]	–	298 (282)	–	298 (282)
Boiler Blowdown	–	11 (10)	–	11 (10)
Process Vents[B]	–	0.4 (0.4)	–	0.4 (0.4)
Ambient Losses[C]	–	311 (295)	–	311 (295)
Total	**–**	**839 (796)**	**0.0 (0.0)**	**4,937 (4,680)**
Unaccounted Energy[D]	**–**	*82 (77)*	–	*82 (77)*

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-63. Case 5A energy and mass balance diagram (identical to Case 4A)

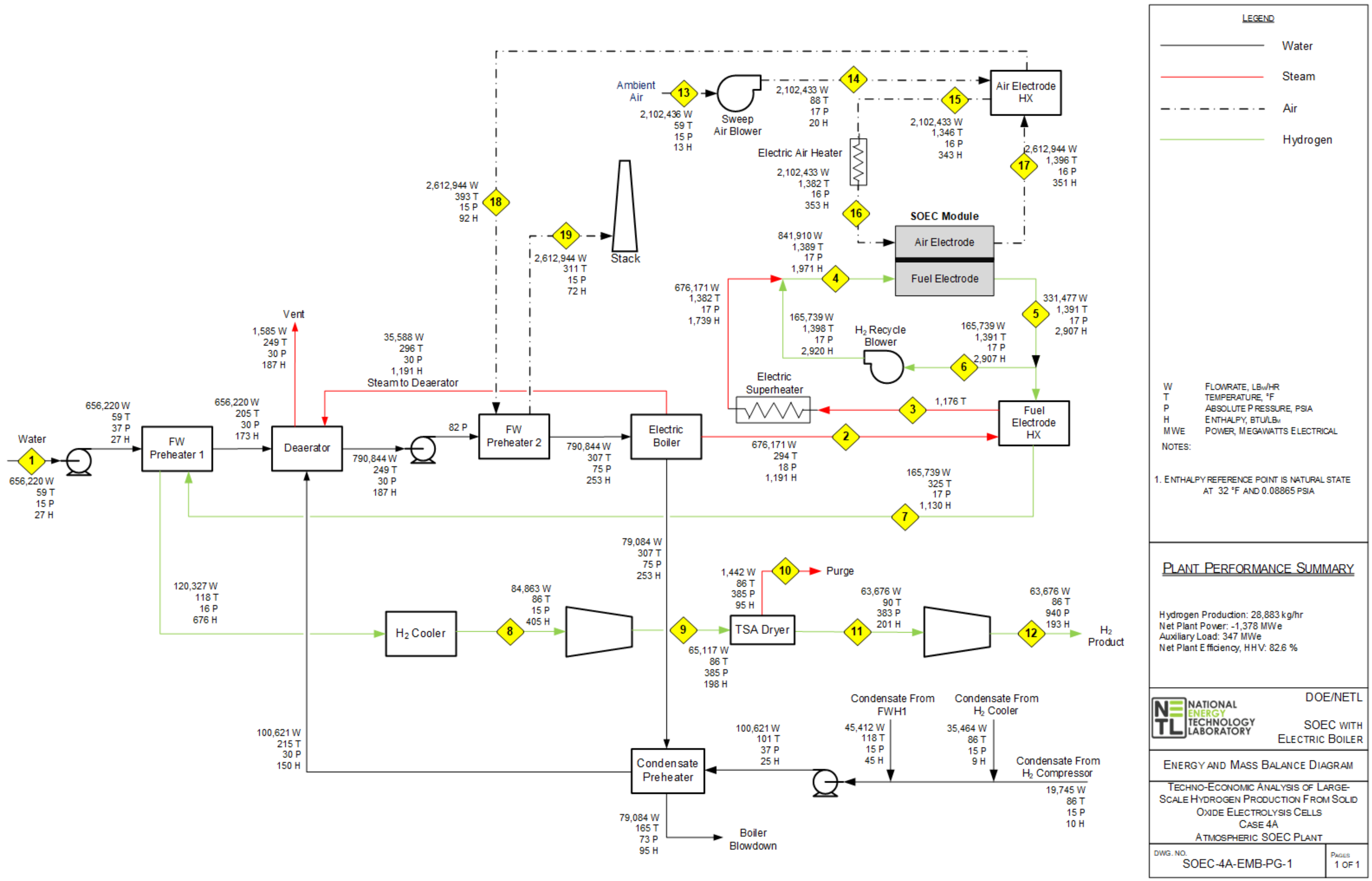


Exhibit A-64. Case 5A total plant cost details

	Case:	SOEC-EB-5A	Pathway Step 5 SOEC						Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	693,186	Plant Size (MW net):			1,378			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 H_2/day]	$/kW (net)
	1	SOEC Module										
1.1	SOEC Stack	$0	$0	$0	$0	$89,183	$17,837	$0	$16,053	$123,073	$177	$89
1.2	Container	$0	$0	$0	$0	$2,675	$535	$0	$482	$3,692	$5	$3
1.3	Insulation	$0	$0	$0	$0	$1,189	$238	$0	$214	$1,641	$2	$1
1.4	Module Assembly	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.5	Air Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.6	Fuel Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.8	Module Current Collectors	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.9	Module I&C	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.10	Rectifier	$0	$0	$0	$0	$20,215	$4,043	$0	$3,639	$27,896	$40	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$125,153**	**$25,031**	**$0**	**$22,528**	**$172,712**	**$249**	**$125**
	2	SOEC Balance of Plant										
2.1	Air-Electrode Sweep Blower	$0	$0	$0	$0	$926	$185	$0	$167	$1,278	$2	$1
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$21,530	$4,306	$0	$3,875	$29,712	$43	$22
2.3	Hydrogen Recycle Blower	$0	$0	$0	$0	$589	$118	$0	$106	$812	$1	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$13,831	$2,766	$0	$2,490	$19,086	$28	$14
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,288	$258	$0	$232	$1,778	$3	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
2.7	Section I&C	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$39,452**	**$7,890**	**$0**	**$7,101**	**$54,444**	**$79**	**$39**
	3	Feedwater & Miscellaneous BOP Systems										
3.1	Feedwater System	$0	$0	$0	$0	$4,147	$829	$0	$746	$5,722	$8	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,607	$921	$0	$1,106	$6,634	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,787	$357	$0	$322	$2,467	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,487	$1,897	$0	$2,277	$13,662	$20	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$993	$199	$0	$179	$1,370	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,617	$923	$0	$1,108	$6,648	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$25,637**	**$5,127**	**$0**	**$5,737**	**$36,502**	**$53**	**$26**
	4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems										
4.1	Feedwater Heaters	$0	$0	$0	$0	$504	$101	$0	$91	$695	$1	$1
4.2	Electric Boiler	$0	$0	$0	$0	$31,636	$6,327	$0	$5,694	$43,658	$63	$32
4.3	Electric Superheaters	$0	$0	$0	$0	$1,703	$341	$0	$306	$2,349	$3	$2
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$653	$131	$0	$118	$901	$1	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$302	$60	$0	$54	$416	$1	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$47	$357	$1	$0

	Case:	SOEC-EB-5A	Pathway Step 5 SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	693,186	Plant Size (MW net):			1,378		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 H_2/day]	$/kW (net)
4.7	Hydrogen Compressor	$0	$0	$0	$0	$20,404	$4,081	$0	$3,673	$28,157	$41	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$55,460**	**$11,092**	**$0**	**$9,983**	**$76,534**	**$110**	**$56**
7	Ductwork, & Stack											
7.3	Ductwork	$0	$0	$0	$0	$676	$135	$0	$122	$932	$1	$1
7.4	Stack	$0	$0	$0	$0	$4,519	$904	$0	$813	$6,236	$9	$5
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$576	$115	$0	$138	$830	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,771**	**$1,154**	**$0**	**$1,073**	**$7,998**	**$12**	**$6**
9	Cooling Water System											
9.1	Cooling Towers	$0	$0	$0	$0	$3,359	$672	$0	$605	$4,635	$7	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$368	$74	$0	$66	$508	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,289	$858	$0	$772	$5,919	$9	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,717	$343	$0	$309	$2,370	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$583	$117	$0	$105	$804	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$235	$47	$0	$42	$324	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$555	$111	$0	$133	$799	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$11,105**	**$2,221**	**$0**	**$2,032**	**$15,359**	**$22**	**$11**
11	Accessory Electric Plant											
11.2	Station Service Equipment	$0	$0	$0	$0	$11,667	$2,333	$0	$2,100	$16,100	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$18,004	$3,601	$0	$3,241	$24,846	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,392	$2,878	$0	$2,591	$19,861	$29	$14
11.5	Wire & Cable	$0	$0	$0	$0	$15,428	$3,086	$0	$2,777	$21,291	$31	$15
11.6	Protective Equipment	$0	$0	$0	$0	$1,166	$233	$0	$210	$1,609	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,689	$538	$0	$484	$3,710	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,094	$419	$0	$377	$2,889	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$440	$88	$0	$106	$634	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$65,880**	**$13,176**	**$0**	**$11,885**	**$90,941**	**$131**	**$66**
12	Instrumentation & Control											
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,469	$294	$73	$264	$2,100	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$725	$145	$0	$130	$1,000	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$318	$64	$16	$57	$455	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,330	$2,266	$566	$2,039	$16,201	$23	$12
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,538	$908	$227	$817	$6,490	$9	$5

	Case:	SOEC-EB-5A	Pathway Step 5 SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	693,186	Plant Size (MW net):			1,378			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 H_2/day]	$/kW (net)
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,085	$417	$104	$375	$2,981	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,464**	**$4,093**	**$987**	**$3,683**	**$29,227**	**$42**	**$21**
13	**Improvements to Site**											
13.1	Site Preparation	$0	$0	$0	$0	$16,949	$3,390	$0	$4,068	$24,406	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,692	$1,138	$0	$1,366	$8,196	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,822	$964	$0	$1,157	$6,944	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,463**	**$5,493**	**$0**	**$6,591**	**$39,546**	**$57**	**$29**
14	**Buildings & Structures**											
14.4	Administration Building	$0	$0	$0	$0	$767	$153	$0	$138	$1,059	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$23	$5	$0	$4	$32	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$450	$90	$0	$81	$621	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,129	$226	$0	$203	$1,558	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$848	$170	$0	$153	$1,171	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$631	$126	$0	$114	$871	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,090	$218	$0	$196	$1,505	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,940**	**$988**	**$0**	**$889**	**$6,817**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$381,325**	**$76,265**	**$987**	**$71,503**	**$530,080**	**$765**	**$385**

Exhibit A-65. Case 5A owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,888	$6	$3
1 Month Maintenance Materials	$592	$1	$0
1 Month Non-Fuel Consumables	$189	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$10,602	$15	$8
Total	**$15,271**	**$22**	**$11**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$218	$0	$0
0.5% of TPC (spare parts)	$2,650	$4	$2
Total	**$2,868**	**$4**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$483	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$79,512	$115	$58
Financing Costs	$14,312	$21	$10
Total Overnight Costs (TOC)	**$642,826**	**$927**	**$466**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$687,696**	**$992**	**$499**

Exhibit A-66. Case 5A initial and annual O&M costs

Case:	**SOEC-EB-5A**		**Pathway Step 5 SOEC**		**Cost Base:**		**Dec 2018**
Plant Size (kg H_2/day):	**693,186**	**Plant Size (MW net):**		**1,378**	**Capacity Factor (%):**		**95%**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.16	$1.59
Maintenance Labor:					$4,028,609	$5.81	$2.92
Administrative & Support Labor:					$1,555,200	$2.24	$1.13
Property Taxes and Insurance:					$10,601,602	$15.29	$7.69
Total:					**$18,377,601**	**$26.51**	**$13.33**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh)**
Maintenance Material:					$6,753,844	$0.03	$0.59
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	79.18	$7.99	$9,571,347	$0.04	$0.83
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,379	$1.90	$0	$908,273	$0.004	$0.079
Makeup and Wastewater Treatment Chemicals (ton):	0	4.11	$550	$0	$783,205	$0.003	$0.068
Hydrogen Drying Sorbent (lb):	48263	132.23	$10	$482,633	$458,502	$0.002	$0.040
Subtotal:				**$482,633**	**$2,149,980**	**$0.009**	**$0.187**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	132.23	$0.02	$0	$871	$0.00	$0.00
Subtotal:				**$0**	**$871**	$0.00	**$0.00**
Variable Operating Costs Total:				**$482,633**	**$18,476,042**	**$0.04**	**$0.78**
Electricity Cost							
Electricity (MWh):	0	33,081	$60.00	$0	$688,254,191	$2.86	$60.00
Total:				**$0**	**$688,254,191**	**$2.86**	**$60.00**

Exhibit A-67. Case 5A LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.17	5%
Fixed	0.08	2%
Variable	0.08	2%
Electricity	2.86	90%
Total	**3.18**	**N/A**

CASE 6A

Exhibit A-68. Case 6A stream table

	1	2	3	4	5	6	7	8	9
V-L Mole Fraction									
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH_4	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
C_3H_8	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.4250	0.8500	0.8500	0.8500	0.9655	0.9986
H_2O	1.0000	1.0000	1.0000	0.5750	0.1500	0.1500	0.1500	0.0345	0.0014
N_2	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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,498	17,000	17,000	34,000	34,000	17,000	17,000	14,967	14,470
V-L Flowrate (kg/h)	297,221	306,258	306,258	381,326	150,136	75,068	75,068	38,437	29,494
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	145	637	755	757	757	163	30	30
Pressure (MPa, abs)	0.10	0.13	0.12	0.12	0.12	0.12	0.12	0.10	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,770.89	3,788.61	4,588.08	6,779.77	6,779.77	2,627.72	943.00	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,200.46	-12,182.73	-10,190.40	-3,132.08	-3,132.08	-7,284.14	-3,194.04	-87.51
Density (kg/m^3)	1,003.6	0.7	0.3	0.2	0.1	0.1	0.1	0.1	2.1
V-L Molecular Weight	18.015	18.015	18.015	11.216	4.416	4.416	4.416	2.568	2.038
V-L Flowrate (lb_{mol}/h)	36,373	37,478	37,478	74,957	74,957	37,478	37,478	32,996	31,901
V-L Flowrate (lb/h)	655,261	675,184	675,184	840,680	330,993	165,496	165,496	84,739	65,022
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	294	1,179	1,391	1,395	1,395	325	86	86
Pressure (psia)	14.7	18.2	17.4	17.2	17.0	17.0	16.8	14.8	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,191.3	1,628.8	1,972.5	2,914.8	2,914.8	1,129.7	405.4	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,675.2	-5,237.6	-4,381.1	-1,346.6	-1,346.6	-3,131.6	-1,373.2	-37.6
Density (lb/ft^3)	62.650	0.041	0.018	0.010	0.004	0.004	0.009	0.006	0.132

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

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

Exhibit A-68. Case 6A stream table (cont'd)

	10	11	12	13	14	15	16	17	18	19
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077
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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,306	14,306	33,002	33,002	33,002	33,002	40,229	40,229	40,229
V-L Flowrate (kg/h)	653	28,841	28,841	952,256	952,255	952,255	952,255	1,183,482	1,183,482	1,183,482
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	31	730	750	761	204	158
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.12	0.11	0.11	0.11	0.11	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	47.31	797.36	820.37	820.40	216.90	170.99
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	-85.41	664.64	687.65	709.14	105.63	59.72
Density (kg/m³)	4.7	2.1	5.0	1.2	1.4	0.4	0.4	0.4	0.8	0.8
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,538	31,538	72,758	72,757	72,757	72,757	88,689	88,689	88,689
V-L Flowrate (lb/h)	1,440	63,583	63,583	2,099,365	2,099,362	2,099,362	2,099,362	2,609,132	2,609,132	2,609,132
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	88	1,346	1,382	1,401	399	317
Pressure (psia)	385.0	383.3	939.7	14.7	17.2	16.4	15.9	15.5	15.3	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	20.3	342.8	352.7	352.7	93.2	73.5
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	-36.7	285.7	295.6	304.9	45.4	25.7
Density (lb/ft³)	0.292	0.129	0.314	0.076	0.084	0.024	0.023	0.023	0.049	0.052

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

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

Exhibit A-69. Case 6A plant performance summary

Performance Summary	
Total Gross Power, kWe	**0**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	239,960
Hydrogen Compression, kWe	62,467
Balance of Plant, kWe	44,173
Total Auxiliaries, MWe	**347**
Net Power, MWe	**-1,377.5**
Hydrogen Production, kg/h (lb/h)	**28,841 (63,583)**
Energy Efficiency,[A] % HHV (% LHV)	82.5 (69.8)
Electric Input per Kilogram, kWh/kg	47.8
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,136,799 (961,246)
Raw Water Withdrawal, m^3/min (gpm)	7.2 (1,912)
Raw Water Consumption, m^3/min (gpm)	6.1 (1,616)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-70. Case 6A power summary

Power Summary	
Total Gross Power, MWe	**0**
Auxiliary Load Summary	
Air Electrode Blowers, kWe	4,690
Circulating Water Pumps, kWe	600
Cooling Tower Fans, kWe	310
Electric Boiler, kWe	239,960
Electric Steam Superheater, kWe	21,718
Electric Sweep Heater, kWe	6,088
Feedwater Pumps, kWe	72
Fuel Electrode Recycle Blowers, kWe	656
Ground Water Pumps, kWe	170
Hydrogen Compressor, kWe	62,467
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,580
Total Auxiliaries, MWe	347
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,378**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-71. Case 6A carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (262)	Air-Electrode Sweep Exhaust (CO_2)	119 (262)
Total	**119 (262)**	**Total**	**119 (262)**

Exhibit A-72. Case 6A 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)
Electrolysis Steam	5.0 (1,311)	–	5.0 (1,311)	–	5.0 (1,311)
Deaerator Vent	–	–	–	0.0 (3.2)	0.0 (-3.2)
Boiler Blowdown	–	–	–	0.6 (158)	-0.6 (-158)
Cooling Tower	2.3 (601)	–	2.3 (601)	0.5 (135)	1.8 (466)
Total	**7.2 (1,912)**	**–**	**7.2 (1,912)**	**1.1 (296)**	**6.1 (1,616)**

Exhibit A-73. Case 6A overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	27 (26)	–	27 (26)
Auxiliary Power	–	–	4,959 (4,700)	4,959 (4,700)
Total	**0.0 (0.0)**	**57 (54)**	**4,959 (4,700)**	**5,016 (4,754)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,092 (3,879)	13 (12)	–	4,105 (3,891)
Sweep Exhaust	–	202 (192)	–	202 (192)
Motor Losses and Design Allowances	–	7.1 (7.1)	–	7.1 (7.1)
Cooling Tower Load[A]	–	297 (282)	–	297 (282)
Boiler Blowdown	–	11 (10)	–	11 (10)
Process Vents[B]	–	0.4 (0.4)	–	0.4 (0.4)
Ambient Losses[C]	–	311 (295)	–	311 (295)
Total	**–**	**842 (798)**	**0.0 (0.0)**	**4,934 (4,677)**
Unaccounted Energy[D]	**–**	*81 (77)*	–	*81 (77)*

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-74. Case 6A energy and mass balance diagram

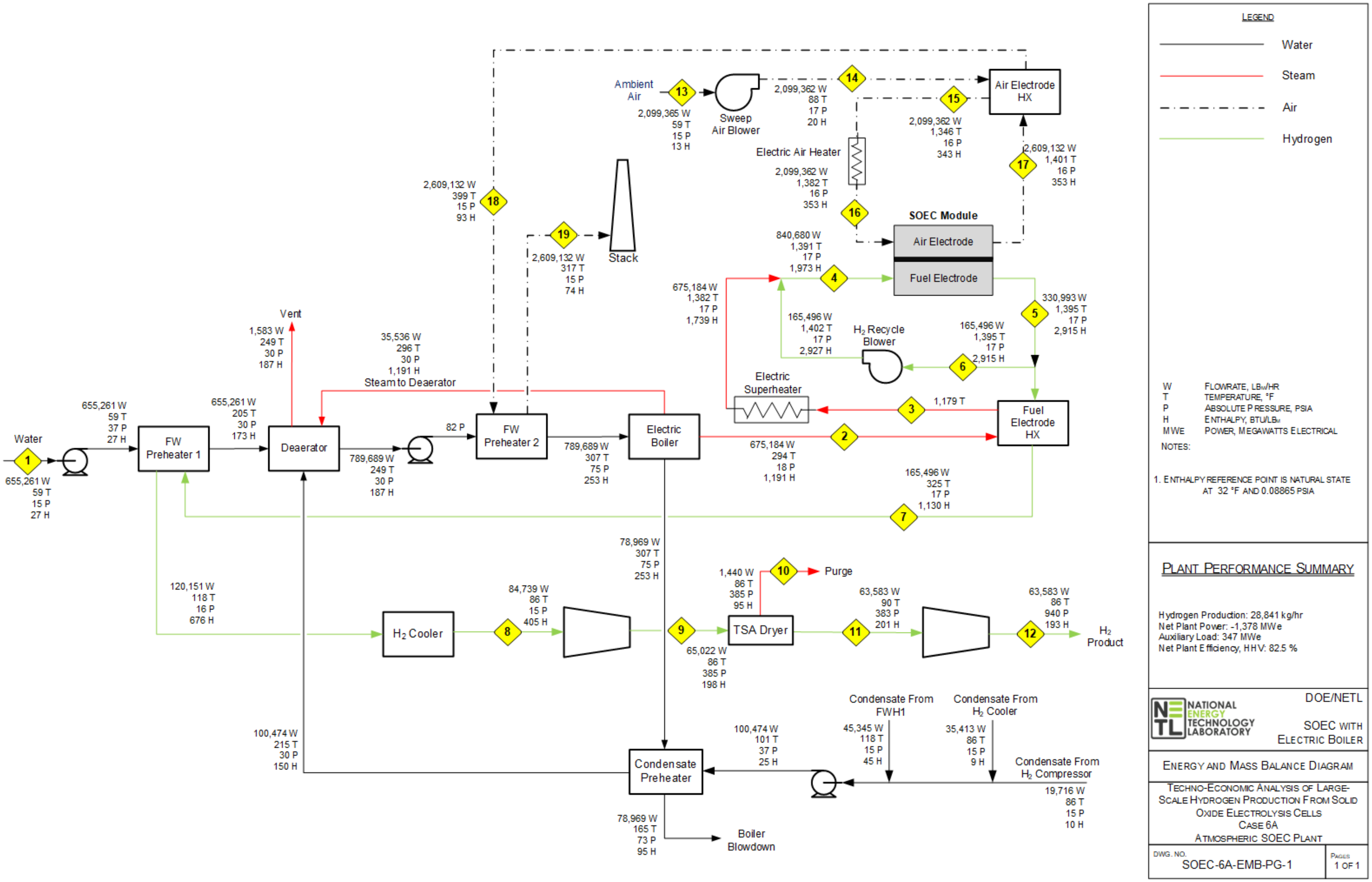


Exhibit A-75. Case 6A total plant cost details

	Case:	SOEC-EB-6A	Pathway Step 6 SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	692,174	Plant Size (MW net):			1,378			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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$14,864	$2,973	$0	$2,675	$20,512	$30	$15
1.2	Container	$0	$0	$0	$0	$1,338	$268	$0	$241	$1,846	$3	$1
1.3	Insulation	$0	$0	$0	$0	$595	$119	$0	$107	$820	$1	$1
1.4	Module Assembly	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.5	Air Distribution	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.6	Fuel Distribution	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$1
1.8	Module Current Collectors	$0	$0	$0	$0	$743	$149	$0	$134	$1,026	$1	$1
1.9	Module I&C	$0	$0	$0	$0	$743	$149	$0	$134	$1,026	$1	$1
1.10	Rectifier	$0	$0	$0	$0	$10,107	$2,021	$0	$1,819	$13,948	$20	$10
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$32,849**	**$6,570**	**$0**	**$5,913**	**$45,332**	**$65**	**$33**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Blower	$0	$0	$0	$0	$811	$162	$0	$146	$1,119	$2	$1
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$20,480	$4,096	$0	$3,686	$28,262	$41	$21
2.3	Hydrogen Recycle Blower	$0	$0	$0	$0	$473	$95	$0	$85	$653	$1	$0
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$13,831	$2,766	$0	$2,490	$19,087	$28	$14
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$855	$171	$0	$154	$1,180	$2	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$428	$86	$0	$77	$590	$1	$0
2.7	Section I&C	$0	$0	$0	$0	$428	$86	$0	$77	$590	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$37,306**	**$7,461**	**$0**	**$6,715**	**$51,482**	**$74**	**$37**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,142	$828	$0	$746	$5,716	$8	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,602	$920	$0	$1,104	$6,627	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,785	$357	$0	$321	$2,463	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,476	$1,895	$0	$2,274	$13,646	$20	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$992	$198	$0	$178	$1,368	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,612	$922	$0	$1,107	$6,641	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$25,609**	**$5,122**	**$0**	**$5,731**	**$36,462**	**$53**	**$26**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$484	$97	$0	$87	$668	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$31,599	$6,320	$0	$5,688	$43,607	$63	$32
4.3	Electric Superheaters	$0	$0	$0	$0	$1,679	$336	$0	$302	$2,317	$3	$2
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$653	$131	$0	$117	$900	$1	$1
4.5	Hydrogen Cooler	$0	$0	$0	$0	$301	$60	$0	$54	$416	$1	$0

Case:		SOEC-EB-6A	Pathway Step 6 SOEC					Estimate Type:		Conceptual		
Plant Size (kg H_2/day):		692,174	Plant Size (MW net):			1,378		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 H_2/day]	$/kW (net)
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$20,383	$4,077	$0	$3,669	$28,129	$41	$20
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$55,357**	**$11,071**	**$0**	**$9,964**	**$76,393**	**$110**	**$55**
7	**Ductwork, & Stack**											
7.3	Ductwork	$0	$0	$0	$0	$679	$136	$0	$122	$937	$1	$1
7.4	Stack	$0	$0	$0	$0	$4,539	$908	$0	$817	$6,263	$9	$5
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$579	$116	$0	$139	$833	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,796**	**$1,159**	**$0**	**$1,078**	**$8,033**	**$12**	**$6**
9	**Cooling Water System**											
9.1	Cooling Towers	$0	$0	$0	$0	$3,355	$671	$0	$604	$4,630	$7	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$367	$73	$0	$66	$507	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,286	$857	$0	$772	$5,915	$9	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,716	$343	$0	$309	$2,368	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$583	$117	$0	$105	$804	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$235	$47	$0	$42	$324	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$554	$111	$0	$133	$798	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$11,096**	**$2,219**	**$0**	**$2,030**	**$15,345**	**$22**	**$11**
11	**Accessory Electric Plant**											
11.2	Station Service Equipment	$0	$0	$0	$0	$11,662	$2,332	$0	$2,099	$16,094	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$17,997	$3,599	$0	$3,239	$24,836	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,386	$2,877	$0	$2,590	$19,853	$29	$14
11.5	Wire & Cable	$0	$0	$0	$0	$15,422	$3,084	$0	$2,776	$21,283	$31	$15
11.6	Protective Equipment	$0	$0	$0	$0	$1,166	$233	$0	$210	$1,609	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,688	$538	$0	$484	$3,709	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,093	$419	$0	$377	$2,888	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$440	$88	$0	$106	$634	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$65,854**	**$13,171**	**$0**	**$11,880**	**$90,905**	**$131**	**$66**
12	**Instrumentation & Control**											
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,468	$294	$73	$264	$2,099	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$724	$145	$0	$130	$1,000	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$318	$64	$16	$57	$455	$1	$0

	Case:	SOEC-EB-6A	Pathway Step 6 SOEC					Estimate Type:			Conceptual		
	Plant Size (kg H_2/day):	692,174	Plant Size (MW net):			1,378		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 H_2/day]	$/kW (net)	
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,325	$2,265	$566	$2,039	$16,195	$23	$12	
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,537	$907	$227	$817	$6,487	$9	$5	
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,084	$417	$104	$375	$2,980	$4	$2	
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,456**	**$4,091**	**$987**	**$3,682**	**$29,216**	**$42**	**$21**	
13							**Improvements to Site**						
13.1	Site Preparation	$0	$0	$0	$0	$16,944	$3,389	$0	$4,067	$24,399	$35	$18	
13.2	Site Improvements	$0	$0	$0	$0	$5,690	$1,138	$0	$1,366	$8,194	$12	$6	
13.3	Site Facilities	$0	$0	$0	$0	$4,821	$964	$0	$1,157	$6,942	$10	$5	
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,455**	**$5,491**	**$0**	**$6,589**	**$39,535**	**$57**	**$29**	
14							**Buildings & Structures**						
14.4	Administration Building	$0	$0	$0	$0	$767	$153	$0	$138	$1,058	$2	$1	
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$23	$5	$0	$4	$32	$0	$0	
14.6	Water Treatment Buildings	$0	$0	$0	$0	$450	$90	$0	$81	$621	$1	$0	
14.7	Machine Shop	$0	$0	$0	$0	$1,129	$226	$0	$203	$1,558	$2	$1	
14.8	Warehouse	$0	$0	$0	$0	$848	$170	$0	$153	$1,170	$2	$1	
14.9	Other Buildings & Structures	$0	$0	$0	$0	$631	$126	$0	$114	$871	$1	$1	
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,090	$218	$0	$196	$1,504	$2	$1	
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,938**	**$988**	**$0**	**$889**	**$6,814**	**$10**	**$5**	
	Total	**$0**	**$0**	**$0**	**$0**	**$286,716**	**$57,343**	**$987**	**$54,472**	**$399,518**	**$577**	**$290**	

Exhibit A-76. Case 6A owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,268	$5	$2
1 Month Maintenance Materials	$447	$1	$0
1 Month Non-Fuel Consumables	$188	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$7,990	$12	$6
Total	**$11,893**	**$17**	**$9**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$218	$0	$0
0.5% of TPC (spare parts)	$1,998	$3	$1
Total	**$2,215**	**$3**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$482	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$59,928	$87	$44
Financing Costs	$10,787	$16	$8
Total Overnight Costs (TOC)	**$485,122**	**$701**	**$352**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$518,985**	**$750**	**$377**

Exhibit A-77. Case 6A initial and annual O&M costs

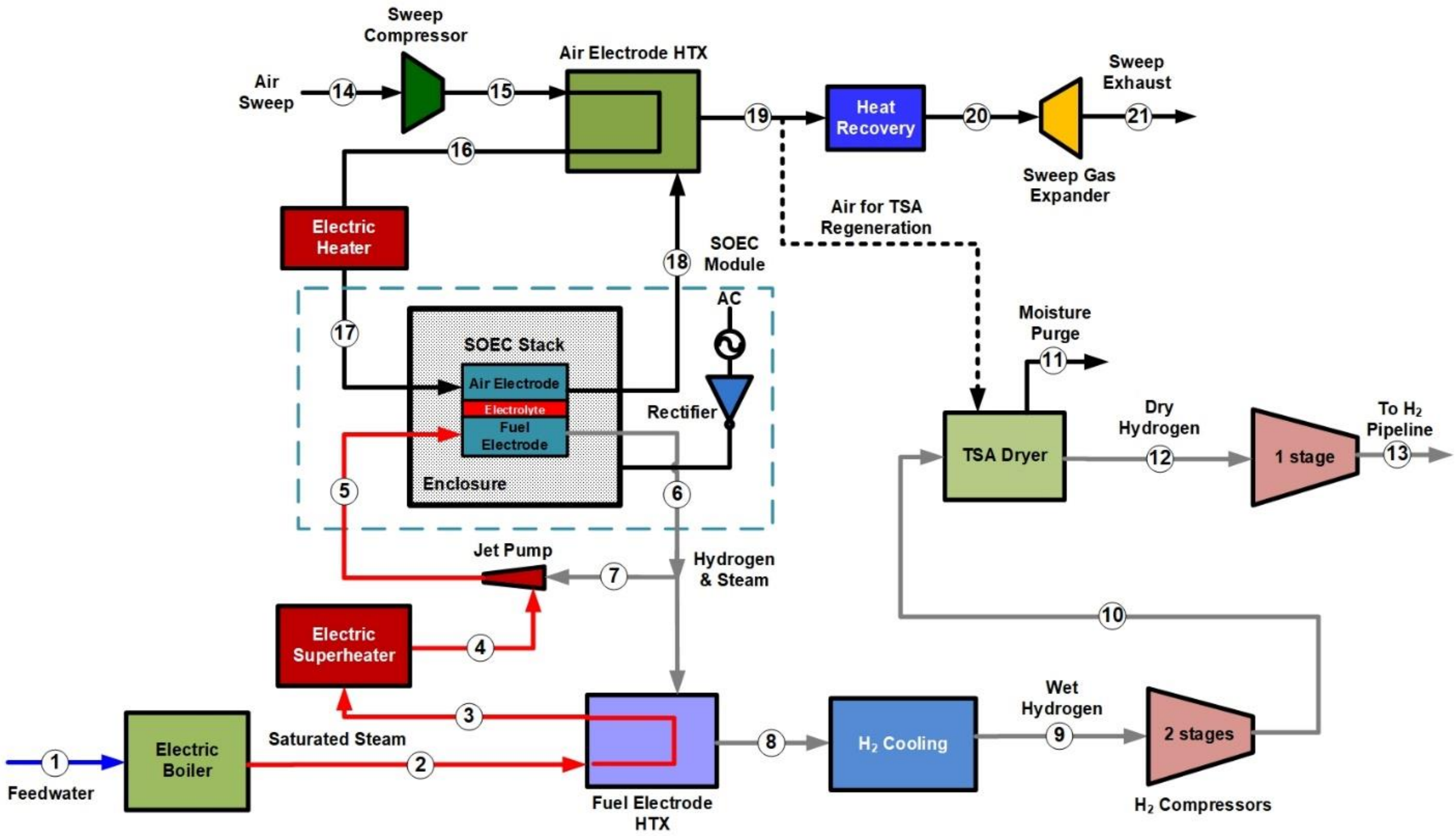
Case:	SOEC-EB-6A		Pathway Step 6 SOEC		Cost Base:	Dec 2018	
Plant Size (kg H_2/day):	692,174	Plant Size (MW net):		1,378	Capacity Factor (%):	95%	
Operating & Maintenance Labor							
Operating Labor				Operating Labor Requirements per Shift			
Operating Labor Rate (base):		38.50	$/hour	Skilled Operator:			1.0
Operating Labor Burden:		30.00	% of base	Operator:			2.0
Labor O-H Charge Rate:		25.00	% of labor	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	($/[kg H_2/day])	($/kW-net)
Annual Operating Labor:					$2,192,190	$3.17	$1.59
Maintenance Labor:					$3,036,334	$4.39	$2.20
Administrative & Support Labor:					$1,307,131	$1.89	$0.95
Property Taxes and Insurance:					$7,990,352	$11.54	$5.80
Total:					**$14,526,007**	**$20.99**	**$10.54**
Variable Operating Costs							
					($)	($/kg H_2)	($/MWh)
Maintenance Material:					$5,090,324	$0.02	$0.44
Stack Replacement							
	Life (yr)		$/$kW_{AC}$	$/yr per kW			
SOEC Stack Replacement Cost:		9.34	14.75	$1.49	$1,785,251	$0.01	$0.16
Consumables							
	Initial Fill	Per Day	Per Unit	Initial Fill			
Water (gallon/1000):	0	1,377	$1.90	$0	$906,946	$0.00	$0.08
Makeup and Wastewater Treatment Chemicals (ton):	0	4.10	$550	$0	$782,061	$0.00	$0.07
Hydrogen Drying Sorbent (lb):	48193	132.0	$10	$481,928	$457,832	$0.00	$0.04
Subtotal:				**$481,928**	**$2,146,839**	**$0.01**	**$0.19**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	132.0	$0.02	$0	$870	$0.00	$0.00
Subtotal:				**$0**	**$870**	**$0.00**	**$0.00**
Variable Operating Costs Total:				**$481,928**	**$9,023,285**	**$0.03**	**$0.63**
Electricity Cost							
Electricity (MWh):	0	33,061	$60.00	$0	$687,831,730	$2.87	$60.00
Total:				**$0**	**$687,831,730**	**$2.87**	**$60.00**

Exhibit A-78. Case 6A LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.13	4%
Fixed	0.06	2%
Variable	0.04	1%
Electricity	2.87	93%
Total	**3.09**	**N/A**

PRESSURIZED CASES

Exhibit A-79. BFD for all pressurized cases



CASE 0P

Exhibit A-80. Case 0P stream table

	1	2	3	4	5	6	7	8	9	10
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.4000	0.8000	0.8000	0.8000	0.9954	0.9986
H_2O	1.0000	1.0000	1.0000	1.0000	0.6000	0.2000	0.2000	0.2000	0.0046	0.0014
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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,510	17,961	17,961	17,961	35,922	35,922	17,961	17,961	14,435	14,389
V-L Flowrate (kg/h)	297,424	323,575	323,575	323,575	417,253	187,359	93,678	93,679	30,152	29,328
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	187	730	845	851	861	861	193	30	30
Pressure (MPa, abs)	0.10	1.17	1.16	1.14	0.80	0.80	0.80	0.80	0.78	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,820.32	3,990.49	4,260.52	4,848.98	6,881.55	6,881.56	2,839.71	512.84	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,151.02	-11,980.85	-11,710.82	-10,038.35	-4,261.44	-4,261.43	-8,303.28	-457.12	-87.51
Density (kg/m^3)	1,003.6	5.9	2.5	2.2	1.0	0.4	0.4	1.1	0.6	2.1
V-L Molecular Weight	18.015	18.015	18.015	18.015	11.616	5.216	5.216	5.216	2.089	2.038
V-L Flowrate (lb_{mol}/h)	36,397	39,598	39,598	39,598	79,194	79,194	39,596	39,597	31,823	31,722
V-L Flowrate (lb/h)	655,707	713,360	713,360	713,360	919,885	413,056	206,525	206,528	66,473	64,657
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	369	1,346	1,553	1,564	1,581	1,581	380	86	86
Pressure (psia)	14.7	170.0	168.0	166.0	116.0	115.8	115.8	115.6	113.6	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,212.5	1,715.6	1,831.7	2,084.7	2,958.5	2,958.5	1,220.9	220.5	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,653.9	-5,150.8	-5,034.7	-4,315.7	-1,832.1	-1,832.1	-3,569.8	-196.5	-37.6
Density (lb/ft^3)	62.650	0.366	0.157	0.139	0.062	0.028	0.028	0.067	0.040	0.132

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

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

Exhibit A-80. Case 0P stream table (cont'd)

	11	12	13	14	15	16	17	18	19	20	21
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077	0.0077
CH_4	0.0000	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	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	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	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	164	14,225	14,225	32,817	32,819	32,819	32,819	40,006	40,006	40,006	40,006
V-L Flowrate (kg/h)	649	28,679	28,679	946,917	946,973	946,973	946,973	1,176,933	1,176,933	1,176,933	1,176,933
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	160	830	850	861	328	271	80
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.81	0.80	0.80	0.80	0.80	0.79	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	177.60	913.61	936.99	936.77	344.57	285.23	92.61
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	44.88	780.89	804.27	825.50	233.30	173.96	-18.66
Density (kg/m^3)	4.7	2.1	5.0	1.2	6.5	2.5	2.5	2.5	4.7	5.2	1.0
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	361	31,361	31,361	72,350	72,354	72,354	72,354	88,198	88,198	88,198	88,198
V-L Flowrate (lb/h)	1,432	63,225	63,225	2,087,595	2,087,717	2,087,717	2,087,717	2,594,694	2,594,694	2,594,694	2,594,694
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	320	1,526	1,562	1,583	622	519	177
Pressure (psia)	385.0	383.3	939.7	14.7	117.3	116.5	116.0	115.8	115.6	115.1	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	76.4	392.8	402.8	402.7	148.1	122.6	39.8
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	19.3	335.7	345.8	354.9	100.3	74.8	-8.0
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.404	0.157	0.154	0.155	0.292	0.322	0.063

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

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

Exhibit A-81. Case 0P plant performance summary

Performance Summary	
Total Gross Power, kWe	**62**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	239,238
Hydrogen Compression, kWe	30,022
Balance of Plant, kWe	111,199
Total Auxiliaries, MWe	**380**
Net Power, MWe	**-1,349**
Hydrogen Production, kg/h (lb/h)	**28,679 (63,225)**
Energy Efficiency,[A] % HHV (% LHV)	83.8 (70.8)
Electric Input per Kilogram, kWh/kg	47.1
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,130,411 (955,844)
Raw Water Withdrawal, m^3/min (gpm)	7.2 (1,907)
Raw Water Consumption, m^3/min (gpm)	6.1 (1,604)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-82. Case 0P power summary

Power Summary	
Sweep Gas Expander, MWe	62
Total Gross Power, MWe	**62**
Auxiliary Load Summary	
Air Electrode Compressors, kWe	69,765
Circulating Water Pumps, kWe	590
Cooling Tower Fans, kWe	300
Electric Boiler, kWe	239,238
Electric Steam Superheater, kWe	24,271
Electric Sweep Heater, kWe	6,151
Feedwater Pumps, kWe	173
Fuel Electrode Recycle Blowers, kWe	0
Ground Water Pumps, kWe	170
Hydrogen Compressor, kWe	30,022
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,490
Total Auxiliaries, MWe	**380**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,349**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-83. Case 0P carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	118 (261)	Air-Electrode Sweep Exhaust (CO_2)	118 (261)
Total	**118 (261)**	**Total**	**118 (261)**

Exhibit A-84. Case 0P 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)
Electrolysis Steam	5.0 (1,311)	–	5.0 (1,311)	–	5.0 (1,311)
Deaerator Vent	–	–	–	0.0 (3.3)	0.0 (-3.3)
Boiler Blowdown	–	–	–	0.6 (165)	-0.6 (-165)
Cooling Tower	2.3 (595)	–	2.3 (595)	0.5 (134)	1.7 (461)
Total	**7.2 (1,907)**	**–**	**7.2 (1,907)**	**1.1 (302)**	**6.1 (1,604)**

Exhibit A-85. Case 0P overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	29 (28)	–	29 (28)
Raw Water Makeup	–	27 (26)	–	27 (26)
Auxiliary Power	–	–	4,858 (4,604)	4,858 (4,604)
Total	**0.0 (0.0)**	**57 (54)**	**4,858 (4,604)**	**4,914 (4,658)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,069 (3,857)	13 (12)	–	4,082 (3,869)
Sweep Exhaust	–	109 (103)	–	109 (103)
Motor Losses and Design Allowances	–	13 (13)	–	13 (13)
Cooling Tower Load[A]	–	294 (279)	–	294 (279)
Boiler Blowdown	–	13 (12)	–	13 (12)
Process Vents[B]	–	0.6 (0.5)	–	0.6 (0.5)
Ambient Losses[C]	–	318 (301)	–	318 (301)
Total	**4,069 (3,857)**	**761 (722)**	**0.0 (0.0)**	**4,830 (4,579)**
Unaccounted Energy[D]	–	–	–	84 (79)

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-86. Case 0P energy and mass balance

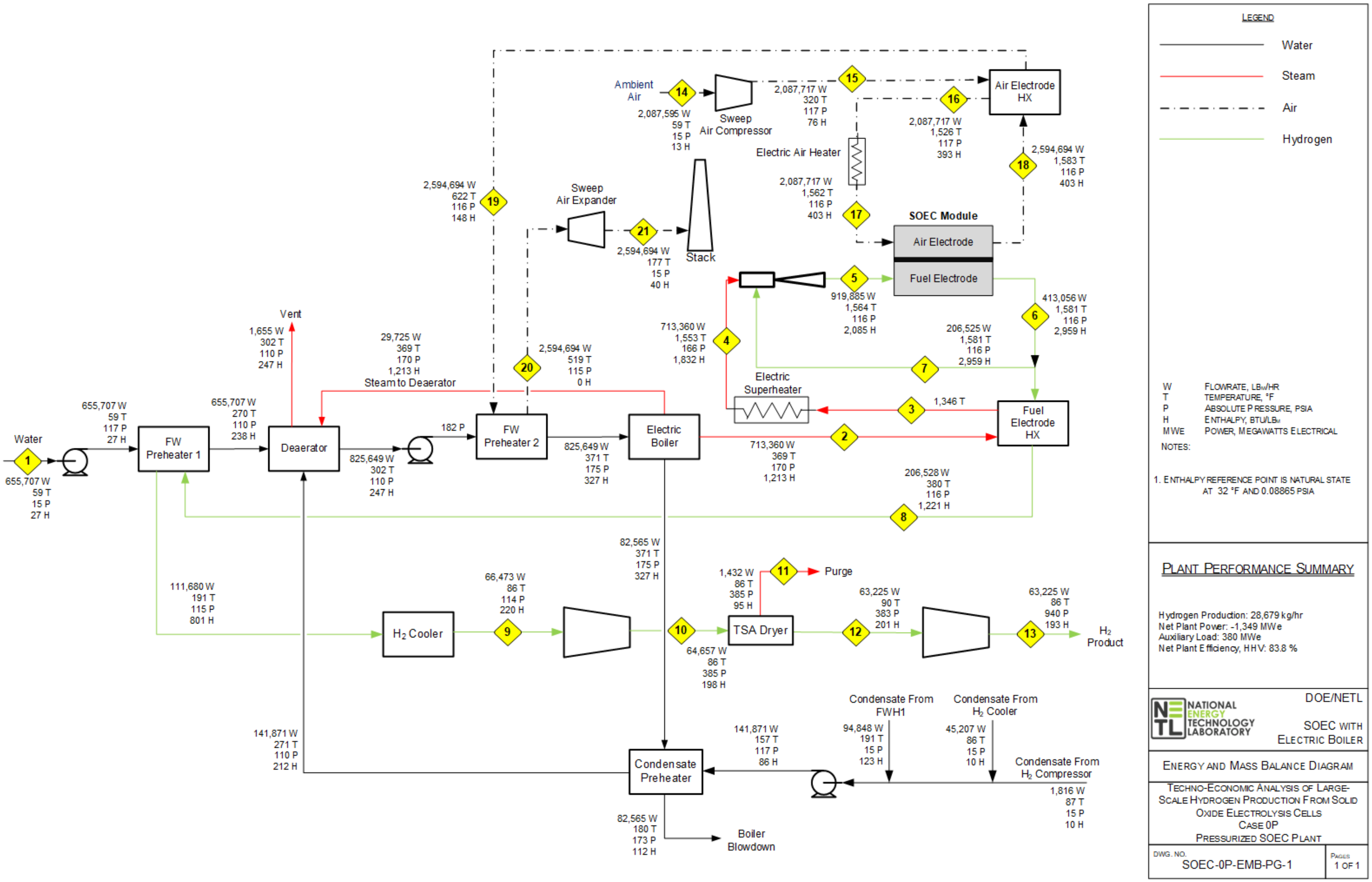


Exhibit A-87. Case 0P total plant cost details

	Case:	SOEC-EB-0P	State-of-the-Art Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	688,284	Plant Size (MW net):			1,349			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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$172,792	$34,558	$0	$31,103	$238,453	$346	$177
1.2	Container	$0	$0	$0	$0	$24,597	$4,919	$0	$4,427	$33,943	$49	$25
1.3	Insulation	$0	$0	$0	$0	$2,304	$461	$0	$415	$3,179	$5	$2
1.4	Module Assembly	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.5	Air Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.6	Fuel Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.8	Module Current Collectors	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.9	Module I&C	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.10	Rectifier	$0	$0	$0	$0	$39,166	$7,833	$0	$7,050	$54,049	$79	$40
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$261,898**	**$52,380**	**$0**	**$47,142**	**$361,419**	**$525**	**$268**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Compressor	$0	$0	$0	$0	$7,735	$1,547	$0	$1,392	$10,674	$16	$8
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$20,605	$4,121	$0	$3,709	$28,435	$41	$21
2.3	Hydrogen Recycle Jet Pump	$0	$0	$0	$0	$809	$162	$0	$146	$1,117	$2	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$22,498	$4,500	$0	$4,050	$31,047	$45	$23
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,951	$390	$0	$351	$2,693	$4	$2
2.6	Section and Overall Assembly	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
2.7	Section I&C	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
2.8	Sweep Gas Expander	$0	$0	$0	$0	$6,577	$1,315	$0	$1,184	$9,076	$13	$7
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$62,127**	**$12,425**	**$0**	**$11,183**	**$85,735**	**$125**	**$64**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,272	$854	$0	$769	$5,895	$9	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,592	$918	$0	$1,102	$6,613	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,857	$371	$0	$334	$2,563	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,455	$1,891	$0	$2,269	$13,615	$20	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$1,032	$206	$0	$186	$1,424	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,677	$935	$0	$1,123	$6,735	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$25,885**	**$5,177**	**$0**	**$5,783**	**$36,845**	**$54**	**$27**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$391	$78	$0	$70	$540	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$32,745	$6,549	$0	$5,894	$45,188	$66	$33
4.3	Electric Superheaters	$0	$0	$0	$0	$2,709	$542	$0	$488	$3,738	$5	$3
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$984	$197	$0	$177	$1,358	$2	$1

	Case:	SOEC-EB-0P	State-of-the-Art Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	688,284		Plant Size (MW net):		1,349			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 H_2/day]	$/kW (net)
4.5	Hydrogen Cooler	$0	$0	$0	$0	$264	$53	$0	$48	$365	$1	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$257	$51	$0	$46	$354	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$15,227	$3,045	$0	$2,741	$21,013	$31	$16
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$52,577**	**$10,515**	**$0**	**$9,464**	**$72,557**	**$105**	**$54**
	7						Ductwork, & Stack					
7.3	Ductwork	$0	$0	$0	$0	$588	$118	$0	$106	$811	$1	$1
7.4	Stack	$0	$0	$0	$0	$3,931	$786	$0	$707	$5,424	$8	$4
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$501	$100	$0	$120	$722	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,019**	**$1,004**	**$0**	**$934**	**$6,957**	**$10**	**$5**
	9						Cooling Water System					
9.1	Cooling Towers	$0	$0	$0	$0	$3,330	$666	$0	$599	$4,595	$7	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$365	$73	$0	$66	$503	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,264	$853	$0	$768	$5,885	$9	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,705	$341	$0	$307	$2,353	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$582	$116	$0	$105	$803	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$233	$47	$0	$42	$322	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$551	$110	$0	$132	$793	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$11,029**	**$2,206**	**$0**	**$2,018**	**$15,253**	**$22**	**$11**
	11						Accessory Electric Plant					
11.2	Station Service Equipment	$0	$0	$0	$0	$11,509	$2,302	$0	$2,072	$15,883	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$17,760	$3,552	$0	$3,197	$24,509	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,197	$2,839	$0	$2,555	$19,592	$28	$15
11.5	Wire & Cable	$0	$0	$0	$0	$15,220	$3,044	$0	$2,740	$21,003	$31	$16
11.6	Protective Equipment	$0	$0	$0	$0	$1,150	$230	$0	$207	$1,588	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,652	$530	$0	$477	$3,660	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,065	$413	$0	$372	$2,850	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$434	$87	$0	$104	$625	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$64,989**	**$12,998**	**$0**	**$11,724**	**$89,711**	**$130**	**$66**
	12						Instrumentation & Control					
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,448	$290	$72	$261	$2,071	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$716	$143	$0	$129	$989	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$314	$63	$16	$57	$449	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,173	$2,235	$559	$2,011	$15,977	$23	$12

	Case:	SOEC-EB-0P	State-of-the-Art Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	688,284	Plant Size (MW net):			1,349		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 H_2/day]	$/kW (net)
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,475	$895	$224	$806	$6,400	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,056	$411	$103	$370	$2,940	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,182**	**$4,036**	**$973**	**$3,633**	**$28,825**	**$42**	**$21**
13	**Improvements to Site**											
13.1	Site Preparation	$0	$0	$0	$0	$16,783	$3,357	$0	$4,028	$24,168	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,637	$1,127	$0	$1,353	$8,117	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,775	$955	$0	$1,146	$6,876	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,195**	**$5,439**	**$0**	**$6,527**	**$39,161**	**$57**	**$29**
14	**Buildings & Structures**											
14.4	Administration Building	$0	$0	$0	$0	$761	$152	$0	$137	$1,051	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$23	$5	$0	$4	$31	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$449	$90	$0	$81	$620	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,121	$224	$0	$202	$1,547	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$842	$168	$0	$152	$1,162	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$628	$126	$0	$113	$866	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,097	$219	$0	$198	$1,514	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,921**	**$984**	**$0**	**$886**	**$6,791**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$535,824**	**$107,165**	**$973**	**$99,293**	**$743,254**	**$1,080**	**$551**

Exhibit A-88. Case 0P owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$4,901	$7	$4
1 Month Maintenance Materials	$831	$1	$1
1 Month Non-Fuel Consumables	$188	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$14,865	$22	$11
Total	**$20,784**	**$30**	**$15**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$217	$0	$0
0.5% of TPC (spare parts)	$3,716	$5	$3
Total	**$3,933**	**$6**	**$3**
Other Costs			
Initial Cost for Catalyst and Chemicals	$479	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$111,488	$162	$83
Financing Costs	$20,068	$29	$15
Total Overnight Costs (TOC)	**$900,306**	**$1,308**	**$667**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$963,150**	**$1,399**	**$714**

Exhibit A-89. Case 0P initial and annual O&M costs

Case:	SOEC-EB-0P		State-of-the-Art Pressurized SOEC		Cost Base:		Dec 2018
Plant Size (kg H_2/day):	688,284	Plant Size (MW net):		1,349	Capacity Factor (%):		90%
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.185	$1.625
Maintenance Labor:					$5,648,732	$8.207	$4.186
Administrative & Support Labor:					$1,960,230	$2.848	$1.453
Property Taxes and Insurance:					$14,865,083	$21.597	$11.016
Total:					**$24,666,235**	**$35.837**	**$18.280**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh-net)**
Maintenance Material:					$8,971,515	$0.03968	$0.84332
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		2.33	157.25	$67.76	$79,177,245	$0.35018	$7.44264
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,373	$1.90	$0	$856,802	$0.00379	$0.08054
Makeup and Wastewater Treatment Chemicals (ton):	0	4.09	$550	$0	$738,822	$0.00327	$0.06945
Hydrogen Drying Sorbent (lb):	47,922	131.3	$10	$479,220	$431,298	$0.00191	$0.04054
Subtotal:				**$479,220**	**$2,026,923**	**$0.00896**	**$0.19053**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	131.3	$0.02	$0	$819	$0.00000	$0.00008
Subtotal:				**$0**	**$819**	**$0.00000**	**$0.00008**
Variable Operating Costs Total:				**$479,220**	**$90,176,502**	**$0.04865**	**$1.03393**
Electricity Cost							
Electricity (MWh):	0	32,385	$60.00	$0	$638,299,443	$2.82307	$60.00000
Total:				**$0**	**$638,299,443**	**$2.82307**	**$60.00000**

Exhibit A-90. Case 0P LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.25	7%
Fixed	0.11	3%
Variable	0.40	11%
Electricity	2.82	79%
Total	**3.58**	**N/A**

Case 1P

Exhibit A-91. Case 1P stream table

	1	2	3	4	5	6	7	8	9	10
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.4000	0.8000	0.8000	0.8000	0.9954	0.9986
H_2O	1.0000	1.0000	1.0000	1.0000	0.6000	0.2000	0.2000	0.2000	0.0046	0.0014
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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,510	17,961	17,961	17,961	35,922	35,922	17,961	17,961	14,435	14,389
V-L Flowrate (kg/h)	297,424	323,575	323,575	323,575	417,253	187,359	93,678	93,679	30,152	29,328
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	187	730	845	851	861	861	193	30	30
Pressure (MPa, abs)	0.10	1.17	1.16	1.14	0.80	0.80	0.80	0.80	0.78	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,820.32	3,990.49	4,260.52	4,848.98	6,881.55	6,881.56	2,839.71	512.84	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,151.02	-11,980.85	-11,710.82	-10,038.35	-4,261.44	-4,261.43	-8,303.28	-457.12	-87.51
Density (kg/m³)	1,003.6	5.9	2.5	2.2	1.0	0.4	0.4	1.1	0.6	2.1
V-L Molecular Weight	18.015	18.015	18.015	18.015	11.616	5.216	5.216	5.216	2.089	2.038
V-L Flowrate (lb_{mol}/h)	36,397	39,598	39,598	39,598	79,194	79,194	39,596	39,597	31,823	31,722
V-L Flowrate (lb/h)	655,707	713,360	713,360	713,360	919,885	413,056	206,525	206,528	66,473	64,657
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	369	1,346	1,553	1,564	1,581	1,581	380	86	86
Pressure (psia)	14.7	170.0	168.0	166.0	116.0	115.8	115.8	115.6	113.6	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,212.5	1,715.6	1,831.7	2,084.7	2,958.5	2,958.5	1,220.9	220.5	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,653.9	-5,150.8	-5,034.7	-4,315.7	-1,832.1	-1,832.1	-3,569.8	-196.5	-37.6
Density (lb/ft³)	62.650	0.366	0.157	0.139	0.062	0.028	0.028	0.067	0.040	0.132

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

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

Exhibit A-91. Case 1P stream table (cont'd)

	11	12	13	14	15	16	17	18	19	20	21
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077	0.0077
CH_4	0.0000	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	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	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	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	164	14,225	14,225	32,817	32,819	32,819	32,819	40,006	40,006	40,006	40,006
V-L Flowrate (kg/h)	649	28,679	28,679	946,917	946,973	946,973	946,973	1,176,933	1,176,933	1,176,933	1,176,933
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	160	830	850	861	328	271	80
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.81	0.80	0.80	0.80	0.80	0.79	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	177.60	913.61	936.99	936.77	344.57	285.23	92.61
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	44.88	780.89	804.27	825.50	233.30	173.96	-18.66
Density (kg/m^3)	4.7	2.1	5.0	1.2	6.5	2.5	2.5	2.5	4.7	5.2	1.0
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	361	31,361	31,361	72,350	72,354	72,354	72,354	88,198	88,198	88,198	88,198
V-L Flowrate (lb/h)	1,432	63,225	63,225	2,087,595	2,087,717	2,087,717	2,087,717	2,594,694	2,594,694	2,594,694	2,594,694
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	320	1,526	1,562	1,583	622	519	177
Pressure (psia)	385.0	383.3	939.7	14.7	117.3	116.5	116.0	115.8	115.6	115.1	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	76.4	392.8	402.8	402.7	148.1	122.6	39.8
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	19.3	335.7	345.8	354.9	100.3	74.8	-8.0
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.404	0.157	0.154	0.155	0.292	0.322	0.063

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

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

Exhibit A-92. Case 1P plant performance summary

Performance Summary	
Total Gross Power, kWe	**62**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	239,238
Hydrogen Compression, kWe	30,022
Balance of Plant, kWe	111,199
Total Auxiliaries, MWe	**380**
Net Power, MWe	**-1,349**
Hydrogen Production, kg/h (lb/h)	**28,679 (63,225)**
Energy Efficiency,[A] % HHV (% LHV)	83.8 (70.8)
Electric Input per Kilogram, kWh/kg	47.1
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,130,411 (955,844)
Raw Water Withdrawal, m^3/min (gpm)	7.2 (1,907)
Raw Water Consumption, m^3/min (gpm)	6.1 (1,604)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-93. Case 1P power summary

Power Summary	
Sweep Gas Expander, MWe	62
Total Gross Power, MWe	**62**
Auxiliary Load Summary	
Air Electrode Compressors, kWe	69,765
Circulating Water Pumps, kWe	590
Cooling Tower Fans, kWe	300
Electric Boiler, kWe	239,238
Electric Steam Superheater, kWe	24,271
Electric Sweep Heater, kWe	6,151
Feedwater Pumps, kWe	173
Fuel Electrode Recycle Blowers, kWe	0
Ground Water Pumps, kWe	170
Hydrogen Compressor, kWe	30,022
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,490
Total Auxiliaries, MWe	**380**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,349**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-94. Case 1P carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	118 (261)	Air-Electrode Sweep Exhaust (CO_2)	118 (261)
Total	**118 (261)**	**Total**	**118 (261)**

Exhibit A-95. Case 1P 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)
Electrolysis Steam	5.0 (1,311)	–	5.0 (1,311)	–	5.0 (1,311)
Deaerator Vent	–	–	–	0.0 (3.3)	0.0 (-3.3)
Boiler Blowdown	–	–	–	0.6 (165)	-0.6 (-165)
Cooling Tower	2.3 (595)	–	2.3 (595)	0.5 (134)	1.7 (461)
Total	**7.2 (1,907)**	**–**	**7.2 (1,907)**	**1.1 (302)**	**6.1 (1,604)**

Exhibit A-96. Case 1P overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	29 (28)	–	29 (28)
Raw Water Makeup	–	27 (26)	–	27 (26)
Auxiliary Power	–	–	4,858 (4,604)	4,858 (4,604)
Total	**0.0 (0.0)**	**57 (54)**	**4,858 (4,604)**	**4,914 (4,658)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,069 (3,857)	13 (12)	–	4,082 (3,869)
Sweep Exhaust	–	109 (103)	–	109 (103)
Motor Losses and Design Allowances	–	13 (13)	–	13 (13)
Cooling Tower Load[A]	–	294 (279)	–	294 (279)
Boiler Blowdown	–	13 (12)	–	13 (12)
Process Vents[B]	–	0.6 (0.5)	–	0.6 (0.5)
Ambient Losses[C]	–	318 (301)	–	318 (301)
Total	**4,069 (3,857)**	**761 (722)**	**0.0 (0.0)**	**4,830 (4,579)**
Unaccounted Energy[D]	–	–	–	84 (79)

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-97. Case 1P energy and mass balance (identical to Case 0P)

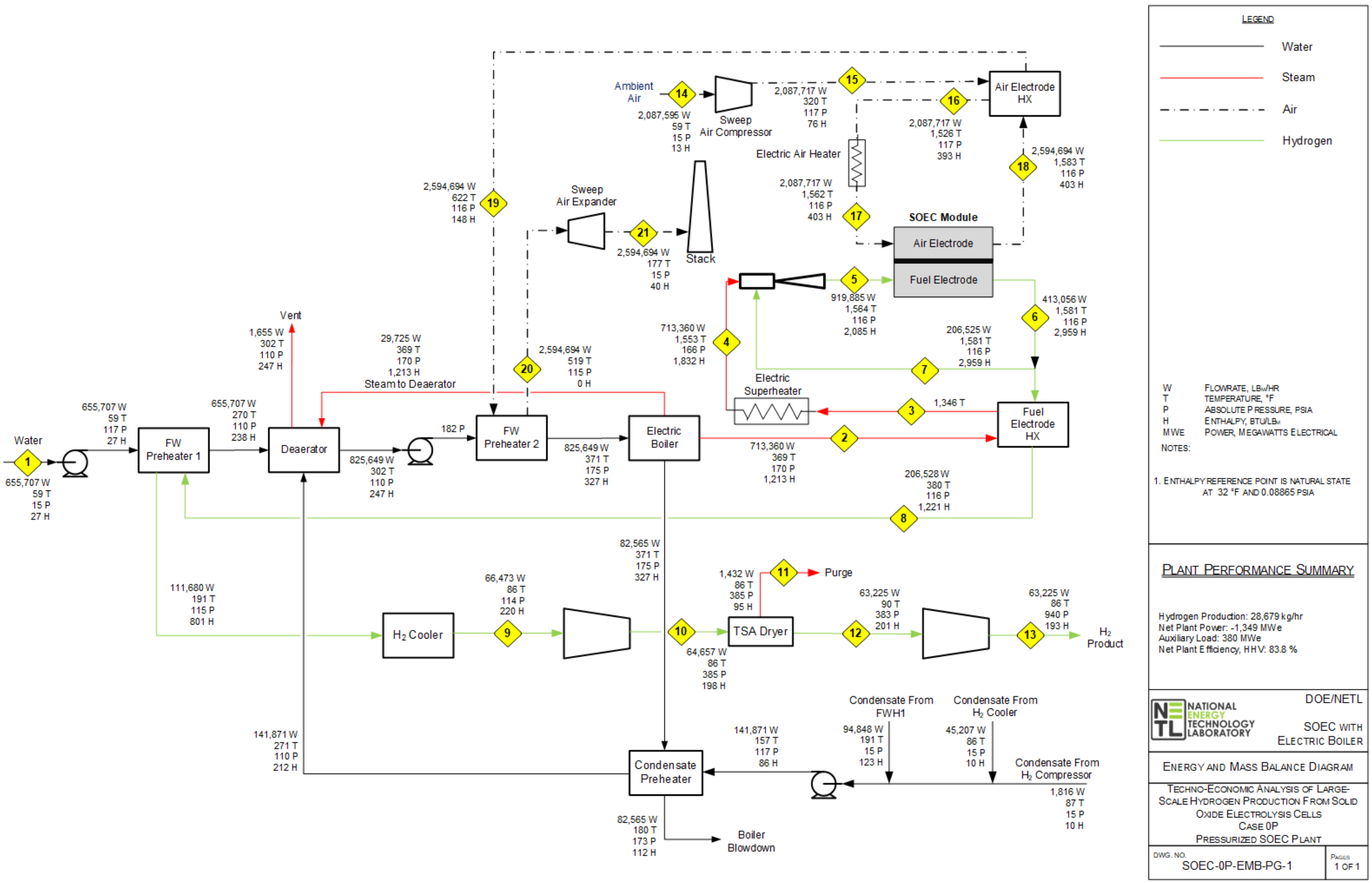


Exhibit A-98. Case 1P total plant cost details

	Case:	SOEC-EB-1P	Pathway Step 1 Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	688,284	Plant Size (MW net):			1,349		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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$172,792	$34,558	$0	$31,103	$238,453	$346	$177
1.2	Container	$0	$0	$0	$0	$24,597	$4,919	$0	$4,427	$33,943	$49	$25
1.3	Insulation	$0	$0	$0	$0	$2,304	$461	$0	$415	$3,179	$5	$2
1.4	Module Assembly	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.5	Air Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.6	Fuel Distribution	$0	$0	$0	$0	$5,760	$1,152	$0	$1,037	$7,948	$12	$6
1.8	Module Current Collectors	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.9	Module I&C	$0	$0	$0	$0	$2,880	$576	$0	$518	$3,974	$6	$3
1.10	Rectifier	$0	$0	$0	$0	$39,166	$7,833	$0	$7,050	$54,049	$79	$40
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$261,898**	**$52,380**	**$0**	**$47,142**	**$361,419**	**$525**	**$268**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Compressor	$0	$0	$0	$0	$7,735	$1,547	$0	$1,392	$10,674	$16	$8
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$20,605	$4,121	$0	$3,709	$28,435	$41	$21
2.3	Hydrogen Recycle Jet Pump	$0	$0	$0	$0	$809	$162	$0	$146	$1,117	$2	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$22,498	$4,500	$0	$4,050	$31,047	$45	$23
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,951	$390	$0	$351	$2,693	$4	$2
2.6	Section and Overall Assembly	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
2.7	Section I&C	$0	$0	$0	$0	$976	$195	$0	$176	$1,347	$2	$1
2.8	Sweep Gas Expander	$0	$0	$0	$0	$6,577	$1,315	$0	$1,184	$9,076	$13	$7
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$62,127**	**$12,425**	**$0**	**$11,183**	**$85,735**	**$125**	**$64**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,272	$854	$0	$769	$5,895	$9	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,592	$918	$0	$1,102	$6,613	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,857	$371	$0	$334	$2,563	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,455	$1,891	$0	$2,269	$13,615	$20	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$1,032	$206	$0	$186	$1,424	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,677	$935	$0	$1,123	$6,735	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$25,885**	**$5,177**	**$0**	**$5,783**	**$36,845**	**$54**	**$27**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$391	$78	$0	$70	$540	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$32,745	$6,549	$0	$5,894	$45,188	$66	$33
4.3	Electric Superheaters	$0	$0	$0	$0	$2,709	$542	$0	$488	$3,738	$5	$3
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$984	$197	$0	$177	$1,358	$2	$1

	Case:	SOEC-EB-1P	Pathway Step 1 Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	688,284		Plant Size (MW net):		1,349			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 H_2/day]	$/kW (net)
4.5	Hydrogen Cooler	$0	$0	$0	$0	$264	$53	$0	$48	$365	$1	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$257	$51	$0	$46	$354	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$15,227	$3,045	$0	$2,741	$21,013	$31	$16
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$52,577**	**$10,515**	**$0**	**$9,464**	**$72,557**	**$105**	**$54**
	7						**Ductwork, & Stack**					
7.3	Ductwork	$0	$0	$0	$0	$588	$118	$0	$106	$811	$1	$1
7.4	Stack	$0	$0	$0	$0	$3,931	$786	$0	$707	$5,424	$8	$4
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$501	$100	$0	$120	$722	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,019**	**$1,004**	**$0**	**$934**	**$6,957**	**$10**	**$5**
	9						**Cooling Water System**					
9.1	Cooling Towers	$0	$0	$0	$0	$3,330	$666	$0	$599	$4,595	$7	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$365	$73	$0	$66	$503	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,264	$853	$0	$768	$5,885	$9	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,705	$341	$0	$307	$2,353	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$582	$116	$0	$105	$803	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$233	$47	$0	$42	$322	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$551	$110	$0	$132	$793	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$11,029**	**$2,206**	**$0**	**$2,018**	**$15,253**	**$22**	**$11**
	11						**Accessory Electric Plant**					
11.2	Station Service Equipment	$0	$0	$0	$0	$11,509	$2,302	$0	$2,072	$15,883	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$17,760	$3,552	$0	$3,197	$24,509	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,197	$2,839	$0	$2,555	$19,592	$28	$15
11.5	Wire & Cable	$0	$0	$0	$0	$15,220	$3,044	$0	$2,740	$21,003	$31	$16
11.6	Protective Equipment	$0	$0	$0	$0	$1,150	$230	$0	$207	$1,588	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,652	$530	$0	$477	$3,660	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,065	$413	$0	$372	$2,850	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$434	$87	$0	$104	$625	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$64,989**	**$12,998**	**$0**	**$11,724**	**$89,711**	**$130**	**$66**
	12						**Instrumentation & Control**					
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,448	$290	$72	$261	$2,071	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$716	$143	$0	$129	$989	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$314	$63	$16	$57	$449	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,173	$2,235	$559	$2,011	$15,977	$23	$12

	Case:	SOEC-EB-1P	Pathway Step 1 Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	688,284	Plant Size (MW net):			1,349			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 H_2/day]	$/kW (net)
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,475	$895	$224	$806	$6,400	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,056	$411	$103	$370	$2,940	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,182**	**$4,036**	**$973**	**$3,633**	**$28,825**	**$42**	**$21**
	13					**Improvements to Site**						
13.1	Site Preparation	$0	$0	$0	$0	$16,783	$3,357	$0	$4,028	$24,168	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,637	$1,127	$0	$1,353	$8,117	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,775	$955	$0	$1,146	$6,876	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,195**	**$5,439**	**$0**	**$6,527**	**$39,161**	**$57**	**$29**
	14					**Buildings & Structures**						
14.4	Administration Building	$0	$0	$0	$0	$761	$152	$0	$137	$1,051	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$23	$5	$0	$4	$31	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$449	$90	$0	$81	$620	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,121	$224	$0	$202	$1,547	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$842	$168	$0	$152	$1,162	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$628	$126	$0	$113	$866	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,097	$219	$0	$198	$1,514	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,921**	**$984**	**$0**	**$886**	**$6,791**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$535,824**	**$107,165**	**$973**	**$99,293**	**$743,254**	**$1,080**	**$551**

Exhibit A-99. Case 1P owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$4,901	$7	$4
1 Month Maintenance Materials	$831	$1	$1
1 Month Non-Fuel Consumables	$188	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$14,865	$22	$11
Total	**$20,784**	**$30**	**$15**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$217	$0	$0
0.5% of TPC (spare parts)	$3,716	$5	$3
Total	**$3,933**	**$6**	**$3**
Other Costs			
Initial Cost for Catalyst and Chemicals	$479	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$111,488	$162	$83
Financing Costs	$20,068	$29	$15
Total Overnight Costs (TOC)	**$900,306**	**$1,308**	**$667**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$963,150**	**$1,399**	**$714**

Exhibit A-100. Case 1P initial and annual O&M costs

Case:	**SOEC-EB-1P**		**Pathway Step 1 Pressurized SOEC**		**Cost Base:**	**Dec 2018**	
Plant Size (kg H_2/day):	**688,284**	**Plant Size (MW net):**		**1,349**	**Capacity Factor (%):**	**90%**	
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.19	$1.62
Maintenance Labor:					$5,648,732	$8.21	$4.19
Administrative & Support Labor:					$1,960,230	$2.85	$1.45
Property Taxes and Insurance:					$14,865,083	$21.60	$11.02
Total:					**$24,666,235**	**$35.84**	**$18.28**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh-net)**
Maintenance Material:					$8,971,515	$0.04	$0.84
Stack Replacement							
	Life (yr)		**$/$kW_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	157.25	$15.87	$18,544,484	$0.08	$1.74
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,373	$1.90	$0	$856,802	$0.004	$0.081
Makeup and Wastewater Treatment Chemicals (ton):	0	4.09	$550	$0	$738,822	$0.003	$0.069
Hydrogen Drying Sorbent (lb):	47,922	131.3	$10	$479,220	$431,298	$0.002	$0.041
Subtotal:				**$479,220**	**$2,026,923**	**$0.009**	**$0.191**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	131.3	$0.02	$0	$819	$0.00000	$0.00008
Subtotal:				**$0**	**$819**	**$0.00000**	**$0.00008**
Variable Operating Costs Total:				**$479,220**	**$90,176,502**	**$0.05**	**$1.03**
Electricity Cost							
Electricity (MWh):	0	32,385	$60.00	$0	$638,299,443	$2.82	$60.00
Total:				**$0**	**$638,299,443**	**$2.82**	**$60.00**

Exhibit A-101. Case 1P LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.25	8%
Fixed	0.11	3%
Variable	0.13	4%
Electricity	2.82	85%
Total	**3.31**	**N/A**

CASE 2P

Exhibit A-102. Case 2P stream table

	1	2	3	4	5	6	7	8	9	10
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.4000	0.8000	0.8000	0.8000	0.9954	0.9986
H_2O	1.0000	1.0000	1.0000	1.0000	0.6000	0.2000	0.2000	0.2000	0.0046	0.0014
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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,458	17,905	17,905	17,905	35,811	35,811	17,905	17,905	14,390	14,344
V-L Flowrate (kg/h)	296,499	322,569	322,569	322,569	415,959	186,779	93,390	93,390	30,059	29,237
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	187	734	842	851	865	865	193	30	30
Pressure (MPa, abs)	0.10	1.17	1.16	1.14	0.80	0.80	0.80	0.80	0.78	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,820.32	3,998.48	4,253.89	4,850.03	6,909.09	6,909.09	2,839.71	512.84	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,151.02	-11,972.86	-11,717.45	-10,037.27	-4,233.90	-4,233.90	-8,303.28	-457.12	-87.51
Density (kg/m^3)	1,003.6	5.9	2.5	2.2	1.0	0.4	0.4	1.1	0.6	2.1
V-L Molecular Weight	18.015	18.015	18.015	18.015	11.615	5.216	5.216	5.216	2.089	2.038
V-L Flowrate (lb_{mol}/h)	36,284	39,474	39,474	39,474	78,949	78,949	39,475	39,475	31,724	31,624
V-L Flowrate (lb/h)	653,668	711,143	711,143	711,143	917,032	411,778	205,889	205,889	66,268	64,457
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	369	1,352	1,548	1,564	1,589	1,589	380	86	86
Pressure (psia)	14.7	170.0	168.0	166.0	116.0	115.8	115.8	115.6	113.6	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,212.5	1,719.0	1,828.8	2,085.1	2,970.4	2,970.4	1,220.9	220.5	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,653.9	-5,147.4	-5,037.6	-4,315.2	-1,820.2	-1,820.2	-3,569.8	-196.5	-37.6
Density (lb/ft^3)	62.650	0.366	0.156	0.139	0.062	0.027	0.027	0.067	0.040	0.132

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

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

Exhibit A-102. Case 2P stream table (cont'd)

	11	12	13	14	15	16	17	18	19	20	21
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077	0.0077
CH_4	0.0000	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	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	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	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	163	14,181	14,181	32,715	32,715	32,715	32,715	39,877	39,877	39,877	39,877
V-L Flowrate (kg/h)	647	28,590	28,590	943,973	943,974	943,974	943,974	1,173,156	1,173,156	1,173,156	1,173,156
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	160	830	850	866	333	276	84
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.81	0.80	0.80	0.80	0.80	0.79	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	177.60	913.61	936.99	942.30	350.07	290.72	96.17
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	44.88	780.89	804.27	831.03	238.80	179.46	-15.09
Density (kg/m^3)	4.7	2.1	5.0	1.2	6.5	2.5	2.5	2.5	4.6	5.1	1.0
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	360	31,264	31,264	72,125	72,125	72,125	72,125	87,915	87,915	87,915	87,915
V-L Flowrate (lb/h)	1,427	63,030	63,030	2,081,105	2,081,107	2,081,107	2,081,107	2,586,366	2,586,366	2,586,366	2,586,366
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	320	1,526	1,562	1,591	631	529	183
Pressure (psia)	385.0	383.3	939.7	14.7	117.3	116.5	116.0	115.8	115.6	115.1	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	76.4	392.8	402.8	405.1	150.5	125.0	41.3
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	19.3	335.7	345.8	357.3	102.7	77.2	-6.5
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.404	0.157	0.154	0.155	0.290	0.319	0.063

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

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

Exhibit A-103. Case 2P plant performance summary

Performance Summary	
Total Gross Power, kWe	**62**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	238,494
Hydrogen Compression, kWe	29,929
Balance of Plant, kWe	109,547
Total Auxiliaries, MWe	**378**
Net Power, MWe	**-1,346**
Hydrogen Production, kg/h (lb/h)	**28,590 (63,030)**
Energy Efficiency,[A] % HHV (% LHV)	83.7 (70.8)
Electric Input per Kilogram, kWh/kg	47.1
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,126,917 (952,890)
Raw Water Withdrawal, m^3/min (gpm)	7.2 (1,901)
Raw Water Consumption, m^3/min (gpm)	6.1 (1,599)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-104. Case 2P power summary

Power Summary	
Sweep Gas Expander, MWe	62
Total Gross Power, MWe	**62**
Auxiliary Load Summary	
Air Electrode Compressors, kWe	69,548
Circulating Water Pumps, kWe	590
Cooling Tower Fans, kWe	300
Electric Boiler, kWe	238,494
Electric Steam Superheater, kWe	22,885
Electric Sweep Heater, kWe	6,131
Feedwater Pumps, kWe	172
Fuel Electrode Recycle Blowers, kWe	0
Ground Water Pumps, kWe	170
Hydrogen Compressor, kWe	29,929
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,460
Total Auxiliaries, MWe	**378**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,346**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-105. Case 2P carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	118 (260)	Air-Electrode Sweep Exhaust (CO_2)	118 (260)
Total	**118 (260)**	**Total**	**118 (260)**

Exhibit A-106. Case 2P 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)
Electrolysis Steam	4.9 (1,307)	–	4.9 (1,307)	–	4.9 (1,307)
Deaerator Vent	–	–	–	0.0 (3.3)	0.0 (-3.3)
Boiler Blowdown	–	–	–	0.6 (165)	-0.6 (-165)
Cooling Tower	2.2 (593)	–	2.2 (593)	0.5 (133)	1.7 (460)
Total	**7.2 (1,901)**	**–**	**7.2 (1,901)**	**1.1 (301)**	**6.1 (1,599)**

Exhibit A-107. Case 2P overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	29 (28)	–	29 (28)
Raw Water Makeup	–	27 (26)	–	27 (26)
Auxiliary Power	–	–	4,847 (4,594)	4,847 (4,594)
Total	**0.0 (0.0)**	**56 (53)**	**4,847 (4,594)**	**4,904 (4,648)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,057 (3,845)	13 (12)	–	4,070 (3,857)
Sweep Exhaust	–	113 (107)	–	113 (107)
Motor Losses and Design Allowances	–	13 (13)	–	13 (13)
Cooling Tower Load[A]	–	293 (278)	–	293 (278)
Boiler Blowdown	–	13 (12)	–	13 (12)
Process Vents[B]	–	0.6 (0.5)	–	0.6 (0.5)
Ambient Losses[C]	–	317 (301)	–	317 (301)
Total	**–**	**763 (724)**	**0.0 (0.0)**	**4,820 (4,569)**
Unaccounted Energy[D]	**–**	*84 (79)*	–	*84 (79)*

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-108. Case 2P energy and mass balance

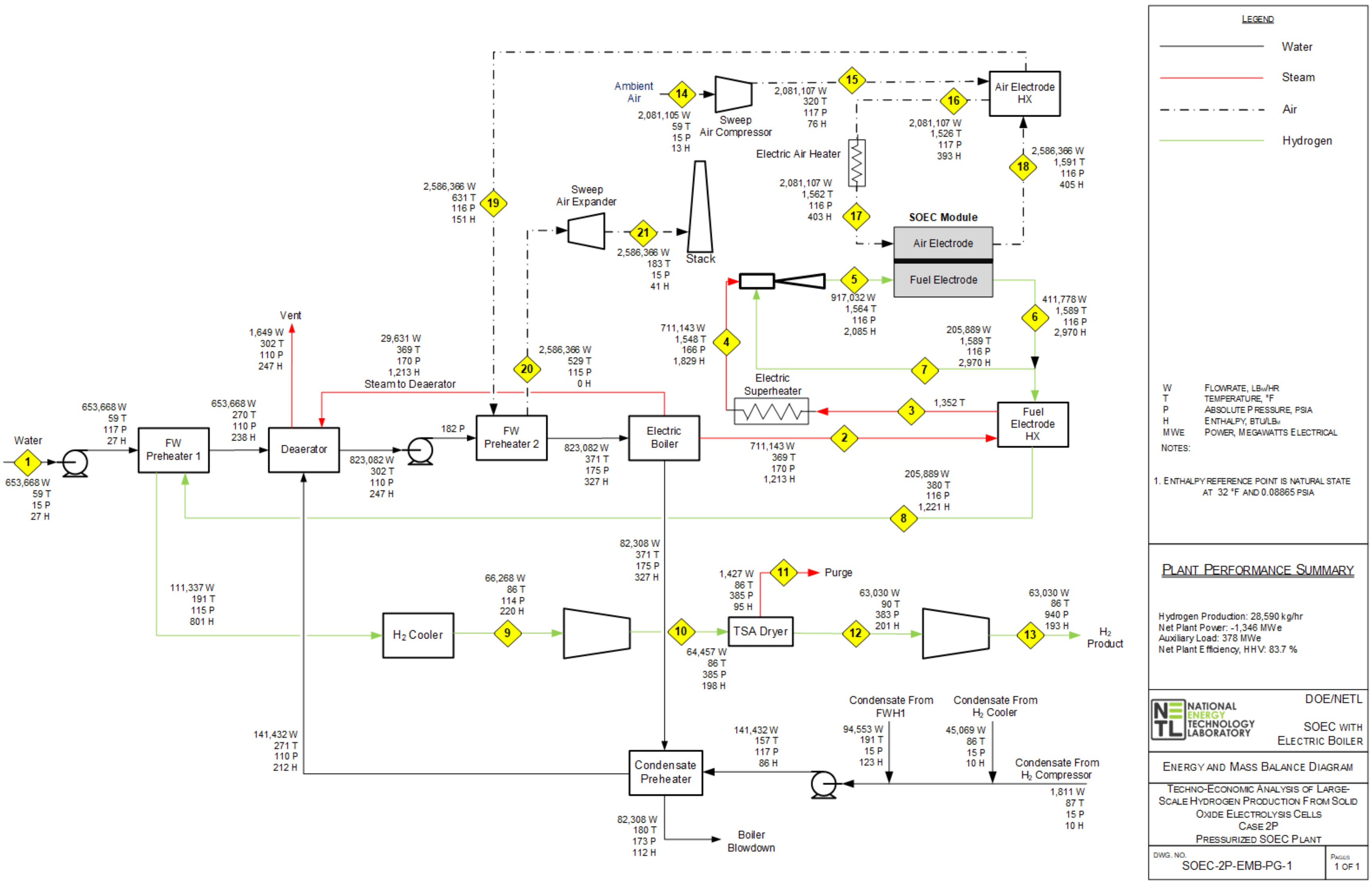


Exhibit A-109. Case 2P total plant cost details

	Case:	SOEC-EB-2P	Pathway Step 2 Pressurized SOEC				Estimate Type:			Conceptual		
	Plant Size (kg H_2/day):	686,157	Plant Size (MW net):			1,346	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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$83,609	$16,722	$0	$15,050	$115,381	$168	$86
1.2	Container	$0	$0	$0	$0	$11,902	$2,380	$0	$2,142	$16,424	$24	$12
1.3	Insulation	$0	$0	$0	$0	$1,115	$223	$0	$201	$1,538	$2	$1
1.4	Module Assembly	$0	$0	$0	$0	$2,787	$557	$0	$502	$3,846	$6	$3
1.5	Air Distribution	$0	$0	$0	$0	$2,787	$557	$0	$502	$3,846	$6	$3
1.6	Fuel Distribution	$0	$0	$0	$0	$2,787	$557	$0	$502	$3,846	$6	$3
1.8	Module Current Collectors	$0	$0	$0	$0	$1,393	$279	$0	$251	$1,923	$3	$1
1.9	Module I&C	$0	$0	$0	$0	$1,393	$279	$0	$251	$1,923	$3	$1
1.10	Rectifier	$0	$0	$0	$0	$18,951	$3,790	$0	$3,411	$26,153	$38	$19
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$126,725**	**$25,345**	**$0**	**$22,810**	**$174,880**	**$255**	**$130**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Compressor	$0	$0	$0	$0	$7,718	$1,544	$0	$1,389	$10,650	$16	$8
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$19,120	$3,824	$0	$3,442	$26,386	$38	$20
2.3	Hydrogen Recycle Jet Pump	$0	$0	$0	$0	$594	$119	$0	$107	$820	$1	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$22,473	$4,495	$0	$4,045	$31,013	$45	$23
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,238	$248	$0	$223	$1,709	$2	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$619	$124	$0	$111	$855	$1	$1
2.7	Section I&C	$0	$0	$0	$0	$619	$124	$0	$111	$855	$1	$1
2.8	Sweep Gas Expander	$0	$0	$0	$0	$6,608	$1,322	$0	$1,189	$9,119	$13	$7
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$58,990**	**$11,798**	**$0**	**$10,618**	**$81,407**	**$119**	**$60**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,262	$852	$0	$767	$5,882	$9	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,582	$916	$0	$1,100	$6,598	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,852	$370	$0	$333	$2,556	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,431	$1,886	$0	$2,264	$13,581	$20	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$1,029	$206	$0	$185	$1,420	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,667	$933	$0	$1,120	$6,720	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$25,824**	**$5,165**	**$0**	**$5,769**	**$36,758**	**$54**	**$27**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$387	$77	$0	$70	$534	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$32,664	$6,533	$0	$5,879	$45,076	$66	$33
4.3	Electric Superheaters	$0	$0	$0	$0	$2,557	$511	$0	$460	$3,529	$5	$3
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$981	$196	$0	$177	$1,354	$2	$1

	Case:	SOEC-EB-2P	Pathway Step 2 Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	686,157	Plant Size (MW net):			1,346			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 H_2/day]	$/kW (net)
4.5	Hydrogen Cooler	$0	$0	$0	$0	$263	$53	$0	$47	$363	$1	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$256	$51	$0	$46	$353	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$15,194	$3,039	$0	$2,735	$20,968	$31	$16
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$52,302**	**$10,460**	**$0**	**$9,414**	**$72,177**	**$105**	**$54**
	7					Ductwork, & Stack						
7.3	Ductwork	$0	$0	$0	$0	$591	$118	$0	$106	$815	$1	$1
7.4	Stack	$0	$0	$0	$0	$3,949	$790	$0	$711	$5,450	$8	$4
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$504	$101	$0	$121	$725	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$5,044**	**$1,009**	**$0**	**$938**	**$6,990**	**$10**	**$5**
	9					Cooling Water System						
9.1	Cooling Towers	$0	$0	$0	$0	$3,322	$664	$0	$598	$4,585	$7	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$364	$73	$0	$65	$502	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,258	$852	$0	$766	$5,876	$9	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,702	$340	$0	$306	$2,348	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$581	$116	$0	$105	$802	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$233	$47	$0	$42	$321	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$550	$110	$0	$132	$792	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$11,009**	**$2,202**	**$0**	**$2,015**	**$15,226**	**$22**	**$11**
	11					Accessory Electric Plant						
11.2	Station Service Equipment	$0	$0	$0	$0	$11,493	$2,299	$0	$2,069	$15,861	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$17,736	$3,547	$0	$3,192	$24,476	$36	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,178	$2,836	$0	$2,552	$19,565	$29	$15
11.5	Wire & Cable	$0	$0	$0	$0	$15,199	$3,040	$0	$2,736	$20,974	$31	$16
11.6	Protective Equipment	$0	$0	$0	$0	$1,149	$230	$0	$207	$1,585	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,649	$530	$0	$477	$3,655	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,063	$413	$0	$371	$2,846	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$434	$87	$0	$104	$624	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$64,899**	**$12,980**	**$0**	**$11,708**	**$89,587**	**$131**	**$67**
	12					Instrumentation & Control						
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,446	$289	$72	$260	$2,068	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$716	$143	$0	$129	$988	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$313	$63	$16	$56	$448	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,156	$2,231	$558	$2,008	$15,953	$23	$12

	Case:	SOEC-EB-2P	Pathway Step 2 Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	686,157	Plant Size (MW net):			1,346			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 H_2/day]	$/kW (net)
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,469	$894	$223	$804	$6,390	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,053	$411	$103	$369	$2,935	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,153**	**$4,031**	**$972**	**$3,627**	**$28,783**	**$42**	**$21**
13	Improvements to Site											
13.1	Site Preparation	$0	$0	$0	$0	$16,767	$3,353	$0	$4,024	$24,144	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,631	$1,126	$0	$1,351	$8,109	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,770	$954	$0	$1,145	$6,869	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,168**	**$5,434**	**$0**	**$6,520**	**$39,122**	**$57**	**$29**
14	Buildings & Structures											
14.4	Administration Building	$0	$0	$0	$0	$761	$152	$0	$137	$1,050	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$23	$5	$0	$4	$31	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$448	$90	$0	$81	$618	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,120	$224	$0	$202	$1,545	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$841	$168	$0	$151	$1,161	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$628	$126	$0	$113	$866	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,096	$219	$0	$197	$1,513	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,917**	**$983**	**$0**	**$885**	**$6,785**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$397,031**	**$79,406**	**$972**	**$74,306**	**$551,715**	**$804**	**$410**

Exhibit A-110. Case 2P owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,991	$6	$3
1 Month Maintenance Materials	$617	$1	$0
1 Month Non-Fuel Consumables	$187	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$11,034	$16	$8
Total	**$15,829**	**$23**	**$12**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$216	$0	$0
0.5% of TPC (spare parts)	$2,759	$4	$2
Total	**$2,975**	**$4**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$478	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$82,757	$121	$61
Financing Costs	$14,896	$22	$11
Total Overnight Costs (TOC)	**$668,950**	**$975**	**$497**
TASC Multiplier (IOU, 35 year)		1.070	
Total As-Spent Cost (TASC)	**$715,644**	**$1,043**	**$532**

Exhibit A-111. Case 2P initial and annual O&M costs

Case:	SOEC-EB-2P		Pathway Step 2 Pressurized SOEC		Cost Base:	Dec 2018	
Plant Size (kg H_2/day):	686,157	Plant Size (MW net):		1,346	Capacity Factor (%):	90%	
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.19	$1.63
Maintenance Labor:					$4,193,034	$6.11	$3.11
Administrative & Support Labor:					$1,596,306	$2.33	$1.19
Property Taxes and Insurance:					$11,034,299	$16.08	$8.20
Total:					**$19,015,829**	**$27.71**	**$14.12**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh-net)**
Maintenance Material:					$6,659,524	$0.03	$0.63
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	78.38	$7.91	$8,973,137	$0.04	$0.85
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,368	$1.90	$0	$854,144	$0.004	$0.080
Makeup and Wastewater Treatment Chemicals (ton):	0	4.08	$550	$0	$736,529	$0.003	$0.069
Hydrogen Drying Sorbent (lb):	47,774	130.89	$10	$477,739	$429,965	$0.002	$0.041
Subtotal:				**$477,739**	**$2,020,639**	**$0.009**	**$0.190**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	130.89	$0.02	$0	$817	$0.00	$0.00
Subtotal:				**$0**	**$817**	$0.00	**$0.00**
Variable Operating Costs Total:				**$477,739**	**$17,654,117**	**$0.04**	**$0.82**
Electricity Cost							
Electricity (MWh):	0	32,315	$60.00	$0	$636,923,976	$2.83	$60.00
Total:				**$0**	**$636,923,976**	**$2.83**	**$60.00**

Exhibit A-112. Case 2P LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.19	6%
Fixed	0.08	3%
Variable	0.08	2%
Electricity	2.83	89%
Total	**3.17**	**N/A**

CASE 3P

Exhibit A-113. Case 3P stream table

	1	2	3	4	5	6	7	8	9	10
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.4000	0.8000	0.8000	0.8000	0.9954	0.9986
H_2O	1.0000	1.0000	1.0000	1.0000	0.6000	0.2000	0.2000	0.2000	0.0046	0.0014
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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,590	18,048	18,048	18,048	36,097	36,097	18,049	18,049	14,505	14,459
V-L Flowrate (kg/h)	298,870	325,148	325,148	325,148	419,285	188,273	94,137	94,137	30,299	29,471
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	187	647	748	751	757	757	193	30	30
Pressure (MPa, abs)	0.10	1.17	1.16	1.14	0.80	0.80	0.80	0.80	0.78	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,820.32	3,801.12	4,032.11	4,524.99	6,227.39	6,227.39	2,839.71	512.84	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,151.02	-12,170.23	-11,939.24	-10,362.31	-4,915.60	-4,915.60	-8,303.28	-457.12	-87.51
Density (kg/m^3)	1,003.6	5.9	2.7	2.4	1.1	0.5	0.5	1.1	0.6	2.1
V-L Molecular Weight	18.015	18.015	18.015	18.015	11.615	5.216	5.216	5.216	2.089	2.038
V-L Flowrate (lb_{mol}/h)	36,574	39,790	39,790	39,790	79,580	79,580	39,790	39,790	31,978	31,877
V-L Flowrate (lb/h)	658,895	716,829	716,829	716,829	924,365	415,071	207,536	207,536	66,798	64,973
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	369	1,197	1,378	1,384	1,395	1,395	380	86	86
Pressure (psia)	14.7	170.0	168.0	166.0	116.0	115.8	115.8	115.6	113.6	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,212.5	1,634.2	1,733.5	1,945.4	2,677.3	2,677.3	1,220.9	220.5	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,653.9	-5,232.3	-5,132.9	-4,455.0	-2,113.3	-2,113.3	-3,569.8	-196.5	-37.6
Density (lb/ft^3)	62.650	0.366	0.171	0.152	0.068	0.030	0.030	0.067	0.040	0.132

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

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

Exhibit A-113. Case 3P stream table (cont'd)

	11	12	13	14	15	16	17	18	19	20	21
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077	0.0077
CH_4	0.0000	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	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	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	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	164	14,295	14,295	32,977	32,977	32,977	32,977	40,196	40,196	40,196	40,196
V-L Flowrate (kg/h)	653	28,818	28,818	951,522	951,523	951,523	951,523	1,182,537	1,182,537	1,182,537	1,182,537
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	160	730	750	758	303	246	63
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.81	0.80	0.80	0.80	0.80	0.79	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	177.60	797.73	820.76	817.71	318.72	259.38	75.84
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	44.88	665.01	688.04	706.45	207.46	148.11	-35.42
Density (kg/m^3)	4.7	2.1	5.0	1.2	6.5	2.8	2.7	2.7	4.9	5.4	1.1
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,514	31,514	72,702	72,702	72,702	72,702	88,618	88,618	88,618	88,618
V-L Flowrate (lb/h)	1,439	63,534	63,534	2,097,747	2,097,749	2,097,749	2,097,749	2,607,048	2,607,048	2,607,048	2,607,048
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	320	1,346	1,382	1,397	577	474	146
Pressure (psia)	385.0	383.3	939.7	14.7	117.3	116.5	116.0	115.8	115.6	115.1	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	76.4	343.0	352.9	351.6	137.0	111.5	32.6
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	19.3	285.9	295.8	303.7	89.2	63.7	-15.2
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.404	0.173	0.169	0.171	0.305	0.337	0.067

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

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

Exhibit A-114. Case 3P plant performance summary

Performance Summary	
Total Gross Power, kWe	**59**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	240,401
Hydrogen Compression, kWe	30,168
Balance of Plant, kWe	108,057
Total Auxiliaries, MWe	**379**
Net Power, MWe	**-1,350**
Hydrogen Production, kg/h (lb/h)	**28,818 (63,534)**
Energy Efficiency,[A] % HHV (% LHV)	84.1 (71.1)
Electric Input per Kilogram, kWh/kg	46.9
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,135,929 (950,510)
Raw Water Withdrawal, m^3/min (gpm)	7.3 (1,916)
Raw Water Consumption, m^3/min (gpm)	6.1 (1,612)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-115. Case 3P power summary

Power Summary	
Sweep Gas Expander, MWe	59
Total Gross Power, MWe	**59**
Auxiliary Load Summary	
Air Electrode Compressors, kWe	70,104
Circulating Water Pumps, kWe	600
Cooling Tower Fans, kWe	310
Electric Boiler, kWe	240,401
Electric Steam Superheater, kWe	20,863
Electric Sweep Heater, kWe	6,087
Feedwater Pumps, kWe	173
Fuel Electrode Recycle Blowers, kWe	0
Ground Water Pumps, kWe	170
Hydrogen Compressor, kWe	30,168
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,460
Total Auxiliaries, MWe	**379**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,350**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-116. Case 3P carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (262)	Air-Electrode Sweep Exhaust (CO_2)	119 (262)
Total	**119 (262)**	**Total**	**119 (262)**

Exhibit A-117. Case 3P 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)
Electrolysis Steam	5.0 (1,318)	–	5.0 (1,318)	–	5.0 (1,318)
Deaerator Vent	–	–	–	0.0 (3.3)	0.0 (-3.3)
Boiler Blowdown	–	–	–	0.6 (166)	-0.6 (-166)
Cooling Tower	2.3 (598)	–	2.3 (598)	0.5 (135)	1.8 (464)
Total	**7.3 (1,916)**	**–**	**7.3 (1,916)**	**1.1 (304)**	**6.1 (1,612)**

Exhibit A-118. Case 3P overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	27 (26)	–	27 (26)
Auxiliary Power	–	–	4,861 (4,607)	4,861 (4,607)
Total	**0.0 (0.0)**	**57 (54)**	**4,861 (4,607)**	**4,917 (4,661)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,089 (3,876)	13 (12)	–	4,102 (3,888)
Sweep Exhaust	–	90 (85)	–	90 (85)
Motor Losses and Design Allowances	–	13 (13)	–	13 (13)
Cooling Tower Load[A]	–	296 (280)	–	296 (280)
Boiler Blowdown	–	13 (12)	–	13 (12)
Process Vents[B]	–	0.6 (0.5)	–	0.6 (0.5)
Ambient Losses[C]	–	319 (302)	–	319 (302)
Total	**–**	**744 (706)**	**0.0 (0.0)**	**4,833 (4,582)**
Unaccounted Energy[D]	–	*84 (79)*	–	*84 (79)*

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-119. Case 3P energy and mass balance

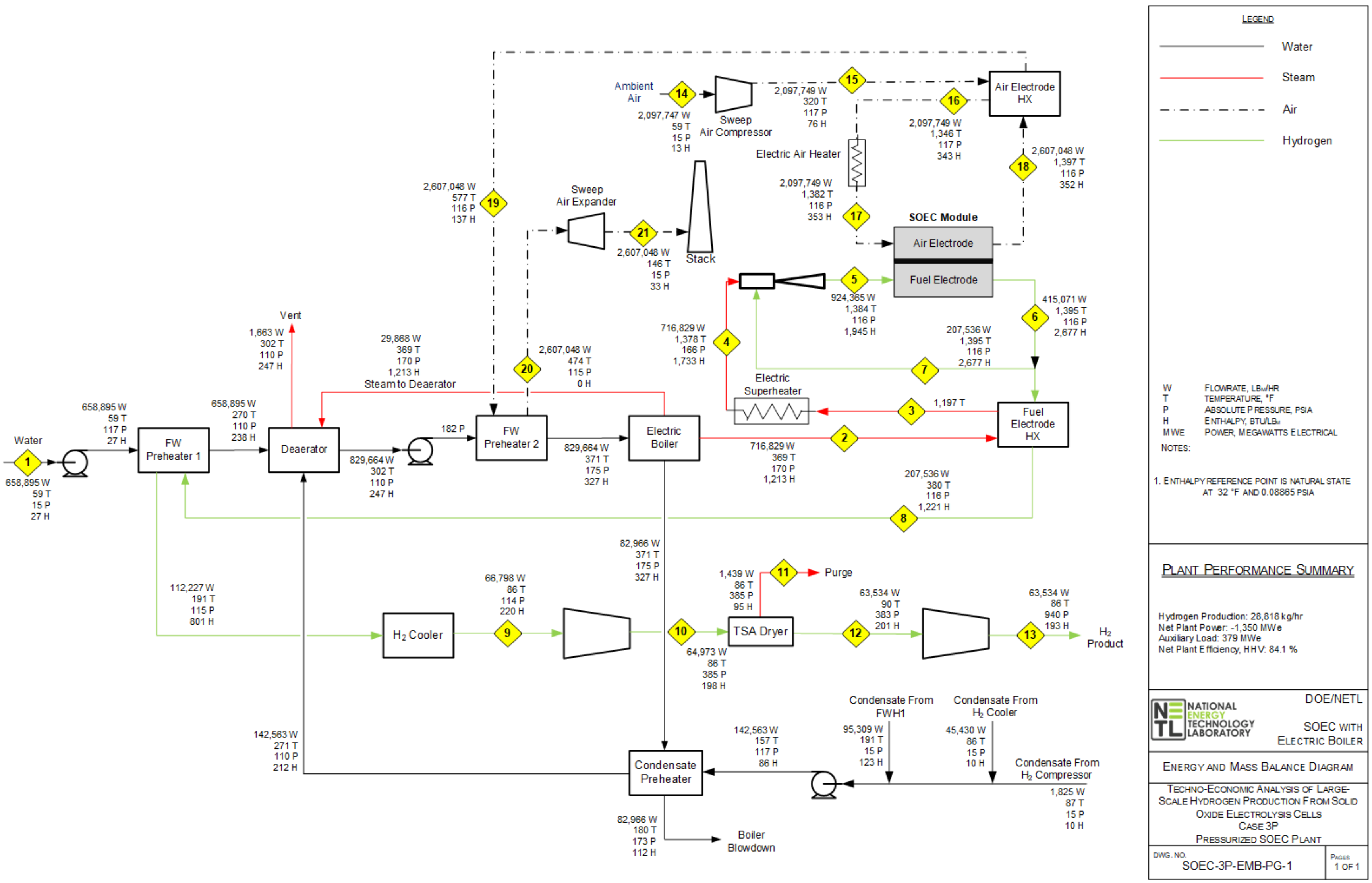


Exhibit A-120. Case 3P total plant cost details

	Case:	SOEC-EB-3P	Pathway Step 3 Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	691,644	Plant Size (MW net):			1,350		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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$89,183	$17,837	$0	$16,053	$123,073	$178	$91
1.2	Container	$0	$0	$0	$0	$12,695	$2,539	$0	$2,285	$17,519	$25	$13
1.3	Insulation	$0	$0	$0	$0	$1,189	$238	$0	$214	$1,641	$2	$1
1.4	Module Assembly	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.5	Air Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.6	Fuel Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.8	Module Current Collectors	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$2
1.9	Module I&C	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$2
1.10	Rectifier	$0	$0	$0	$0	$20,215	$4,043	$0	$3,639	$27,896	$40	$21
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$135,173**	**$27,035**	**$0**	**$24,331**	**$186,539**	**$270**	**$138**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Compressor	$0	$0	$0	$0	$7,761	$1,552	$0	$1,397	$10,710	$15	$8
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$20,112	$4,022	$0	$3,620	$27,754	$40	$21
2.3	Hydrogen Recycle Jet Pump	$0	$0	$0	$0	$611	$122	$0	$110	$843	$1	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$21,458	$4,292	$0	$3,862	$29,612	$43	$22
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,288	$258	$0	$232	$1,778	$3	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
2.7	Section I&C	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
2.8	Sweep Gas Expander	$0	$0	$0	$0	$6,379	$1,276	$0	$1,148	$8,804	$13	$7
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$58,898**	**$11,780**	**$0**	**$10,602**	**$81,279**	**$118**	**$60**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,286	$857	$0	$771	$5,915	$9	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,609	$922	$0	$1,106	$6,637	$10	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,865	$373	$0	$336	$2,574	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,492	$1,898	$0	$2,278	$13,668	$20	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$1,037	$207	$0	$187	$1,431	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,693	$939	$0	$1,126	$6,759	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$25,982**	**$5,196**	**$0**	**$5,804**	**$36,982**	**$53**	**$27**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$415	$83	$0	$75	$572	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$32,872	$6,574	$0	$5,917	$45,364	$66	$34
4.3	Electric Superheaters	$0	$0	$0	$0	$1,663	$333	$0	$299	$2,294	$3	$2
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$660	$132	$0	$119	$911	$1	$1

	Case:	SOEC-EB-3P	Pathway Step 3 Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	691,644	Plant Size (MW net):			1,350		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 H_2/day]	$/kW (net)
4.5	Hydrogen Cooler	$0	$0	$0	$0	$266	$53	$0	$48	$367	$1	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$46	$356	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$15,279	$3,056	$0	$2,750	$21,085	$30	$16
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$51,413**	**$10,283**	**$0**	**$9,254**	**$70,950**	**$103**	**$53**
	7					Ductwork, & Stack						
7.3	Ductwork	$0	$0	$0	$0	$570	$114	$0	$103	$786	$1	$1
7.4	Stack	$0	$0	$0	$0	$3,811	$762	$0	$686	$5,259	$8	$4
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$486	$97	$0	$117	$700	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,867**	**$973**	**$0**	**$905**	**$6,746**	**$10**	**$5**
	9					Cooling Water System						
9.1	Cooling Towers	$0	$0	$0	$0	$3,342	$668	$0	$601	$4,611	$7	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$366	$73	$0	$66	$505	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$4,274	$855	$0	$769	$5,899	$9	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,710	$342	$0	$308	$2,360	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$583	$117	$0	$105	$805	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$234	$47	$0	$42	$323	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$552	$110	$0	$133	$795	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$11,061**	**$2,212**	**$0**	**$2,024**	**$15,297**	**$22**	**$11**
	11					Accessory Electric Plant						
11.2	Station Service Equipment	$0	$0	$0	$0	$11,514	$2,303	$0	$2,072	$15,889	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$17,767	$3,553	$0	$3,198	$24,519	$35	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,203	$2,841	$0	$2,556	$19,600	$28	$15
11.5	Wire & Cable	$0	$0	$0	$0	$15,225	$3,045	$0	$2,741	$21,011	$30	$16
11.6	Protective Equipment	$0	$0	$0	$0	$1,151	$230	$0	$207	$1,588	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,653	$531	$0	$478	$3,662	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,066	$413	$0	$372	$2,851	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$434	$87	$0	$104	$626	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$65,014**	**$13,003**	**$0**	**$11,729**	**$89,745**	**$130**	**$66**
	12					Instrumentation & Control						
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,449	$290	$72	$261	$2,072	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$717	$143	$0	$129	$989	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$314	$63	$16	$57	$449	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,177	$2,235	$559	$2,012	$15,983	$23	$12

	Case:	SOEC-EB-3P	Pathway Step 3 Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	691,644	Plant Size (MW net):			1,350			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 H_2/day]	$/kW (net)
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,477	$895	$224	$806	$6,402	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,056	$411	$103	$370	$2,941	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,190**	**$4,038**	**$974**	**$3,634**	**$28,836**	**$42**	**$21**
13	Improvements to Site											
13.1	Site Preparation	$0	$0	$0	$0	$16,788	$3,358	$0	$4,029	$24,175	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,638	$1,128	$0	$1,353	$8,119	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,776	$955	$0	$1,146	$6,878	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,203**	**$5,441**	**$0**	**$6,529**	**$39,172**	**$57**	**$29**
14	Buildings & Structures											
14.4	Administration Building	$0	$0	$0	$0	$762	$152	$0	$137	$1,051	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$23	$5	$0	$4	$32	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$451	$90	$0	$81	$622	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,121	$224	$0	$202	$1,547	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$842	$168	$0	$152	$1,162	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$628	$126	$0	$113	$867	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,099	$220	$0	$198	$1,517	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,925**	**$985**	**$0**	**$887**	**$6,797**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$404,725**	**$80,945**	**$974**	**$75,699**	**$562,343**	**$813**	**$416**

Exhibit A-121. Case 3P owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$4,041	$6	$3
1 Month Maintenance Materials	$629	$1	$0
1 Month Non-Fuel Consumables	$189	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$11,247	$16	$8
Total	**$16,105**	**$23**	**$12**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$218	$0	$0
0.5% of TPC (spare parts)	$2,812	$4	$2
Total	**$3,029**	**$4**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$482	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$84,351	$122	$62
Financing Costs	$15,183	$22	$11
Total Overnight Costs (TOC)	$681,794	$986	$505
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	$729,384	$1,055	$540

Exhibit A-122. Case 3P initial and annual O&M costs

Case:	SOEC-EB-3P		Pathway Step 3 Pressurized SOEC		Cost Base:		Dec 2018
Plant Size (kg H_2/day):	**691,644**	**Plant Size (MW net):**		**1,350**	**Capacity Factor (%):**		**90%**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
						Annual Cost	
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.17	$1.62
Maintenance Labor:					$4,273,804	$6.18	$3.17
Administrative & Support Labor:					$1,616,499	$2.34	$1.20
Property Taxes and Insurance:					$11,246,853	$16.26	$8.33
Total:					**$19,329,346**	**$27.95**	**$14.32**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh-net)**
Maintenance Material:					$6,787,807	$0.03	$0.64
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	79.01	$7.97	$9,571,347	$0.04	$0.90
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,379	$1.90	$0	$860,974	$0.004	$0.081
Makeup and Wastewater Treatment Chemicals (ton):	0	4.11	$550	$0	$742,419	$0.003	$0.070
Hydrogen Drying Sorbent (lb):	48,156	131.93	$10	$481,560	$433,404	$0.002	$0.041
Subtotal:				**$481,560**	**$2,036,797**	**$0.009**	**$0.191**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	131.93	$0.02	$0	$823	$0.00	$0.00
Subtotal:				**$0**	**$823**	$0.00	**$0.00**
Variable Operating Costs Total:				**$481,560**	**$18,396,774**	**$0.04**	**$0.83**
Electricity Cost							
Electricity (MWh):	0	32,404	$60.00	$0	$638,684,740	$2.81	$60.00
Total:				**$0**	**$638,684,740**	**$2.81**	**$60.00**

Exhibit A-123. Case 3P LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.19	6%
Fixed	0.09	3%
Variable	0.08	3%
Electricity	2.81	89%
Total	**3.17**	**N/A**

CASE 4P

Exhibit A-124. Case 4P stream table

	1	2	3	4	5	6	7	8	9	10
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.4250	0.8500	0.8500	0.8500	0.9954	0.9986
H_2O	1.0000	1.0000	1.0000	1.0000	0.5750	0.1500	0.1500	0.1500	0.0046	0.0014
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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,446	16,968	16,968	16,968	33,935	33,935	16,968	16,968	14,489	14,443
V-L Flowrate (kg/h)	296,278	305,678	305,678	305,678	380,603	149,851	74,925	74,925	30,265	29,438
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	187	642	748	751	759	759	193	30	30
Pressure (MPa, abs)	0.10	1.17	1.16	1.14	0.80	0.80	0.80	0.80	0.78	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,820.32	3,790.16	4,032.11	4,575.34	6,791.58	6,791.58	2,834.87	512.84	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,151.02	-12,181.19	-11,939.24	-10,203.14	-3,120.27	-3,120.27	-7,076.98	-457.12	-87.51
Density (kg/m³)	1,003.6	5.9	2.8	2.4	1.1	0.4	0.4	0.9	0.6	2.1
V-L Molecular Weight	18.015	18.015	18.015	18.015	11.216	4.416	4.416	4.416	2.089	2.038
V-L Flowrate (lb_{mol}/h)	36,257	37,407	37,407	37,407	74,815	74,815	37,407	37,407	31,942	31,841
V-L Flowrate (lb/h)	653,182	673,904	673,904	673,904	839,086	330,365	165,182	165,182	66,722	64,899
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	369	1,188	1,378	1,385	1,397	1,397	380	86	86
Pressure (psia)	14.7	170.0	168.0	166.0	116.0	115.8	115.8	115.6	113.6	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,212.5	1,629.5	1,733.5	1,967.0	2,919.9	2,919.9	1,218.8	220.5	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,653.9	-5,237.0	-5,132.9	-4,386.6	-1,341.5	-1,341.5	-3,042.6	-196.5	-37.6
Density (lb/ft³)	62.650	0.366	0.172	0.152	0.066	0.026	0.026	0.057	0.040	0.132

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

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

Exhibit A-124. Case 4P stream table (cont'd)

	11	12	13	14	15	16	17	18	19	20	21
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077	0.0077
CH_4	0.0000	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	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	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	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	164	14,278	14,278	32,940	32,940	32,940	32,940	40,152	40,152	40,152	40,152
V-L Flowrate (kg/h)	652	28,786	28,786	950,452	950,461	950,461	950,461	1,181,245	1,181,245	1,181,245	1,181,245
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	160	730	750	761	306	254	69
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.81	0.80	0.80	0.80	0.80	0.79	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	177.60	797.73	820.76	820.82	321.85	267.78	81.29
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	44.88	665.01	688.04	709.55	210.58	156.52	-29.97
Density (kg/m³)	4.7	2.1	5.0	1.2	6.5	2.8	2.7	2.7	4.9	5.3	1.0
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	362	31,478	31,478	72,620	72,620	72,620	72,620	88,521	88,521	88,521	88,521
V-L Flowrate (lb/h)	1,437	63,462	63,462	2,095,387	2,095,408	2,095,408	2,095,408	2,604,200	2,604,200	2,604,200	2,604,200
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	320	1,346	1,382	1,402	583	489	156
Pressure (psia)	385.0	383.3	939.7	14.7	117.3	116.5	116.0	115.8	115.6	115.1	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	76.4	343.0	352.9	352.9	138.4	115.1	34.9
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	19.3	285.9	295.8	305.1	90.5	67.3	-12.9
Density (lb/ft³)	0.292	0.129	0.314	0.076	0.404	0.173	0.169	0.170	0.303	0.332	0.065

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

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

Exhibit A-125. Case 4P plant performance summary

Performance Summary	
Total Gross Power, kWe	**60**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	225,915
Hydrogen Compression, kWe	30,134
Balance of Plant, kWe	107,422
Total Auxiliaries, MWe	**363**
Net Power, MWe	**-1,334**
Hydrogen Production, kg/h (lb/h)	**28,786 (63,462)**
Energy Efficiency,[A] % HHV (% LHV)	85.0 (71.9)
Electric Input per Kilogram, kWh/kg	46.3
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,134,641 (959,421)
Raw Water Withdrawal, m^3/min (gpm)	6.8 (1,808)
Raw Water Consumption, m^3/min (gpm)	5.8 (1,536)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-126. Case 4P power summary

Power Summary	
Sweep Gas Expander, MWe	60
Total Gross Power, MWe	**60**
Auxiliary Load Summary	
Air Electrode Compressors, kWe	70,025
Circulating Water Pumps, kWe	500
Cooling Tower Fans, kWe	260
Electric Boiler, kWe	225,915
Electric Steam Superheater, kWe	20,544
Electric Sweep Heater, kWe	6,080
Feedwater Pumps, kWe	163
Fuel Electrode Recycle Blowers, kWe	0
Ground Water Pumps, kWe	160
Hydrogen Compressor, kWe	30,134
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,400
Total Auxiliaries, MWe	**363**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,334**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-127. Case 4P carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (262)	Air-Electrode Sweep Exhaust (CO_2)	119 (262)
Total	**119 (262)**	**Total**	**119 (262)**

Exhibit A-128. Case 4P 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)
Electrolysis Steam	4.9 (1,306)	–	4.9 (1,306)	–	4.9 (1,306)
Deaerator Vent	–	–	–	0.0 (3.1)	0.0 (-3.1)
Boiler Blowdown	–	–	–	0.6 (156)	-0.6 (-156)
Cooling Tower	1.9 (501)	–	1.9 (501)	0.4 (113)	1.5 (388)
Total	**6.8 (1,807)**	**–**	**6.8 (1,807)**	**1.0 (272)**	**5.8 (1,536)**

Exhibit A-129. Case 4P overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	26 (24)	–	26 (24)
Auxiliary Power	–	–	4,803 (4,552)	4,803 (4,552)
Total	**0.0 (0.0)**	**55 (52)**	**4,803 (4,552)**	**4,858 (4,605)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,085 (3,872)	13 (12)	–	4,098 (3,884)
Sweep Exhaust	–	96 (91)	–	96 (91)
Motor Losses and Design Allowances	–	13 (13)	–	13 (13)
Cooling Tower Load[A]	–	248 (235)	–	248 (235)
Boiler Blowdown	–	12 (12)	–	12 (12)
Process Vents[B]	–	0.5 (0.5)	–	0.5 (0.5)
Ambient Losses[C]	–	308 (292)	–	308 (292)
Total	**–**	**690 (655)**	**0.0 (0.0)**	**4,775 (4,527)**
Unaccounted Energy[D]	**–**	*83 (78)*	–	*83 (78)*

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-130. Case 4P energy and mass balance

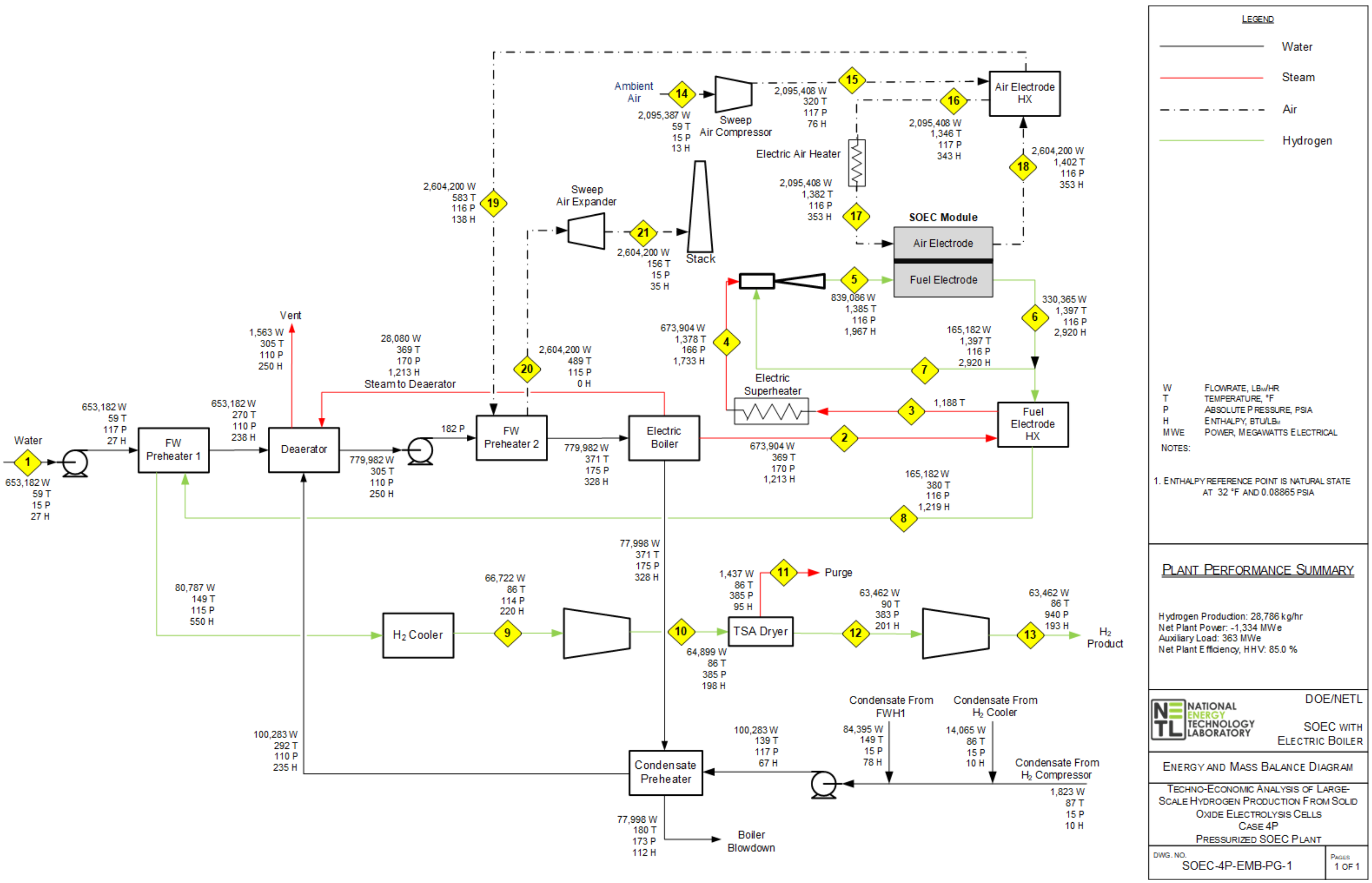


Exhibit A-131. Case 4P total plant cost details

	Case:	SOEC-EB-4P	Pathway Step 4 Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	690,860	Plant Size (MW net):			1,334			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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$89,183	$17,837	$0	$16,053	$123,073	$178	$92
1.2	Container	$0	$0	$0	$0	$12,695	$2,539	$0	$2,285	$17,519	$25	$13
1.3	Insulation	$0	$0	$0	$0	$1,189	$238	$0	$214	$1,641	$2	$1
1.4	Module Assembly	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.5	Air Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.6	Fuel Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.8	Module Current Collectors	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$2
1.9	Module I&C	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$2
1.10	Rectifier	$0	$0	$0	$0	$20,215	$4,043	$0	$3,639	$27,896	$40	$21
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$135,173**	**$27,035**	**$0**	**$24,331**	**$186,539**	**$270**	**$140**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Compressor	$0	$0	$0	$0	$7,755	$1,551	$0	$1,396	$10,702	$15	$8
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$19,159	$3,832	$0	$3,449	$26,440	$38	$20
2.3	Hydrogen Recycle Jet Pump	$0	$0	$0	$0	$588	$118	$0	$106	$811	$1	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$19,151	$3,830	$0	$3,447	$26,428	$38	$20
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,288	$258	$0	$232	$1,778	$3	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
2.7	Section I&C	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
2.8	Sweep Gas Expander	$0	$0	$0	$0	$6,446	$1,289	$0	$1,160	$8,896	$13	$7
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$55,675**	**$11,135**	**$0**	**$10,022**	**$76,832**	**$111**	**$58**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,107	$821	$0	$739	$5,668	$8	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,417	$883	$0	$1,060	$6,360	$9	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,765	$353	$0	$318	$2,436	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,060	$1,812	$0	$2,174	$13,046	$19	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$981	$196	$0	$177	$1,353	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,337	$867	$0	$1,041	$6,246	$9	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$24,667**	**$4,933**	**$0**	**$5,509**	**$35,109**	**$51**	**$26**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$455	$91	$0	$82	$628	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$31,288	$6,258	$0	$5,632	$43,177	$62	$32
4.3	Electric Superheaters	$0	$0	$0	$0	$1,629	$326	$0	$293	$2,248	$3	$2
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$660	$132	$0	$119	$911	$1	$1

	Case:	SOEC-EB-4P	Pathway Step 4 Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	690,860	Plant Size (MW net):			1,334		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 H_2/day]	$/kW (net)
4.5	Hydrogen Cooler	$0	$0	$0	$0	$139	$28	$0	$25	$192	$0	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$46	$355	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$15,267	$3,053	$0	$2,748	$21,068	$30	$16
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$49,696**	**$9,939**	**$0**	**$8,945**	**$68,580**	**$99**	**$51**
	7					**Ductwork, & Stack**						
7.3	Ductwork	$0	$0	$0	$0	$576	$115	$0	$104	$795	$1	$1
7.4	Stack	$0	$0	$0	$0	$3,851	$770	$0	$693	$5,315	$8	$4
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$491	$98	$0	$118	$707	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,919**	**$984**	**$0**	**$915**	**$6,817**	**$10**	**$5**
	9					**Cooling Water System**						
9.1	Cooling Towers	$0	$0	$0	$0	$2,937	$587	$0	$529	$4,053	$6	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$322	$64	$0	$58	$445	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$3,920	$784	$0	$706	$5,409	$8	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,538	$308	$0	$277	$2,122	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$570	$114	$0	$103	$786	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$210	$42	$0	$38	$290	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$497	$99	$0	$119	$715	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$9,993**	**$1,999**	**$0**	**$1,828**	**$13,820**	**$20**	**$10**
	11					**Accessory Electric Plant**						
11.2	Station Service Equipment	$0	$0	$0	$0	$11,426	$2,285	$0	$2,057	$15,768	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$17,632	$3,526	$0	$3,174	$24,332	$35	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,094	$2,819	$0	$2,537	$19,450	$28	$15
11.5	Wire & Cable	$0	$0	$0	$0	$15,109	$3,022	$0	$2,720	$20,851	$30	$16
11.6	Protective Equipment	$0	$0	$0	$0	$1,142	$228	$0	$206	$1,576	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,633	$527	$0	$474	$3,634	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,051	$410	$0	$369	$2,830	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$431	$86	$0	$103	$621	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$64,518**	**$12,904**	**$0**	**$11,639**	**$89,061**	**$129**	**$67**
	12					**Instrumentation & Control**						
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,437	$287	$72	$259	$2,055	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$712	$142	$0	$128	$982	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$311	$62	$16	$56	$445	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,085	$2,217	$554	$1,995	$15,852	$23	$12

	Case:	SOEC-EB-4P	Pathway Step 4 Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	690,860	Plant Size (MW net):			1,334		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 H_2/day]	$/kW (net)
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,440	$888	$222	$799	$6,350	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,040	$408	$102	$367	$2,917	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,026**	**$4,005**	**$966**	**$3,605**	**$28,601**	**$41**	**$21**
	13					**Improvements to Site**						
13.1	Site Preparation	$0	$0	$0	$0	$16,696	$3,339	$0	$4,007	$24,042	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,607	$1,121	$0	$1,346	$8,074	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,750	$950	$0	$1,140	$6,840	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,053**	**$5,411**	**$0**	**$6,493**	**$38,957**	**$56**	**$29**
	14					**Buildings & Structures**						
14.4	Administration Building	$0	$0	$0	$0	$758	$152	$0	$137	$1,047	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$20	$4	$0	$4	$27	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$434	$87	$0	$78	$598	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,116	$223	$0	$201	$1,540	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$839	$168	$0	$151	$1,158	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$626	$125	$0	$113	$864	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,058	$212	$0	$191	$1,461	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,851**	**$970**	**$0**	**$873**	**$6,694**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$396,570**	**$79,314**	**$966**	**$74,160**	**$551,010**	**$798**	**$413**

Exhibit A-132. Case 4P owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,987	$6	$3
1 Month Maintenance Materials	$616	$1	$0
1 Month Non-Fuel Consumables	$180	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$11,020	$16	$8
Total	**$15,804**	**$23**	**$12**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$210	$0	$0
0.5% of TPC (spare parts)	$2,755	$4	$2
Total	**$2,965**	**$4**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$481	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$82,651	$120	$62
Financing Costs	$14,877	$22	$11
Total Overnight Costs (TOC)	**$668,088**	**$967**	**$501**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$714,722**	**$1,035**	**$536**

Exhibit A-133. Case 4P initial and annual O&M costs

Case:	SOEC-EB-4P		Pathway Step 4 Pressurized SOEC		Cost Base:	Dec 2018	
Plant Size (kg H_2/day):	**690,860**	**Plant Size (MW net):**		**1,334**	**Capacity Factor (%):**	**90%**	
Operating & Maintenance 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:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**(\$/[kg H_2/day])**	**(\$/kW-net)**
Annual Operating Labor:					\$2,192,190	\$3.17	\$1.64
Maintenance Labor:					\$4,187,673	\$6.06	\$3.14
Administrative & Support Labor:					\$1,594,966	\$2.31	\$1.20
Property Taxes and Insurance:					\$11,020,191	\$15.95	\$8.26
Total:					**\$18,995,019**	**\$27.49**	**\$14.24**
Variable Operating Costs							
					($)	**(\$/kg H_2)**	**(\$/MWh-net)**
Maintenance Material:					\$6,651,009	\$0.03	\$0.63
Stack Replacement							
	Life (yr)		**\$/kW_{AC}**	**\$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	78.92	\$7.97	\$9,571,347	\$0.04	\$0.91
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,301	\$1.90	\$0	\$812,259	\$0.004	\$0.077
Makeup and Wastewater Treatment Chemicals (ton):	0	3.88	\$550	\$0	\$700,412	\$0.003	\$0.067
Hydrogen Drying Sorbent (lb):	48,101	131.78	\$10	\$481,014	\$432,912	\$0.002	\$0.041
Subtotal:				**\$481,014**	**\$1,945,584**	**\$0.009**	**\$0.185**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	131.78	\$0.02	\$0	\$823	\$0.00	\$0.00
Subtotal:				**\$0**	**\$823**	\$0.00	**\$0.00**
Variable Operating Costs Total:				**\$481,014**	**\$18,168,763**	**\$0.04**	**\$0.82**
Electricity Cost							
Electricity (MWh):	0	32,019	\$60.00	\$0	\$631,088,013	\$2.78	\$60.00
Total:				**\$0**	**\$631,088,013**	**\$2.78**	**\$60.00**

Exhibit A-134. Case 4P LCOH breakdown

Component	LCOH, \$/kg H_2	Percentage
Capital	0.18	6%
Fixed	0.08	3%
Variable	0.08	3%
Electricity	2.78	89%
Total	**3.13**	**N/A**

CASE 5P

Exhibit A-135. Case 5P stream table

	1	2	3	4	5	6	7	8	9	10
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.4250	0.8500	0.8500	0.8500	0.9954	0.9986
H_2O	1.0000	1.0000	1.0000	1.0000	0.5750	0.1500	0.1500	0.1500	0.0046	0.0014
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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,446	16,968	16,968	16,968	33,935	33,935	16,968	16,968	14,489	14,443
V-L Flowrate (kg/h)	296,278	305,678	305,678	305,678	380,603	149,851	74,925	74,925	30,265	29,438
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	187	642	748	751	759	759	193	30	30
Pressure (MPa, abs)	0.10	1.17	1.16	1.14	0.80	0.80	0.80	0.80	0.78	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,820.32	3,790.16	4,032.11	4,575.34	6,791.58	6,791.58	2,834.87	512.84	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,151.02	-12,181.19	-11,939.24	-10,203.14	-3,120.27	-3,120.27	-7,076.98	-457.12	-87.51
Density (kg/m³)	1,003.6	5.9	2.8	2.4	1.1	0.4	0.4	0.9	0.6	2.1
V-L Molecular Weight	18.015	18.015	18.015	18.015	11.216	4.416	4.416	4.416	2.089	2.038
V-L Flowrate (lb_{mol}/h)	36,257	37,407	37,407	37,407	74,815	74,815	37,407	37,407	31,942	31,841
V-L Flowrate (lb/h)	653,182	673,904	673,904	673,904	839,086	330,365	165,182	165,182	66,722	64,899
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	369	1,188	1,378	1,385	1,397	1,397	380	86	86
Pressure (psia)	14.7	170.0	168.0	166.0	116.0	115.8	115.8	115.6	113.6	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,212.5	1,629.5	1,733.5	1,967.0	2,919.9	2,919.9	1,218.8	220.5	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,653.9	-5,237.0	-5,132.9	-4,386.6	-1,341.5	-1,341.5	-3,042.6	-196.5	-37.6
Density (lb/ft³)	62.650	0.366	0.172	0.152	0.066	0.026	0.026	0.057	0.040	0.132

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

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

Exhibit A-135. Case 5P stream table (cont'd)

	11	12	13	14	15	16	17	18	19	20	21
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077	0.0077
CH_4	0.0000	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	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	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	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	164	14,278	14,278	32,940	32,940	32,940	32,940	40,152	40,152	40,152	40,152
V-L Flowrate (kg/h)	652	28,786	28,786	950,452	950,461	950,461	950,461	1,181,245	1,181,245	1,181,245	1,181,245
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	160	730	750	761	306	254	69
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.81	0.80	0.80	0.80	0.80	0.79	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	177.60	797.73	820.76	820.82	321.85	267.78	81.29
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	44.88	665.01	688.04	709.55	210.58	156.52	-29.97
Density (kg/m^3)	4.7	2.1	5.0	1.2	6.5	2.8	2.7	2.7	4.9	5.3	1.0
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	362	31,478	31,478	72,620	72,620	72,620	72,620	88,521	88,521	88,521	88,521
V-L Flowrate (lb/h)	1,437	63,462	63,462	2,095,387	2,095,408	2,095,408	2,095,408	2,604,200	2,604,200	2,604,200	2,604,200
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	320	1,346	1,382	1,402	583	489	156
Pressure (psia)	385.0	383.3	939.7	14.7	117.3	116.5	116.0	115.8	115.6	115.1	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	76.4	343.0	352.9	352.9	138.4	115.1	34.9
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	19.3	285.9	295.8	305.1	90.5	67.3	-12.9
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.404	0.173	0.169	0.170	0.303	0.332	0.065

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

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

Exhibit A-136. Case 5P plant performance summary

Performance Summary	
Total Gross Power, kWe	**60**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	225,915
Hydrogen Compression, kWe	30,134
Balance of Plant, kWe	107,422
Total Auxiliaries, MWe	**363**
Net Power, MWe	**-1,334**
Hydrogen Production, kg/h (lb/h)	**28,786 (63,462)**
Energy Efficiency,[A] % HHV (% LHV)	85.0 (71.9)
Electric Input per Kilogram, kWh/kg	46.3
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,134,641 (959,421)
Raw Water Withdrawal, m^3/min (gpm)	6.8 (1,808)
Raw Water Consumption, m^3/min (gpm)	5.8 (1,536)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-137. Case 5P power summary

Power Summary	
Sweep Gas Expander, MWe	60
Total Gross Power, MWe	**60**
Auxiliary Load Summary	
Air Electrode Compressors, kWe	70,025
Circulating Water Pumps, kWe	500
Cooling Tower Fans, kWe	260
Electric Boiler, kWe	225,915
Electric Steam Superheater, kWe	20,544
Electric Sweep Heater, kWe	6,080
Feedwater Pumps, kWe	163
Fuel Electrode Recycle Blowers, kWe	0
Ground Water Pumps, kWe	160
Hydrogen Compressor, kWe	30,134
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,400
Total Auxiliaries, MWe	**363**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,334**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-138. Case 5P carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (262)	Air-Electrode Sweep Exhaust (CO_2)	119 (262)
Total	**119 (262)**	**Total**	**119 (262)**

Exhibit A-139. Case 5P 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)
Electrolysis Steam	4.9 (1,306)	–	4.9 (1,306)	–	4.9 (1,306)
Deaerator Vent	–	–	–	0.0 (3.1)	0.0 (-3.1)
Boiler Blowdown	–	–	–	0.6 (156)	-0.6 (-156)
Cooling Tower	1.9 (501)	–	1.9 (501)	0.4 (113)	1.5 (388)
Total	**6.8 (1,807)**	**–**	**6.8 (1,807)**	**1.0 (272)**	**5.8 (1,536)**

Exhibit A-140. Case 5P overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	26 (24)	–	26 (24)
Auxiliary Power	–	–	4,803 (4,552)	4,803 (4,552)
Total	**0.0 (0.0)**	**55 (52)**	**4,803 (4,552)**	**4,858 (4,605)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,085 (3,872)	13 (12)	–	4,098 (3,884)
Sweep Exhaust	–	96 (91)	–	96 (91)
Motor Losses and Design Allowances	–	13 (13)	–	13 (13)
Cooling Tower Load[A]	–	248 (235)	–	248 (235)
Boiler Blowdown	–	12 (12)	–	12 (12)
Process Vents[B]	–	0.5 (0.5)	–	0.5 (0.5)
Ambient Losses[C]	–	308 (292)	–	308 (292)
Total	**–**	**690 (655)**	**0.0 (0.0)**	**4,775 (4,527)**
Unaccounted Energy[D]	**–**	*83 (78)*	–	*83 (78)*

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-141. Case 5P energy and mass balance (identical to Case 4P)

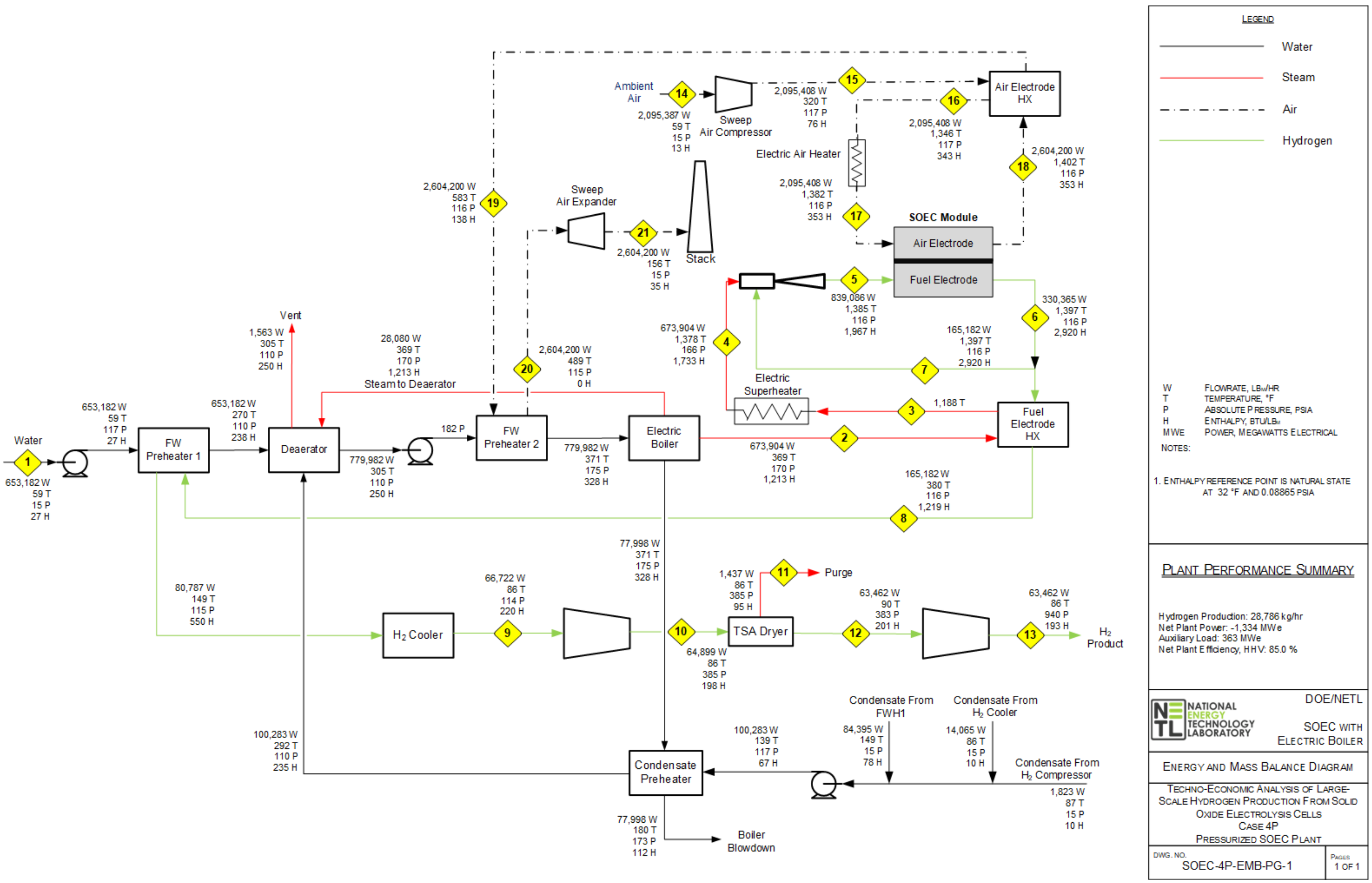


Exhibit A-142. Case 5P total plant cost details

	Case:	SOEC-EB-5P	Pathway Step 5 Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	690,860	Plant Size (MW net):			1,334		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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$89,183	$17,837	$0	$16,053	$123,073	$178	$92
1.2	Container	$0	$0	$0	$0	$12,695	$2,539	$0	$2,285	$17,519	$25	$13
1.3	Insulation	$0	$0	$0	$0	$1,189	$238	$0	$214	$1,641	$2	$1
1.4	Module Assembly	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.5	Air Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.6	Fuel Distribution	$0	$0	$0	$0	$2,973	$595	$0	$535	$4,102	$6	$3
1.8	Module Current Collectors	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$2
1.9	Module I&C	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$2
1.10	Rectifier	$0	$0	$0	$0	$20,215	$4,043	$0	$3,639	$27,896	$40	$21
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$135,173**	**$27,035**	**$0**	**$24,331**	**$186,539**	**$270**	**$140**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Compressor	$0	$0	$0	$0	$7,755	$1,551	$0	$1,396	$10,702	$15	$8
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$19,159	$3,832	$0	$3,449	$26,440	$38	$20
2.3	Hydrogen Recycle Jet Pump	$0	$0	$0	$0	$588	$118	$0	$106	$811	$1	$1
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$19,151	$3,830	$0	$3,447	$26,428	$38	$20
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$1,288	$258	$0	$232	$1,778	$3	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
2.7	Section I&C	$0	$0	$0	$0	$644	$129	$0	$116	$889	$1	$1
2.8	Sweep Gas Expander	$0	$0	$0	$0	$6,446	$1,289	$0	$1,160	$8,896	$13	$7
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$55,675**	**$11,135**	**$0**	**$10,022**	**$76,832**	**$111**	**$58**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,107	$821	$0	$739	$5,668	$8	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,417	$883	$0	$1,060	$6,360	$9	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,765	$353	$0	$318	$2,436	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,060	$1,812	$0	$2,174	$13,046	$19	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$981	$196	$0	$177	$1,353	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,337	$867	$0	$1,041	$6,246	$9	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$24,667**	**$4,933**	**$0**	**$5,509**	**$35,109**	**$51**	**$26**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$455	$91	$0	$82	$628	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$31,288	$6,258	$0	$5,632	$43,177	$62	$32
4.3	Electric Superheaters	$0	$0	$0	$0	$1,629	$326	$0	$293	$2,248	$3	$2
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$660	$132	$0	$119	$911	$1	$1

	Case:	SOEC-EB-5P	Pathway Step 5 Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	690,860	Plant Size (MW net):			1,334			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 H_2/day]	$/kW (net)
4.5	Hydrogen Cooler	$0	$0	$0	$0	$139	$28	$0	$25	$192	$0	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$46	$355	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$15,267	$3,053	$0	$2,748	$21,068	$30	$16
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$49,696**	**$9,939**	**$0**	**$8,945**	**$68,580**	**$99**	**$51**
7						Ductwork, & Stack						
7.3	Ductwork	$0	$0	$0	$0	$576	$115	$0	$104	$795	$1	$1
7.4	Stack	$0	$0	$0	$0	$3,851	$770	$0	$693	$5,315	$8	$4
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$491	$98	$0	$118	$707	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,919**	**$984**	**$0**	**$915**	**$6,817**	**$10**	**$5**
9						Cooling Water System						
9.1	Cooling Towers	$0	$0	$0	$0	$2,937	$587	$0	$529	$4,053	$6	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$322	$64	$0	$58	$445	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$3,920	$784	$0	$706	$5,409	$8	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,538	$308	$0	$277	$2,122	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$570	$114	$0	$103	$786	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$210	$42	$0	$38	$290	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$497	$99	$0	$119	$715	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$9,993**	**$1,999**	**$0**	**$1,828**	**$13,820**	**$20**	**$10**
11						Accessory Electric Plant						
11.2	Station Service Equipment	$0	$0	$0	$0	$11,426	$2,285	$0	$2,057	$15,768	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$17,632	$3,526	$0	$3,174	$24,332	$35	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,094	$2,819	$0	$2,537	$19,450	$28	$15
11.5	Wire & Cable	$0	$0	$0	$0	$15,109	$3,022	$0	$2,720	$20,851	$30	$16
11.6	Protective Equipment	$0	$0	$0	$0	$1,142	$228	$0	$206	$1,576	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,633	$527	$0	$474	$3,634	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,051	$410	$0	$369	$2,830	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$431	$86	$0	$103	$621	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$64,518**	**$12,904**	**$0**	**$11,639**	**$89,061**	**$129**	**$67**
12						Instrumentation & Control						
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,437	$287	$72	$259	$2,055	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$712	$142	$0	$128	$982	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$311	$62	$16	$56	$445	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,085	$2,217	$554	$1,995	$15,852	$23	$12

	Case:	SOEC-EB-5P	Pathway Step 5 Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	690,860	Plant Size (MW net):			1,334			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 H_2/day]	$/kW (net)
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,440	$888	$222	$799	$6,350	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,040	$408	$102	$367	$2,917	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,026**	**$4,005**	**$966**	**$3,605**	**$28,601**	**$41**	**$21**
13						**Improvements to Site**						
13.1	Site Preparation	$0	$0	$0	$0	$16,696	$3,339	$0	$4,007	$24,042	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,607	$1,121	$0	$1,346	$8,074	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,750	$950	$0	$1,140	$6,840	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,053**	**$5,411**	**$0**	**$6,493**	**$38,957**	**$56**	**$29**
14						**Buildings & Structures**						
14.4	Administration Building	$0	$0	$0	$0	$758	$152	$0	$137	$1,047	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$20	$4	$0	$4	$27	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$434	$87	$0	$78	$598	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,116	$223	$0	$201	$1,540	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$839	$168	$0	$151	$1,158	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$626	$125	$0	$113	$864	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,058	$212	$0	$191	$1,461	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,851**	**$970**	**$0**	**$873**	**$6,694**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$396,570**	**$79,314**	**$966**	**$74,160**	**$551,010**	**$798**	**$413**

Exhibit A-143. Case 5P owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,987	$6	$3
1 Month Maintenance Materials	$616	$1	$0
1 Month Non-Fuel Consumables	$180	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$11,020	$16	$8
Total	**$15,804**	**$23**	**$12**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$210	$0	$0
0.5% of TPC (spare parts)	$2,755	$4	$2
Total	**$2,965**	**$4**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$481	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$82,651	$120	$62
Financing Costs	$14,877	$22	$11
Total Overnight Costs (TOC)	**$668,088**	**$967**	**$501**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$714,722**	**$1,035**	**$536**

Exhibit A-144. Case 5P initial and annual O&M costs

Case:		SOEC-EB-5P	Pathway Step 5 Pressurized SOEC		Cost Base:		Dec 2018
Plant Size (kg H_2/day):	**690,860**	**Plant Size (MW net):**		**1,334**	**Capacity Factor (%):**		**95%**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.17	$1.64
Maintenance Labor:					$4,187,673	$6.06	$3.14
Administrative & Support Labor:					$1,594,966	$2.31	$1.20
Property Taxes and Insurance:					$11,020,191	$15.95	$8.26
Total:					**$18,995,019**	**$27.49**	**$14.24**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh-net)**
Maintenance Material:					$7,020,510	$0.03	$0.63
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	78.92	$7.97	$9,571,347	$0.04	$0.86
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,301	$1.90	$0	$857,385	$0.004	$0.077
Makeup and Wastewater Treatment Chemicals (ton):	0	3.88	$550	$0	$739,324	$0.003	$0.067
Hydrogen Drying Sorbent (lb):	48,101	131.78	$10	$481,014	$456,963	$0.002	$0.041
Subtotal:				**$481,014**	**$2,053,672**	**$0.009**	**$0.185**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	131.78	$0.02	$0	$868	$0.00	$0.00
Subtotal:				**$0**	**$868**	$0.00	**$0.00**
Variable Operating Costs Total:				**$481,014**	**$18,646,397**	**$0.04**	**$0.82**
Electricity Cost							
Electricity (MWh):	0	32,019	$60.00	$0	$666,148,458	$2.78	$60.00
Total:				**$0**	**$666,148,458**	**$2.78**	**$60.00**

Exhibit A-145. Case 5P LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.17	6%
Fixed	0.08	3%
Variable	0.08	3%
Electricity	2.78	89%
Total	**3.11**	**N/A**

CASE 6P

Exhibit A-146. Case 6P stream table

	1	2	3	4	5	6	7	8	9	10
V-L Mole Fraction										
Ar	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	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
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2	0.0000	0.0000	0.0000	0.0000	0.4250	0.8500	0.8500	0.8500	0.9954	0.9986
H_2O	1.0000	1.0000	1.0000	1.0000	0.5750	0.1500	0.1500	0.1500	0.0046	0.0014
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
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	16,506	17,030	17,030	17,030	34,060	34,060	17,030	17,030	14,542	14,496
V-L Flowrate (kg/h)	297,366	306,800	306,800	306,800	382,001	150,402	75,201	75,201	30,376	29,546
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	15	187	638	749	750	754	754	193	30	30
Pressure (MPa, abs)	0.10	1.17	1.16	1.14	0.80	0.80	0.80	0.80	0.78	2.65
Steam Table Enthalpy (kJ/kg)[A]	62.80	2,820.32	3,781.19	4,034.43	4,570.00	6,754.95	6,754.95	2,834.87	512.84	461.06
AspenPlus Enthalpy (kJ/kg)[B]	-16,017.34	-13,151.02	-12,190.16	-11,936.91	-10,208.48	-3,156.89	-3,156.89	-7,076.98	-457.12	-87.51
Density (kg/m³)	1,003.6	5.9	2.8	2.4	1.1	0.4	0.4	0.9	0.6	2.1
V-L Molecular Weight	18.015	18.015	18.015	18.015	11.216	4.416	4.416	4.416	2.089	2.038
V-L Flowrate (lb_{mol}/h)	36,390	37,545	37,545	37,545	75,089	75,089	37,545	37,545	32,059	31,958
V-L Flowrate (lb/h)	655,580	676,378	676,378	676,378	842,168	331,579	165,789	165,789	66,967	65,137
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	59	369	1,181	1,380	1,382	1,388	1,388	380	86	86
Pressure (psia)	14.7	170.0	168.0	166.0	116.0	115.8	115.8	115.6	113.6	385.0
Steam Table Enthalpy (Btu/lb)[A]	27.0	1,212.5	1,625.6	1,734.5	1,964.7	2,904.1	2,904.1	1,218.8	220.5	198.2
AspenPlus Enthalpy (Btu/lb)[B]	-6,886.2	-5,653.9	-5,240.8	-5,131.9	-4,388.9	-1,357.2	-1,357.2	-3,042.6	-196.5	-37.6
Density (lb/ft³)	62.650	0.366	0.173	0.152	0.066	0.026	0.026	0.057	0.040	0.132

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

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

Exhibit A-146. Case 6P stream table (cont'd)

	11	12	13	14	15	16	17	18	19	20	21
V-L Mole Fraction											
Ar	0.0000	0.0000	0.0000	0.0094	0.0094	0.0094	0.0094	0.0077	0.0077	0.0077	0.0077
CH_4	0.0000	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	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	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	0.0000
CO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CO_2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002
H_2	0.8780	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	0.1220	0.0000	0.0000	0.0104	0.0104	0.0104	0.0104	0.0085	0.0085	0.0085	0.0085
N_2	0.0000	0.0000	0.0000	0.7722	0.7722	0.7722	0.7722	0.6335	0.6335	0.6335	0.6335
O_2	0.0000	0.0000	0.0000	0.2077	0.2077	0.2077	0.2077	0.3500	0.3500	0.3500	0.3500
Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate (kg_{mol}/h)	165	14,331	14,331	33,061	33,061	33,061	33,061	40,298	40,298	40,298	40,298
V-L Flowrate (kg/h)	654	28,892	28,892	953,941	953,941	953,941	953,941	1,185,520	1,185,520	1,185,520	1,185,520
Solids Flowrate (kg/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°C)	30	32	30	15	160	730	750	754	298	246	64
Pressure (MPa, abs)	2.65	2.64	6.48	0.10	0.81	0.80	0.80	0.80	0.80	0.79	0.10
Steam Table Enthalpy (kJ/kg)[A]	221.56	466.49	447.97	31.06	177.60	797.73	820.76	812.65	313.65	259.58	75.98
AspenPlus Enthalpy (kJ/kg)[B]	-8,784.39	109.42	90.90	-101.67	44.88	665.01	688.04	701.38	202.38	148.32	-35.29
Density (kg/m^3)	4.7	2.1	5.0	1.2	6.5	2.8	2.7	2.7	4.9	5.4	1.1
V-L Molecular Weight	3.968	2.016	2.016	28.854	28.854	28.854	28.854	29.419	29.419	29.419	29.419
V-L Flowrate (lb_{mol}/h)	363	31,594	31,594	72,886	72,886	72,886	72,886	88,841	88,841	88,841	88,841
V-L Flowrate (lb/h)	1,442	63,695	63,695	2,103,079	2,103,080	2,103,080	2,103,080	2,613,623	2,613,623	2,613,623	2,613,623
Solids Flowrate (lb/h)	0	0	0	0	0	0	0	0	0	0	0
Temperature (°F)	86	90	86	59	320	1,346	1,382	1,389	568	475	147
Pressure (psia)	385.0	383.3	939.7	14.7	117.3	116.5	116.0	115.8	115.6	115.1	14.7
Steam Table Enthalpy (Btu/lb)[A]	95.3	200.6	192.6	13.4	76.4	343.0	352.9	349.4	134.8	111.6	32.7
AspenPlus Enthalpy (Btu/lb)[B]	-3,776.6	47.0	39.1	-43.7	19.3	285.9	295.8	301.5	87.0	63.8	-15.2
Density (lb/ft^3)	0.292	0.129	0.314	0.076	0.404	0.173	0.169	0.171	0.308	0.337	0.066

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

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

Exhibit A-147. Case 6P plant performance summary

Performance Summary	
Total Gross Power, kWe	**60**
Electrolysis Load, MWe	**1,031**
Electric Boiler, kWe	226,744
Hydrogen Compression, kWe	30,245
Balance of Plant, kWe	108,760
Total Auxiliaries, MWe	**366**
Net Power, MWe	**-1,337**
Hydrogen Production, kg/h (lb/h)	**28,892 (63,695)**
Energy Efficiency,[A] % HHV (% LHV)	85.2 (72.0)
Electric Input per Kilogram, kWh/kg	46.3
Thermal Input per Kilogram, kWh/kg	0.0
Natural Gas Feed Flow, kg/h (lb/h)	0 (0)
Thermal Output, HHV kWt (LHV kWt)	1,138,813 (962,949)
Raw Water Withdrawal, m^3/min (gpm)	6.9 (1,814)
Raw Water Consumption, m^3/min (gpm)	5.8 (1,541)

[A]Energy Efficiency = Hydrogen Heating Value / (Fuel Heating Value + Electricity Input)

Exhibit A-148. Case 6P power summary

Power Summary	
Sweep Gas Expander, MWe	60
Total Gross Power, MWe	**60**
Auxiliary Load Summary	
Air Electrode Compressors, kWe	70,282
Circulating Water Pumps, kWe	500
Cooling Tower Fans, kWe	260
Electric Boiler, kWe	226,744
Electric Steam Superheater, kWe	21,582
Electric Sweep Heater, kWe	6,102
Feedwater Pumps, kWe	163
Fuel Electrode Recycle Blowers, kWe	0
Ground Water Pumps, kWe	160
Hydrogen Compressor, kWe	30,245
Miscellaneous Balance of Plant,[A] kWe	290
Transformer Losses, kWe	9,420
Total Auxiliaries, MWe	**366**
Solid Oxide Electrolysis, MWe	**1,031**
Net Power, MWe	**-1,337**

[A]Includes plant control systems, lighting, HVAC, and miscellaneous low voltage loads

Exhibit A-149. Case 6P carbon balance

Carbon In		Carbon Out	
	kg/h (lb/h)		kg/h (lb/h)
Air-Electrode Sweep Air (CO_2)	119 (263)	Air-Electrode Sweep Exhaust (CO_2)	119 (263)
Total	**119 (263)**	**Total**	**119 (263)**

Exhibit A-150. Case 6P 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)
Electrolysis Steam	5.0 (1,311)	–	5.0 (1,311)	–	5.0 (1,311)
Deaerator Vent	–	–	–	0.0 (3.1)	0.0 (-3.1)
Boiler Blowdown	–	–	–	0.6 (157)	-0.6 (-157)
Cooling Tower	1.9 (503)	–	1.9 (503)	0.4 (113)	1.5 (390)
Total	**6.9 (1,814)**	**–**	**6.9 (1,814)**	**1.0 (273)**	**5.8 (1,541)**

Exhibit A-151. Case 6P overall energy balance

	HHV	Sensible + Latent	Power	Total
Heat In, GJ/h (MMBtu/h)				
Air-Electrode Sweep Air	–	30 (28)	–	30 (28)
Raw Water Makeup	–	26 (24)	–	26 (24)
Auxiliary Power	–	–	4,814 (4,562)	4,814 (4,562)
Total	**0.0 (0.0)**	**55 (53)**	**4,814 (4,562)**	**4,869 (4,615)**
Heat Out, GJ/h (MMBtu/h)				
Hydrogen Product	4,100 (3,886)	13 (12)	–	4,113 (3,898)
Sweep Exhaust	–	90 (85)	–	90 (85)
Motor Losses and Design Allowances	–	13 (13)	–	13 (13)
Cooling Tower Load[A]	–	249 (236)	–	249 (236)
Boiler Blowdown	–	12 (12)	–	12 (12)
Process Vents[B]	–	0.5 (0.5)	–	0.5 (0.5)
Ambient Losses[C]	–	308 (292)	–	308 (292)
Total	**–**	**686 (651)**	**0.0 (0.0)**	**4,786 (4,537)**
Unaccounted Energy[D]	**–**	*83 (78)*	–	*83 (78)*

[A]Includes H_2 cooling, H_2 compressor intercoolers, and miscellaneous cooling loads
[B]Process vents include the deaerator vent and TSA purge
[C]Ambient losses include all losses to the environment through radiation, convection, etc. Sources of these losses include the transformers and rectifiers
[D]By difference

Exhibit A-152. Case 6P energy and mass balance

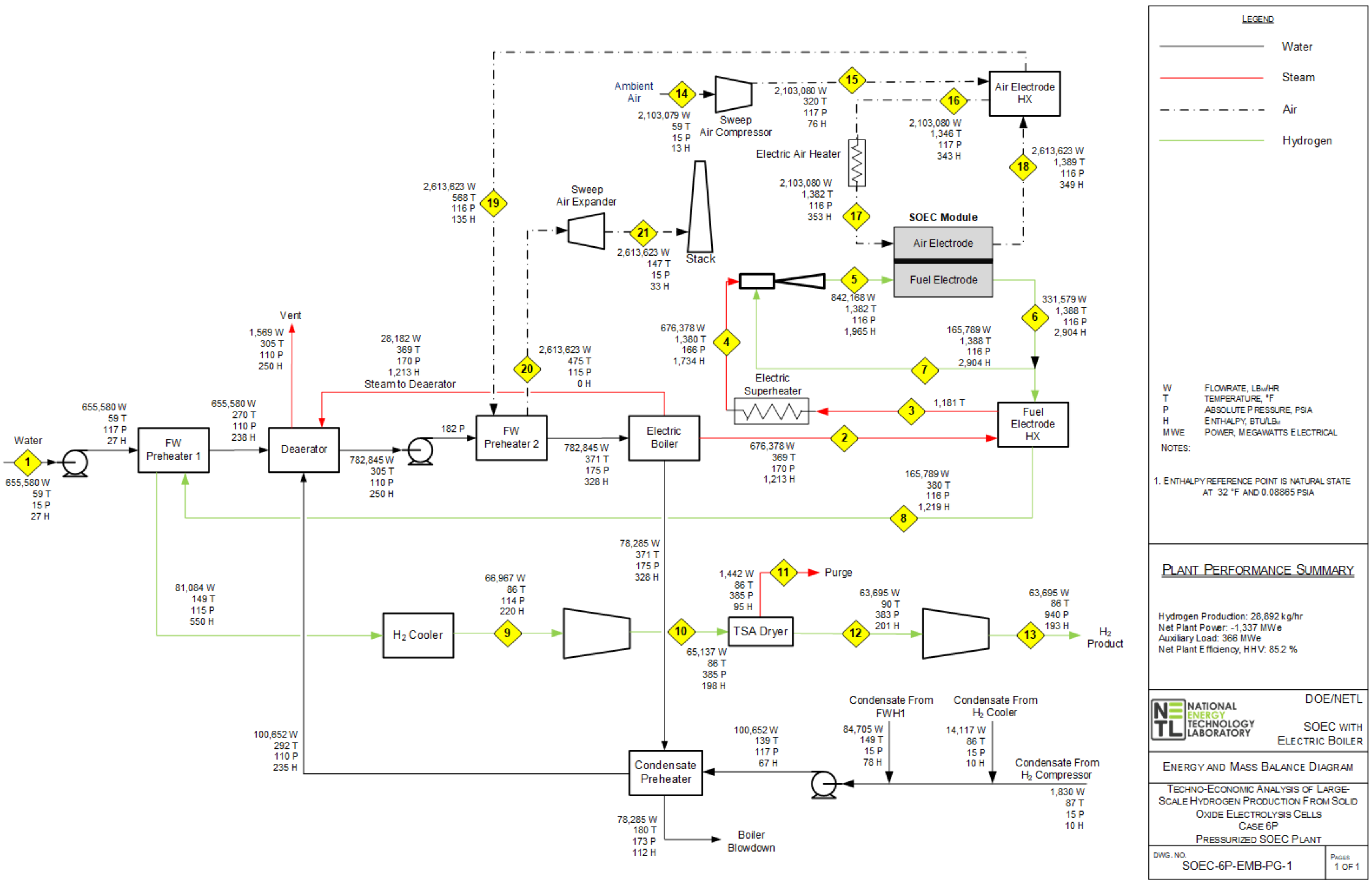


Exhibit A-153. Case 6P total plant cost details

	Case:	SOEC-EB-6P	Pathway Step 6 Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	693,400	Plant Size (MW net):			1,337			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 H_2/day]	$/kW (net)
1	SOEC Module											
1.1	SOEC Stack	$0	$0	$0	$0	$14,864	$2,973	$0	$2,675	$20,512	$30	$15
1.2	Container	$0	$0	$0	$0	$6,348	$1,270	$0	$1,143	$8,760	$13	$7
1.3	Insulation	$0	$0	$0	$0	$595	$119	$0	$107	$820	$1	$1
1.4	Module Assembly	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$2
1.5	Air Distribution	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$2
1.6	Fuel Distribution	$0	$0	$0	$0	$1,486	$297	$0	$268	$2,051	$3	$2
1.8	Module Current Collectors	$0	$0	$0	$0	$743	$149	$0	$134	$1,026	$1	$1
1.9	Module I&C	$0	$0	$0	$0	$743	$149	$0	$134	$1,026	$1	$1
1.10	Rectifier	$0	$0	$0	$0	$10,107	$2,021	$0	$1,819	$13,948	$20	$10
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$37,859**	**$7,572**	**$0**	**$6,815**	**$52,245**	**$75**	**$39**
2	SOEC Balance of Plant											
2.1	Air-Electrode Sweep Compressor	$0	$0	$0	$0	$7,775	$1,555	$0	$1,399	$10,729	$15	$8
2.2	Sweep Heat Exchanger	$0	$0	$0	$0	$21,943	$4,389	$0	$3,950	$30,281	$44	$23
2.3	Hydrogen Recycle Jet Pump	$0	$0	$0	$0	$474	$95	$0	$85	$655	$1	$0
2.4	Hydrogen Heat Exchanger	$0	$0	$0	$0	$19,169	$3,834	$0	$3,450	$26,453	$38	$20
2.5	Air, Exhaust, & Fuel Flow Piping	$0	$0	$0	$0	$855	$171	$0	$154	$1,180	$2	$1
2.6	Section and Overall Assembly	$0	$0	$0	$0	$428	$86	$0	$77	$590	$1	$0
2.7	Section I&C	$0	$0	$0	$0	$428	$86	$0	$77	$590	$1	$0
2.8	Sweep Gas Expander	$0	$0	$0	$0	$6,392	$1,278	$0	$1,151	$8,822	$13	$7
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$57,463**	**$11,493**	**$0**	**$10,343**	**$79,300**	**$114**	**$59**
3	Feedwater & Miscellaneous BOP Systems											
3.1	Feedwater System	$0	$0	$0	$0	$4,118	$824	$0	$741	$5,682	$8	$4
3.2	Water Makeup & Pretreating	$0	$0	$0	$0	$4,429	$886	$0	$1,063	$6,377	$9	$5
3.3	Other Feedwater Subsystems	$0	$0	$0	$0	$1,771	$354	$0	$319	$2,444	$4	$2
3.4	Service Water Systems	$0	$0	$0	$0	$9,086	$1,817	$0	$2,181	$13,084	$19	$10
3.5	Other Boiler Plant Systems	$0	$0	$0	$0	$984	$197	$0	$177	$1,358	$2	$1
3.7	Wastewater Treatment Equipment	$0	$0	$0	$0	$4,349	$870	$0	$1,044	$6,262	$9	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$24,736**	**$4,947**	**$0**	**$5,524**	**$35,208**	**$51**	**$26**
4	Electric Boiler, Hydrogen Production, and Miscellaneous Systems											
4.1	Feedwater Heaters	$0	$0	$0	$0	$464	$93	$0	$84	$641	$1	$0
4.2	Electric Boiler	$0	$0	$0	$0	$31,380	$6,276	$0	$5,648	$43,304	$62	$32
4.3	Electric Superheaters	$0	$0	$0	$0	$1,697	$339	$0	$306	$2,342	$3	$2
4.4	Electric Sweep Heaters	$0	$0	$0	$0	$662	$132	$0	$119	$913	$1	$1

	Case:	SOEC-EB-6P	Pathway Step 6 Pressurized SOEC						Estimate Type:	Conceptual		
	Plant Size (kg H_2/day):	693,400	Plant Size (MW net):			1,337			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 H_2/day]	$/kW (net)
4.5	Hydrogen Cooler	$0	$0	$0	$0	$140	$28	$0	$25	$193	$0	$0
4.6	Hydrogen TSA Dryer	$0	$0	$0	$0	$258	$52	$0	$47	$357	$1	$0
4.7	Hydrogen Compressor	$0	$0	$0	$0	$15,306	$3,061	$0	$2,755	$21,123	$30	$16
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$49,908**	**$9,982**	**$0**	**$8,983**	**$68,873**	**$99**	**$52**
7	Ductwork, & Stack											
7.3	Ductwork	$0	$0	$0	$0	$571	$114	$0	$103	$788	$1	$1
7.4	Stack	$0	$0	$0	$0	$3,819	$764	$0	$687	$5,270	$8	$4
7.5	Ductwork & Stack Foundations	$0	$0	$0	$0	$487	$97	$0	$117	$701	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,877**	**$975**	**$0**	**$907**	**$6,759**	**$10**	**$5**
9	Cooling Water System											
9.1	Cooling Towers	$0	$0	$0	$0	$2,945	$589	$0	$530	$4,064	$6	$3
9.2	Circulating Water Pumps	$0	$0	$0	$0	$323	$65	$0	$58	$446	$1	$0
9.3	Circulating Water System Auxiliaries	$0	$0	$0	$0	$3,927	$785	$0	$707	$5,419	$8	$4
9.4	Circulating Water Piping	$0	$0	$0	$0	$1,541	$308	$0	$277	$2,127	$3	$2
9.5	Make-up Water System	$0	$0	$0	$0	$570	$114	$0	$103	$787	$1	$1
9.6	Component Cooling Water System	$0	$0	$0	$0	$211	$42	$0	$38	$291	$0	$0
9.7	Circulating Water System Foundations	$0	$0	$0	$0	$498	$100	$0	$119	$717	$1	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$10,014**	**$2,003**	**$0**	**$1,832**	**$13,850**	**$20**	**$10**
11	Accessory Electric Plant											
11.2	Station Service Equipment	$0	$0	$0	$0	$11,442	$2,288	$0	$2,060	$15,790	$23	$12
11.3	Switchgear & Motor Control	$0	$0	$0	$0	$17,657	$3,531	$0	$3,178	$24,367	$35	$18
11.4	Conduit & Cable Tray	$0	$0	$0	$0	$14,115	$2,823	$0	$2,541	$19,478	$28	$15
11.5	Wire & Cable	$0	$0	$0	$0	$15,131	$3,026	$0	$2,724	$20,881	$30	$16
11.6	Protective Equipment	$0	$0	$0	$0	$1,144	$229	$0	$206	$1,578	$2	$1
11.7	Standby Equipment	$0	$0	$0	$0	$2,637	$527	$0	$475	$3,639	$5	$3
11.8	Main Power Transformers	$0	$0	$0	$0	$2,053	$411	$0	$370	$2,834	$4	$2
11.9	Electrical Foundations	$0	$0	$0	$0	$432	$86	$0	$104	$622	$1	$0
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$64,611**	**$12,922**	**$0**	**$11,656**	**$89,189**	**$129**	**$67**
12	Instrumentation & Control											
12.4	Other Major Component Control Equipment	$0	$0	$0	$0	$1,439	$288	$72	$259	$2,058	$3	$2
12.5	Signal Processing Equipment	$0	$0	$0	$0	$713	$143	$0	$128	$984	$1	$1
12.6	Control Boards, Panels & Racks	$0	$0	$0	$0	$312	$62	$16	$56	$446	$1	$0
12.7	Distributed Control System Equipment	$0	$0	$0	$0	$11,103	$2,221	$555	$1,999	$15,877	$23	$12

	Case:	SOEC-EB-6P	Pathway Step 6 Pressurized SOEC					Estimate Type:		Conceptual		
	Plant Size (kg H_2/day):	693,400	Plant Size (MW net):			1,337		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 H_2/day]	$/kW (net)
12.8	Instrument Wiring & Tubing	$0	$0	$0	$0	$4,447	$889	$222	$801	$6,360	$9	$5
12.9	Other Instrumentation & Controls Equipment	$0	$0	$0	$0	$2,043	$409	$102	$368	$2,921	$4	$2
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$20,057**	**$4,011**	**$967**	**$3,610**	**$28,646**	**$41**	**$21**
13						**Improvements to Site**						
13.1	Site Preparation	$0	$0	$0	$0	$16,713	$3,343	$0	$4,011	$24,067	$35	$18
13.2	Site Improvements	$0	$0	$0	$0	$5,613	$1,123	$0	$1,347	$8,083	$12	$6
13.3	Site Facilities	$0	$0	$0	$0	$4,755	$951	$0	$1,141	$6,847	$10	$5
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$27,082**	**$5,416**	**$0**	**$6,500**	**$38,997**	**$56**	**$29**
14						**Buildings & Structures**						
14.4	Administration Building	$0	$0	$0	$0	$759	$152	$0	$137	$1,047	$2	$1
14.5	Circulation Water Pumphouse	$0	$0	$0	$0	$20	$4	$0	$4	$27	$0	$0
14.6	Water Treatment Buildings	$0	$0	$0	$0	$435	$87	$0	$78	$600	$1	$0
14.7	Machine Shop	$0	$0	$0	$0	$1,117	$223	$0	$201	$1,541	$2	$1
14.8	Warehouse	$0	$0	$0	$0	$839	$168	$0	$151	$1,158	$2	$1
14.9	Other Buildings & Structures	$0	$0	$0	$0	$626	$125	$0	$113	$865	$1	$1
14.10	Waste Treating Building & Structures	$0	$0	$0	$0	$1,060	$212	$0	$191	$1,462	$2	$1
	Subtotal	**$0**	**$0**	**$0**	**$0**	**$4,856**	**$971**	**$0**	**$874**	**$6,701**	**$10**	**$5**
	Total	**$0**	**$0**	**$0**	**$0**	**$301,463**	**$60,293**	**$967**	**$57,045**	**$419,768**	**$605**	**$314**

Exhibit A-154. Case 6P owner's costs

Description	$/1,000	$/[kg H_2/day]	$/kW
Pre-Production Costs			
6 Months All Labor	$3,364	$5	$3
1 Month Maintenance Materials	$469	$1	$0
1 Month Non-Fuel Consumables	$181	$0	$0
1 Month Waste Disposal	$0	$0	$0
25% of 1 Months Fuel Cost at 100% CF	$0	$0	$0
2% of TPC	$8,395	$12	$6
Total	**$12,409**	**$18**	**$9**
Inventory Capital			
60-Day Supply of Fuel and Consumables at 100% CF	$211	$0	$0
0.5% of TPC (spare parts)	$2,099	$3	$2
Total	**$2,309**	**$3**	**$2**
Other Costs			
Initial Cost for Catalyst and Chemicals	$483	$1	$0
Land	$300	$0	$0
Other Owner's Costs	$62,965	$91	$47
Financing Costs	$11,334	$16	$8
Total Overnight Costs (TOC)	**$509,568**	**$735**	**$381**
TASC Multiplier (IOU, 35 year)	1.070		
Total As-Spent Cost (TASC)	**$545,137**	**$786**	**$408**

Exhibit A-155. Case 6P initial and annual O&M costs

Case:	SOEC-EB-6P		Pathway Step 6 Pressurized SOEC		Cost Base:		Dec 2018
Plant Size (kg H_2/day):	**693,400**	**Plant Size (MW net):**		**1,337**	**Capacity Factor (%):**		**95%**
Operating & Maintenance Labor							
Operating Labor				**Operating Labor Requirements per Shift**			
Operating Labor Rate (base):		38.50	**$/hour**	Skilled Operator:			1.0
Operating Labor Burden:		30.00	**% of base**	Operator:			2.0
Labor O-H Charge Rate:		25.00	**% of labor**	Foreman:			1.0
				Lab Techs, etc.:			1.0
				Total:			**5.0**
Fixed Operating Costs							
					Annual Cost		
					($)	**($/[kg H_2/day])**	**($/kW-net)**
Annual Operating Labor:					$2,192,190	$3.162	$1.639
Maintenance Labor:					$3,190,236	$4.601	$2.386
Administrative & Support Labor:					$1,345,606	$1.941	$1.006
Property Taxes and Insurance:					$8,395,358	$12.108	$6.279
Total:					**$15,123,390**	**$21.810**	**$11.310**
Variable Operating Costs							
					($)	**($/kg H_2)**	**($/MWh-net)**
Maintenance Material:					$5,348,337	$0.02224	$0.48064
Stack Replacement							
	Life (yr)		**$/kW$_{AC}$**	**$/yr per kW**			
SOEC Stack Replacement Cost:		9.34	14.77	$1.49	$1,785,251	$0.00743	$0.16044
Consumables							
	Initial Fill	**Per Day**	**Per Unit**	**Initial Fill**			
Water (gallon/1000):	0	1,306	$1.90	$0	$860,534	$0.00358	$0.07733
Makeup and Wastewater Treatment Chemicals (ton):	0	3.89	$550	$0	$742,039	$0.00309	$0.06668
Hydrogen Drying Sorbent (lb):	48,278	132.3	$10	$482,782	$458,643	$0.00191	$0.04122
Subtotal:				**$482,782**	**$2,061,216**	**$0.00857**	**$0.18524**
Waste Disposal							
Hydrogen Drying Sorbent (lb):	0	132.3	$0.02	$0	$871	$0.00000	$0.00008
Subtotal:				**$0**	**$871**	$0.00000	**$0.00008**
Variable Operating Costs Total:				**$482,782**	**$9,195,676**	**$0.03082**	**$0.66595**
Electricity Cost							
Electricity (MWh):	0	32,091	$60.00	$0	$667,652,688	$2.77684	$60.00000
Total:				**$0**	**$667,652,688**	**$2.77684**	**$60.00000**

Exhibit A-156. Case 6P LCOH breakdown

Component	LCOH, $/kg H_2	Percentage
Capital	0.13	4%
Fixed	0.06	2%
Variable	0.04	1%
Electricity	2.78	92%
Total	**3.01**	**N/A**

www.netl.doe.gov

Albany, OR • Anchorage, AK • Morgantown, WV • Pittsburgh, PA • Sugar Land, TX

(800) 553-7681

NATIONAL ENERGY TECHNOLOGY LABORATORY